Journal of Food Engineering 370 (2024) 111974

Contents lists available at ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

Ohmic cooking of carrots: Limitations in the use of power input and cooking value for process characterization

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ARTICLE INFO

Keywords:
Carrot
Ohmic heating
Texture
Cooking value
Power input

ABSTRACT

Ohmic cooking is considered a fast and homogeneous process. However, achieving heating uniformity depends on several process parameters and intrinsic product characteristics. Furthermore, reference indicators for evaluating the ohmic process and generating reliable comparisons with conventional cooking are still lacking. The objective of this study was to investigate the reliability of the use of power input and cooking value as process indicators. The results showed that the specific ohmic power did affect only the heating rate but not the heating uniformity and the tissue softening rate. Therefore, the power input as process acceleration tool is not sufficient as stand-alone process indicator because other critical parameters (i.e., electrical conductivity) need to be taken into account to display the complex product-process-interactions. The cooking value was proven to be not valid as indicator for ohmic heating, as it does not take into account additional effects not attributable to only thermal exposure.

1. Introduction

Over the last few years, there has been increasing interest in the application of technologies for rapid and uniform heating of foods. Heat transfer in conventional systems by conduction and convection is very slow and leads to high quality losses due to overheating of the surface of the product. This is particularly relevant when heating large solid products where conventional heating generates large temperature differences between the center (cold zone) and the periphery (hot zone). Therefore, in order for the center to reach the required temperature, the surface of the food must be over-treated, which negatively affects its sensory and nutritional quality (Xiao et al., 2017). Thus, ohmic heating (OH) is a suitable alternative to conventional systems as it has two main advantages: fast heating rates and higher temperature uniformity. This type of heating is based on the direct conversion of electrical energy into thermal energy by the Joule effect (Sastry and Li, 1996).

Vegetables such as carrots are an important source of vitamins, phytochemicals, fibers and minerals (Singh et al., 2021). However, consumers often apply culinary treatments such as cooking for their consumption, which in many cases involve long processing times and high temperatures (Suleman et al., 2020). Therefore, appropriate processing or cooking treatments are a significant contribution to improve the sensory and nutritional qualities of food. Texture is one of the sensory properties most affected by heat treatment of vegetables. Thermal treatments induce changes in the structure and composition of pectins that cause cell membrane rupture and cell wall degradation (Anthon et al., 2005). Several studies have observed that thermal degradation of carrot texture occurs in two stages: a rapid softening followed by a much slower rate of softening (Peng et al., 2014). In the processing of vegetables, depending on the thermal process, a greater or lesser degree of softening will be of interest. For instance, for blanching vegetables, treatments that cause the minimum effect on the texture are sought, while for cooking vegetables, a high degree of softening is desired. Therefore, it will be important to optimize the heat treatment applied to achieve the desired effect. Currently, there is a need to optimize the ohmic cooking process of vegetables, namely frequency, voltage, and temperature, in order to provide the maximum quality of each food product with the best sensory perception.

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https://doi.org/10.1016/j.jfoodeng.2024.111974
Received 30 August 2023; Received in revised form 19 January 2024; Accepted 20 January 2024

The effect of OH on the texture of vegetables has not been fully clarified, as there are studies in which increased softening was observed (Farahnaky et al., 2012) or studies in which no effect on texture was reported (Astráin-Redín et al., 2023). In addition, some research reports that the greater softening produced by OH is due to the electroporation caused in the cytoplasmic membrane of the plant cells when they are exposed to an external electric field (Lebovka et al., 2005a). However, the applied electric fields are not intense enough for the electroporation of plant cells (Ben Ammar et al., 2011) which makes it a very controversial issue that is still unresolved. In fact, the electroporation effect has not been completely demonstrated in OH treatments since it is difficult to discriminate between merely thermal and additional electrical effects (Schottroff and Jaeger, 2021).

In addition, there are still open challenges related to the cooking of vegetables by OH as they represent food raw materials with inhomogeneous tissue properties (e.g. cell size or electrical conductivity). Moreover, the lack of suitable process indicators for OH represents the main limitation for the development of validation concepts and the characterization of product-process interactions, especially in comparison to conventional thermal reference processes. In fact, chemical and physical changes in the product can be caused by the OH process and corresponding indicators are still not available but strongly needed for process optimization and tailored process design for targeted vegetable processing. Moreover, processing parameters such as pulse frequency, power input and electric field strength have not been thoroughly studied for ohmic cooking yet and could have a considerable impact on both the uniformity and the heating rate and on the sensory and nutritional quality of the food.

Therefore, the aim of this article was to investigate the use of specific power input and cooking-value (c-value) as tools for evaluation of product-process interactions and for comparison with conventional cooking, respectively. The aim was achieved by analyzing the effect of the application of different specific power inputs on texture and tissue damage of carrots and finally, comparing an optimized ohmic cooking process with a conventional boiling in terms of physical properties and power consumption.

2. Materials and methods

2.1. Raw material

Commercially available carrots (*Daucus carota* L. var. Nantes) were purchased at local (Vienna, Austria) supermarket. Peeled carrots of 40 mm diameter were selected and cylinders of 3 cm × 3 cm (length x diameter) were cut with a stainless-steel punch to perform the experiments. Only non-damaged carrots with similar sizes and similar external appearance were selected. To ensure a uniform ripening level, physicochemical analyses such as total soluble solids (8.4 ± 0.1 °Brix), pH (6.42 ± 0.04) and moisture content (89.5 ± 0.2 %) were assessed for carrots randomly selected from each batch. The carrot root consists of two distinct layers: a central stele and a peripheral cortex. The central stele is composed of three different cell tissues (Fig. 1): parenchyma (1), xylem vessels (2), outer cells of the vascular tissue and phloem vessels (3) (Voda et al., 2012). Fig. 1 shows the areas that constitute the central and outer parts used in the experiments of this article. The purchased carrots were stored at 4 °C until cutting.

2.2. Measurement of electrical conductivity

The electrical conductivity of the saline solution was measured using a hand-held conductivity meter (EL3 portable conductivity meter, Mettler Toledo, Columbus, Ohio, USA).

Electrical conductivity of the carrot samples was determined using an indirect method. For this, a self-built OH device was used. It is composed of an arbitrary function generator AFG-3021 (GW INSTEK, Taiwan) and two amplifiers (Töllner, New York) which allow to apply a maxmimum voltage amplitude of 200 V_{pp} (100 V_{RMS}) and power of 640 W and a multimeter Data Acquisition System Model DAQ6510 (Keithley, England). Oltage pulses with a square wave geometry at 80 V_{pp} was applied in order to avoid any OH effect. The conductance of the sample was measured at 12 kHz during heating up to 110 °C. Measurements were taken every 4 s. The equation used to calculate the electrical conductivity (S/m) was as follows (Olivera et al., 2013):

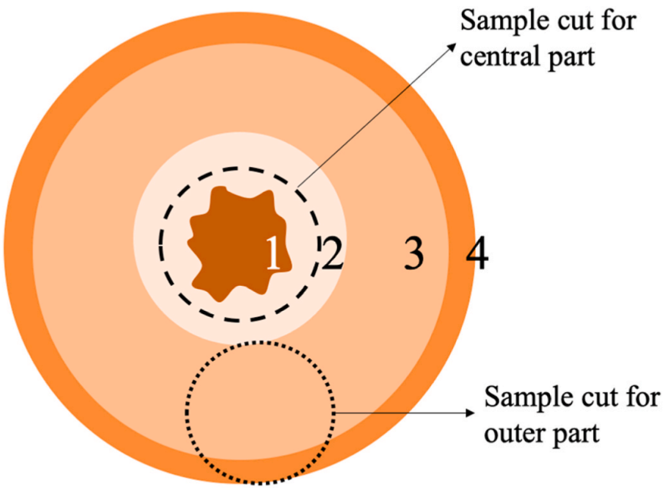

Fig. 1. Schematic representation of the four tissue regions of a carrot: 1- parenchyma; 2- xylem vessels; 3- outer cells of the vascular tissue and phloem vessels, and 4- cortex tissue. The circles with dashed lines indicate the areas from which samples were taken for analysis.

$$\boldsymbol{\sigma} = \frac{\mathbf{I} \times \mathbf{L}}{\mathbf{A} \times \mathbf{V}} \tag{1}$$

where I is the intensity of the current (A), V is the voltage (V), L is the gap between the electrodes (m), and A is the surface area of the electrodes (m^2).

The electrical conductivity of both the core and the outer part of the carrot was determined (Fig. 1) based on the previous equation. For this, the treatment chamber chosen was cylindrical with parallel electrodes of 1.5 cm in length and 1 cm in diameter. At least 3 replicates of each sample was conducted.

2.3. Heating trials

OH was conducted using a pilot scale generator (German Institute of Food Technologies e.V. DIL, Quakenbruck, Germany) which was built to apply constant power during treatment. This device applied bipolar rectangular pulses with a repetition rate of 12 kHz and peak voltage of either 500 V and 1000 V. The pulse width was automatically adjusted by the generator in the range of 10–40 μs to apply a constant power while keeping the peak voltage constant. Voltage and current applied to the treatment chamber were monitored using a high voltage probe (Tektronix P6015A, Beaverton, USA) and a current transformer (model no. 0.5–0.1 W, Stangenes Industries Inc., Palo Alto, CA, USA) connected to a 2-channel digital oscilloscope (Tektronix TBS 1102B-EDU, Beaverton, USA).

The three different power levels were selected according to Gratz et al. (2021a) and automatically adjusted by the OH generator by keeping the voltage level constant at 488 V and modulating the pulse width according to changes in the current flow intensity. Three different power levels were applied: 1, 1.5 and 2 kW/kg. The power levels reflect the amount of power delivered to the entire content in the treatment chamber (carrots and saline solution). The treatment chamber used was a rectangular stainless steel parallel electrode chamber of 24 × 12 × 9 cm with an electrode gap of 9 cm. Hence, the applied electric field strength was 54.2 V/cm. For the treatments, 5 carrot samples were placed inside the treatment chamber and filled with aqueous NaCl solutions (saline solutions) at different electrical conductivities (0.5, 0.8 and 1.0 mS/cm) up to a final weight of 1.5 kg. The electrical conductivity of 0.8 mS/cm was selected to match the conductivity of the carrot tissue determined at 20 °C. To obtain the different conductivities, 140 mg/L (0.5 mS/cm), 210 mg/L (0.8 mS/cm) and 300 mg/L (1.0 mS/cm) of NaCl were added to tap water (initial conductivity = 0.323 mS/cm). The samples were placed in a row in order not to obstruct the flow of current between them (Fig. 2). The carrot samples were placed on a grid inside the chamber to be in contact with the saline solution over their entire surface without contact to the bottom of the treatment chamber to avoid inconsistent conditions. After cooking, the samples were immediately placed in ice water until their temperature was reduced to 10 ± 2 °C. At least 3 replicates of each ohmic power were performed and 5 samples of carrots were heated in each replicate. For conventional cooking, a pot with water boiling at 100 °C was used and the same ratio of carrots/saline medium (1:12.5) as for ohmic cooking was used. Subsequently, the physical analyses were carried out.

2.4. Temperature measurement

The initial temperature of the samples and the saline solution was 20 ± 2 °C. During the cooking treatments, the temperature of the sample was recorded in different locations, in the geometric centre (T_1) and in the outer part (T_2) as well as in the saline medium (T_3) (Fig. 2). In order to avoid interference of the electric field on the temperature measurement, PFA (Perfluoroalkoxy alkane)-coated K-type thermocouples (model no. HSTC-TT-KI, Omega Engineering, Inc., Norwalk, CT, USA) connected to a USB data logger (USB–TC, Measurement Computing, Inc., Norton, MA, USA) were used. Temperature values were recorded every second using LabVIEW Full software (Na-tional Instruments, Inc., Austin, TX, USA). To ensure comparability, the same temperature measurement setup was used for the OH and the conventional cooking experiments.

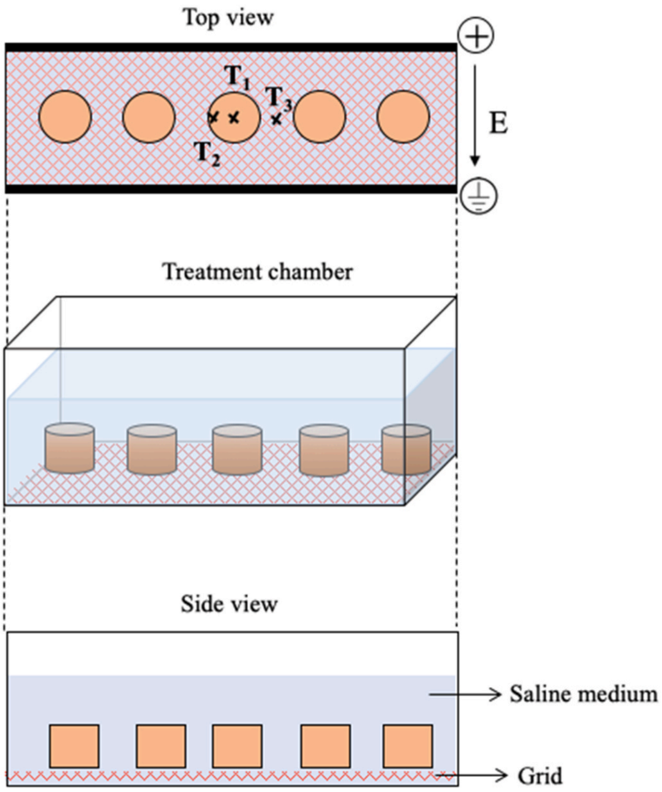

Fig. 2. Scheme of the experimental OH setup and thermocouples positioning (T_1, T_2, T_3).

2.5. Texture analyses

Textural properties of raw and cooked carrots were determined using a TA.XTplus Texture Analyzer (Stable Micro Systems Ltd., Surrey, UK). To characterize the cylinders, a puncture test were carried out in both inner and outer part of the carrot cylinders. 2 mm diameter punch probe with a flat end was employed. Test speed was set to 2 mm/s and 5 kg and 50 kg load cells were used depending on the degree of cooking of the samples. Each cilinder was puntured up to a distance of 10 mm. The hardness of the samples was calculated from the force-distance curves and 5 replicates of each sample were made.

In the present study, in order to compared among treatments, the rate of texture softening was determined by the first order reaction constant k [1/min] according to Equation (2) (Nisha et al., 2006):

$$\mathbf{ln}\left(\frac{\mathbf{H_x}}{\mathbf{H_{x0}}}\right) = -\,\mathbf{kt} \tag{2}$$

where t is the treatment time (min), H_x (N x sec) is the hardness at time t, H_{x0} (N x sec) is the hardness of raw sample.

The texture degradation (k) was also determined as a function of the specific energy input (kJ/kg), for which Equation (2) was adapted as follows:

$$\mathbf{ln}\left(\frac{\mathbf{H_x}}{\mathbf{H_{x0}}}\right) = -\,\mathbf{kE} \tag{3}$$

where E is the specific energy input (kJ/kg), H_x (N x sec) is the hardness at energy input E, H_{x0} (N x sec) is the hardness of raw sample.

2.6. Determination of cell disintegration index (Z_p)

Tissue damage of carrot samples was determined by measuring the cell disintegration index (Z_p) which indicates the proportion of permeabilized cells based on the frequency dependence of the electrical conductivity of intact as well as permeabilized plant tissues (Equation (4)) (Angersbach et al., 1999).

$$\mathbf{Z_p = 1 - \left(\frac{K_h}{K'_h}\right) \bullet \frac{(K'_h - K'_l)}{K_h - K_l}\ ;0 \leq Z_p \leq 1} \tag{4}$$

where K_l, K'_l are the electrical conductivities of untreated and treated material, respectively, in a low-frequency field (1–5 kHz), and K_h, K'_h are the electrical conductivities of untreated and treated material, respectively, in a high-frequency field (3–50 MHz).

The electrical conductivity was measured with an impedance measurement device (Impedance Analyser, Sigma Check, Germany). The frequency was in the range of 1.4 kHz–11.2 MHz. The samples were obtained by cutting a cylindrical shape (diameter 1.0 cm, length 1.0 cm) from the core and the outer part of the carrots. The Z_p value varies between 0 for intact tissues and 1 for a tissue with all the cells permeabilized. At least 10 repetitions were conducted for both raw and cooked samples.

2.7. Determination of the cooking degree by calcutating the c-value

In order to be able to compare among the different ohmic power levels and the conventional cooking, the c-value (min) was determined for each treatment. This parameter indicates the cooking degree considering a comparable impact of temperature and time on a resulting parameter, in this case tissue softening. For the determination, the temperature-time curves were taken for both the outer and the central part of the carrot samples. The following equation was used (Tucker and Featherstone, 2010):

$$\mathbf{c-value} = \int_0^t \mathbf{10}^{\left(\frac{T-T_{ref}}{z}\right)} dt \tag{5}$$

where t is the treatment time (min), T is the temperature (°C), T_{ref} is was set at 100 °C and z applied was 31.6 °C (Mittal, 1994). The z-value corresponds to the temperature change that induces a 10-fold change of the c-value.

2.8. Statistical analyses

GraphPad PRISM software was used for statistical analyses (one-way ANOVA with Tukey post-test and Student *t*-test) ($p = 0.05$). Error bars in the figures correspond to the mean standard deviation.

3. Results and discussion

3.1. The electrical conductivity of carrots at different temperatures

The electrical conductivity of food is one of the most relevant properties for the application of OH, which depends on the temperature, frequency and food composition (Zareifard et al., 2014). In this study, as the OH was applied at 12 kHz, the electrical conductivity was measured at the same frequency. On the other hand, solid foods like vegetables are composed of different tissue structures with different components, which means that the electrical properties may vary from one part to another. Fig. 3 shows the influence of temperature on the electrical conductivity of both the core and outer part of the carrot and the saline solution (initial electrical conductivity of 0.8 mS/cm) in which the samples were immersed during cooking.

As expected, as the temperature increases, the electrical conductivity of both matrices (carrot and treatment medium) increased due to the higher ionic mobility (Parrott, 1992). In liquid products, the relationship between electrical conductivity and temperature is linear, as it was the case of the saline solution in Fig. 3. However, the behavior is quite different in vegetables, where usually a biphasic relationship/kinetic is found (Gratz et al., 2021a). Thus, there is a first phase in which the electrical conductivity hardly rises with increasing temperature, but once 60–70 °C is reached, a sharp increase occurs, as also shown in Fig. 3. This biphasic kinetics of temperature-dependent increase in electrical conductivity in solid foods has been observed in carrots and other vegetables such as potato (Gratz et al., 2021a). This is believed to be due to cell rupture and alterations in membrane permeability, which would favor the release of intracellular ionic compounds and, therefore would increase the total conductivity of the tissue (Zareifard et al., 2014).

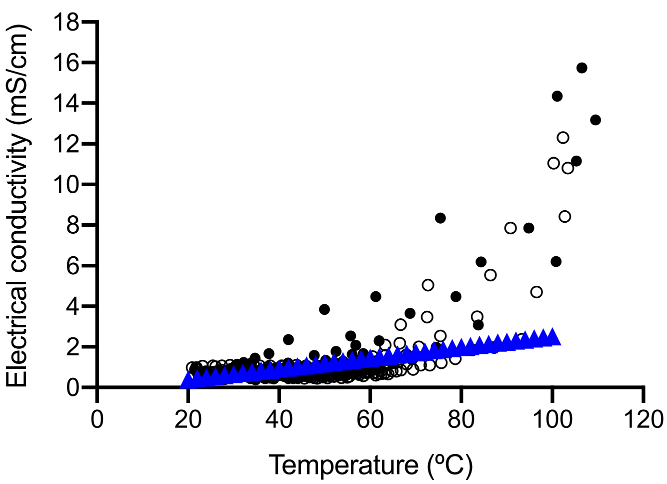

Fig. 3. Changes **in the electrical conductivity of** carrot cylinders taken from the core (●), outer part (○) during OH heating. The figure also includes the electrical conductivity of the saline medium in which the carrot cylinders were heated/immersed (▲).

Although at the beginning of cooking the electrical conductivity of both carrot and saline medium matched, the difference between the two was very significant when 100 °C were reached. This means that at 100 °C the conductivities of the center and the outer part of the carrot and the saline medium were 11.84 ± 3.59 mS/cm, 8.16 ± 3.03 mS/cm and 2.50 ± 0.01 mS/cm, respectively. In the next section, the potential of changing the initial electrical conductivity of the saline medium as a way to achieve a more uniform heating (both of different parts of the carrot and as compared to the medium) will be discussed.

When analyzing the behavior of the core and outer part of the carrot (Fig. 3), it can be observed that the increase in electrical conductivity of the inner part of the carrot as temperature increased tended to be higher than that of the outer part, but the differences were not statistically significant ($p < 0.05$). Thus, at room temperature (20 °C) the electrical conductivity of the central and external part was 0.82 ± 0.06 and 0.77 ± 0.18 mS/cm, while at 80 °C the conductivities were 6.20 ± 3.31 mS/cm and 3.30 ± 1.54 mS/cm, respectively. There are hardly any studies where the electrical conductivity of both parts of the carrot are analyzed. Although they cannot be directly compared to our results, Moens et al. (2020) measured the electrical conductivity of carrot puree obtained from the central zone (vascular) and the external zone (cortex). The results showed that the central zone had a higher electrical conductivity (23.2 mS/cm) than the outer zone (19.0 mS/cm) indicating a greater presence of ionic compounds in the central zone of the carrot.

Literature values for the electrical conductivity of intact carrots ranged from 0.03 to 0.27 mS/cm measured by platinum dual-needle probe connected to an EC meter (Wiktor et al., 2016), and 1.3 mS/cm measured indirectly by current intensity and voltage values (Palaniappan and Sastry, 1991). The values obtained in this study (0.77–0.82 mS/cm) are in the range of those reported in the literature.

3.2. Influence of power input and electrical conductivity of the saline medium on heating uniformity

One of the advantages of OH over conventional cooking is the improvement of heating uniformity. Fig. 4 shows the heating of carrots by the conventional system in which the temperature heterogeneity between the core and the outer part is significantly high (>10 °C). For

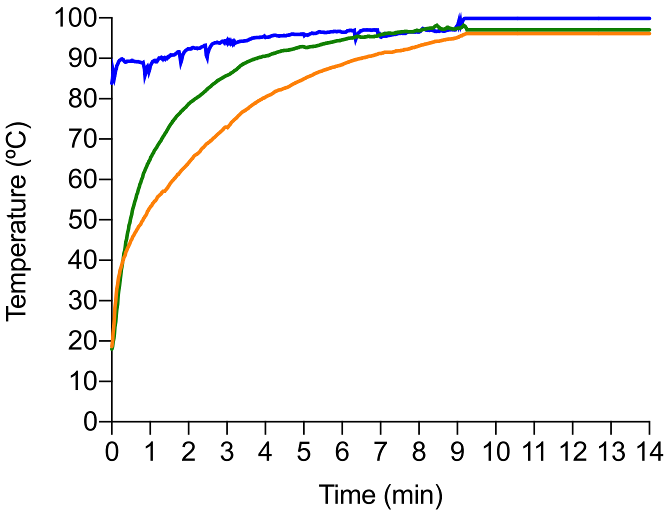

Fig. 4. Heating curves of carrot cylinders immersed in water at 100 °C. The temperature was measured in the core (orange line) and outer part (green line) of the carrot and in the water (blue line). The data points shown in the figure are mean values (n = 4). The coefficient of variation (CV) is <3 % for all the data points.

instance, when the outer part of the carrot reached 90 °C, the core was still at 79 °C. When applying OH, it was possible to reduce this temperature gradient and to achieve a uniform cooking rate of the core and the outer part of the carrot. However, the electrical conductivity of the saline medium and the applied ohmic power have an impact on the heating rate.

Fig. 5 shows the heating curves of the carrot (core and outer part) and of the aqueous NaCl solution (different conductivities: 0.5, 0.8 and 1 mS/cm) when three different powers (1, 1.5 and 2 kW/kg) were applied. In the previous section, an initial electrical conductivity of 0.82 ± 0.06 and 0.77 ± 0.18 mS/cm was determined for the core and the outer part of carrots, respectively. That is the reason why the initial conductivities of the saline medium used were in the range of 0.5–1 mS/cm. As can be observed in Fig. 5, regardless of the applied power, the saline medium with an electrical conductivity of 0.5 mS/cm allowed the most uniform heating to be applied. To reach 80 °C in all components at 0.5 mS/cm (Fig. 5a–d, g), 5.5 ± 0.5 min, 3.5 ± 0.1 min and 2.7 ± 0.2 min were needed when applying powers of 1, 1.5 and 2 kw/kg, respectively. In contrast, when 80 °C were reached in the saline medium of 1 mS/cm (Fig. 5c–f, i), the core of the carrot had 68 °C at 1 kW/kg, 60 °C at 1.5 kW/kg and 62 °C at 2 kW/kg. Thus, the heating in these cases was not homogenous, leading to temperature gradients of up to 20 °C. In this case, the mismatch of electrical conductivities between the carrot and the saline medium resulted in a higher heating rate of the saline medium and therefore, some of the heating of the outer part of the carrot was due to conventional heat transfer mechanisms. However, in order to achieve volumetric heating effects and uniform heating rates throughout during OH of the sample, the adjustment of the electrical conductivity of the saline medium is essential.

To analyze the heating curves from Fig. 5 in more detail, the heating rates of all the components were calculated for all the heating conditions studied. The values obtained are shown in Table 1. As mentioned above at 0.5 mS/cm the heating was more uniform with heating rates of 12.73, 12.29 and 12.00 °C/min for 1 kW/kg, 18.34, 18.65 and 18.06 for 1.5 kW/kg and 24.56, 23.94 and 24.48 C/min for 2 kW/kg, for the core and outer part of the carrot and the saline medium, respectively.

As expected, increasing the ohmic power also increased the heating rate i.e. for an electrical conductivity of the saline medium of 0.5 mS/cm the heating rates at 1, 1.5 and 2 kW/kg were: in the center of the carrots: 12.73, 18.34 and 24.56 °C/min; in the outer part of the carrots: 12.29, 18.65 and 23.94 °C/min and in the saline medium: 12.00, 18.06 and 24.48 °C/min, respectively. Regarding the heating uniformity, it was not improved by increasing the power. When OH was applied under conditions in which the electrical conductivity of the medium and the food were optimized, increasing the power did not affect the heating uniformity (heating results with 0.5 mS/cm). On the other hand, when the conditions were not optimized and the electrical conductivity of the medium was higher than those of the food, as was the case at 1 mS/cm, increasing the potential increases the temperature heterogeneity. Gratz et al. (2021a) evaluated different power (1–5 kW/kg) for heating potato at 12 kHz and observed 2.1-fold increases in heating rate when applying 1 and 2 kW/kg (rates of 9 and 19.2 °C/min, respectively). However, the influence of power on heating uniformity was not studied. Indeed, in the literature, there are scarce studies concerning the assessment of power in the uniformity of ohmic heating of vegetables.

Although it is known that OH technology generates volumetric heating, the electrical conductivity of the saline solution must be carefully selected, otherwise, cold or hot spots could be generated in the center or at the surface of solid food. Gratz et al. (2021a) applied OH (333 V/cm, 1 kW/kg and 12 kHz) on potato cubes and determined an

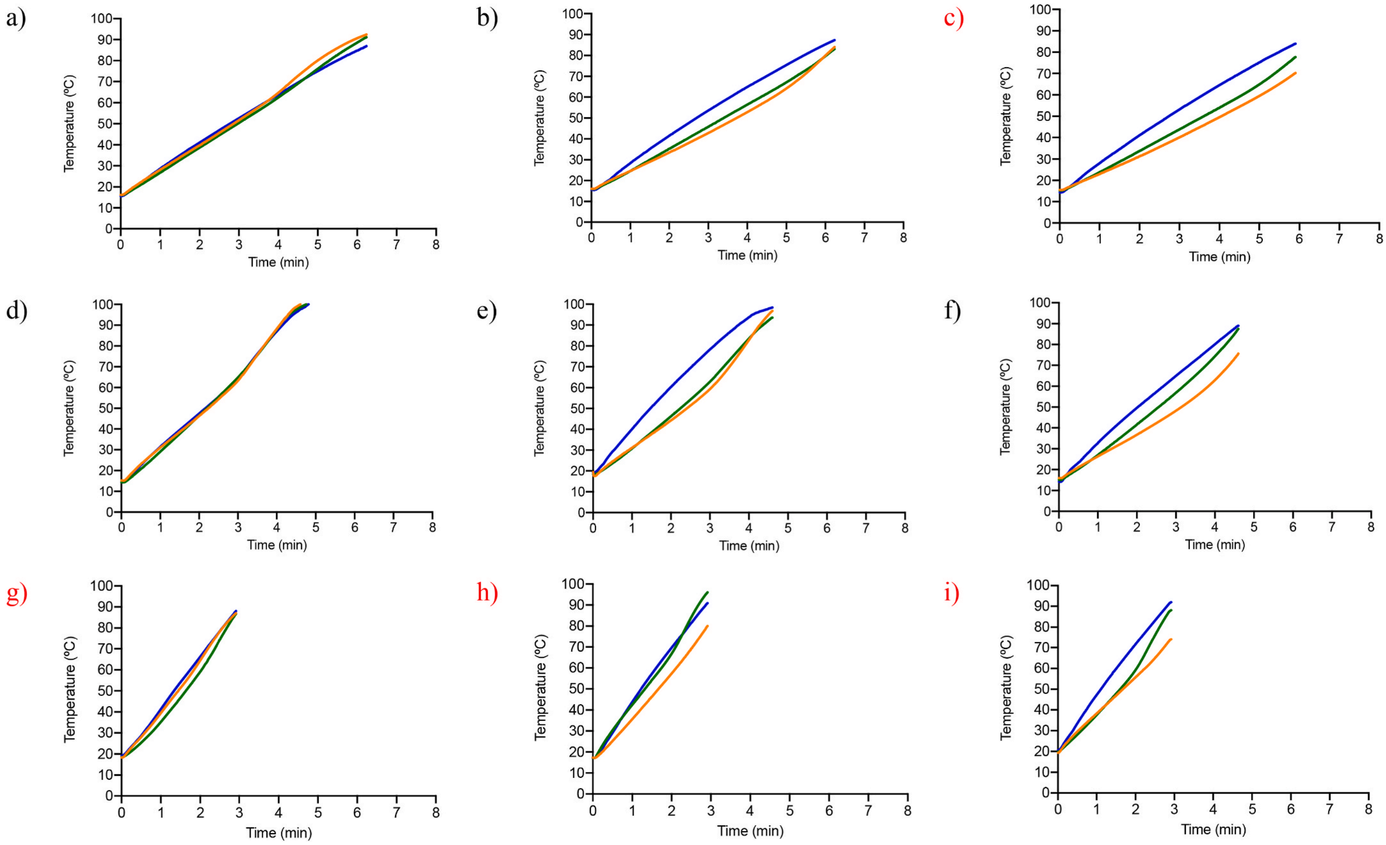

Fig. 5. Heating curves of carrot cylinders immersed in NaCl aqueous solution at different conductivities: 0.5 mS/cm (a, d, g), 0.8 mS/cm (b, e, h), 1.0 mS/cm (c, f, i) when different specific power inputs were applied: 1 kW/kg (a, b, c), 1.5 kW/kg (d, e, f), 2 kW/kg (g, h, i). The temperature was measured in the core (orange line) and outer part (green line) of the carrot and in the saline medium (blue line). The data points shown in the figure are mean values (n = 4). The coefficient of variation (CV) is <3 % for all the data points.

Table 1
Heating rates (°C/min) of carrot cylinders immersed in saline solutions when different ohmic heating treatments were applied.

	Specific power input (kW/kg)								
	1			1.5			2		
	Initial electrical conductivity of saline medium (mS/cm at 20 °C)								
	0.5	0.8	1	0.5	0.8	1	0.5	0.8	1
Core	12.73 ± 0.04	10.36 ± 0.06	9.18 ± 0.06	18.34 ± 0.08	16.66 ± 0.12	12.17 ± 0.11	24.56 ± 0.22	21.81 ± 0.22	18.09 ± 0.29
Outer part	12.29 ± 0.02	10.7 ± 0.03	10.40 ± 0.04	18.6 ± 0.06	16.93 ± 0.19	15.54 ± 0.08	23.94 ± 0.16	26.72 ± 0.12	23.43 ± 0.19
Saline Medium	12.00 ± 0.00	12.00 ± 0.00	12.00 ± 0.00	18.06 ± 0.08	18.11 ± 0.13	16.13 ± 0.06	24.48 ± 0.05	26.06 ± 0.06	24.91 ± 0.07

electrical conductivity at 11 kHz of 3.65 mS/cm and 2.60 mS/cm for the central and external part of the sample. Based on these results, it was observed that the most uniform heating was achieved at 2.5 mS/cm for both the core and the outer part of the potato. Moreover, Astráin-Redín et al. (2023) applied OH at 1.5 kV/cm and 100 Hz on carrots and reported that carrots heated up faster than the saline medium for conductivities below 6 mS/cm. Therefore, the influence of the conductivity of the saline medium has a higher impact in respect to the applied power in order to achieve uniform heating.

Considering all the above, under the conditions evaluated in this study, the most uniform carrot heating was achieved by using a treatment medium with an initial electrical conductivity of 0.5 mS/cm. Therefore, the rest of the studies were carried out using aqueous NaCl solutions with this electrical conductivity.

3.3. Impact of ohmic power on carrot texture

After the evaluation of the corresponding electrical conductivity of the saline medium and the carrot samples at 12 kHz, the impact of the different ohmic power levels on the texture of carrot cylinders during ohmic cooking was analyzed (Fig. 6). As can be seen, the kinetics of the thermal degradation of the texture was similar to that reported in the literature, which described two first-order kinetics running consecutively (Rahardjo and Sastry, 1993). In the first phase, a rapid softening occurred, while in the second phase, the softening rate slowly decreased until a minimum value. Table 2 shows the softening rates of the first phase expressed as a function of treatment time and as a function of the specific energy input.

The hardness of raw carrots was higher in the core (342.36 ± 19.16 N x sec) than on the outer part (293.30 ± 3.01 N x sec). This difference in hardness depending on the carrot tissue had already been described in the literature (Moens et al., 2020). As the initial hardness of the different parts of the carrots was different, they were analyzed separately to determine whether the impact of OH was similar in each part or whether one of them was more sensitive to heat. In addition, the data have been plotted both against treatment time (Fig. 6a and **c**) and against specific energy input (Fig. 6b and **d**).

As can be seen in Fig. 6a (core part) and Fig. 6c (outer part), when applying higher power levels, the softening of the carrot was faster over the treatment time. For 1. 1.5 and 2 kW/kg the softening rates were 0.273, 0.890, 1.198 min^{-1} and 0.601, 0.724, 1.096 min^{-1} for the core and the outer part, respectively. The higher softening rate with increasing power can be attributed to the faster heating rate achieved under these conditions as shown in Fig. 6. However, when the values

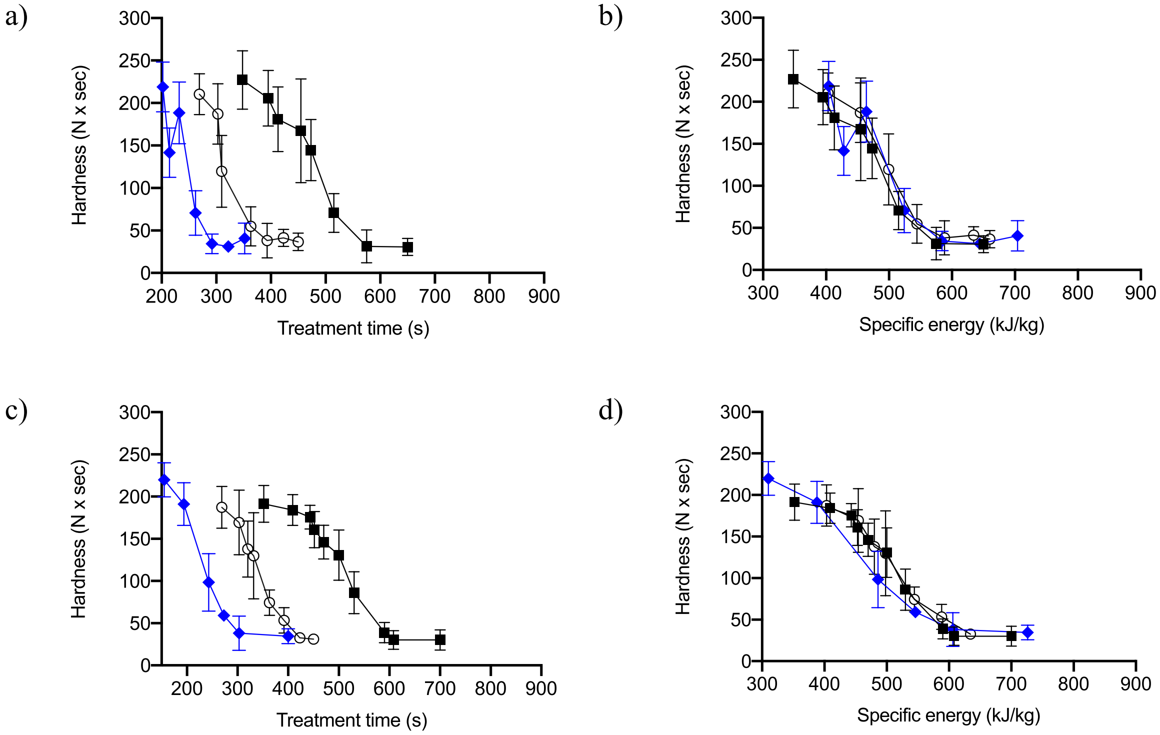

Fig. 6. Hardness (N x sec) of carrot cylinders during ohmic cooking at different specific power inputs: 1 kW/kg (■), 1.5 kW/kg (○), 2 kW/kg (◆). a and b) core of the carrot; c and d) outer part of the carrot. b and d: hardness plotted against the specific energy input.

Table 2
First order kinetics texture softening rates (k) and correlation coefficients (R^2) for carrots cylinders (core and outer part) heated by OH with different power input levels. The k at the top of the table has been calculated according to Equation (2) and the k at the bottom according to Equation (3).

Specific power input (kW/kg)	Core		Outer part	
	k [1/min]	R^2	k [1/min]	R^2
1	$0.273^{A} \pm 0.041$	0.91	$0.601^{C} \pm 0.064$	0.96
1.5	$0.890^{BE} \pm 0.108$	0.96	$0.724^{CE} \pm 0.067$	0.96
2	$1.198^{BD} \pm 0.228$	0.92	$1.096^{D} \pm 0.112$	0.98
Specific power input (kW/kg)	Core		Outer part	
	10^{-2} k [1/(kJ/kg)]	R^2	10^{-2} k [1/(kJ/kg)]	R^2
1	$1.051^{A} \pm 0.156$	0.92	$1.005^{A} \pm 0.105$	0.96
1.5	$1.003^{A} \pm 0.148$	0.94	$0.805^{A} \pm 0.075$	0.96
2	$0.998^{A} \pm 0.190$	0.92	$0.840^{A} \pm 0.080$	0.97

The same letter indicates no significant differences ($p < 0.05$) between the data.

were set against the specific energy input (Fig. 6b and **d**), the kinetics of tissue softening appeared to be more similar among the different applied powers. In fact, according to the values in Table 2, there were no statistically significant differences ($p < 0.05$) among the softening rates regardless of the power applied. Thus, the overall values were between 0.805×10^{-2} and 1.051×10^{-2} $(kJ/kg)^{-1}$. Similar results were obtained by Farahnaky et al. (2012) when they evaluated the OH of carrots at two different voltages (220 V and 380 V) applied at a frequency of 50 Hz. The results showed that increasing the voltage led to a higher softening rate (0.372 min^{-1} vs. 0.485 min^{-1}). Gratz et al. (2021b) evaluated the texture of potatoes cooked by OH at 12 kHz and different power levels (1–5 kW/kg). For this purpose, they plotted the cutting energy (mJ) as a function of the specific energy input (kJ/kg). For the lowest power of 1 kW/kg, an increase in cutting energy was produced in the early stages of cooking. However, as it was observed in the current study with carrots, no influence of power (2–5 kW/kg) on potato texture was found.

For the core and outer part, the texture degradation rates were similar for 1.5 and 2 kW/kg but for 1 kW/kg the central part was slower than the outer part (Table 2). To the best of our knowledge, there is no research in the literature that has analyzed the impact of ohmic cooking on the texture of the external and internal part of the carrot. Nevertheless, in a study conducted by Moens et al. (2020), carrots were conventionally cooked in hot water at 95 °C and texture softening was evaluated in both the core and the outer part of the carrot. The results were similar in both areas with a softening rate of 0.1758 min^{-1} and 0.1610 min^{-1}, respectively. Hence, it seems that the effect of both ohmic and conventional cooking affected in the same way on the different tissues of the carrot.

In both the central and the outer part, from a specific energy input of 460 kJ/kg onwards (80 °C), the softening rate increased sharply to a minimum of 34.55 ± 5.88 and 32.38 ± 2.32 N x sec, respectively, after applying 600 kJ/kg. Carrot samples reaching these very low hardness values were distinctly overcooked.

3.4. Impact of ohmic power on tissue damage (Z_p)

The application of heat at temperatures above 50 °C leads to the onset of damage to plant tissues which results in an increase in the cell disintegration index (Z_p) over the processing time (Lebovka et al., 2004). In addition, the application of OH could favor the permeabilization of the plant tissue by causing its electroporation, which would lead to a higher cell disintegration index (Gavahian et al., 2019). Thus, Fig. 7 shows the evolution of the Z_p of the core and outer part of the carrot when applying different powers (1–2 kW/kg) plotted against the treatment time or against the specific energy input.

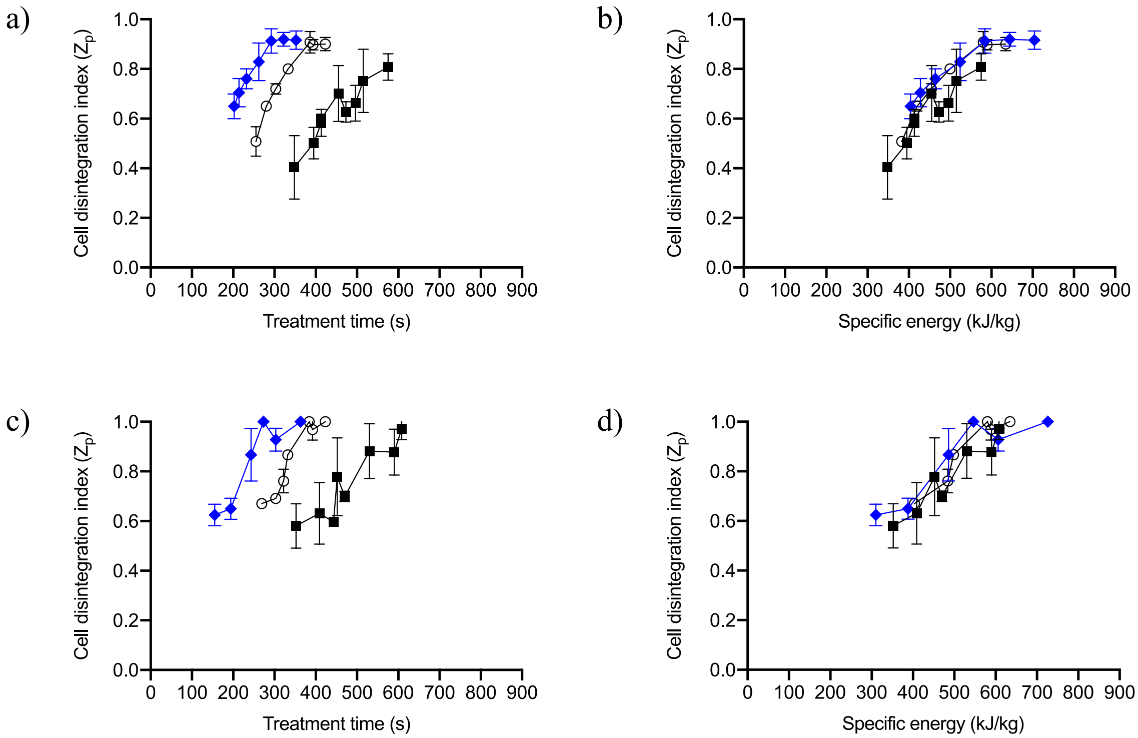

Fig. 7. Cell disintegration index (Z_p) of carrot cylinders during ohmic cooking at different specific power inputs: 1 kW/kg (■), 1.5 kW/kg (○), 2 kW/kg (◆). a and b) core of the carrot; c and d) outer part of the carrot. b and d: hardness plotted against the specific energy input.

Fig. 7a and **c**, which represent the cell damage over the treatment time, show that for the lowest power (1 kW/kg), cell damage occurred later in time due to the slower heating rate at that applied power. For both the core and outer part, the maximum tissue damage was achieved after 290, 400 and 580 s of heating at 1, 1.5 and 2 kW/kg, respectively. Additionally, the energy required to achieve the maximum Z_p value for the core of the carrot was 575–584 kJ/kg while for the outer part was 546–580 kJ/kg. This could mean that the outer part was a bit more sensitive to OH than the core of the carrot although the differences were not significant. In fact, the maximum Z_p value reached for the powers of 1, 1.5 and 2 kW/kg for the core were 0.81 ± 0.05, 0.90 ± 0.02, 0.92 ± 0.04 whereas for the outer part were 0.97 ± 0.03, 1 ± 0.00, 1 ± 0.00, respectively. Thus, the tissue damage was more pronounced on the outer part. This could be associated with the size of the cells of carrot vascular tissue. The application of OH to plant tissues can favor their permeabilization by the phenomenon of electroporation. Electroporation takes place in cell membranes when a threshold electric field is reached, which is lower the larger the cell size (Schwan, 1957). Therefore, for the carrot, the cells of the core tissue have a diameter of 89 μm while those that form the vascular (outer) tissue have a diameter of 163 μm (Moens et al., 2020). In other words, the application of a given electric field would result in increased cell permeabilization in the vascular tissue, hence the Z_p achieved was higher. Although this higher degree of tissue disintegration between the outer and inner part was not reflected in the texture, perhaps because the differences were very slight (Z_p value of 0.8–0.9 compared to Z_p value of 1).

Table 3 shows the tissue disintegration rates calculated starting from a Z_p of 0.65, which follows first order kinetics until the maximum value is reached. Comparing the disintegration rates calculated from the treatment time in Table 3, no statistically significant differences were found when applying powers of 1.5 and 2 kW/kg for both the central and the outer part. The lowest rates were recorded when 1 kW/kg was applied, with values of 0.101 and 0.088 min^{-1} for the core and the outer part, respectively. Moreover, when the Z_p values were plotted against the specific energy, the rates obtained were similar in all cases, with values from 0.14×10^{-2} until 0.193×10^{-2} $(\text{kg/kJ})^{-1}$. As has been described for the texture, when the Z_p values were compared with the applied energies, no difference among them was found, i.e., the ohmic effect was independent of the power if similar energies were applied. Considering the effect of the part of the carrot evaluated, the disintegration rates at the same power were not statistically significantly different ($p < 0.05$) between them.

3.5. Conventional cooking vs. ohmic cooking

In order to compare conventional cooking and OH, texture and cell disintegration index were plotted as a function of the degree of cooking (c-value) (Fig. 8). In the case of ohmic cooking, the power of 2 kW/kg was chosen in order to apply the fastest heating. The heating curves are shown in Fig. 4 for conventional cooking and in Fig. 5g for ohmic cooking.

Table 3
First order cell disintegration rates (Z_p) and correlation coefficients (R^2) for carrots cylinders (core and outer part) heated by ohmic heating with different specific power input levels. The k has been calculated for the lineal kinetics starting from a $Z_p = 0.65$.

Power input (kW/kg)	Core		Outer part	
	k [1/min]	R^2	k [1/min]	R^2
1	$0.101^{A} \pm 0.013$	0.90	$0.088^{A} \pm 0.012$	0.91
1.5	$0.174^{B} \pm 0.022$	0.95	$0.185^{B} \pm 0.033$	0.91
2	$0.168^{B} \pm 0.001$	0.99	$0.200^{B} \pm 0.037$	0.93
Power input (kW/kg)	Core		Outer part	
	10^{-2} k [1/(kJ/kg)]	R^2	10^{-2} k [1/(kJ/kg)]	R^2
1	$0.169^{AB} \pm 0.022$	0.89	$0.150^{AB} \pm 0.030$	0.86
1.5	$0.193^{A} \pm 0.025$	0.95	$0.190^{AB} \pm 0.033$	0.94
2	$0.140^{B} \pm 0.010$	0.99	$0.166^{AB} \pm 0.031$	0.94

The same letter indicates no significant differences ($p < 0.05$) between the data.

Fig. 8a shows that the softening of the carrot produced by ohmic cooking was higher than for conventional heating. For instance, for a cooking degree of 2 min, the hardness of carrots cooked with the conventional system was 150–171 N x sec while with OH it was 34–54 N x sec, i.e. in this case, the softening was 3.2–4.4 fold higher. Furthermore, in OH the final value of hardness was 38–40 N x sec for a c-value of 2.5 ± 0.5 min while in conventional cooking the minimum hardness was 43–50 N x sec for a c-value of 9.0 ± 1.0 min. In other words, with OH it was possible to achieve a higher cooking rate and a final hardness 10.5–35.0 % lower. This phenomenon is demonstrated in Fig. 8b where the tissue damage of carrots caused by both treatments is depicted. These values were consistent with those of the texture (Fig. 8a), i.e. the softer the texture, the greater the tissue damage (higher Z_p). For example, for a c-value of 2 min, the cell disintegration index of conventionally heated carrots was 0.63, whereas for those cooked by OH the values were 0.98. Furthermore, the final values were higher in OH where the maximum tissue damage values were reached ($Z_p = 1$) while in conventional cooking the maximum values reached were 0.81. The electric field applied in this study was too low (54.2 V/cm) to cause electroporation of the plant cells which need to be exposed to minimum fields of 100 V/cm (Ben Ammar et al., 2011). For instance, the application of pulsed electric field treatment (PEF) at electric field strength of 1100 V/cm (time of treatment 10^{-1} s) on carrot samples was observed to cause a softening of the texture. This disintegration of the tissue upon application of an electric field was enhanced by the previous application of heat (55 °C) even at fields of 560 V/cm (Lebovka et al., 2004). However, several studies in the literature have correlated the electroporation induced by the application of OH at very low fields (10–30 V/cm) with the increase of the extraction yield of plant compounds (Cabas and Icier, 2021; Coelho et al., 2021). Nonetheless, in the previous studies, the treatment temperatures were 60–80 °C, lower values than those applied in this study, where 100 °C were reached. In fact, at such high temperatures, the thermal effect is more pronounced than the electrical effect and therefore, it is very difficult to determine whether in our case there is an electroporation of the carrot cells. However, it has been shown that when the applied electric field is very low (70 V/cm), it is necessary to apply long PEF treatment times (>1000 s) during which the sample is exposed to the electric field in order to soften the plant tissue (Lebovka et al., 2005b). This was not applicable in our case either, as during the ohmic cooking applied in this article, the maximum time of application of the electric field was 200 s. In view of the above, under the working conditions used in this article, there was no reason to believe that electroporation of carrot tissue cells was taking place.

Furthermore, it should be noted that the c-value parameter only considers the thermal effects and does not take into account any additional phenomena which might influence the softening kinetics during cooking of vegetable samples. Therefore, using the c-value as the only measurement tool to compare conventional heating and OH might not reflect both heating technologies in the same extent. As can be seen in Fig. 8, when OH was applied, there were additional electrical effects that accelerated the degradation of the tissue of carrots. Therefore, in order to be able to compare vegetable processing with different heating technologies, we suggest using a target texture value which reflects the most important quality characteristic of the sample, e.g. texture, and determine the processing time needed to reach this value when applying both conventional and ohmic heating.

In order to be able to estimate the reduction in cooking time resulting from OH at the different ohmic power levels (1, 1.5 and 2 kW/kg) compared to conventional heating, it was necessary to experimentally determine the optimum degree of cooking by means of the textural value. For this purpose, a sensory analysis was carried out by an internal trained panel, which determined that the optimal degree of cooking of

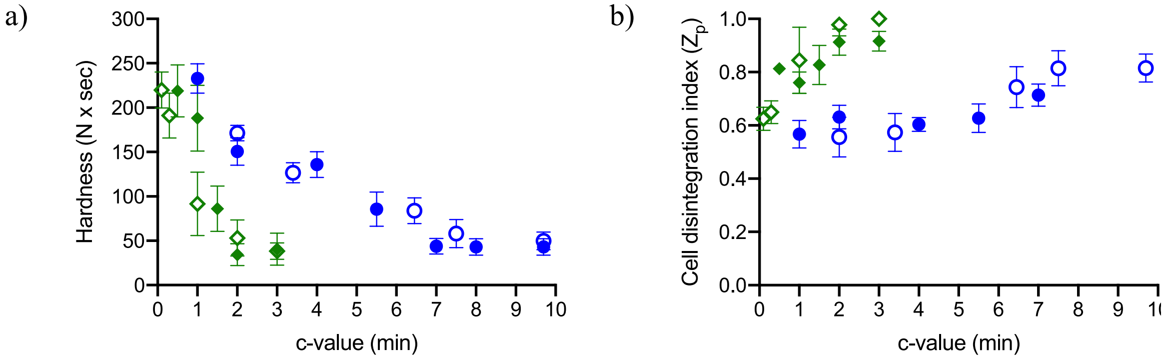

Fig. 8. Hardness (N x sec) (a) and cell disintegration index (Zp-value) (b) of carrot cylinders at different cooking degrees (c-value) when conventional cooking (core ●, and outer part, ○) and ohmic cooking at 2 kW/kg (core◆, and outer part, ◇) were applied.

the carrot corresponded to a texture value of 49 N x sec. Thus, Table 4 shows the cooking times required for each treatment to achieve this target texture value in the core and the outer part of the carrot. As can be seen, in ohmic cooking, the heating is much more uniform, having to apply a small overheating in the center of 0.56, 0.42 and 0.26 min for 1 kW/kg, 1.5 kW/kg and 2 kW/kg, respectively. In contrast, in conventional cooking, as the heating comes from the surrounding hot medium to the inside of the carrot, a surface overheating of 1.2 min has to be applied. Furthermore, the ohmic cooking of carrots under the studied conditions reduced cooking times by 30.92 %, 53.03 % and 62.96 % for 1, 1.5 and 2 kW/kg, respectively.

Additionally, the cooking process by OH showed a significant reduction in the energy consumption necessary to obtain the desired cooking degree. Specifically, the target cooking value at the core of the carrot was reached by applying 591.7 Wh in the conventional cooking (without considering the energy for the heating of the water) and 231.3, 234.4 and 250.0 Wh in the OH (1; 1.5; 2 kW/kg, respectively). These values represent an energy consumption reduction of 60.9 % (1.0 kW/kg), 60.4 % (1.5 kW/kg) and 57.7 % (2.0 kW/kg).

This reduction in cooking time and power consumption is of great interest to the food industry, as it shortens processing times and reduces energy and economic costs. Therefore, this is a significant gain for implementing OH on an industrial scale.

Table 4
Cooking time (min) required to achieve a hardness value of 49 N x sec in carrot cylinders cooked with conventional and ohmic heating.

	Cooking time (min)	
	Core	Outer part
OH (1 kW/kg)	9.25 ± 0.13	9.81 ± 0.16
OH (1.5 kW/kg)	6.25 ± 0.24	6.67 ± 0.22
OH (2 kW/kg)	5.00 ± 0.45	5.26 ± 0.72
Conventional	14.2 ± 0.24	13.0 ± 0.30

4. Conclusions

The application of ohmic cooking of vegetables involves several factors to be considered to achieve uniform and efficient heating. Matching the electrical conductivity between sample and saline medium is a crucial point to be ensured for further classification of product-process-interactions during OH. While working with optimized conditions, the ohmic power input affected only the heating rate but not the heating uniformity or the rates for tissue softening and cell disintegration. The power input can therefore be used as tool for process acceleration.

Additionally, this study proved that the use of the c-value, often implemented to compare OH and conventional cooking, is not a valid indicator as it does not take into account effects that are not attributable to thermal exposure. Thus, in the present study it was observed that ohmic cooking resulted in a higher softening and cell disintegration of the tissue compared to conventional boiling. However, under the working conditions used (low electric field strengths and short pulse width), electroporation of the plant cells cannot be considered a possible mechanism. Therefore, other electrical phenomena may be occurring that could cause the cell structure to be damaged more rapidly, but further research is needed on this point. It would be recommended to investigate the current flow inside the treatment chamber through mathematical models to exclude effects deriving from deviations in the distribution of current intensity and electric field strength. Finally, it has been observed that the application of ohmic heating allowed to significantly shorten the cooking time and reduce the power consumption, which is a promising result for its industrial implementation, as it would allow the reduction of energy and economic costs.

Further studies are still necessary to develop reliable process indicators for tailored process design for targeted processing of vegetables, especially when comparing OH and conventional heating, and to better understand the phenomena behind the additional softening effects generated by OH.

CRediT authorship contribution statement

Leire Astráin-Redín: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Kate Waldert:** Writing – review & editing, Investigation, Conceptualization. **Marianna Giancaterino:** Writing – review & editing, Investigation, Conceptualization. **Guillermo Cebrián:** Writing – review & editing. **Ignacio Álvarez-Lanzarote:** Writing – review & editing. **Henry Jaeger:** Writing – review & editing, Conceptualization.

Declaration of competing interest

We know of no conflicts of interest associated with this publication, and there has been no significant financial support for this work that could have influenced its outcome. As corresponding author, I confirm that the manuscript hast been read and approved for submission by all the named authors.

Data availability

Data will be made available on request.

Acknowledgement

This work was created within a research project of the Austrian Competence Centre for Feed and Food Quality, Safety and Innovation

(FFoQSI). The COMET-K1 competence centre FFoQSI is funded by the Austrian federal ministries BMK, BMDW and the Austrian provinces Lower Austria, Upper Austria and Vienna within the scope of COMET - Competence Centers for Excellent Technologies. The programme COMET is handled by the Austrian Research Promotion Agency FFG. Part of the equipment used in this study was provided by the EQ-BOKU VIBT GmbH and the BOKU Core Facility Food & Bio Processing.

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