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Ohmic Heating of Basil-Based Sauces: Influence of the Electric Field Strength on the Electrical Conductivity

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The Moderate Electric Field (MEF) processing of foods consists in the application of an electric potential gradient ($\Delta V/L$) ranging from 1 to 1000 V/cm on a food item (homogeneous or heterogeneous) placed between two electrodes, its main effect being the food heating due to the dissipation of a part of the electric energy into heat within the food item. The heating performances of such a system depend on several process and system parameters, including the applied $\Delta V/L$, the food electrical conductivity, and its thermo-physical properties. In this study, the effects due to the salt composition and to the applied $\Delta V/L$ to a heterogeneous food (constituted by a basil-based sauce, mainly fibers dispersed in a slightly salted water-oil emulsion) treated in a custom MEF system on the food heating rate are investigated. The samples were prepared at different salinities (3.25, 1.63, 0.86 and 0.43% w/w respectively). In the explored range of compositions, the heating rate increased linearly with the square power of applied $\Delta V/L$. A slight linearity deviation above 55°C was observed for the basil-based sauce at 1.63% and 5.20 V/cm, associated with bubble formation within the ohmic system and the electrolytic reactions occurring at the electrode-solution interface during the MEF heating process.
The salt content as well as the ratio between water and oil in the sample formulation played a crucial role in determining the thermo-electrical behavior of the basil-based sauce samples. Samples with salinity of 1.63%, compared to samples at 3.25%, exhibited a higher electrical conductivity, being due to a minor concentration of the non-conductive phase (namely the oil phase as well as the dispersed vegetable fibers into the solution) that exerts a major degree of electrical insulation. As the salinity decreases from 1.63% to 0.43%, samples were characterized by lower electrical conductivities, being due to a reduced ionic mobility when the salt contained into the sample is drastically reduced.

1. Introduction

According to the definition given by Sensoy and Sastry (2004), MEF is a thermal-electrical technique in which a food material is subjected to the passage of an alternating electric current. The food product acts as an electrical resistance and the electrical energy is converted into thermal energy. However, MEF may be characterized or not by thermal effects due to the heating process. In this way, MEF might comprise both heating processes at high temperatures, that is, ohmic heating, or controlled low temperatures to minimize the thermal effects (Sensoy and Sastry, 2004). MEF applications include blanching, evaporation, drying, thawing extraction, peeling and fermentation. Moreover, several food systems such as fruits, vegetables, milk, meat, poultry, and fish products have been processed by means of batch ohmic heating (Sastry, 2014). MEF heating process is an emerging technology with considerable potential for the food industry, its main advantages being the rapid and relatively uniform heating together with the lower capital cost compared to other heating methods such as microwave and radio frequency heating (Marra et al., 2009). However, the performance of this method depends on various factors, such as shape, size, and composition of the food item as well as the physical configuration of the MEF equipment.
Basil-based sauce is made from fresh basil leaves, extra virgin olive oil, garlic, pine nuts, cheese (Parmigiano and Pecorino cheese), pine nuts, garlic, and extra virgin olive oil. Whatever the blending process applied to its ingredients, pesto is a heterogeneous system, seen as a water-oil emulsion in which food particulates are

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dispersed. Demand of pesto has progressively increased worldwide, being considered second as pasta sauce to tomato sauce only (Masino et al., 2007). However, fresh basil pesto usually needs to be processed to improve its microbiological safety and shelf-life. There is very little information about the preservation of basil pesto sauce (Zardetto and Barbanti, 2020) even if outbreaks involving sauces made by fresh herbs clearly show that the global marketing of such products should not be underestimated as a vehicle of foodborne illness (Eckner et al., 2015). Food preservation techniques -including pasteurization (Franceschini et al., 2011) and aseptic packaging, vacuum packaging, modified atmosphere packaging and refrigeration (Fabiano et al., 2000), are employed to prevent pesto from spoiling and, therefore, to enhance its shelf-life. However, these processes may affect the organoleptic properties of pesto sauces, the most evident being the pesto colour which could vary from the pale green to a dark brownish green. The texture degradation and the colour change are due to the variation in the content of the fresh basil pigments, i.e., chlorophylls and carotenoids (Zeppa and Turon, 2014). The fresh green pesto is highly appreciated for its characteristic colour, taste, and texture, and losing these attributes may lead to a lower demand from the consumers.

Conventional heating is the most common processing technology in the food industry (Ling et al., 2015). Classic convective methods comprise plate heat exchangers, still the most popular methods in the heating of foodstuff. The major drawbacks of conventional heating are the low energy efficiency and long drying times (Gavahian et al., 2018). MEF heating is an efficient technique used to extend the shelf-life of prepared vegetables. To our knowledge, no data are available in the literature on heating behaviour of fresh basil pesto under a MEF heating process. Before considering experiments devoted to studying how MEF heating can impact the shelf life of a product like pesto there is the need of feeling the lack of knowledge on the behaviour of pesto undergoing this process. In fact, during the heating process, it is necessary to understand the different phenomena taking place inside the MEF cell, such as the temperature distribution and the heating rate in the food sample that also affect, consequently, its electrical conductivity. It is also important to consider the balance between the heating time, safety of the food and the energy usage to select proper processing parameters. Therefore, in this present work, we studied the effect of the $\Delta V/L$ on the thermo-physical properties of several pesto sauce samples. Different temperature-time histories and heating rates were compared, and electrical conductivity behavior was also evaluated.

2. Materials and methods

2.1 Sample preparation

Basil pesto sauce was purchased from a local market in Fisciano (Italy) and stored at room temperature (25 °C) prior to experiments. Pesto composition and relative properties at room temperature before the MEF heating are indicated in Table 1. The sauce was diluted with deionized water to obtain samples at different salinities (evaluated as salt mass on total solution mass) and content of macronutrients (see Table 2), and they were mixed until a homogeneous mixture was obtained. In this way, it was possible to appreciate the effect of salinity on the electrical conductivity during the heating process. A total mass of 190 g was poured into the MEF cell and heated at 3.12, 4.16 and 5.20 V/cm.

Table 1: Pesto sauce composition and its thermal properties.

	Fats	Carbohydrates	Water	Fibers	Proteins	Salt*
Mass [g]	46	9.8	31.25	5	4.7	3.25

Thermal conductivity was 0.31 (±0.01) W/(m °C) (at 25 °C) and volumetric heat capacity was 2.86 (±0.07) MJ/(m^3 °C) (at 25 °C).
*Salt is already contained in pesto sauce. Reported amounts are average values on a basis of 100 g of pesto, according to the nutritional values datasheet.

Table 2: Diluted sample compositions.

Pesto [g]	Salt [g]	Water [g]	Total mass [g]	Salinity % [(w/w)×100]
190	6.18	0	190	3.25
95	3.09	95	190	1.63
50	1.63	140	190	0.86
25	0.81	165	190	0.43

2.2 MEF heating system and process

The scheme of the MEF system used in this work is shown in Figures 1a and 1c. The MEF system is mainly composed by: a variable transformer (VAM20F-1N, Input, 230V AC, 50/60Hz, K-FACTOR Castellarano, Italy);

an insulated chamber to contain the heating system; a MEF cell made of glass with internal dimensions of 10 cm × 6 cm × 5.1 cm (length × height × width respectively) and two removable steel electrodes (Figure 1b) with a thickness of 0.19 cm each, resulting in a distance between the electrodes of 9.62 cm. A Teflon cap was designed with a central opening for the insertion of a T-type thermocouple (TC Misure e Controlli srl, Torino, Italy) at the sample centre, wired to a data logger system (TC-08 Thermocouple data logger, Pico Technology Ltd, St. Neots, UK).
For each $\Delta V/L$, the reported values of temperature versus heating time refer to the average over three replicates.

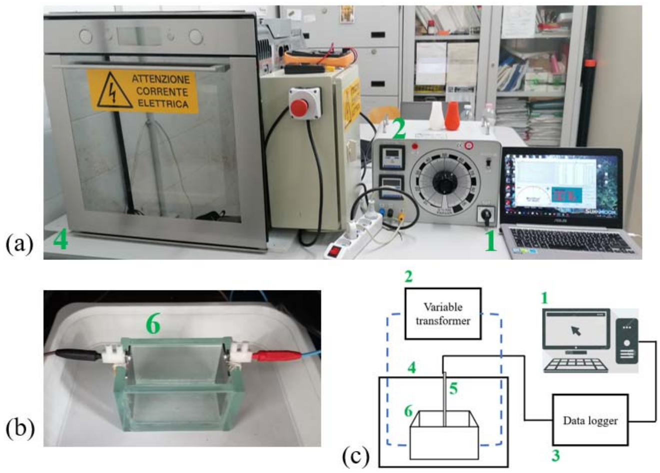

Figure 1: Pictures of the adopted instrumentation: (a) assembly of the MEF heating equipment, showing the (1) data acquisition system, (2) the variable transformer and (4) the insulated chamber. (b) Detail of the (6) MEF cell with the electrodes. (c) Schematic diagram of the experimental setup representing the insertion of (5) the thermocouple into the cell.

2.3 Electrical conductivity

The electrical conductivity (σ) was evaluated from temperature, voltage and current data recorded at 30 s intervals. Voltage and current readings were acquired by using a digital multimeter (model Bt-90EPC, Holdpeak, Zhuhai, China) and a data acquisition software, Pc-link-v1.1 (Holdpeak, Zhuhai, China). Electrical conductivity was calculated according to the following equation:

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

where I is the current passing through the food item, V is the applied voltage, L is the length between the electrodes and A is the area of the electrodes occupied by the sample. The ratio L/A is known as the cell constant of the MEF heating unit. The cell constant of the MEF heater was 60.1 m^{-1} when filled with a mass of 190 g. The cell was calibrated by using several aqueous solutions of NaCl in deionized water (concentrations were 1%, 2.5% and 5% w/w respectively). Measured values were compared to corresponding published values (Weast, 1989). The calibration results revealed that there was a difference between standard electrical conductivity of the NaCl solutions and the experimental data of maximum 5%. The electrodes were thoroughly rinsed using a brush and dematerialized with twice-distilled water after each run. The reported values of electrical conductivity refer to the average over three replicates.

3. Results and discussion

3.1. Heating rate

Figure 2 reports the temperature evolution of the tested samples (error bars represent 2x the standard deviation).
Experimental data comparison shows the two significant effects of the salt composition (3.25, 1.63, 0.86 and 0.43% w/w) and of the applied $\Delta V/L$ (3.12 V/cm, 4.16 V/cm and 5.20 V/cm) on the heating rates. When samples with salinity up to 1.63% are considered, an increase in the applied potential gradient corresponds to an evident increase in heating rate. The value of the applied $\Delta V/L$ has a limited effect on the heating of the pure pesto, due to its composition in fat, which acts as an insulator. Also a higher concentration (and

dispersion) of vegetable solid particles exerts a higher electrical resistance to the passage of the electrical current leading, consequently, to a lower heat rate, also reported in (Zhu et al., 2010). As the salinity decreases to 1.63%, the temperature rise was higher and shorter heating time was required to reach higher temperature values in comparison with values observed at 3.25%.

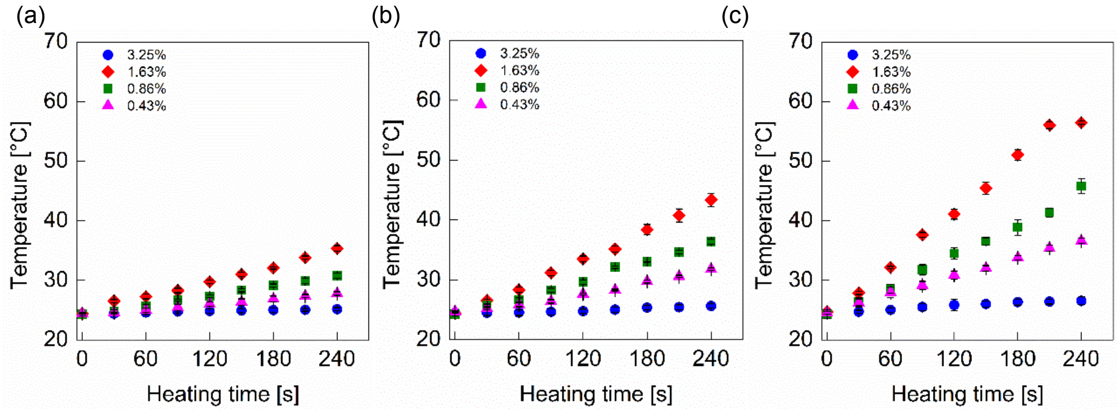

Figure 2: Heating rates of the basil-based sauce samples at the different ΔV/L: (a) 3.12 V/cm, (b) 4.16 V/cm and (c) 5.20 V/cm.

As the salinity gradually decreases to 0.43%, temperature evolutions are characterized by a slower rise. This effect may be ascribed to a lower salt concentration within the liquid medium that exerts a minor ionic mobility when the electrical current passes through the food item. When higher $\Delta V/L$ were applied, the same behavior was observed. Overall, whatever the applied potential gradient, the temperature at the sample core increases linearly with the heating time. A slightly nonlinear deviation for temperature-time profile of sample at 1.63% and 5.20 V/cm (Figure 2c) can be observed at temperature above 55 °C. This nonlinear behavior may be related to air bubble formation, a phenomenon which was observed during MEF heating. These bubbles do not conduct electrical current and, therefore, may disable electrical conductivity rise. The formation of gas bubbles may be attributed to several mechanisms such as (i) hydrogen bubbles as byproduct of electrochemical reactions occurring at the interface between the foodstuff and the surface of the electrode (Palaniappan and Sastry, 1991); (ii) formation of bubbles due to the temperature gradients occurring through the MEF cell in which hotter spots promote water boiling while part of the cell is still a temperature below the boiling point (Zhao and Kolbe, 1999), these temperature gradients may be due to distortions of the electric field caused by the solely present solid fraction within the liquid phase of the food system (Fryer et al., 1993); (iii) cell lysis, in which the breakdown of cell wall components, due to the stress applied by the electrical field, can lead to an efflux of cytoplasm components and to the release of non-conductive gas bubbles from the structure of the food material (Halden et al., 1990). Table 3 reports the heating rates (HR) obtained by the linear fitting of the experimental data. R^2 values indicate a good agreement between the measured values and the linear fitting. The listed HRs strengthen the observations made for the temperature evolutions. On one hand, the effect of the applied voltage is readily evident, as expected, higher $\Delta V/L$ induced a higher passage of the electrical current through the sample (Sastry, 2014). On the other hand, the salinity also influenced the ionic mobility throughout the food item. At 3.12 V/cm, it can be observed that HR goes from 3.60×10^{-3} °C/s to 4.34×10^{-2} °C/s (at 3.25 and 1.63% w/w). Therefore, as the salinity further decreases, the HR reaches lower values first at 2.51×10^{-2} °C/s and then at 1.41×10^{-2} °C/s (at 0.86 and 0.43% w/w respectively). Moreover, the same trend is observed at 4.16 V/cm and 5.20 V/cm as well.

Table 3: Heating rates of basil-based sauce samples at the applied ΔV/L.

Salinity % [w/w]	3.12 V/cm		4.16 V/cm		5.20 V/cm	
	HR [°C/s]	R^2	HR [°C/s]	R^2	HR [°C/s]	R^2
3.25	3.60×10^{-3}	0.974	4.71×10^{-3}	0.968	6.97×10^{-3}	0.978
1.63	4.34×10^{-2}	0.995	7.58×10^{-2}	0.996	1.54×10^{-1}	0.999
0.86	2.51×10^{-2}	0.999	4.75×10^{-2}	0.999	8.15×10^{-2}	0.999
0.43	1.41×10^{-2}	0.977	2.85×10^{-2}	0.981	5.07×10^{-2}	0.999

3.2 Electrical conductivity

The change in σ with the temperature and the salinity is shown in Figure 3 (error bars represent 2x the standard deviation). As the change in the electrical conductivity is independent of the applied *ΔV/L*, the set of data obtained ad the several applied voltages (3.12 V/cm, 4.16 V/cm and 5.20 V/cm) are reported together at each specific salinity. For all the considered samples, the electrical conductivity shows a positive linear dependence on temperature, which is a typical effect attributed to a reduced drag for the ions' movement within the medium (Darvishi et al., 2013).

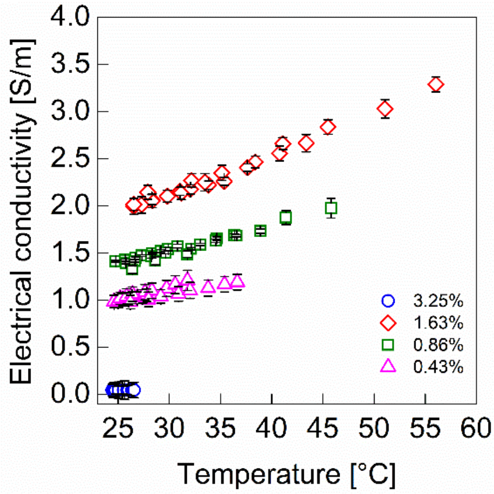

Figure 3: Electrical conductivities of the basil-based sauce samples.

Experimental data were linearly fitted by the following equation:

$$\sigma = \sigma_0 + mT \quad (2)$$

where σ_0 and m respectively represent the intercept and the slope of the linear model. Results of the fitting procedure are reported in Table 4. R^2 values indicate a good agreement between the measured values and the linear fitting procedure. Also, in this case, data are consistent with the analysis. Indeed, it can be observed that m goes from 2.68×10^{-4} S/(m °C) to 4.28×10^{-2} S/(m °C) (at 3.25% and 1.63% respectively). In practice, the fat content and the vegetable solid particles are characterized by a lower electrical conductivity than liquids for particulate foods. For this reason, samples at 1.36% of salinity are characterized by higher values of electrical conductivity, as a lower fat concentration leads to a minor degree of resistance to the electrical current. After that, the m lowers to 2.39×10^{-2} S/(m °C) and then to 1.68×10^{-2} S/(m °C) (at 0.86% and 0.43% respectively). This gradual reduction in the slope is attributed to a decreasing salinity that induces a minor passage of the electric current.

Table 4: Electrical conductivities of basil-based sauce samples.

Salinity % [w/w]	σ_0 [S/m]	m [S/(m °C)]	R^2
3.25	0.041	2.68×10^{-4}	0.963
1.63	0.828	4.28×10^{-2}	0.984
0.86	0.808	2.39×10^{-2}	0.977
0.43	0.585	1.68×10^{-2}	0.972

4. Conclusions

This work discussed the heating process of a heterogenous food system (basil-based sauce) assisted by moderate electric field, in a custom equipment calibrated on purpose. First, in the investigated range of $\Delta V/L$, the different temperature-time evolutions were characterized by a linear behavior, except for the sample with a salinity of 1.63% and treated at 5.20 V/cm. A slight deviation from linearity with respect to the temperature was observed above 55°C. This deviation was associated with bubble formation during the MEF heating process. The heating rates of the samples at different salinities, undergoing different applied $\Delta V/L$, were characterized in terms of electrical conductivity. The pure pesto exhibited a scarce response to MEF heating, due to the high fat concentration and its effect on the electrical conductivity of the sample. The sample with salinity of 1.63% exhibited the higher electrical conductivity. This occurrence is due to a minor concentration of the oil phase as well as the dispersed vegetable fibers into the solution that are responsible for a major degree of electrical insulation. As the salinity decreases to 0.86% and to 0.43%, samples were characterized by lower electrical conductivities, resulting from slower heating rates. This depletion may be ascribed to the reduced salinity that usually enhances the ionic mobility when a food item is subjected to the passage of the electrical current.

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