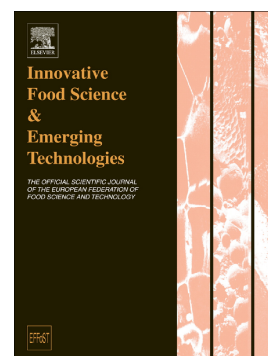


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Effects of ohmic heating on technological properties of whole egg

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Abbreviation list: A, strength of rheological interactions; G^* , complex modulus; G' , elastic modulus; G'' , viscous modulus; LSD, least significant difference; MANOVA, multifactor analysis of variance; WHC, water holding capacity; z, number of interacting rheological units.

Abstract

The aim of this work was to study the effects of different ohmic heating conditions on color, rheology, foaming, and gelling properties of whole egg. Industrial products treated by conventional heat pasteurization and the corresponding raw materials were also evaluated. Ohmic treatments accomplished in a static cell (65.5 °C x 3 min, 70 °C x 1 min, and 67 °C x 4.5 min) increased whole egg apparent viscosity (up to 190%), but also foam overrun (up to 28%) and gel hardness (up to 15%). The performance improvement was confirmed by treatments carried out in a continuous pilot plant (71 °C x 0.6 min, 68 °C x 1.4 min) and the products resulted stable during storage at 4 °C for 30 days. In conclusion, this study demonstrated that ohmic heating is a suitable alternative to conventional pasteurization. Low temperature treatments are preferable to avoid possible rheological issues due to protein denaturation.

Industrial relevance

Whole egg is a protein ingredient with multiple technological properties, used in many foods. Due to safety reasons, food manufacturers often use pasteurized liquid egg products, microbiologically safer and easier to handle with respect to shell eggs. In order to satisfy the required sanitary levels for liquid egg products, thermal pasteurization treatments are needed. However, since egg proteins are very sensitive to high temperatures, attention must be paid to avoid coagulation entailing deleterious effects against egg quality. In this study, different ohmic heating treatments were evaluated as milder alternatives to conventional pasteurization. The lab- and pilot-scale experiments and the subsequent statistical analyses of the obtained results contributed to assess the effects of the different ohmic treatments on technological features (e.g. color,

rheology, foaming, and gelling properties) of liquid whole egg. This study demonstrated that ohmic heating is a suitable technology for whole egg treatment, paving the way for new opportunities in order to produce safe food ingredients with improved technological functionalities.

Keywords: color; foaming properties; gelling properties; ohmic heating; pasteurization; rheology.

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1. Introduction

Eggs are protein ingredients with multiple technological properties such as coloring, foaming, gelling, thickening, binding, adhesion, and emulsification. Because of such properties, whole egg and its fractions (i.e. albumen and yolk) are used as functional ingredients in many foods such as bakery products, meringues, meat products, and pasta (Yang & Baldwin, 1995).

Due to the role of eggs as vehicles for foodborne diseases (EFSA & ECDC, 2012; Jackson, Griffin, Cole, Walsh, & Chai, 2013), food manufacturers often substitute shell eggs with pasteurized liquid egg products, microbiologically safer and easier to handle (Nemeth, Friedrich, Pásztor-Huszár, Pipoly, Suhajda, & Balla, 2011). Besides good agricultural and handling practices, pasteurization treatments are needed to achieve the required sanitary level for liquid egg products (Regulation (EC) No 853/2004) and to extend their shelf life. The most common treatment applied in the egg industry is thermal pasteurization, which has a high efficacy in inactivating pathogens (Espina, Monfort, Álvarez, García-Gonzalo, & Pagán, 2014). USDA pasteurization requirements for whole egg are 60 °C for 3.5 min in order to achieve a 5 decimal reductions of *Salmonella* (CFR, 2012). These treatment conditions are milder than those usually applied in Europe, where 2.5-6 min holding times at 64.4-68 °C are typical (Froning, Peters, Muriana, Eskridge, Travnicek, & Sumner, 2002). Since egg proteins are very sensitive to high temperatures, attention must be paid to avoid coagulation entailing deleterious effects against egg quality. For instance, a severe heat treatment can cause the loss of foaming, emulsifying, and gelling capacities, thus limiting the functionalities of liquid egg products as food ingredients (Espina et al., 2014). For these reasons, there

is an increasing demand for alternative pasteurization methods able to ensure product safety while decreasing thermal degradation.

Ohmic heating is a promising alternative to conventional heat pasteurization. Thermal energy is generated directly inside the food, overcoming limits related to low heat transfer coefficients and high wall temperatures. Other advantages include improved retention of quality and nutritional parameters, shorter processing times and higher yields (Cullen, Tiwari, & Valdramidis, 2012). Few papers in the scientific literature deal with the ohmic heating of liquid egg products and, to the best of our knowledge, none of them considered the scaling up on a pilot plant and the quality characteristics of the treated products. Llave, Fukuda, Fukuoka, Shibata-Ishiwatari, and Sakai (2018) studied color changes in egg yolks based on degree of thermal protein denaturation during ohmic heating, but they considered a very small-scale experiment, treating about 5 g of product at a time, and no other technological features were measured. Icier and Bozkurt (2011) and Bozkurt and Icier (2012) also worked on a little amount of sample (20 mL), examining the effects of conventional and ohmic heating methods on the rheological behavior and fluid dynamics of liquid whole egg.

The aim of this work was the evaluation of the effects of different ohmic heating conditions on color, rheology, foaming, and gelling properties of liquid whole egg.

Ohmic heating was carried out under different temperature/time combinations, by using both a 1 kg-static cell and a pilot plant. Products treated by industrial conventional heat pasteurization were evaluated as references, as well as the corresponding raw materials.

Moreover, samples obtained by the pilot plant were stored at 4 ± 1 °C for 30 days and analyzed every 7-8 days in order to assess their stability in terms of technological properties.

2. Materials and methods

2.1 Whole egg samples

Four different batches of raw liquid and homogenized whole egg kindly provided always by the same egg product industry were used for the ohmic treatments. The first three batches (10 L each; named 1, 2, and 3) were used to repeat the ohmic treatments in the static cell, in order to account for the reproducibility of heat treatments and the effect of different batches of raw material. Each batch was treated under three different temperature \times time conditions: 65.5 °C \times 3 min (coded 65.5-3), 70 °C \times 1 min (coded 70-1), and 67 °C \times 4.5 min (coded 67-4.5). The experimental ohmic-treated samples, the corresponding raw materials (coded RAW_S), and the corresponding commercial whole egg products pasteurized by a conventional heat treatment in plate heat exchanger at 65.5 °C \times 3 min (used as reference and named REF_S) were analyzed for technological properties the day after production.

The last batch (300 L) of raw whole egg (coded RAW_C) was ohmic-treated in a continuous pilot plant under two different temperature \times time conditions: 71 °C \times 0.6 min (coded 71-0.6) and 68 °C \times 1.4 min (coded 68-1.4). Also in this case, RAW_C, the corresponding commercial product obtained by a conventional heat treatment in plate exchanger (at 65.5 °C \times 3 min; REF_C), and the experimental ohmic-treated samples were analyzed for technological properties the day after production. Besides, a commercial whole egg product pasteurized by a combination of conventional heat treatment in plate exchanger and ohmic treatment (coded REF_CO) as well as the corresponding raw material (coded RAW_CO) were also analyzed.

Moreover, the experimental samples treated in the continuous ohmic pilot plant (71-0.6 and 68-1.4) as well as REF_C and REF_CO were analyzed during storage at 4 ± 1 °C up to 30 days.

2.2 Ohmic treatments

Ohmic treatments were carried out at the Experimental Station for the Food Preservation Industry (SSICA, Parma, Italy), using a 1 kg static cell and a continuous pilot plant by Emmepiemme S.r.l. (Piacenza, Italy) equipped with three ohmic heater columns. Fig. 1 shows the equipment used. The static cell was made of a PET cylindrical chamber with an internal diameter of 86 mm and a length of 200 mm. It was equipped with two plate stainless steel (AISI 316) electrodes and a power supply working at a frequency of 20 kHz, square wave, with two different tension scale: 0-90 V (max 16 A) and 0-180 V (max 8 A). The maximum power was 1500 W. Stainless steel electrodes were used also in the pilot plant, being the cheapest food-grade solution. A special power supply coupled with these kind of electrodes assures the total absence of electrochemical phenomena, thus guaranteeing no metal migration in the treated product. No further details about the pilot plant can be here reported, due to pending patents.

In the static cell, the following treatment conditions were tested: 65.5 °C \times 3 min (coded 65.5-3), 70 °C \times 1 min (coded 70-1), and 67 °C \times 4.5 min (coded 67-4.5). The first treatment was carried out according to the standard temperature \times time conditions commonly used by industries producing pasteurized liquid whole egg. The treatment 70-1 was chosen based on preliminary trials (data not shown) in order to have an equivalent exposure time $F_{70}^{8.7}$ of 1 min, which is effective in reducing *Listeria*

monocytogenes ATCC 37696 by 6 log cycles. Enumeration of *Listeria monocytogenes* was performed according to the standard method UNI EN ISO 11290-2:2017 (2017).

The treatment 67-4.5 was carried out in order to simulate possible harder industrial treatments carried out in Europe (Froning et al., 2002). The treatment temperature was always reached in 9 ± 1 min. An intermittent energy supply assured the maintenance of the temperature during the holding time, as checked by using K thermocouples.

Immediately after the treatments, samples were cooled down in trays previously refrigerated in a cold chamber at -40 °C and maintained over an ice layer until whole egg reached a temperature of $1-2$ °C (under manual agitation). Then the samples were packed in sterile bags and stored at 4 ± 1 °C until the day after processing for the analyses. Each treatment was performed in triplicate on three different whole egg batches.

In the continuous ohmic pilot plant, two different temperature \times time combinations were tested: 71 °C \times 0.6 min (coded 71-0.6) and 68 °C \times 1.4 min (coded 68-1.4). As for the treatment 70-1 carried out in the static cell, both the operating conditions set up in the pilot plant guaranteed an equivalent exposure time $F_{70}^{8.7^\circ C}$ of 1 min. Due to the different technical design of the static cell and pilot plant (e.g. pilot plant pump flow rate and length of holding tubes), it was not possible to reproduce the same temperature \times time conditions in both the equipment. The treatment temperatures, measured by PT100 sensors placed at the beginning and the end of the holding tubes, were all reached in a few seconds. Usually, in a conventional heat plate exchanger with similar flow rates whole egg takes about 25 min to be heated, thus confirming the mildness of the ohmic heating. The short holding times and the heat insulation of the holding tubes assured the constant temperature during treatment. At the end of the treatments, samples were

cooled down at 15 °C and conveyed to a moving sterile chamber for the packaging in 1 L sterile bags. Bags were quickly refrigerated at 1-2 °C in a blast chiller and then stored at 4±1 °C until the moment of the analyses. Due to the high volumes required (about 100 L for each tested condition), the treatments were carried out in single but all the technological features were measured at least in triplicate on different whole egg bags.

2.3 Color

Whole egg color was assessed by means of a tristimulus colorimeter ChromaMeter II (Konica Minolta, Tokyo, Japan), with standard illuminant C. The sample (about 30 g) was placed in a darkened container provided with an optical glass. Results are expressed in CIE L*a*b* scale as the mean of three determinations. The CIE total color difference (ΔE^*) was also calculated using equation (1):

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (1)$$

2.4 Apparent viscosity

Whole egg flow curves were determined at 20 °C by means of a Physica MCR 300 rheometer (Anton Paar, Graz, Austria) equipped with a cone-plate geometry (CP50-1), ranging shear rate from 20 to 500 s⁻¹. Results are expressed in terms of apparent viscosity (mPa s) calculated at 290 s⁻¹ as the average of three replicates. This value of shear rate was chosen because it represents an average pipe wall shear rate during fluid food pumping (Alamprese, Pompei, & Guatelli, 2001).

2.5 Foaming properties

Foaming properties were evaluated in triplicate at 20 °C, according to Alamprese, Casiraghi, and Rossi (2012). Briefly, 50 mL of whole egg were whipped in a Cream Tester CT II (Gerber Instrument, Langhag, Switzerland) for 4 min. Foam height was determined in four different points by using a caliper and foam volume was calculated taking into account the Cream Tester vessel diameter (7.4 cm). Foaming capacity was expressed as overrun (%), corresponding to the percentage increase of whole egg volume after whipping. The measure of the electric current (mA) needed by the instrument to maintain a given speed of the rotating elements during 4 min whipping was used as an index of foam consistency. Foam instability was measured by transferring a known volume of foam (250 mL) into a transparent graduated conical vessel, which was then maintained at 4 °C in a cold room for 2 h. Foaming instability (%) was calculated as the percentage ratio between the liquid whole egg separated after storage and the initial volume of whole egg originating the foam.

2.6 Coagulation temperature and gelling properties

Coagulation temperature (°C) of whole egg samples was evaluated in triplicate as reported by Alamprese et al. (2012). Oscillatory temperature sweep tests were carried out by means of a Physica MCR 300 rheometer (Anton Paar, Graz, Austria) equipped with a plate-plate geometry (PP50) gapped to 1 mm. Temperature was increased from 20 to 90 °C with constant heating rate (2 °C/min), oscillation frequency (1 Hz), and strain (3%). Elastic (G') and viscous (G'') moduli were determined and the coagulation temperature was taken as the temperature at which the first derivative of G' was at its maximum.

Gelling properties were evaluated following Alamprese et al. (2012) procedures. Whole egg gels were prepared in quadruplicate, pouring about 65 mL of sample into a cylindrical Pyrex container (13 cm length; 2.5 cm internal diameter) with screw caps at both ends. The sealed container was dipped in a water bath at 90 °C for 30 min. After cooling in ice water, the egg gel cylinder was extruded from the container and used for the subsequent evaluations. Mechanical properties were measured at room temperature (24 ± 1 °C) with a 3365 Instron Universal Testing Machine (Instron Division of ITW Test and Measurement Italia S.r.l., Trezzano sul Naviglio, Italy) by an uniaxial compression test carried out on six gel cylinders (2.5 cm diameter; 2.5 cm height). A compression plate of 9.3 cm diameter was used, attached to a 100 N load cell. Crosshead speed was set at 20 mm/min and a maximum strain of 40% was applied. Results are expressed as load at 40% strain (N) and Young modulus (kPa), representing the hardness and the strength of the gel, respectively. Water holding capacity (WHC) of gels was measured in quadruplicate by centrifugation of gel cylinders (2.5 cm diameter; 2.5 cm height) at 10,000 g for 30 min at 20 °C. Results are expressed as the percentage ratio between weights of the gel after and before centrifugation. Viscoelastic properties of gels were evaluated in triplicate by means of oscillatory shear tests carried out with a Physica MCR 300 rheometer (Anton Paar, Graz, Austria) equipped with a 25 mm serrated parallel plate geometry (PP25/P), gapped to 2 mm. Strain sweep tests were run at a frequency of 1 Hz, ranging the strain from 0.01 to 100%. Frequency sweep tests were carried out in the linear viscoelastic region (1% strain), over a frequency range of 0.1-10 Hz. Mechanical spectra were then analyzed according to the “weak gel” theory (Gabriele, de Cindio, & D’Antona, 2001) as reported in Alamprese et al. (2012), in

order to calculate the number of interacting rheological units (z) and the strength of these interactions (A) according to the equation (2):

$$G^* = A \cdot \omega^{\frac{1}{z}} \quad (2)$$

where G^* is the complex modulus, ω is the frequency, z is related to the number of interacting rheological units within the three-dimensional network of the gel, and A is the strength of these interactions.

2.7 Statistical analyses

Experimental results obtained by the whole egg samples treated in the ohmic static cell and the corresponding raw and reference samples were processed by multifactor analysis of variance (MANOVA), studying the effects of the whole egg batch and treatment conditions. The least significance difference (LSD) test was applied to evaluate significant differences ($P < 0.001$) among the averages (Statgraphics Centurion 18, Statgraphics Technologies, Inc., The Plains, VA, USA).

Analytical data referred to the whole egg samples ohmic-treated in the pilot plant and the corresponding raw and reference samples were subjected to one-way analysis of variance (ANOVA) followed by LSD test (Statgraphics Centurion 18, Statgraphics Technologies, Inc., The Plains, VA, USA) in order to assess significant differences ($P < 0.001$) at time 0, i.e. just after production. Data acquired during storage at 4 ± 1 °C were processed by MANOVA, studying the effects of treatment conditions, storage time, and their interaction. LSD test was applied to evaluate significant differences ($P < 0.001$) among the averages (Statgraphics Centurion 18, Statgraphics Technologies, Inc., The Plains, VA, USA).

3. Results and discussion

3.1 Ohmic treatments in the static cell

Three different batches of raw liquid whole egg were used to repeat in the static cell all the ohmic heat treatments carried out under different temperature \times time conditions as described in §2.2. The obtained experimental pasteurized samples (65.5-3, 70-1, and 67-4.5) were characterized in terms of color, apparent viscosity, foaming and gelling properties. Due to a colorimeter failure, color was evaluated only for two of the three batches. The results were compared to those of the corresponding batches of raw material (RAW_S) and of product conventionally pasteurized in a heat plate exchanger (REF_S) (Tables 1 and 2).

Whole egg color is an important feature because consumers associate it to the quality and freshness of this ingredient. It is mainly defined by the color of yolk and it affects the color of the final food products in which whole egg is used. Feed and nutrition technology of laying hens clearly influence whole egg color, but also egg and egg product processing can cause significant color changes (Dvořák, Suchý, Straková, & Kopřiva, 2012). In this study, the whole egg batches 2 and 3 showed similar values of color parameters, except for b^* that was significantly ($P < 0.001$) higher in batch 2 (Table 1). However, the difference observed was not high and it can be considered a normal variation since Dvořák et al. (2012) found standard errors of b^* ranging from 0.5 to 1.6 in homogeneous groups of egg yolk samples. Results related to the different treatment conditions revealed a significantly ($P < 0.001$) lower a^* value for the conventionally pasteurized whole egg (REF_S) with respect to the raw material (RAW_S), indicating a higher green component. As for the ohmic treatments, significant color changes were observed only for samples 70-1 and 67-4.5, for which a

lower ($P < 0.001$) b^* value was measured in comparison to RAW_S. This is in contrast with Dvořák et al. (2012), who observed an increase in L^* and b^* values and a gradual reduction in a^* values with higher ohmic heating temperatures. Lower values of a^* and b^* compared to a non-treated product were found by Monfort, Mañas, Condón, Raso, and Álvarez (2012) for liquid whole egg conventionally pasteurized (60 °C for 3.5 min and 64 °C for 2 min) or treated by a combination of Pulsed Electric Field and heating (52 °C for 3.5 min, 55 °C for 2 min, or 60 °C for 1 min) in presence of triethyl citrate (2 g/100 g). According to de Souza and Fernández (2011), changes in color should be detectable by the naked eye for sample REF_S, whose ΔE^* value was > 3 (i.e. 4.2), and at a less extent for samples 70-1 and 67-4.5 (ΔE^* values 3.3 and 3.4, respectively). The lower intensity of a^* and b^* values in the treated whole eggs can be ascribed to the partial thermal degradation of carotenoids, which are sensitive especially to high temperatures (≥ 75 °C) (Fратиanni, Cinquanta, & Panfili, 2010; Monfort et al., 2012). Whole egg rheological behavior is a very important technological feature affecting thickening properties of this ingredient and industrial plant set up (Icier & Bozkurt, 2011). Whole egg apparent viscosity did not change significantly in the three considered batches, whereas the ohmic treatments caused a significant increase ($P < 0.001$) of this parameter, probably ascribed to a partial coagulation of the egg proteins. These results indicate that the applied treatment conditions are too much severe for the heat sensitivity of the product. Actually, Icier and Bozkurt (2011) reported a sharp increase in the consistency of a liquid whole egg ohmic-treated at 60 °C, probably due to the protein denaturation occurring at this temperature. The conventional heat treatment (sample REF_S) did not affect apparent viscosity, but this could be due to the higher shear stresses involved in the continuous treatment with the plate heat exchanger, which

can disrupt possible protein agglomerates caused by thermal coagulation (Lechevalier, Jeantet, Arhaliass, Legrand, & Nau, 2007).

Eggs produce high-volume and high-stability foams, able to coagulate with heat, important for foods such as angel cakes, sponge cakes, meringues, soufflés, and omelets (Froning et al., 2002). The three batches of whole egg used for the experiments did not show any significant differences ($P > 0.001$) in terms of foam consistency index, overrun, and instability (Table 1). On the contrary, the conventional pasteurization treatment (sample REF_S) caused a significant ($P < 0.001$) worsening of the foaming properties compared to those of the raw whole egg sample (RAW_S), whereas the ohmic heating beneficially affected foam overrun of the treated samples 65.5-3 and 70-1. These results are probably due to the reduced shear stress applied to the products treated in the ohmic static cell with respect to REF_S. Actually, Lechevalier et al. (2007) demonstrated that during egg white drying the presence of shear rates during pumping and filtering was the only processing factor significantly affecting foaming properties of the dried product. The Authors suggested as possible causes the complex protein tertiary structure modifications due to protein unfolding and aggregation: the higher hydrodynamic radius, the lower surface hydrophobicity, and the lower flexibility of the aggregated proteins are indeed harmful for protein diffusion and rearrangement at the air–water interface.

Gelling properties were evaluated in terms of whole egg gelling temperature, as well as water holding capacity (WHC), mechanical characteristics, and rheological behavior of the obtained gels (Table 2). Slight significant differences ($P < 0.001$) were observed among the three considered whole egg batches, indicating variability of raw materials. The observed differences are probably due to different freshness levels of the shell eggs

used, possibly linked to different storage lengths (Lechevalier et al., 2007). In particular, the higher gelling temperature observed for batch 3 ($P < 0.001$) could reflect a partial transformation of ovalbumin, the main protein of egg white responsible for gelling properties, into the more heat stable intermediate form. Actually, it is well known that ovalbumin changes during storage into a more heat stable form called s-ovalbumin, passing through an intermediate species. Shitamori, Kojima, and Nakamura (1984) found that ovalbumin has a denaturation peak measured by differential scanning calorimetry of 81.6 °C, whereas the intermediate form between ovalbumin and s-ovalbumin has a major denaturation peak at 84.4 °C.

As for the effects of the different thermal treatments, no changes were observed for gelling temperature and gel WHC, while gel mechanical and rheological characteristics were similarly affected. In particular, gel hardness (load) and strength (Young modulus) of REF_S were not significantly different ($P > 0.001$) from those of RAW_S, while significantly harder and stronger gels ($P < 0.001$) were obtained from ohmic-treated whole egg samples. Strain and frequency sweep curves of the gels obtained from the ohmic-treated whole egg samples were very similar (Fig. 2). However, the ohmic-treated samples gave gels with rheological interactions slightly stronger than those of RAW_S and REF_S (higher values of A), but with a similar or lower number of interacting rheological units (z values) (Table 2). These findings are in agreement with a previous work demonstrating that a partial ovalbumin denaturation improves gelling properties of egg products (Alamprese et al., 2012).

In order to sum up, it is possible to conclude that ohmic treatments carried out in the static cell worsened the apparent viscosity of whole egg, while improving both foaming and gelling properties. Also when the same heating conditions usually applied in a plate

heat exchanger were considered, ohmic heating resulted in a product with better technological properties.

3.2 Ohmic treatments in the pilot plant

Based on the good results obtained in the static ohmic treatment of whole egg, new trials were performed in a continuous pilot plant, treating about 100 L of product for each temperature \times time combination. In particular, two different temperature \times time treatments were applied (71 °C \times 0.6 min and 68 °C \times 1.4 min), both assuring the reduction of 6 log cycles of *Listeria monocytogenes*. The results obtained were compared with those of the raw (sample RAW_C) and conventionally pasteurized product (sample REF_C). Moreover, another commercial pasteurized product was considered (sample REF_CO) together with the corresponding raw material (sample RAW_CO). REF_CO is produced by a combination of conventional heat treatment in plate exchanger and ohmic treatment, but the actual processing conditions are covered by industrial secret. Sample characterization in terms of technological properties is reported in Tables 3 and 4.

Color of the whole egg products treated in the continuous pilot plant (71-0.6 and 68-1.4) was significantly different ($P < 0.001$) from that of the corresponding raw sample (RAW_C) in terms of a^* and b^* values (Table 3). However, a^* values of these experimental samples were more similar to the values of RAW_C if compared with the ones obtained for the conventional pasteurized product (REF_C), indicating a lower thermal degradation of the yolk pigments in ohmic-treated whole eggs. In particular, sample 71-0.6 showed a ΔE^* value of 3.3, lower than that of samples 68-1.4 and REF_C (6.6 and 6.2, respectively). In the case of the sample treated by a combination of

conventional and ohmic heat treatment (REF_CO), ΔE^* was 4.6. Thus, for all samples color differences with respect to the corresponding raw products should be perceived by the naked eye (de Souza & Fernández, 2011), but differences were more evident for samples REF_C and 68-1.4.

Also in this case, the conventional heat treatment by plate exchanger caused a smaller modification of the product rheology (Table 3). However, the differences in apparent viscosity observed after treatments in the ohmic pilot plant were generally lower than the changes measured for the ohmic static cell. This is in agreement with the previously formulated hypothesis that the shear stresses associated to the continuous process help in disrupting possible protein agglomerates caused by thermal coagulation. In particular, among the ohmic-treated products, sample 68-1.4 resulted the most similar for apparent viscosity to the correspondent raw product (RAW_C). Its rheological behavior was in between the two commercial products (REF_C and REF_CO), thus demonstrating its marketing suitability.

The results about foaming properties confirmed that the ohmic heat treatment significantly improved ($P < 0.001$) foam consistency and overrun in comparison to the conventional pasteurization process (Table 3). Foam instability was not different from that of the raw products, except for sample 68-1.4 that showed a higher instability with respect to RAW_C, but not different from the corresponding commercial product (REF_C).

As regards gelling properties (Table 4), sample 68-1.4 resulted to be not significantly ($P > 0.001$) different from the raw material (sample RAW_C) and the conventional product (sample REF_C). Sample 71-0.6 was also very similar to RAW_C and REF_C, apart from a slightly higher hardness of the gel (load), coupled with a higher force (A)

and number (z) of the rheological interactions. The commercial product REF_CO, on the contrary, produced gels with a slightly lower hardness in comparison with the corresponding raw whole egg (RAW_CO). These results showed that in the continuous ohmic pilot plant a lower denaturation degree of proteins was obtained in comparison with the treatment in the static cell, thus causing little or no changes in gelling properties of the whole egg.

3.3 Whole egg technological properties during refrigerated storage

Whole egg samples treated in the continuous pilot plant were stored at 4 ± 1 °C for 30 days and analyzed every 7-8 days (Tables 5-6). The obtained results were statistically analyzed in order to highlight the main effects of treatment conditions and storage time, as well as the interaction treatment \times storage time. As expected, the treatment conditions accounted for the higher variations of the technological properties among samples, reflecting the considerations already done in the previous section (§3.2). All the products resulted quite stable during storage, with limited changes of the technological properties, often without a clear trend over the storage time. The yellow component of the color (b^*), gelling temperature, and Young modulus of gels remained constant over all the storage time, which thus resulted a non-significant factor ($P > 0.05$). The interaction treatment \times storage time resulted highly significant ($P < 0.001$) for all the tested properties, with the exception of the gelling temperature that did not change during storage for all the samples. The significant treatment \times storage time interaction effect is due to a different behavior of the samples during storage. For apparent viscosity, the sample 71-0.6 showed a slight increase as a function of time, from 20.9 ± 0.8 to 27.6 ± 2.7 mPa s (Fig. 3). However, for all the other features no clear

systematic trends were identified, indicating that the different pasteurization treatments did not affect the storage stability of whole egg from a technological point of view.

Conclusions

In conclusion, the results of this study demonstrated that ohmic heating is a suitable technology for the preservation or even improvement of whole egg technological properties. Indeed, the ohmic treatments performed in the continuous pilot plant gave whole egg products with gelling performances similar to the raw and conventionally treated samples, while foaming capacity was even better. Heat treatments always caused some changes in the whole egg color, but the lowest difference with respect to the raw product was observed in one of the continuously ohmic-heated sample. Ohmic heating caused an increase in apparent viscosity, but this detrimental effect can be reduced by using the appropriate operating conditions. In particular, low temperature treatments are more suitable in order to minimize possible problems due to protein denaturation, which can lower product fluidity with consequent issues in production plant managing. Thus, temperature \times time combinations must be optimized in order to develop effective and efficient egg product pasteurization processes, able to maximize the synergistic effect on microbial inactivation and to minimize possible detrimental effects on functional properties.

This novel pasteurization technology widens the opportunities for food manufacturers of producing safe foods with improved technological functionalities. However, for large-scale applications, there are still some technical and economic issues to overcome.

Declarations of interest

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Legends to Figures

Fig. 1. Pictures of the ohmic equipment used: a) static cell; b) continuous pilot plant (Emmepiemme S.r.l.)

Fig. 2. Rheological behavior of gels obtained from raw, conventionally pasteurized, and statically ohmic-treated whole egg samples: a) strain sweep curves (G^* , complex modulus); b) frequency sweep curves (elastic, G' , and viscous, G'' , moduli are represented by full and empty symbols, respectively). Sample identification: ○ RAW_S, raw liquid whole egg; ○ REF_S, commercial whole egg product pasteurized by a conventional heat treatment in plate exchanger (at $65.5\text{ °C} \times 3\text{ min}$); △ 65.5-3, experimental whole egg sample treated in the static ohmic cell at $65.5\text{ °C} \times 3\text{ min}$; □ 70-1, experimental whole egg sample treated in the static ohmic cell at $70\text{ °C} \times 1\text{ min}$; ◇ 67-4.5, experimental whole egg sample treated in the static ohmic cell at $67\text{ °C} \times 4.5\text{ min}$. Relative standard deviation values $< 10\%$ ($n=9$).

Fig. 3. Apparent viscosity of commercial pasteurized and continuously ohmic-heated liquid whole eggs during storage at $4 \pm 1\text{ °C}$. Sample identification: ○ REF_C, commercial whole egg product pasteurized by a conventional heat treatment in plate exchanger (at $65.5\text{ °C} \times 3\text{ min}$); ● REF_CO, commercial whole egg product pasteurized by a combination of conventional heat treatment and ohmic heating; □ 71-0.6, experimental whole egg sample treated in the continuous ohmic pilot plant at $71\text{ °C} \times 0.6\text{ min}$; 68-1.4, experimental whole egg sample treated in the continuous ohmic pilot plant at $68\text{ °C} \times 1.4\text{ min}$. Relative standard deviation values $< 10\%$ ($n=3$).

Table 1. Mean values and standard errors of color, apparent viscosity, and foaming properties of raw, conventionally pasteurized, and statically ohmic-heated liquid whole eggs as a function of batch and treatment conditions.

Experimental factor	L*	a*	b*	Apparent viscosity (mPa s)	Foam consistency index (mA)	Foam overrun (%)	Foam instability (%)
Batch							
1	n.d.	n.d.	n.d.	23±2 ^a	288±8 ^a	425±15 ^a	80±2 ^a
2	61.0±0.3 ^a	- 2.2±0.4 ^a	42.2±0.2 ^b	19±2 ^a	274±8 ^a	415±15 ^a	82±2 ^a
3	60.6±0.3 ^a	- 3.0±0.4 ^a	40.8±0.2 ^a	14±2 ^a	251±8 ^a	374±15 ^a	81±2 ^a
Treatment							
RAW_S	61.1±0.4 ^a _b	- 0.5±0.7 ^b	42.5±0.3 ^b	10±2 ^b	278±10 ^b	369±19 ^b	79±2 ^a
REF_S	63.1±0.4 ^b	- 4.1±0.7 ^a	41.9±0.3 ^a _b	10±2 ^b	199±10 ^a	240±19 ^a	91±2 ^b
65.5-3	59.4±0.4 ^a	- 2.6±0.7 ^a _b	42.1±0.3 ^a _b	20±2 ^a	293±10 ^b	488±19 ^c	81±2 ^{ab}
70-1	60.0±0.4 ^a	- 2.9±0.7 ^a _b	40.6±0.3 ^a	24±2 ^a	299±10 ^b	474±19 ^c	75±2 ^a
67-4.5	59.9±0.4 ^a	- 3.1±0.7 ^a _b	40.7±0.3 ^a	29±2 ^a	288±10 ^b	453±19 ^b _c	78±2 ^a

RAW_S, raw liquid whole egg used for ohmic treatments in the static cell and for production of the commercial product pasteurized by a conventional heat treatment in plate exchanger; REF_S, commercial whole egg product pasteurized by a conventional heat treatment in plate exchanger (at 65.5 °C × 3 min); 65.5-3, experimental whole egg sample treated in the static ohmic cell at 65.5 °C × 3 min; 70-1, experimental whole egg sample treated in the ohmic cell at 70 °C × 1 min; 67-4.5, experimental whole egg sample treated in the ohmic cell at 67 °C × 4.5 min.

n.d., not determined.

^{a-c}: for each experimental factor, different letters on the same column indicate significant differences amongst mean values as identified by LSD test ($P < 0.001$).

Table 2. Mean values and standard errors of gelling properties of raw, conventionally pasteurized, and statically ohmic-heated liquid whole eggs as a function of batch and treatment conditions.

Experimental factor	Coagulation temperature (°C)	WHC (%)	Load (N)	Young modulus (kPa)	A (kPa s ^{1/2})	z
Batch						
1	80.8±0.1 ^a	96.4±0.2 ^a	15.3±0.1 ^c	53.1±0.4 ^c	14.3±0.2 ^b	16.3±0.1 ^a
2	81.5±0.1 ^b	95.8±0.2 ^a	12.7±0.1 ^a	44.5±0.4 ^a	11.9±0.2 ^a	18.1±0.1 ^c
3	83.0±0.1 ^c	95.9±0.2 ^a	14.0±0.1 ^b	48.3±0.4 ^b	13.8±0.2 ^b	17.1±0.1 ^b
Treatment						
RAW_S	81.8±0.2 ^a	96.2±0.3 ^a	13.0±0.2 ^a	45.7±0.6 ^a	12.8±0.3 ^{ab}	17.2±0.2 ^b
REF_S	81.8±0.2 ^a	96.1±0.3 ^a	12.9±0.1 ^a	46.2±0.6 ^a	12.4±0.3 ^a	18.2±0.2 ^c
65.5-3	81.7±0.2 ^a	95.6±0.3 ^a	14.9±0.1 ^b	51.0±0.6 ^b	13.5±0.3 ^{bc}	16.9±0.2 ^{ab}
70-1	81.7±0.2 ^a	96.3±0.3 ^a	14.2±0.1 ^b	49.5±0.6 ^b	14.3±0.3 ^c	16.3±0.2 ^a
67-4.5	81.7±0.2 ^a	96.0±0.3 ^a	15.0±0.1 ^b	50.9±0.6 ^b	13.5±0.3 ^{bc}	17.2±0.2 ^b

RAW_S, raw liquid whole egg used for ohmic treatments in the static cell and for production of the commercial product pasteurized by a conventional heat treatment in plate exchanger;

REF_S, commercial whole egg product pasteurized by a conventional heat treatment in plate

exchanger (at 65.5 °C × 3 min); 65.5-3, experimental whole egg sample treated in the static ohmic cell at 65.5 °C × 3 min; 70-1, experimental whole egg sample treated in the static ohmic cell at 70 °C × 1 min; 67-4.5, experimental whole egg sample treated in the static ohmic cell at 67 °C × 4.5 min.

WHC, water holding capacity; A, strength of rheological interactions; z, number of interacting rheological units.

^{a-c}: for each experimental factor, different letters on the same column indicate significant differences amongst mean values as identified by LSD test ($P < 0.001$).

Table 3. Mean values and standard errors of color, apparent viscosity, and foaming properties of raw, commercial pasteurized, and continuously ohmic-heated liquid whole eggs.

Treatment	L*	a*	b*	Apparent viscosity (mPa s)	Foam consistency index (mA)	Foam overrun (%)	Foam instability (%)
RAW_C	62.8±0.2 _b	- 3.7±0.1 _b	40.7±0.4 ^a	9.4±0.2 ^a	307±1 ^d	413±5 ^c	71±2 ^a
RAW_CO	60.8±0.2 _a	- 1.7±0.1 ^e	45.2±0.4 ^c _d	8.9±0.2 ^a	275±1 ^b	378±5 ^b	78±2 ^a
REF_C	62.1±0.2 _b	- 4.1±0.1 ^a _b	46.8±0.4 ^d	10.6±0.2 _a	216±1 ^a	317±5 ^a	99±2 ^b
REF_CO	63.1±0.2 _b	- 2.2±0.1 ^d	41.3±0.4 ^a _b	18.1±0.2 _c	336±1 ^f	505±5 ^e	83±2 ^a
71-0.6	62.5±0.2 _b	- 4.5±0.1 ^a	43.9±0.4 ^b _c	20.6±0.2 _d	317±1 ^e	465±5 ^d	77±2 ^a
68-1.4	59.6±0.2 _a	- 3.1±0.1 ^c	46.4±0.4 ^c _d	13.9±0.2 _b	294±1 ^c	484±5 ^d _e	99±2 ^b

RAW_C, raw liquid whole egg used for continuous ohmic treatment in the pilot plant and for production of the commercial product pasteurized by a conventional heat treatment in plate exchanger; RAW_CO, raw liquid whole egg used for the production of the commercial product pasteurized by a combination of conventional heat treatment in plate exchanger and ohmic treatment; REF_C, commercial whole egg product pasteurized in a plate heat exchanger (at 65.5°C × 3 min); REF_CO, commercial whole egg product pasteurized by a combination of conventional heat treatment and ohmic heating; 71-0.6, experimental whole egg sample treated in the continuous ohmic pilot plant at 71 °C × 0.6 min; 68-1.4, experimental whole egg sample treated in the continuous ohmic pilot plant at 68 °C × 1.4 min.

^{a-f}: for each experimental factor, different letters on the same column indicate significant differences amongst mean values as identified by LSD test ($P < 0.001$).

Table 4. Mean values and standard errors of gelling properties of raw, commercial pasteurized, and continuously ohmic-heated liquid whole eggs.

Treatment	Coagulation temperature (°C)	WHC (%)	Load (N)	Young modulus (kPa)	A (kPa s ^{1/2})	z
RAW_C	80.9±0.5 ^a	95.5±0.4 ^a	13.2±0.1 ^c	49.8±0.7 ^b	10.3±0.5 ^a	11±1 ^a
RAW_CO	83.2±0.5 ^a	94.8±0.4 ^a	10.5±0.1 ^b	37.1±0.7 ^a	10.8±0.5 ^a	19±1 ^{ab}
REF_C	80.9±0.5 ^a	95.2±0.4 ^a	13.2±0.1 ^c	48.0±0.7 ^b	13.3±0.5 ^{ab}	17±1 ^{ab}
REF_CO	82.7±0.5 ^a	93.9±0.4 ^a	10.0±0.1 ^a	34.7±0.7 ^a	11.1±0.5 ^a	20±1 ^{ab}
71-0.6	80.9±0.5 ^a	94.8±0.4 ^a	13.7±0.1 ^d	49.0±0.7 ^b	17.3±0.5 ^c	24±1 ^b
68-1.4	80.6±0.5 ^a	95.9±0.4 ^a	13.2±0.1 ^c	46.6±0.7 ^b	13.6±0.5 ^{ab}	17±1 ^{ab}

RAW_C, raw liquid whole egg used for continuous ohmic treatment in the pilot plant and for production of the commercial product pasteurized by a conventional heat treatment in plate exchanger; RAW_CO, raw liquid whole egg used for the production of the commercial product pasteurized by a combination of conventional heat treatment in plate exchanger and ohmic treatment; REF_C, commercial whole egg product pasteurized in a plate heat exchanger (at 65.5°C × 3 min); REF_CO, commercial whole egg product pasteurized by a conventional heat treatment in plate exchanger; 71-0.6, experimental whole egg sample treated in the continuous ohmic pilot plant at 71 °C × 0.6 min; 68-1.4, experimental whole egg sample treated in the continuous ohmic pilot plant at 68 °C × 1.4 min.

WHC, water holding capacity; A, strength of rheological interactions; z, number of interacting rheological units.

^{a-d}: for each experimental factor, different letters on the same column indicate significant differences amongst mean values as identified by LSD test ($P < 0.001$).

Table 5. Mean values and standard errors of color, apparent viscosity and foaming properties of commercial pasteurized and continuously ohmic-heated liquid whole eggs, as a function of treatment and storage time at 4 ± 1 °C.

Experimental factor	L*	a*	b*	Apparent viscosity (mPa s)	Foam consistency index (mA)	Foam overrun (%)	Foam instability (%)
Treatment							
REF_C	61.9±0.1 _b	- 4.3±0.1 _a	46.7±0.1 _d	10.3±0.5 _a	217±1 ^a	317±9 ^a	95±1 ^b
REF_CO	63.0±0.1 _d	- 2.1±0.1 _c	41.4±0.1 _a	17.6±0.5 _c	336±1 ^d	508±9 ^d	79±1 ^a
71-0.6	62.5±0.1 _c	- 4.3±0.1 _a	43.7±0.1 _b	22.4±0.5 _d	322±1 ^c	487±9 ^c	92±1 ^b
68-1.4	59.3±0.1 _a	- 2.9±0.1 _b	45.9±0.1 _c	12.8±0.5 _b	292±1 ^b	457±9 ^b	101±1 ^c
Time (days)							
0	61.8±0.1 _c	- 3.5±0.1 _a	44.6±0.1 _a	15.8±0.6 _b	291±1 ^{ab}	443±10 ^b	89±2 ^a
8	61.7±0.1 _c	- 3.5±0.1 _a	44.5±0.1 _a	14.3±0.6 _a	290±1 ^a	408±10 ^a	96±2 ^b
15	61.7±0.1 _b	- 3.4±0.1 _b	44.4±0.1 _a	15.8±0.6 _b	291±1 ^{ab}	454±10 ^a _b	93±2 ^{ab}
22	61.6±0.1 _b	- 3.4±0.1 _b	44.3±0.1 _a	16.5±0.6 _c	292±1 ^b	454±10 ^b	91±2 ^a
30	61.5±0.1 _a	- 3.3±0.1 _c	44.3±0.1 _a	16.4±0.6 _c	294±1 ^b	452±10 ^a _b	89±2 ^a

REF_C, commercial whole egg product pasteurized by conventional treatment in a plate heat exchanger; REF_CO, commercial whole egg product pasteurized by a combination of conventional heat treatment in plate exchanger and ohmic treatment; 71-0.6, whole egg treated in the continuous ohmic pilot plant at 71 °C × 0.6 min; 68-1.4, whole egg treated in the continuous ohmic pilot plant at 68 °C × 1.4 min.

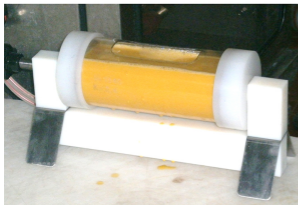
^{a-d}: for each experimental factor, different letters on the same column indicate significant differences amongst mean values as identified by LSD test ($P < 0.001$).

Highlights

- Static and continuous ohmic treatments affect whole egg technological properties.
- Ohmic heating worsens viscosity, but improves foaming and gelling properties.
- Treated whole egg samples were stable during storage at 4 °C for 30 days.
- Ohmic heating can be a suitable alternative to conventional pasteurization.

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a



b



Figure 1

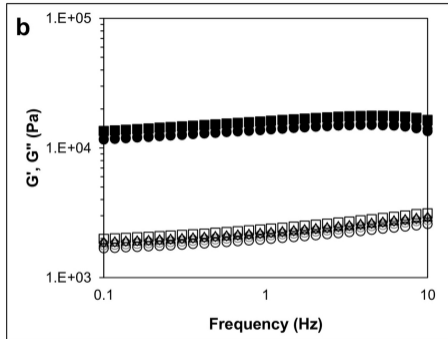
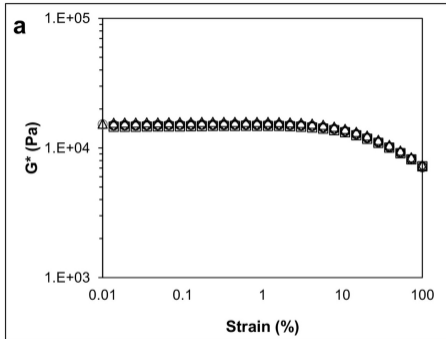


Figure 2

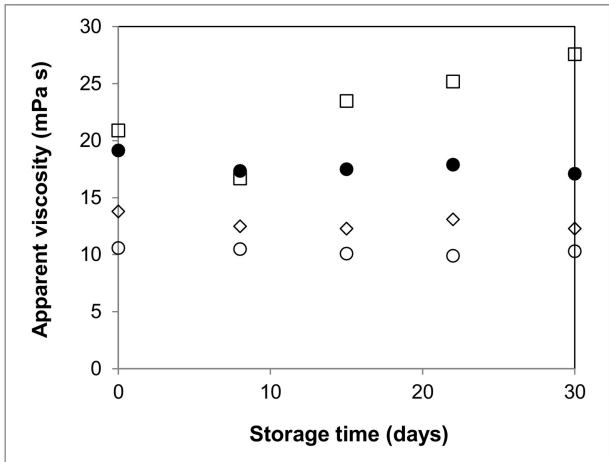


Figure 3