Application of ohmic heating for concentration of milk

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Abstract The concentration of milk through evaporation is the most commonly employed unit operation for the production of a wide array of traditional and industrial dairy products. Major problems associated with thermal evaporation are a loss of aroma, flavor and color change. Ohmic heating (OH) has an immense potential for rapid and uniform heating of liquid, semi-solid and particulate foods, yielding microbiologically safe and high-quality product. The effect of ohmic heating on physico-chemical, rheological, sensorial and microbial properties during concentration of cow milk, buffalo milk and mixed milk (50:50) was studied and compared to conventional evaporation. OH significantly increased free fatty acids (FFA), apparent viscosity, hydroxymethylfurfural (HMF) content, instrumental color values i.e. redness (a^*) and yellowness (b^*) values. However, pH value and whiteness (L^*) of the concentrated milk decreased significantly. OH caused a drastic reduction in microbiological counts and treated milk can be kept for a longer period.

Keywords Color · Concentrated milk · HMF · Ohmic heating · Rheology

Introduction

Thermal interventions are frequently applied in dairy and food industry to deliver the safe and quality products. The form of heat transfer is either conduction or convection, either of which requires longer heating-up time, exerting detrimental effects on quality of the finished product. The research and developments in non-conventional or alternative processing techniques are mostly focused to address the limitations of an existing process, at the same time offer desirable attributes to the products. The ohmic heating (OH) method is a rapid means of heat generation throughout a material. The OH works on the principle of conversion of electrical energy into thermal energy. When electricity passes through the conductive material, agitation of atoms or motion of charged particles occurs causing an increase in temperature (Sastry 2003). Ohmic heating has been recommended for the processing of a wide range of food products because of abundant quantity of water and polar components such as minerals, proteins in them. The important prerequisite for application of OH is that the material must be electrically conductive which is limiting factor in the processing of foods with low water and ionic content. Compositional suitability of milk as evident by high moisture content, the presence of ionic components and electrical conductivity in the range of 4–5.5 mS/cm (Nielen et al. 1992) makes it an ideal candidate for ohmic heating.

The potential applications of OH in the food industry can be processing of fluids containing particulates and high viscosity fluids (Palaniappan and Sastry 2002; Wang et al. 2001), but not high fat, low moisture and salt foods (Lima 2004). Remy et al. (2011) reported 3-log reduction in bacterial count, low β -lactoglobulin denaturation (< 20%), no neoformed Maillard products generation in milk.

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Moreover, there was no fouling within the ohmic heater, operated at constant soluble calcium level and the steady chemical environment of milk, even after continuous pasteurization of skim milk for 6 h. Due to its high energy efficiency, retention of nutrients, higher performance coefficient, improved product quality by reducing the microbial load to the great extent, OH becoming the alternative to conventional heating.

The present study was conducted with the primary objective of elucidating the effects of ohmic heating on physico-chemical, rheological, sensory and microbiological quality of concentrated milk.

Materials and methods

Fresh cow and buffalo milk was procured from Livestock Research Centre of National Dairy Research Institute, Karnal, Haryana, standardized to 3.5% fat and 8.5% SNF; 6% fat and 9% SNF, respectively. Furthermore, mixed milk was prepared by mixing standardized cow milk and buffalo milk in 1:1 proportion (4.75% fat and 8.75% SNF). Skim milk powder (SMP) used for standardization of milk was procured from Modern dairy, Karnal, India. The ohmic heater used in this study was fabricated by Chadha Sales Pvt. Ltd., New Delhi, India. Batch type ohmic heater consisted of a processing vessel (320 × 310 × 130 mm, 6 kg volume) made up of polypropylene, fitted with stainless steel electrodes (118.07 × 80.69 × 1.81 mm). The ohmic heater was provided with a control panel having provision for regulating voltage and temperature.

Preparation of concentrated milk

The standardized milk was taken into an ohmic heater and heated from 4 °C to boiling and subsequently concentrated under atmospheric conditions. The whole process was carried out at a constant voltage gradient of 13.33 V/cm and for a period of 75 min. Samples were collected at an interval of 15 min for further analysis. A control sample was prepared using conventional heating.

Analysis of the product

Fat, protein, ash, total solids content and titratable acidity were determined using standard AOAC methods 905.02, 991.20, 945.46, 990.19 and 947.05, respectively (AOAC 1998) and lactose content was determined by Lane-Eynon method (FSSAI 2011a).

pH

The pH (20 °C) of the sample was determined by Cyber-scan pH meter (model: pH2100, Eutech Instruments Pvt. Ltd., Singapore) in triplicate.

Free fatty acids content

Free fatty acid (FFA) content of the sample was determined by the method of Deeth et al. (1975).

Hydroxymethylfurfural value

The quantitative method described by Keeney and Bassette (1959) for measuring the HMF content was used to determine the extent of browning in concentrated milk.

Color

The color of samples (25 °C) was measured using a ColorFlex[®] colorimeter supplied by ColorFlex[®]. The instrument was calibrated with standard black and white tiles as specified by the manufacturer. Data were received in terms of L* (lightness), ranging from 0 (black) to 100 (White), a* (Redness), ranging from + 60 (red) to − 60 (green) and b* (yellowness), ranging from + 60 (yellow) to − 60 (blue) values of the International Commission for Color Measurement (CIE) system. The sample was placed in the transmission port of the optical unit of the instrument and L*, a* and b* values were noted in triplicate.

The concept of measuring the color change as the space modulus vector between initial and final color ordinates is termed as the total color difference (Martins and Silva 2002). The chroma value (C*), a quantitative attribute of colorfulness, describes the intensity of color changes.

The hue angle (h*), a qualitative attribute of color is used to describe whether the object is red, orange, yellow, green, blue, or violet.

Rheological analysis

Apparent viscosity (125 s^{−1}, 20 °C) and flow behavior of samples were determined using Rheometer (Model-MCR 52, Anton Paar, Austria) equipped with CP75-1° cone and plate assembly. The samples were tempered to 20 °C in a water bath, the cream plug was removed and the sample was mixed gently and loaded on a plate, allowed to equilibrate at 20 ± 1 °C for 1 min over it. The assessment of flow behavior of samples was carried out in the range of 0–1000 s^{−1} shear rate for 200 s. After completing the analysis, the data was fitted to rheological models namely Power law, Herschel–Bulkley and Bingham models and values of flow behavior index (n), consistency coefficient

(k), yield stress (σ) and correlation coefficient (R^2) were recorded.

Sensory evaluation

Samples were evaluated for organoleptic attributes by a panel of seven trained panelists from the faculty of Dairy Technology Division. The panelists were presented with 20 mL of samples ($20 \pm 2^\circ\text{C}$) to evaluate flavor, body and texture, color and appearance and overall acceptability using a 9-point hedonic scale.

Microbiological analysis

Samples were analysed for microbiological attributes viz. total plate count (TPC), coliform count, yeast and mold count and anaerobic spore count as per the standard methods given by FSSAI (2011b).

Statistical analysis

The results were analyzed by one-way analysis of variance (ANOVA) statistically employing SPSS software, version 21.0 and data were expressed as Mean $\pm$ Standard Error.

Results and discussion

Effect of ohmic and conventional heating on electrical properties of milk

It is evident from Fig. 1 that the initial voltage applied was 200 V which decreased 195 V for cow milk and mixed milk, while for buffalo milk it increased to 202 V at the end of processing (75 min). The current (ampere) values for all the milk were raised from 4.6 to 16.8 A till 30 min followed by gradual reduction which could be due to fouling of electrodes upon heating. Time required to raise the temperature from 10°C to boiling for the cow, buffalo and mixed milk was 17, 20 and 21 min, respectively. The

power consumed to process cow, buffalo and mixed milk ohmically for 75 min was 2.4, 2.5 and 2.5 kWh, respectively. This could be due to the reduction in conductance at higher fat (non-polar constituent) content in milk samples, as cow milk and buffalo milk were standardized to 3.5 and 6.0 percent fat content (Mabrook and Petty 2003).

Effect of ohmic and conventional heating on compositional characteristics of milk

Concentration of milk significantly ($p < 0.05$) increased all the compositional parameter, however, there was no significant effect of type of heating (conventional and ohmic) for the identical concentration factor (Table 1). The pH, titratable acidity, and FFA contents differed significantly ($p < 0.05$) in all the samples. The decrease in pH upon concentration can be attributed to degradation of lactose to organic acids primarily formic acid, conversion of soluble calcium phosphate to colloidal calcium phosphate, and dephosphorylation of casein (Singh 2004). FFA content of milk increased significantly ($p < 0.05$) in concentrated milk. During heating of milk at elevated temperatures, milk fat globule membrane (MFGM) constituents mainly proteins and phospholipids get damaged, which results into the formation of free fat and subsequently oiling off (Fox et al. 2015). Furthermore, the values of FFA content of concentrated milk were not abundant and no visible free fat observed by sensory panelists.

Effect of ohmic and conventional heating on physico-chemical properties of different milk during concentration

The effect of OH and conventional heating on physico-chemical properties of cow, buffalo and mixed milk during concentration are presented in Fig. 2.

Fig. 1 Changes in **a** voltage, **b** ampere and **c** temperature ($^{\circ}\text{C}$) of milk during ohmic heating

Table 1 Physico-chemical properties of different milk concentrated using ohmic and conventional heating

Type of milk	Sample	Total solids (%)	Protein content (%)	Fat content (%)	Ash content (%)	Lactose content (%)	pH	Titratable acidity (%L.A.)	FFA ($\mu\text{equi./mL}$)
Cow milk	CM0	12.03 ^a $\pm$ 0.67	2.91 ^a $\pm$ 0.11	3.45 ^a $\pm$ 0.15	0.64 ^a $\pm$ 0.04	5.03 ^a $\pm$ 0.21	6.62 ^f $\pm$ 0.00	0.16 ^b $\pm$ 0.00	0.03 ^a $\pm$ 0.00
	CM75	22.08 ^c $\pm$ 0.92	5.37 ^b $\pm$ 0.33	6.35 ^c $\pm$ 0.25	1.19 ^b $\pm$ 0.09	9.17 ^b $\pm$ 0.57	6.56 ^e $\pm$ 0.00	0.46 ^c $\pm$ 0.01	0.56 ^f $\pm$ 0.00
	CCM	22.11 ^c $\pm$ 0.89	5.35 ^b $\pm$ 0.35	6.40 ^c $\pm$ 0.40	1.19 ^b $\pm$ 0.06	9.17 ^b $\pm$ 0.17	6.56 ^{bc} $\pm$ 0.00	0.48 ^d $\pm$ 0.01	0.53 ^d $\pm$ 0.00
Buffalo milk	BM0	15.30 ^b $\pm$ 0.80	3.02 ^a $\pm$ 0.22	6.05 ^c $\pm$ 0.25	0.61 ^a $\pm$ 0.01	5.61 ^a $\pm$ 0.26	6.70 ^e $\pm$ 0.00	0.18 ^b $\pm$ 0.00	0.03 ^a $\pm$ 0.00
	BM75	28.36 ^d $\pm$ 0.86	5.61 ^b $\pm$ 0.29	11.15 ^e $\pm$ 0.35	1.13 ^b $\pm$ 0.003	10.47 ^c $\pm$ 0.47	6.58 ^d $\pm$ 0.00	0.46 ^c $\pm$ 0.01	0.54 ^{de} $\pm$ 0.01
	CBM	28.32 ^d $\pm$ 1.04	5.60 ^b $\pm$ 0.25	11.15 ^e $\pm$ 0.35	1.12 ^b $\pm$ 0.03	10.44 ^c $\pm$ 0.44	6.56 ^{bc} $\pm$ 0.00	0.48 ^d $\pm$ 0.01	0.51 ^b $\pm$ 0.00
Mixed milk (1:1)	MM0	13.52 ^{ab} $\pm$ 0.52	3.04 ^a $\pm$ 0.20	4.80 ^b $\pm$ 0.20	0.62 ^a $\pm$ 0.03	5.06 ^a $\pm$ 0.26	6.60 ^e $\pm$ 0.00	0.17 ^{ab} $\pm$ 0.01	0.03 ^a $\pm$ 0.00
	MM75	24.37 ^c $\pm$ 1.23	5.48 ^b $\pm$ 0.38	8.55 ^d $\pm$ 0.25	1.15 ^b $\pm$ 0.05	9.19 ^b $\pm$ 0.39	6.55 ^b $\pm$ 0.00	0.47 ^{cd} $\pm$ 0.00	0.55 ^e $\pm$ 0.00
	CMM	24.40 ^c $\pm$ 0.90	5.51 ^b $\pm$ 0.29	8.55 ^d $\pm$ 0.25	1.15 ^b $\pm$ 0.05	9.18 ^b $\pm$ 0.28	6.53 ^a $\pm$ 0.00	0.48 ^d $\pm$ 0.00	0.52 ^c $\pm$ 0.00

Mean $\pm$ SE; n = 3; ^{a-g}Values with different superscripts within columns differ significantly ($p < 0.05$)

Apparent viscosity (η_{app})

Apparent viscosity (125 s^{-1} , 20°C) was found in a direct relationship with processing time (Fig. 2a). As the processing time increased, the apparent viscosity increased significantly ($p < 0.05$). The viscosity values were correlated well with total solid. Heating also causes partial denaturation of milk proteins, promote interaction among macromolecules, thus an overall increase in viscosity of concentrated milk. Among the milk samples, buffalo milk exhibited maximum apparent viscosity because it had maximum total solids, protein and fat content.

Hydroxymethylfurfural value

HMF values ($\mu\text{M/L}$ of milk) increased significantly ($p < 0.05$) with processing time. As the processing time increased, the HMF content increased significantly ($p < 0.05$). However, there was no significant effect of type of concentration on HMF content of concentrated milk. HMF content remained constant during initial heating of 30 min, increased slightly at 45 min and increased sharply at 60 and 75 min. HMF is considered a marker of severity of heat treatment for a wide range of sugar and protein containing foods including milk (Morales and Jiménez-Pérez 2001). It is one of the few intermediate compounds (furosine, hydroxymethylfurfural, carboxymethyllysine and acrylamide) formed during Maillard reaction which exert toxicological consequences (Borad et al. 2017). HMF content indicates the extent of heat treatment provided to food particles. Total HMF content of commercial milk samples with different fat content was in the range of $0.95\text{--}2.14 \mu\text{M/L}$ for pasteurized, $3.46\text{--}5.75 \mu\text{M/L}$ for direct UHT treated and $15.52\text{--}21.38 \mu\text{M/L}$ for sterilized milk samples (Morales and Jiménez-Pérez 1999). Results achieved in the present investigation were much higher than the above-reported work, probably because of the prolonged heating.

Color

Whiteness (L^*)

With the increase in OH time, all milk samples became darker as reflected by the decrease in whiteness (L^*) values of all the samples with an initial increase in whiteness after 15 min of OH time (Fig. 2c). The initial whitening of milk samples could be due to the denaturation of the heat labile milk proteins and subsequently its coagulation (Burton 1955b; Rhim et al. 1988b). Concentrated milk prepared using OH and conventional heating differed significantly ($p < 0.05$) in terms of whiteness. Ohmically concentrated milk was less white as compared to conventional heating.

Fig. 2 Effects of OH on physico-chemical parameters **a** apparent viscosity; **b** HMF content; **c** lightness (L^*); **d** redness (a^*); **e** yellowness (b^*); **f** total color difference (ΔE); **g** chroma (C^*) and **h** hue angle (h^*) of different types of milk

The reduction in L^* values of OH sample was in line with HMF production.

Redness (a^*)

Hunter a^* value (redness) of different milk was directly proportional to processing time and it increased significantly ($p < 0.05$) with time (Fig. 2d). There was a significant difference ($p < 0.05$) observed among redness values of the type of concentrated milk as well as the type of heating. Buffalo milk concentrate had maximum redness followed by mixed milk and cow milk. The increase in redness value of milk during heating appeared to follow similar patterns as reported by Rhim et al. (1988a) and Burton (1955a) and observed a linear relationship between heating time and temperature.

Yellowness (b^*)

Yellowness increased significantly ($p < 0.05$) with time owing to the formation of primary Maillard reaction products (Fig. 2e). As expected the b^* values were significantly ($p < 0.05$) higher for cow milk followed by mixed milk and least for buffalo milk because of the presence of carotenoids. There was a significant difference ($p < 0.05$) observed among yellowness values of types of concentrated milk and heating method.

Casein micelles in milk are responsible for the white color of milk. Heat-induced denaturation of whey proteins

and their aggregation to casein micelles, dephosphorylation of casein, breakdown of k-casein, and precipitation of soluble calcium phosphate on casein micelles lead to a reduction in the whiteness of milk. Further, the intensity increases with the commencement and subsequent progression of Maillard reactions.

Colored pigments formed during the advanced stage of Maillard reaction which is responsible for total color development are unsaturated, brown nitrogenous polymers and copolymers and bound to proteins (Morales and van Boekel 1998). This was confirmed by Fogliano et al. (1999) who reported that in the gluten-glucose model system, low molecular weight chromophores entrapped in high molecular weight polymers and trypsin treatment favored their release from the matrix. Later on Frank and Hofmann (2000) investigated the from carried out non-enzymatic browning of L-alanine and D-glucose model system and identified five key chromophores namely (Z)-2-[(2-furyl)methylidene]-5,6-di(2-furyl)-6H-pyran-3-one (**I**), [E]- and [Z]-1,2-bis(2-furyl)-1-pentene-3,4-dione (**IIa/IIb**), 4,5-bis(2-furyl)-2-methyl-3H-furan-2-one (**III**), (S,S)- and (S,R)-2-[4,5-bis(2-furyl)-2-hydroxy-2-methyl-3(2H)-pyrrol-1-yl]propionic acid (**IVa/IVb**) and 2-[(2-furyl)methylidene]-4-hydroxy-5-[(E)-(2-furyl)methylidene]methyl-2H-furan-3-one (**V**) that contributed 16% of the total color of the Maillard mixture. Among five different chromophores identified, compound I (orange), IIa/IIb (intensely yellow), III (strong fluorescent yellow) IVa/IVb (intensely orange) and V contributed 5.9, 6.9, 0.8, 1.7 and 0.7% of overall

Table 2 Rheological properties of different milk concentrated using ohmic and conventional heating

Models	Ostwald			Herschel–Bulkley				Bingham		
Sample	k (Pa s ⁿ)	n	R ²	σ (Pa)	k (Pa s ⁿ)	n	R ²	σ (Pa)	η_{inf} (mPa s)	R ²
CM0	0.189	0.449	0.985	0.0	0.265	0.524	0.995	63.6	2.58	0.973
CM75	0.477	0.283	0.852	725.8	0.721	0.428	0.981	9008.2	5.18	0.581
CCM	0.424	0.318	0.883	49.0	0.336	0.520	0.993	62.5	5.82	0.620
BM0	1.374	0.114	0.626	0.0	0.351	0.487	0.988	0.1	4.00	0.812
BM75	2.074	0.116	0.971	1442.4	0.972	0.143	0.998	2995.4	11.17	0.807
CBM	0.486	0.351	0.907	1286.7	0.100	0.713	0.999	1286.7	5.73	0.974
MM0	0.105	0.525	0.989	0.0	0.480	0.565	0.992	0.0	3.10	0.964
MM75	0.782	0.270	0.954	488.7	0.941	0.244	0.973	2239.1	6.52	0.998
CMM	0.439	0.387	0.885	997.0	0.051	0.807	0.998	1237.3	6.95	0.988

k = Consistency coefficient, n = flow behavior index, σ = yield stress, R^2 = correlation coefficient

color of Maillard mixture. In milk system, similar kind of chromophore could be produced which might be the reason for colored intermediates formed during Maillard reaction of milk and milk products and alteration in color characteristics characterized by a decrease in whiteness (L^*) and increase in redness (a^*) and yellowness (b^*) of the milk and milk products.

Yellowness and redness were significantly ($p < 0.05$) lower in all types of conventionally heated milk concentrate as compared to ohmically heated ones. The electrochemical reaction between SS and milk components and subsequent corrosion of SS electrodes might be the culprit of the brown color of concentrated milk (Pataro et al. 2014).

The total color difference (Fig. 2f), as well as chroma (Fig. 2g), increased with time.

Hue angle (h^*)

The hue angle (h^*) is the qualitative attribute of color and used to define a color with respect to a gray color with the same lightness. Hue angle of 0° or 360° denotes red hue, whereas angles of 90° , 180° , and 270° represent yellow, green and blue hues, respectively. The h^* value of concentrated milk samples are presented in Fig. 2h. The h^* value of all milk were in the yellow region. The h^* value increased during OH which indicated the shifting of the color of all milk samples toward the higher yellowish red region.

Effect of ohmic and conventional heating on rheological properties of milk during concentration

During concentration of milk employing ohmic heating, it was observed that with increasing the shear rate the viscosity decreased drastically and at the higher shear rate it reached near zero. The flow behavior index (n) value was

less than unity that confirmed the non-Newtonian behavior of concentrated milk (Table 2). In general, with time as concentration increased flow behavior index values lowered down; except for Bingham model. In cow milk and mixed milk, consistency coefficient (k) values also enhanced with time and level of concentration, however, it decreased rapidly in the initial stage, increased slowly and peaked at the end of ohmic heating in buffalo milk. The variability could be related to higher levels of proteins and minerals in it and pronounced heat-induced changes, in macromolecules. The correlation coefficient (R^2) of respective models indicated that Herschel–Bulkley model was best-fit one followed by Bingham and Ostwald model. Flow behavior index (n) of the best fit model was < 1 for all the samples, indicating that the flow behavior of concentrated milk was shear thinning.

As TS content increases, the rheological behavior of milk concentrates changes from Newtonian to time-dependent shear thinning (Trinh et al. 2007b). With increase in TS content under time independent conditions flow behavior changes from Newtonian to Power law to Bingham plastic or Herschel–Bulkley behavior (Bienvenue et al. 2003a, b; Trinh et al. 2007a, b). The TS content and consistency coefficient (k) are directly proportional to each other, while flow behavior index (n) is in inverse relationship with TS content (Stepp and Smith 1991; Sierzant and Smith 1993; Hinrichs 1999). The value of k becomes more sensitive to total solids as temperature decreases (Vélez-Ruiz et al. 1997).

Effect of ohmic and conventional heating on sensory attributes of milk during concentration

Sensory evaluation of concentrated milk samples indicated that there was no significant variation in overall acceptability scores of control (conventionally heated) and ohmic treated milk concentrates (Table 3). The ohmically heated

Table 3 Sensory attributes of different milk concentrated using ohmic and conventional heating

Sample	Flavour	Body and texture	Color and appearance	Overall acceptability
CCM	6.8 ^a ± 0.3	7.2 ^a ± 0.4	7.3 ^a ± 0.2	7.1 ^a ± 0.1
CM75	7.3 ^{ab} ± 0.0	7.1 ^a ± 0.3	7.5 ^a ± 0.0	7.3 ^a ± 0.1
CBM	7.3 ^{ab} ± 0.0	7.8 ^a ± 0.0	7.3 ^a ± 0.0	7.4 ^a ± 0.1
BM75	7.8 ^b ± 0.0	7.4 ^a ± 0.1	7.5 ^a ± 0.3	7.5 ^a ± 0.1
CMM	7.1 ^{ab} ± 0.4	7.4 ^a ± 0.4	7.2 ^a ± 0.4	7.3 ^a ± 0.3
MM75	7.7 ^b ± 0.0	7.5 ^a ± 0.5	7.7 ^a ± 0.4	7.7 ^a ± 0.4

Mean ± SE; n = 3; ^{a,b}Values with different superscripts within columns differ significantly ($p < 0.05$)

mixed milk concentrate had the maximum overall acceptability score (7.7) followed by buffalo milk. Flavour score of buffalo milk concentrate (ohmic) was maximum followed by mixed milk because of sweet, nutty and caramelized flavor of the former as reported by panelists. Body and texture score was maximum for the conventionally concentrated buffalo milk followed by mixed milk (OH). It was observed that OH buffalo milk and cow milk contained fine particulate material, probably heat-denatured proteins. Color and appearance score was also reported maximum for mixed milk (OH) followed by buffalo milk (OH).

Effect of ohmic and conventional heating on microbiological properties of milk during concentration

Initial microbial counts in raw milk samples analyzed as SPC, Y&M and coliform counts which decreased from 7.89, 4.10 and 3.75 log CFU/mL to 4.40, absent and absent for cow milk; 8.30, 4.27 and 3.36 to 4.44, absent and absent for buffalo milk; and 8.27, 4.25 and 3.39 to 4.46, absent and absent for mixed milk, respectively after 15 min of ohmic heating. Spore counts were nil in the raw milk itself. All counts were absent in conventionally concentrated milk. The total microbial counts reduction observed was in the range of 3–4 logs. The applied electric field in ohmic heating is expected to cause electroporation of cell membranes, which would be more severe in combination with heating. Yoon et al. (2002) observed a direct and indirect effect of applied electric field on the cell wall, and loss of membrane permeability resulted in leaching out of intracellular materials.

Conclusion

Ohmic heating based concentration led to increase in HMF content and titratable acidity, but the reduction in pH as compared to conventional heating. Formation of Maillard reaction products significantly reduced whiteness (L^*) value and increased the redness (a^*) and yellowness (b^*)

values. FFA content increased during ohmic heating but the values were not abundant and no visible free fat observed by sensory panelists. The concentrated milk exhibited shear thinning behavior with Herschel–Bulkley as the best-fitted model for rheological data. The concentrated milk samples were free from any microbial proliferation.

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References

- AOAC International (1998) Official methods of analysis of AOAC International, Arlington, Va, AOAC International edn, 16th edn. Association of Official Analytical Chemists, Washington
- Bienvenue A, Jimenez-Flores R, Singh H (2003a) Rheological properties of concentrated skim milk: importance of soluble minerals in the changes in viscosity during storage. *J Dairy Sci* 86:3813–3821. [https://doi.org/10.3168/jds.S0022-0302\(03\)73988-5](https://doi.org/10.3168/jds.S0022-0302(03)73988-5)
- Bienvenue A, Jimenez-Flores R, Singh H (2003b) Rheological properties of concentrated skim milk: influence of heat treatment and genetic variants on the changes in viscosity during storage. *J Agric Food Chem* 51:6488–6494. <https://doi.org/10.1021/jf034050>
- Borad SG, Kumar A, Singh AK (2017) Effect of processing on nutritive values of milk protein. Effect of processing on nutritive values of milk protein. *Crit Rev Food Sci Nutr* 57(17):3690–3702. <https://doi.org/10.1080/10408398.2016.1160361>
- Burton H (1955a) Color changes in heated and unheated milk I. The browning of milk on heating. *J Dairy Res* 21(2):194–203. <https://doi.org/10.1017/S0022029900007287>
- Burton H (1955b) Color changes in heated and unheated milk II. The whitening of milk on heating. *J Dairy Res* 22(1):74–81. <https://doi.org/10.1017/S0022029900007573>
- Deeth HC, Fitzgerald CH, Wood AF (1975) A convenient method for determining the extent of lipolysis in milk. *Aust J Dairy Technol* 30(3):109–111
- Fogliano V, Monti SM, Musella T, Randazzo G, Ritieni A (1999) Formation of coloured Maillard reaction products in a gluten-glucose model system. *Food Chem* 66:293–299. [https://doi.org/10.1016/S0308-8146\(99\)00058-8](https://doi.org/10.1016/S0308-8146(99)00058-8)
- Food Safety and Standards Authority of India (2011a) Manual of Methods of Analysis of Foods-Milk and Milk Products. New Delhi, India
- Food Safety and Standards Authority of India (2011b) Manual of Methods of Analysis of Foods-Microbiological Testing. New Delhi, India

- Fox PF, McSweeney PLH, Uniacke-Lowe T, McSweeney PLH, O'Mahony JA (2015) Heat induced changes in milk. In: Dairy chemistry and biochemistry. Springer, Cham Blackie academic & professional publishers, London, pp 350. https://doi.org/10.1007/978-3-319-14892-2_9
- Frank O, Hofmann T (2000) Characterization of key chromophores formed by nonenzymatic browning of hexoses and L-alanine by using the color activity concept. J Agric Food Chem 48(12):6303–6311. <https://doi.org/10.1021/jf0001987>
- Hinrichs J (1999) Influence of volume fraction of constituents on rheological properties and heat stability of concentrated milk. Milchwissenschaft 54(8):450–454
- Keeney M, Bassette R (1959) Detection of intermediate compounds in the early stages of browning reaction in milk products. J Dairy Sci 42:945–960. [https://doi.org/10.3168/jds.S0022-0302\(59\)90678-2](https://doi.org/10.3168/jds.S0022-0302(59)90678-2)
- Lima M (2004) Food preservation aspects of ohmic heating. In: Rahman MS (ed) Handbook of food preservation, 2nd edn. CRC Press, London, pp 741–750
- Mabrook MF, Petty MC (2003) Effect of composition on the electrical conductance of milk. J Food Eng 60(3):321–325. [https://doi.org/10.1016/S0260-8774\(03\)00054-2](https://doi.org/10.1016/S0260-8774(03)00054-2)
- Martins RC, Silva CLM (2002) Modelling colour and chlorophyll losses of frozen green beans (*Phaseolus vulgaris*, L.). Int J Refrig 25(7):966–974. [https://doi.org/10.1016/S0140-7007\(01\)00050-0](https://doi.org/10.1016/S0140-7007(01)00050-0)
- Morales FJ, Jiménez-Pérez S (1999) HMF formation during heat treatment of milk type products as related to milk fat content. J Food Sci 64(5):855–859. <https://doi.org/10.1111/j.1365-2621.1999.tb15927.x>
- Morales FJ, Jiménez-Pérez S (2001) Hydroxymethylfurfural determination in infant milk-based formulas by micellar electrokinetic capillary chromatography. Food Chem 72:525–531. [https://doi.org/10.1016/S0308-8146\(00\)00284-3](https://doi.org/10.1016/S0308-8146(00)00284-3)
- Morales FJ, van Boekel MAJS (1998) A study on advanced Maillard reaction in heated casein/sugar solutions: colour formation. Int Dairy J 8:907–915. [https://doi.org/10.1016/S0958-6946\(99\)00014-X](https://doi.org/10.1016/S0958-6946(99)00014-X)
- Nielen M, Deluyker H, Schukken YH, Brand A (1992) Electrical conductivity of milk: measurement, modifiers and meta-analysis of mastitis detection performance. J Dairy Sci 75(2):606–614. [https://doi.org/10.3168/jds.S0022-0302\(92\)77798-4](https://doi.org/10.3168/jds.S0022-0302(92)77798-4)
- Palaniappan S, Sastry S (2002) Ohmic heating. In: Juneja VK, Sofos JN (eds) Control of foodborne microorganisms. Marcel Dekker, New York, pp 451–460
- Pataro G, Barca GMJ, Pereira RN, Vicente AA, Teixeira JA, Ferrari G (2014) Quantification of metal release from stainless steel electrodes during conventional and pulsed ohmic heating. Innov Food Sci Emerg Technol 21:66–73. <https://doi.org/10.1016/j.ifset.2013.11.009>
- Remy Y, Mucicino F, Pain JP (2011) Continuous heat treatment of skim milk by ohmic heating. SumMilk, Parma
- Rhim JW, Jones VA, Swartzel KR (1988a) Kinetic studies in the color changes of skim milk. Lebensm Wiss Technol 21(6):334–338
- Rhim JW, Jones VA, Swartzel KR (1988b) Initial whitening phenomenon of skim milk on heating. Lebensm Wiss Technol 21(6):339–341
- Sastry SK (2003) Ohmic Heating. In: Heldman DR (ed) Encyclopedia of agricultural, food, and biological engineering. Marcel Dekker, New York, pp 707–711
- Sierzant R, Smith DE (1993) Flow behavior properties and density of whole milk retentates as affected by temperature. Milchwissenschaft 48(1):6–10
- Singh H (2004) Heat stability of milk. Int J Dairy Technol 57:111–119. <https://doi.org/10.1111/j.1471-0307.2004.00143.x>
- Stepp BL, Smith DE (1991) Effect of concentration and temperature on the density and viscosity of skim milk retentates. Milchwissenschaft 46(8):484–487
- Trinh B, Haisman D, Khanh TT (2007a) Rheological characterization of age thickening with special reference to milk concentrates. J Dairy Res 74(1):106–115. <https://doi.org/10.1017/S0022029906002366>
- Trinh B, Haisman D, Khanh TT (2007b) Effect of total solids content and temperature on the rheological behaviour of reconstituted whole milk concentrates. J Dairy Res 74:116–123. <https://doi.org/10.1017/S0022029906002287>
- Vélez-Ruiz JF, Barbosa Cánovas GV, Peleg M (1997) Rheological properties of selected dairy products. Crit Rev Food Sci Nutr 37(4):311–359. <https://doi.org/10.1080/10408399709527778>
- Wang CS, Kuo SZ, Kuo-Huang LL, Wu JSB (2001) Effect of tissue infrastructure on electric conductance of vegetable stems. J Food Sci 66(2):284–288. <https://doi.org/10.1111/j.1365-2621.2001.tb11333.x>
- Yoon SW, Lee CYJ, Kim KM, Lee CH (2002) Leakage of cellular material from *Saccharomyces cerevisiae* by ohmic heating. J Microbiol Biotechnol 12(2):183–188