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Control of oxidation-reduction potential during Cheddar cheese ripening and its effect on the production of volatile flavour compounds

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In cheese, a negative oxidation-reduction (redox) potential is required for the stability of aroma, especially that associated with volatile sulphur compounds. To control the redox potential during ripening, redox agents were added to the salted curd of Cheddar cheese before pressing. The control cheese contained only salt, while different oxidising or reducing agents were added with the NaCl to the experimental cheeses. KIO_3 (at 0·05, 0·1 and 1%, w/w) was used as the oxidising agent while cysteine (at 2%, w/w) and $Na_2S_2O_4$ (at 0·05 and 0·1%, w/w) were used as reducing agents. During ripening the redox potential of the cheeses made with the reducing agents did not differ significantly from the control cheese ($E_h \approx -120$ mV) while the cheeses made with 0·1 and 0·05% KIO_3 had a significantly higher and positive redox potential in the first month of ripening. Cheese made with 1% KIO_3 had positive values of redox potential throughout ripening but no starter lactic acid bacteria survived in this cheese; however, numbers of starter organisms in all other cheeses were similar. Principal component analysis (PCA) of the volatile compounds clearly separated the cheeses made with the reducing agents from cheeses made with the oxidising agents at 2 month of ripening. Cheeses with reducing agents were characterized by the presence of sulphur compounds whereas cheeses made with KIO_3 were characterized mainly by aldehydes. At 6 month of ripening, separation by PCA was less evident. These findings support the hypothesis that redox potential could be controlled during ripening and that this parameter has an influence on the development of cheese flavour.

Keywords: Oxidation-reduction potential, redox agents, Cheddar cheese, volatile flavour compounds.

A fundamental parameter that can influence cheese ripening, and that is not commonly taken into consideration, is oxidation-reduction (redox) potential (E_h). Therefore, monitoring and control of E_h during manufacture and ripening of cheese could be important to understand the effect of this parameter on growth and survival of microorganisms and on its organoleptic characteristics.

Redox potential can affect the levels of volatile flavour compounds in dairy products produced by the growth and activity of starter and non-starter lactic acid bacteria (Boucher et al. 2006; Kieronczyk et al. 2006) and could influence their metabolic pathways of flavour generation (Martin et al. 2011). In a study by Kieronczyk et al. (2006) on the effect of extracellular E_h on *in vitro* amino acid catabolism by two strains of *Lactococcus lactis*, differences were found in the flavour compounds produced under different redox potentials.

The development of a characteristic cheese aroma is influenced by redox potential (Davis, 1932; Kristoffersen, 1967; Green & Manning, 1982) and stable aroma is thought to be due to a negative E_h (−150 to −300 mV) (Beresford et al. 2001). Cheddar cheese has an E_h of about −120 mV and this negative value (Kristoffersen et al. 1964; Green & Manning, 1982; Urbach, 1993) is associated with the production of volatile sulphur compounds (Green & Manning, 1982; Kristoffersen, 1985).

In the literature, addition of chemical compounds like dithiotreitol, potassium ferricyanide, sodium borohydride,

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cysteine (Bolduc et al. 2006b; Kieronczyk et al. 2006; Ignatova et al. 2009) or the use of gasses like oxygen, nitrogen and hydrogen (Ignatova et al. 2009; Jeanson et al. 2009; Martin et al. 2010, 2011; Ebel et al. 2011) or the application of electro-reduction (Bolduc et al. 2006a; Schreyer et al. 2006, 2008; Haratifar et al. 2011) have been used to control the redox potential of dairy products.

However, only a few studies have been conducted on the addition of redox agents to cheese (Galesloot, 1961a; Green & Manning, 1982). Oxidising agents, like nitrate, nitrite or chlorate, were added to milk destined to the production of Edam cheese to prevent butyric acid fermentation and, as a consequence, the decrease in E_h was delayed (Vos, 1948; Galesloot, 1961a); however, in the absence of butyric acid bacteria, nitrate had no effect on the redox potential of Edam cheese (Galesloot, 1960).

Only in one study (Green & Manning, 1982) reducing agents (dithiothreitol, glutathione or cysteine) were added to cheese curd before the pressing stage of the manufacture of Cheddar cheese. The addition of reducing compounds caused a decrease in redox potential to values lower than the control cheese and led to the production of higher concentrations of hydrogen sulphide and methanethiol at 3 months of ripening.

Studies from our laboratory have measured redox potential during Cheddar cheesemaking and ripening (Topcu et al. 2008; McSweeney et al. 2010; Caldeo & McSweeney, 2012). We reported that during Cheddar cheesemaking a significant drop in redox potential (E_h around −120 mV) occurs at the whey drainage stage until the milling stage (Caldeo & McSweeney, 2012); the salting stage causes an increase in redox potential due to oxygen penetration. After salting, the redox potential decreases again to negative value within the first hours of pressing (McSweeney et al. 2010) and this value is maintained during ripening (Topcu et al. 2008; McSweeney et al. 2010).

The objective of this work was to control the redox potential during Cheddar ripening through the addition of oxidising or reducing agents to the salted curd before pressing. Cheeses were analysed to study the effect of the addition of redox agents on the ripening of Cheddar cheese and the development of flavour compounds.

Materials and methods

Cheddar cheese manufacture

Cheddar cheeses were made in the food processing facilities at University College Cork, Ireland, according to a standard Cheddar cheese-making protocol (Kosikowski & Mistry, 1997) utilising four open vats were filled with approximately 100 l of HTST-pasteurised (73·5 °C, 15 s) milk. The curd pieces obtained from the four vats were mixed and then separated into batches of 8 kg. To each batch 2·5% (w/w) of NaCl and oxidising or reducing agents were added. Four trials were manufactured. In the first trial, potassium iodate (KIO_3; Sigma-Aldrich, Steinheim, Germany) at 1% and 0·1% (w/w) were used as the oxidising agents while sodium hydrosulfite ($Na_2S_2O_4$; Sigma-Aldrich) at 0·05% (w/w) was used as the reducing agent. In the second and third trials, KIO_3 at 0·1% and 0·05% (w/w) were used as the oxidising agent while $Na_2S_2O_4$ at 0·1% (w/w) and cysteine (Cys, $C_3H_7NO_2S$; Sigma-Aldrich) at 2% (w/w) were used as reducing agents. In the fourth trial, KIO_3 at 0·1% (w/w) was used as the oxidising agent while $Na_2S_2O_4$ at 0·1% (w/w) and Cys at 2% (w/w) were used as reducing agents. In each trial, a control cheese was made without the addition of redox agents. After 20 min, the curd was moulded and pressed at 490 kPa overnight at room temperature. Cheese blocks were vacuum packed and ripened at 8 °C for up to 6 months.

Measurement of oxidation-reduction potential during ripening

Oxidation-reduction potential was measured following the method of Topcu et al. (2008) and Caldeo & McSweeney (2012). The accuracy of electrodes was checked against a 3 M KCl solution (Topcu et al. 2008) and tap water (Jeanson et al. 2009; Martin et al. 2011) at 25 °C.

The Pt-electrode was inserted directly into a cheese block samples of 10 × 10 cm to a depth of 5 cm and the reference electrode was placed 2·5 cm apart in a hole of 4 cm deep and 1·5 cm wide filled with 3 M KCl solution as described by Topcu et al. (2008).

The electrodes were connected to a data logger (Squirrel Data Logger 2040-2F16 Series, Grant, Data Acquisition, Cambridge, UK) through an amplifier (PHTX-21, Omega, USA) for data acquisition. The measured data were recorded every 5 min.

The redox potential data recorded (without reference to a hydrogen reference electrode) were converted to E_h according to Caldeo & McSweeney (2012) and Abraham et al. (2013) with temperature compensation.

For each cheese, single measurement of redox potential was taken at 1, 14, 30, 60, 120 and 180 d of ripening.

Measurement of microbial growth, compositional analysis and pH

Starter and non-starter lactic acid bacteria (LAB) counts were performed on 14, 30, 60, 120 and 180 d-old cheeses as described by Ciocia et al. (2013).

The composition (pH, protein, salt, moisture and fat) of 14-d-old cheeses was determined in triplicate. The protein content of the cheeses was determined by the macro-Kjeldahl method (IDF, 1986), salt by a potentiometric titration (Fox, 1963), moisture by oven drying at 103 ± 1 °C (IDF, 1982) and fat by the Gerber method (IIRS, 1955).

The pH was measured in triplicate at 1, 14, 30, 60, 120 and 180 d of ripening. pH of the cheeses were measured by probing the cheese directly with a combined glass electrode (PHC3001-8, Radiometer Analytical) connected to a pH metre (PHM210 Standard pH Metre, Radiometer Analytical).

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Determination of volatile compounds by SPME-GC-MS

Cheese samples at 2 and 6 months of ripening were wrapped in aluminium foil, vacuum packed and stored at −20 °C until analysed. Volatile compounds were analysed by solid phase microextraction coupled to gas chromatography-mass spectrometry (SPME GC-MS) at Teagasc Food Research Centre as described by Hou et al. (2014).

Flow cytometry

Flow cytometry (FCM) was measured as described by Kilcawley et al. (2012). Reference control populations of live, permeabilised/damaged, or dead cells were identified as described by Sheehan et al. (2005) and Doolan & Wilkinson (2009).

Statistical analysis

Analysis of variance (one-way ANOVA) of redox potential measurements, microbiological counts, composition and pH of the cheeses were conducted using SPSS Version 20·0 for Mac OS X (SPSS Inc., Chicago, IL, USA). When differences were significant ($P < 0{\cdot}05$), the means were analysed using Tukey's test.

The data for the volatile compounds were analysed by principal component analysis (PCA) by Unscrambler V 6·1 (CAMO AS, N-70421 Trondheim, Norway).

Results and discussion

Cheeses were analysed for composition at 14 d of ripening. Redox potential, microbial growth and pH were monitored at 1, 14, 30, 60, 120 and 180 d. The data reported for E_h and microbial growth are averaged values of three independent trials for all the cheeses, except for cheeses made with the addition of 1% KIO_3 and 0·05% $Na_2S_2O_4$ that were made only in Trial 1. Furthermore, cell viability of control cheeses and cheeses made with the addition of 0·1% KIO_3 was measured at 60 d of ripening.

Chemical composition, pH and microbiological growth of the cheeses

The values of moisture, salt, fat and protein contents of the cheeses were within the range of those typical of Cheddar cheese (data not shown) (Lawrence et al. 2004).

Changes in pH of control and experimental cheeses were measured during ripening (data not shown). The pH of the cheese made with the addition of 1% KIO_3 significantly differed from the control cheese and the other experimental cheeses and had values around 5·8 throughout ripening. During ripening, the pH of control cheese and cheese made with the addition of 0·05% KIO_3 was 5·2–5·3 and the other experimental cheeses had a pH significantly slightly higher (pH around 5·4) than the control. At the end of ripening, the pH of all the cheeses, except the cheese made with the addition of 1% KIO_3, had values between 5·3 and 5·4.

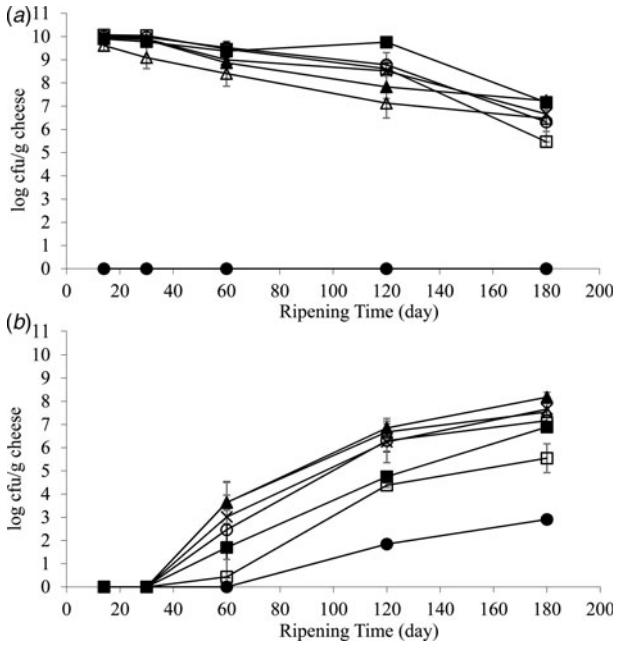

Fig. 1. Numbers of starter (A) and non-starter (B) lactic acid bacteria in control Cheddar cheese (○) and cheeses containing different redox agents during 6 months of ripening. Potassium iodate (KIO_3) at 1 (●), 0·1 (△) and 0·05% (▲) (w/w) were used as the oxidising agents while sodium hydrosulfite ($Na_2S_2O_4$) at 0·1 (□) and 0·05% (■) (w/w) and cysteine (Cys) at 2% (×) (w/w) were added as the reducing agents. Values are average of microbial counts of three independent trials, except for cheeses made with the addition of 1% KIO_3 and 0·05% $Na_2S_2O_4$ that were made only in Trial 1. Counts were measured in duplicate in each cheese.

Growth of starter and non-starter LAB are shown in Fig. 1a, b, respectively. At 14 d of ripening, starter LAB grew to similar values (9–10 log cfu/g cheese) in control cheeses and cheese made with the addition of 0·1 and 0·05% KIO_3, 0·1 and 0·05% $Na_2S_2O_4$ and 2% Cys. During ripening, those cheeses showed a typical decline in starter LAB number. Cheese made with 1% KIO_3 did not contain any viable starter LAB during ripening, suggesting that the quantity of KIO_3 used might have been toxic for the bacteria. Therefore, the cheese made with the addition of KIO_3 at 1% was produced only in the first trial.

During ripening, non-starter LAB levels increased in all the cheeses. However, at 120 and 180 d of ripening, the cheeses made with the addition of 1% KIO_3 and 0·1% $Na_2S_2O_4$ had non-starter LAB numbers lower by five and three log cycles, respectively, compared to the control cheese. Cheese made with the addition of 0·05% $Na_2S_2O_4$ had counts lower by three log cycles than the control cheese at 120 d of ripening. Other experimental cheeses showed a growth of non-starter LAB similar to the control cheese.

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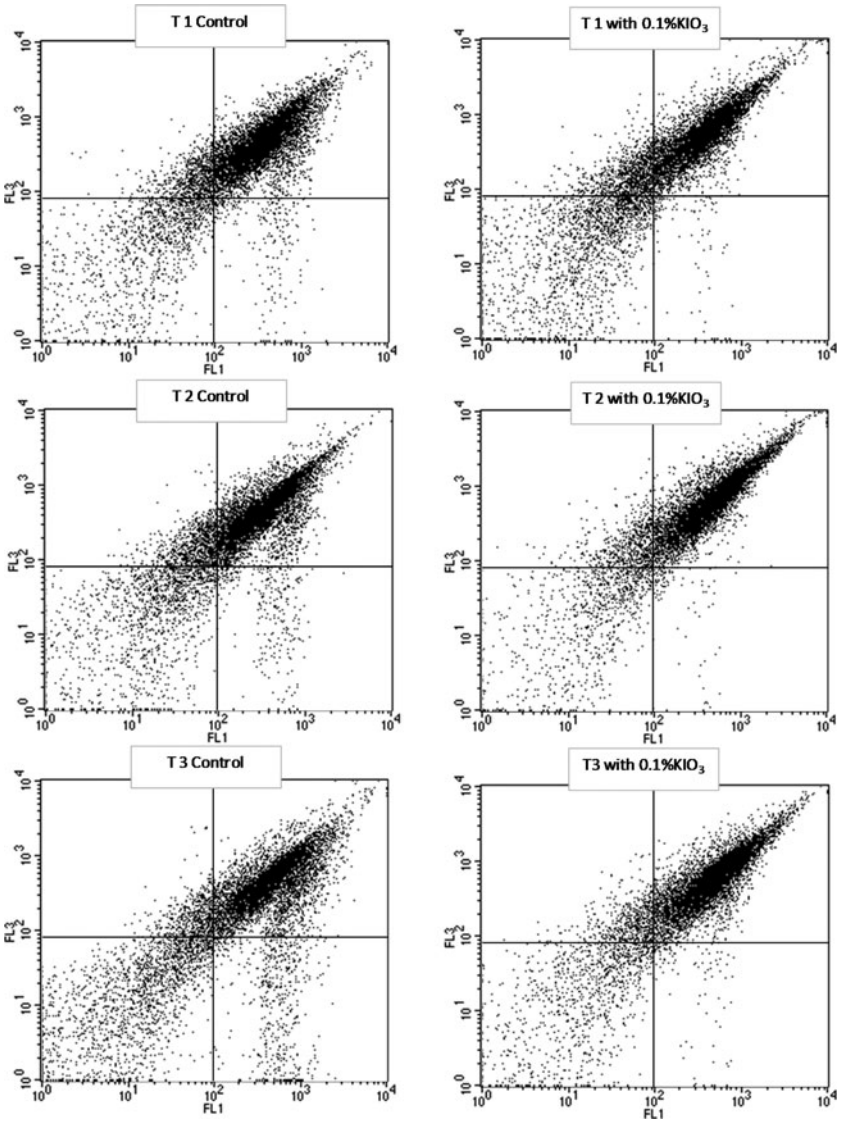

Fig. 2. Flow cytometer mulitparameter dot plots of SYTO 9 fluorescence (FL1) *vs.* propidium iodide fluorescence (FL3) of cells harvested from control cheeses and from cheeses with 0·1% KIO_3 of trial 1 (T1), 2 (T2) and 3 (T3).

Cell viability

Since KIO_3 at 1% appeared to be toxic for starter LAB growth in Trial 1, lower concentrations of KIO_3 were used (0·1 and 0·05%) in subsequent trials. FCM was used to identify bacteria cells in various physiological states in control cheese and cheese made with 0·1% KIO_3. Figure 2 shows the FCM plots of bacterial populations harvested. Lower left quadrant (LL) is mainly debris while lower right (LR) quadrant is normally live intact cells, upper left quadrant (UL) usually contains highly damaged/permeabilized/dead cells and upper right quadrant (UR) usually contains damaged/permeabilized cells which may also be viable (Sheehan et al. 2005; Doolan & Wilkinson, 2009).

In all cheeses distinct populations of permeabilized cells were observed in the UR regions of the dot plots. However, in the control cheeses there was also a distinct population of intact/live cells (LR), whereas fewer of these intact cells were evident in the cheeses made with 0·1% KIO_3. This population of cells could be starter or non-starter LAB (Sheehan et al. 2005).

FCM results indicate that the addition of 0·1% KIO_3 caused a decrease in the population of intact cells and did not affect the damaged/permeabilized and perhaps viable cells.

Control of oxidation-reduction potential during ripening

Figure 3 shows the E_h equilibrium values reached at each time point during cheese ripening.

The redox potential of control cheese was around −130 mV during ripening. This value is in agreement with

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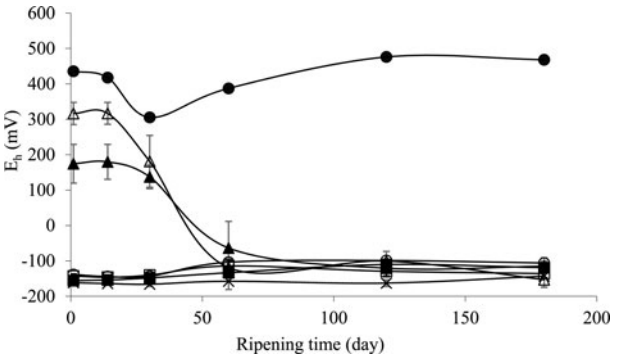

Fig. 3. Equilibrium values of oxidation-reduction potential (E_h) during ripening of control Cheddar cheese (○) and cheeses made with the addition of redox agents. Potassium iodate (KIO_3) at 1 (●), 0·1 (△) and 0·05% (▲) (w/w) were used as the oxidising agents while sodium hydrosulfite ($Na_2S_2O_4$) at 0·1 (□) and 0·05% (■) (w/w) and cysteine (Cys) at 2% (×) (w/w) were added as the reducing agents. Values are average of equilibrium E_h values of three independent trials, except for cheeses made with the addition of 1% KIO_3 and 0·05% $Na_2S_2O_4$ that were made only in Trial 1.

previous studies where E_h of mature Cheddar cheese was measured (Kristoffersen et al. 1964; Topcu et al. 2008; McSweeney et al. 2010). The E_h of cheeses made with the addition of reducing agents did not differ significantly from the control cheese.

Cheese made with the addition of 1% KIO_3 had positive redox potential values, around +400 mV, throughout ripening, probably due to the absence of LAB and the higher pH. Starter LAB were not able to survive during ripening and non-starter LAB only grew slowly at the end of ripening. In a study by Green & Manning (1982), Cheddar cheese made under aseptic conditions and in the absence of starter LAB, had a positive redox potential (+315 mV) at 42 d of ripening. Indeed, as demonstrated by Jeanson et al. (2009), the redox potential of milk treated with different gasses was constant over time in absence of bacterial growth.

In a second trial, lower quantities of KIO_3 (0·05 and 0·1%) were added to the cheeses in order to have an effect on the redox potential without influencing microbial growth. Cheeses made with the addition of 0·1 and 0·05% KIO_3 had a significantly higher redox potential compared to the control cheese and positive values of +316 and +179 mV, respectively, were maintained for the first 2 weeks of ripening (Fig. 3). At 1 month of ripening, E_h of cheeses made with 0·1 and 0·05% KIO_3 decreased slightly and after 2 months the E_h reached values closed to that of the control cheese (Fig. 3). In the past, studies on the addition of oxidising salts to the milk designed for Edam cheese manufacture have been conducted in order to prevent the development of anaerobic butyric acid bacteria (Vos, 1948; Peltola & Antila, 1953; Galesloot, 1960, 1961a, b) and a trend in redox potential similar to our results was found. Among the salts studied by Galesloot (1961a), KNO_3 was able to keep the E_h at values about 100 mV higher than the control cheese for 10 d and after that period the E_h decreased to values close to those of the control cheese. The inability to keep the E_h at constant positive values throughout ripening when oxidising agents were added to the cheese could be due to the bacterial growth in the cheese. The oxidising agents added might be reduced by bacterial redox systems present in the cheese (Jacob, 1979; Martin et al. 2010) or by chemical reaction with indigenous reducing compounds. In our study, the decrease in E_h of the experimental cheeses containing oxidising agents (KIO_3 at 0·05 and 0·01%) occurred in conjunction with the growth of non-starter LAB.

Volatile analysis

Study of the volatile compounds in the cheeses analysed at 2 and 6 months of ripening by SPME GC-MS identified 40 compounds. The compounds identified are typical of Cheddar cheese (Singh et al. 2003; Hannon et al. 2007) and their concentrations are similar to other studies (Hou et al. 2014).

Principal component analysis (PCA) was performed to assess the relationship within and among the cheeses and the volatile compounds identified. PCA of the volatile data was performed at 2 (Fig. 4a) and 6 (Fig. 4b) months on control cheeses and cheeses made with the addition of 0·1 and 0·05% KIO_3, 0·1% $Na_2S_2O_4$ and 2% Cys on the averaged peak areas of separate trials. Cheeses made with 1% KIO_3 and 0·05% $Na_2S_2O_4$ were excluded from the PCA analysis since they were produced only in Trial 1.

At 2 months of ripening, principal components (PC) 1 and 2, which accounted for 37 and 31% of the variation, respectively, clearly separated the cheeses made with the reducing agent from cheeses made with the oxidising agents (Fig. 4a). Cheeses made with the addition of reducing agents were characterized by the presence of sulphur and ketone compounds. Sulphur compounds like dimethylsulfide (DMS) and dimethyltrisulfide (DMTS) are considered important aroma compounds that characterize mature Cheddar cheese (Singh et al. 2003) and the addition of reducing agents favoured the production of sulphur compounds already at 2 months of ripening. Similarly, a study by Green & Manning (1982) reported that at 6 weeks of ripening concentrations of hydrogen sulphide and methanethiol were higher in the cheeses made with the addition of a reducing compound (Cys). Moreover, Martin et al. (2011) found an increase in DMS in yogurt made under reducing conditions throughout 28 d of storage. In contrast to our results, Kieronczyk et al. (2006), in a study on the flavour compounds produced by amino acid catabolism *in vitro* of two strains of *Lactococcus* under reducing and oxidising conditions, found that methanethiol and dimethyldisulfide were mainly produced under oxidising conditions. However, among the volatile sulphur compounds identified by the authors, DMTS was present in higher level in reducing system than in oxidising system.

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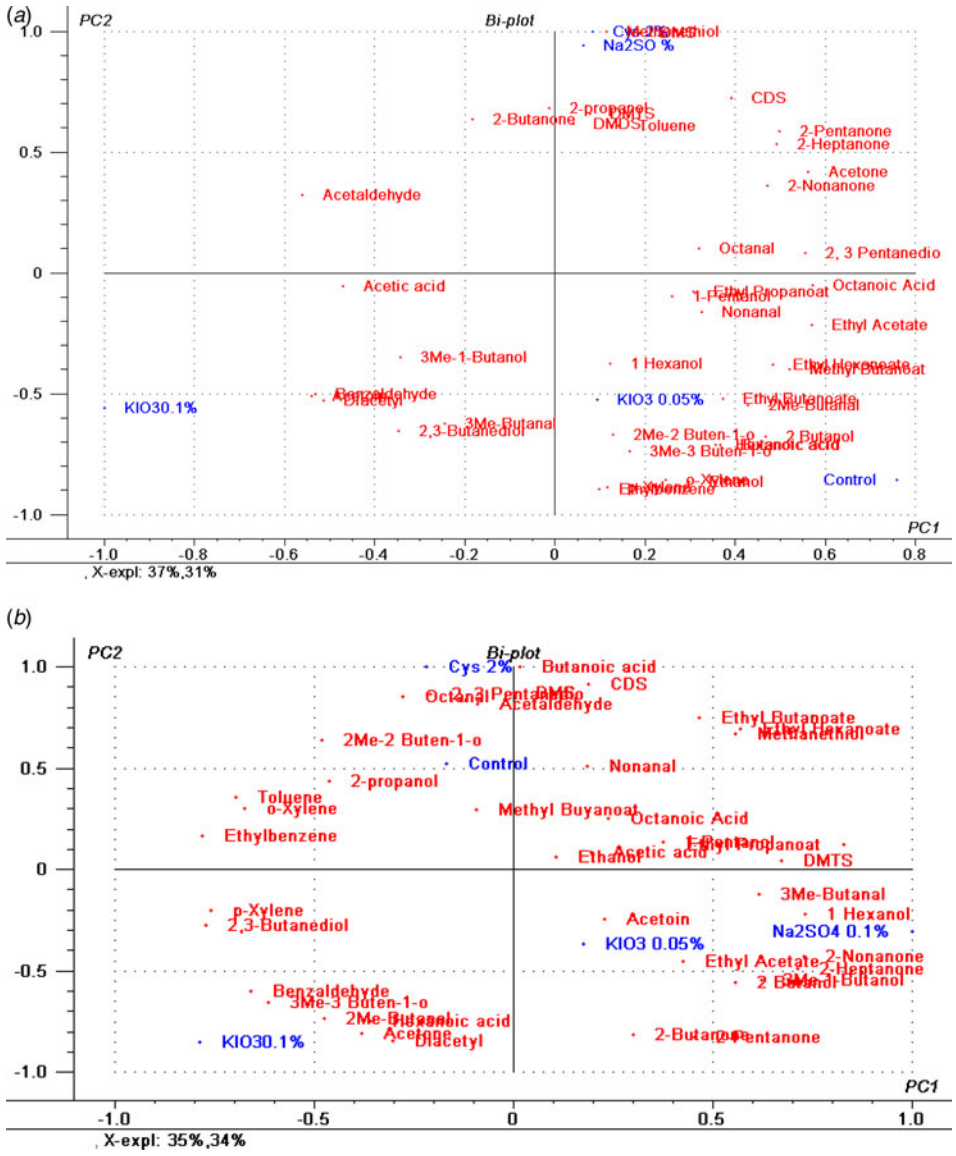

Fig. 4. Principal component analysis of data of volatile compounds identified in control Cheddar cheeses (Control), cheeses made with the addition of potassium iodate at 0·1 (KIO_3 0·1%) and 0·05% (KIO_3 0·05%), cheeses made with the addition of sodium hydrosulfite at 0·1% ($Na_2S_2O_4$ 0·1%) and cheeses made with the addition of 2% cysteine (Cys 2%) at two (A) and six (B) months of ripening. Values are mean of the different trials. At 2 months of ripening, principal components (PC) 1 and 2, accounted for 37 and 31% of the variation, respectively, and at 6 months, PC 1 and 2 accounted for 35 and 34%, respectively. The volatile compounds identified as written in red and the cheeses are shown in blue. Cheeses made with the addition of 1% KIO_3 and 0·05% $Na_2S_2O_4$ were excluded from the analysis as they were made only in one trial.

Moreover, the PCA of volatiles data at 2 month of ripening suggests that cheeses made with oxidising agents were characterized mainly by aldehydes, in particular benzaldehyde and acetaldehyde (Fig. 4a). These results are in agreement with previous studies. Kieronczyk et al. (2006) reported a higher quantity of benzaldehyde when LAB were grown *in vitro* at positive redox potential. A study by Martin et al. (2013) analysed the volatile compounds produced by yogurts under reducing or oxidising conditions, made by the usage of gasses. The authors found that yogurts made under positive redox potential had higher quantities of acetaldehyde and diacetyl and lower level of DMS.

Furthermore, the PCA at 2 month of ripening showed that other volatile compounds like esters and hydrocarbons were present at higher level in the control cheese and cheese made with 0·05% KIO_3 than in other cheeses (Fig. 4a).

At 6 month of ripening, PC 1 and 2 accounted for 35 and 34% of variation in the data, respectively, and separation between the cheeses was less pronounced (Fig. 4b).

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Control cheese and cheese made with the addition of Cys were separated by PC2 from the cheeses made with the addition of oxidising agents and $Na_2S_2O_4$.

Conclusion

In this study addition of oxidising and reducing agents was done at the salting stage of Cheddar cheese manufacture in order to understand the influence of oxidation-reduction potential on Cheddar cheese ripening.

Our findings support the hypothesis that redox potential has an influence on the development of cheese flavour during ripening. This study confirms that a negative redox potential is essential for the development of sulphur compounds (Green & Manning, 1982; Kristoffersen, 1985) and those compounds were present already at 2 months of ripening when reducing agents were added to the cheese at the salting stage.

Moreover, it seems that the cheese microflora has an important effect on the redox potential of Cheddar cheese. In absence of LAB, caused by the addition of a high concentration of KIO_3, the redox potential of our experimental cheese was positive over 6 months of ripening. When KIO_3 was added at 0·1 and 0·05% to the cheese, the E_h was positive for about 2 months of ripening and it decreased to negative values when the number of non-starter LAB increased. This suggests that LAB might be able to use the oxidising agents added, produce reducing metabolites and drive the environmental redox potential to values close to the E_h of the control cheese. Another hypothesis could be the reaction of the oxidising agents with naturally occurring reducing compounds and a consequence reduction on redox potential.

Redox potential can modify microbial activity and metabolic bacteria paths and as consequence act on the flavour development (Ledon & Ibarra, 2006).

In conclusion, understanding and controlling redox potential can be useful to guide aroma formation in dairy products.

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References

Abraham S, Cachon R, Jeanson S, Ebel B, Michelon D, Aubert C, Rojas C, Feron G, Beuvier E, Gervais P & De Coninck J 2013 A procedure for reproducible measurement of redox potential (E_h) in dairy processes. *Dairy Science and Technology* **93** 675–690

Beresford TP, Fitzsimons NA, Brennan NL & Cogan TM 2001 Recent advances in cheese microbiology. *International Dairy Journal* **11** 259–274

Bolduc MP, Bazinet L, Lessard J, Chapuzet JM & Vuillemard JC 2006a Electrochemical modification of the redox potential of pasteurized milk and its evolution during storage. *Journal of Agricultural and Food Chemistry* **54** 4651–4657

Bolduc MP, Raymond Y, Fustier P, Champagne CP & Vuillemard JC 2006b Sensitivity of bifidobacteria to oxygen and redox potential in non-fermented pasteurized milk. *International Dairy Journal* **16** 1038–1048

Boucher B, Brothersen C & Broadbent JR 2006 Influence of starter and non-starter lactic acid bacteria on medium redox. *Australian Journal of Dairy Technology* **61** 116–118

Caldeo V & McSweeney PLH 2012 Changes in oxidation-reduction potential during the simulated manufacture of different cheese varieties. *International Dairy Journal* **25** 16–20

Ciocia F, McSweeney PLH, Piraino P & Parente E 2013 Use of dairy and non-dairy *Lactobacillus plantarum, Lactobacillus paraplantarum* and *Lactobacillus pentosus* strains as adjuncts in Cheddar cheese. *Dairy Science & Technology* **93** 623–640

Davis JG 1932 Studies in Cheddar cheese: I. The oxidation-reduction potentials of ripening Cheddar cheese. *Journal of Dairy Research* **3** 241–253

Doolan IA & Wilkinson MG 2009 Comparison of the effects of various attenuation methods on cell permeability and accessibility of intracellular enzymes in *Lactococcus lactis* strains. *International Dairy Journal* **19** 215–221

Ebel B, Martin F, Le LDT, Gervais P & Cachon R 2011 Use of gases to improve survival of *Bifidobacterium bifidum* by modifying redox potential in fermented milk. *Journal of Dairy Science* **945** 2185–2191

Fox PF 1963 Potentiometric determination of salt in cheese. *Journal of Dairy Science* **46** 744–745

Galesloot THE 1960 Effect of oxidizing salts upon the oxidation-reduction potential of milk inoculated with starter. *Netherlands Milk and Dairy Journal* **14** 176–214

Galesloot THE 1961a Concerning the action of nitrate in preventing butyric acid fermentation in cheese. *Netherlands Milk and Dairy Journal* **15** 395–410

Galesloot THE 1961b Effect of oxidising salts upon the oxidation-reduction potential of cheese and upon the development of butyric acid bacteria in cheese. *Netherlands Milk and Dairy Journal* **15** 31–80

Green ML & Manning DJ 1982 Development of texture and flavour in cheese and other fermented products. *Journal of Dairy Research* **49** 737–748

Hannon JA, Kilcawley KN, Wilkinson MG, Delahunty CM & Beresford TP 2007 Flavour precursor development in Cheddar cheese due to lactococcal starters and the presence and lysis of *Lactobacillus helveticus*. *International Dairy Journal* **17** 316–327

Haratifar S, Bazinet L, Manoury N, Britten M & Angers P 2011 Impact of redox potential electrochemical modification and storage conditions on the oxidation reaction prevention in dairy emulsion. *Dairy Science & Technology* **91** 541–554

Hou J, Hannon JA, McSweeney PLH, Beresford TP & Guinee TP 2014 Effect of curd washing on cheese proteolysis, texture, volatile compounds, and sensory grading in full fat Cheddar cheese. *International Dairy Journal* **34** 190–198

IDF 1982 *Cheese and Processed Cheese. Determination of the Total Solids Content*. Standard 4A:1982. Brussels, Belgium: International Dairy Federation

IDF 1986 *Determination of the Nitrogen Content (Kjeldahl method) and Calculation of Crude Protein Content*. Standard 20A:1986. Brussels, Belgium: International Dairy Federation

Ignatova M, Prévost H, Leguerinel I & Guillou S 2009 Growth and reducing capacity of *Listeria monocytogenes* under different initial redox potential. *Journal of Applied Microbiology* **108** 256–265

IIRS 1955 *Determination of the Percentage of Fat in Cheese*. Irish Standard 69. Dublin, Ireland: Institute for Industrial Research and Standards

Jacob HE 1979 Redox potential. In *Methods in Microbiology*, Vol. **2**, pp. 91–123 (Eds JR Norris & DW Ribbons). London: Academic Press

Jeanson S, Hilgert N, Coquillard M-O, Seukpanya C, Faiveley M, Neveu P, Abraham C, Georgescu V, Fourcassié P & Beuvier E 2009 Milk acidification by *Lactococcus lactis* is improved by decreasing the level of dissolved oxygen rather than decreasing redox potential in the milk prior to inoculation. *International Journal of Food Microbiology* **131** 75–81

Kieronczyk A, Cachon R, Feron G & Yvon M 2006 Addition of oxidizing or reducing molecules to the reaction medium influences amino acid conversion to aroma compounds by *Lactococcus lactis*. *Journal of Applied Microbiology* **101** 1114–1122

https://doi.org/10.1017/S002202991600056X Published online by Cambridge University Press

Kilcawley KN, Nongonierma AB, Hannon JA, Doolan IA & Wilkinson MG 2012 Evaluation of commercial enzyme systems to accelerate Cheddar cheese ripening. *International Dairy Journal* **26** 50–57

Kosikowski FV & Mistry VV 1997 Cheese and fermented milk foods. In *Vol. 2: Procedures and Analysis*, 3rd edition (Ed. FV Kosikowski). Westport: LLC

Kristoffersen T 1967 Interrelationships of flavor and chemical changes in cheese. *Journal of Dairy Science* **50** 279–284

Kristoffersen T 1985 Development of flavor in cheese. *Milchwissenschaft* **40** 197–199

Kristoffersen T, Gould IA & Purvis GA 1964 Cheddar Cheese flavor. III. Active sulfhydryl group production during ripening. *Journal of Dairy Science* **47** 599–603

Lawrence RC, Gilles J, Creamer LK, Crow VL, Heap HA, Honoré CG, Johnston KA & Samal PK 2004 Cheddar cheese and related dry-salted cheese varieties. In *Cheese: Chemistry, Physics and Microbiology, Vol. 2: Major Cheese Groups*, pp. 71–102 (Eds PF Fox, PLH McSweeney, TM Cogan & TP Guinee). Amsterdam: Elsevier Applied Science

Ledon H & Ibarra D 2006 Method for modifying hygienic, physico-chemical and sensory properties of cheese by controlling the redox potential. France Patent WO2006106252

Martin F, Cayot N, Vergoignan C, Journaux L, Gervais P & Cachon R 2010 Impact of oxidoreduction potential and of gas bubbling on rheological properties of non-fat yoghurt. *Food Research International* **43** 218–223

Martin F, Cachon R, Pernin K, De Coninck J, Gervais P, Guichard E & Cayot N 2011 Effect of oxidoreduction potential on aroma biosynthesis by lactic acid bacteria in non fat yogurt. *Journal of Dairy Science* **94** 614–622

Martin F, Ebel B, Rojas C, Gervais P, Cayot N & Cachon R 2013 Redox potential: monitoring and role in development of aroma compounds, rheological properties and survival of oxygen sensitive strains during the manufacture of fermented dairy products. In *Lactic Acid bacteria – R & D for Food, Health and Livestock Purposes*, pp. 73–94 (Ed. JM Kongo). InTech Published online: DOI 10.5772/51137

McSweeney PLH, Caldeo V, Topcu A & Cooke DR 2010 Ripening of cheese: oxidation-reduction potential and calcium phosphate. *Australian Journal of Dairy Technology* **65** 178–184

Peltola E & Antila M 1953 The effect of oxidizing salts on the oxidation-reduction potential and ripening of Emmental cheese. *Proceedings of the 13th International Dairy Congress* **2** 729–731

Schreyer A, Bazinet L, Chapuzet J-M, Lessard J & Britten M 2006 Effect of milk fractions on the oxidoreduction potential evolution during electroreduction of milk. *Desalination* **200** 621–622

Schreyer A, Britten M, Chapuzet J-M, Lessard J & Bazinet L 2008 Electrochemical modification of the redox potential of different milk products and its evolution during storage. *Innovative Food Science and Emerging Technologies* **9** 255–264

Sheehan A, O'Loughlin C, O'Cuinn G, FitzGerald RJ & Wilkinson MG 2005 Cheddar cheese cooking temperature induces differential lactococcal cell permeabilization and autolytic responses as detected by flow cytometry: implications for intracellular enzyme accessibility. *Journal of Applied Microbiology* **99** 1007–1018

Singh TK, Drake MA & Cadwallader KR 2003 Flavor of Cheddar cheese: a chemical and sensory perspective. *Comprehensive Reviews in Food Science and Food Safety* **2** 139–162

Topcu A, McKinnon I & McSweeney PLH 2008 Measurement of the oxidation-reduction potential of Cheddar cheese. *Journal of Food Science* **73** 198–203

Urbach G 1993 Relations between cheese flavour and chemical composition. *International Dairy Journal* **3** 389–422

Vos EA 1948 The influence of potassium nitrate on the butyric acid fermentation in cheese. *Netherlands Milk and Dairy Journal* **2** 223–245