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# Using taste-induced saltiness enhancement for reducing sodium in Cheddar cheese: Effect on physico-chemical and sensorial attributes

Yogesh Khetra [a,*], Suresh Kumar Kanawjia [a], Ritika Puri [b], Rajender Kumar [a], Ganga Sahay Meena [a]

[a] *Dairy Technology, National Dairy Research Institute, Karnal, Haryana, 132001, India*
[b] *School of Food and Nutritional Sciences, University College Cork, Ireland*

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ABSTRACT

Reduced sodium Cheddar cheese (RSCC) was prepared by substituting 75% of sodium chloride (NaCl) with potassium chloride (KCl). To mask the inherent bitterness of KCl and to improve the flavour profile of RSCC, hydrolysed vegetable protein (HVP) as flavour enhancer (FE) and adenosine-5′-monophosphate (AMP) as bitter blocker (BB) were used. The study evaluated physico-chemical and sensory attributes of RSCC and changes in these attributes during ripening. Flavour, colour and appearance, saltiness and bitterness scores of both the samples were at par ($p < 0.05$) throughout the period of ripening, but body and texture scores of RSCC was significantly ($p < 0.05$) lower. This was probably due to increased casein hydration caused by substitution of sodium by potassium. Water activity ($a_w$) of RSCC was found to be significantly higher. The study suggested successful use of FE and BB for increasing the flavour profile of RSCC.



## 1. Introduction

Sodium chloride (NaCl) is an ingredient of utmost importance in cheese that not only governs the development of flavour and texture but also regulates the growth of microorganisms (Guinee & Fox, 2004). Cheddar cheese contains approximately 6 g sodium per kg cheese and thus it is considered as a high sodium containing food (Beardsley, 2017). With the increasing consumption of Cheddar cheese worldwide, there has been an increase in the contribution of cheese to total dietary sodium. Excess dietary sodium causes an increase in blood pressure, hypertension and other cardiovascular diseases (Cruz et al., 2011). The World Health Organisation has recommended a maximum level of 5 g NaCl per day for an adult (WHO, 2012); however, the consumption of sodium in most of the countries is well in excess of the optimum levels required. Thus, efforts have been made to reduce sodium in high sodium containing foods including Cheddar cheese (Busch, Yong, & Goh, 2013).

With NaCl being a vital ingredient in Cheddar cheese, stand-alone reduction results in product of inferior quality. Partial substitution of NaCl with potassium chloride (KCl) has been attempted in several cheese varieties (Beardsley, 2017) and considered as the most preferred method of sodium reduction in Cheddar cheese. However, bitter and metallic flavour and soft and pasty body are the common defects encountered in such cheeses (Cruz et al., 2011).

Taste–taste interactions or cross-modal interactions have been used successfully in reducing sugar and salt in foods. Taste–taste interaction is the combined use of two different tastes so that one stimulates the perception of other. Other than salt replacers, the ingredients that contribute umami taste are also used in low sodium foods to balance the overall flavour and to increase the saltiness perception through umami and salty taste interactions (Keast & Breslin, 2002). Ingredients that provide umami taste are high in glutamate and/or ribotides such as yeast extract and hydrolysed vegetable proteins (Busch et al., 2013; Dötsch et al., 2009).

There have been several studies on reducing the sucrose content in foods using taste–taste interactions, but limited literature is available on reducing sodium in foods through the application of this approach. Lawrence, Salles, Septier, Busch, and Thomas-Danguin (2009) reported saltiness enhancement in aqueous solutions containing salt related odours and postulated that odour-induced saltiness enhancement can be effective in reducing the overall sodium in foods without affecting the level of saltiness perception. However, the results need to be validated in real food systems that may involve complex interactions among food components. Lawrence et al. (2011) attempted to use odour–taste

* Corresponding author. Tel.: +919813902989.
*E-mail address:* yogeshndri@gmail.com (Y. Khetra).

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interactions in solid food model systems termed lipo-proteic matrices (LPM) that were prepared and flavoured with comté cheese flavour. The results suggested that salt-associated odours such as comté cheese can enhance saltiness in complex solid-food matrices containing the lower level of NaCl. A similar approach could be utilised in studying the effect of taste–taste interaction on saltiness enhancement in RSCC and to evaluate its effect on physico-chemical and sensory attributes.

Flavour enhancers (FE) can be used to produce the effect of taste–taste interaction in low or reduced sodium Cheddar cheese made by partial replacement of NaCl with KCl. Flavour enhancers such as monosodium glutamate (MSG), hydrolysed vegetable protein (HVP), yeast extract, disodium inosinate, and disodium guanylate have been tried in combination with KCl in Cheddar cheese (Grummer, Bobowski, Karalus, Vickers, & Schoenfuss, 2013), meat and meat products (McGough, Sato, Rankin, & Sindelar, 2012), soups and salad dressing (Kremer, Mojet, & Shimojo, 2009) to overcome the flavour defects associated with KCl. In enhancing umami, brothy, and savoury tastes, using FE opens the opportunity to produce low or reduced sodium products with high saltiness intensity and masked bitter flavour (Desmond, 2006).

A bitter blocker is a compound that blocks the activation of the gustducin in taste receptor cells and thereby prevents taste nerve stimulation (McGregor, 2004). The most extensively used among them is adenosine-5′-monophosphate (AMP), which improves the taste of mixtures such as NaCl and KCl (McGregor, 2004). These bitter blockers are reported to eliminate the alkaline and bitter off-flavours of KCl solutions (Desmond, 2006).

Khetra, Kanawjia, and Puri (2016) prepared reduced sodium Cheddar cheese (RSCC) by optimising the levels of saloni K (a commercial salt replacer), HVP and AMP. The study revealed successful use of these ingredients for manufacturing Cheddar cheese with upto 75% sodium replacement. The present investigation evaluated the effect of addition of these ingredients on the physico-chemical and sensory characteristics of Cheddar cheese during the ripening period.

## 2. Material and methods

### 2.1. Materials

Fresh cows' milk was procured from the Experimental Dairy, National Dairy Research Institute, Karnal (Haryana), India. Commercial microbial rennet in granular form produced from *Mucor pusillus* var. *Lindt* was procured from Meito Sangyo Co., Ltd., Tokyo, Japan. Edible grade NaCl and KCl salt was obtained from M/S Tata Chemicals, Mumbai, India and Polypharma Pvt. Ltd., Mumbai, India, respectively. Vegetable origin potassium rich salt replacer Saloni K (comprising 45–48% KCl), manufactured from the plant *Kappaphycusalvarezii*, was procured from NMS Pharma, Gujarat, India. Soy-based HVP was procured from Chaitanya Agro-Bio Tech Pvt. Ltd., Maharashtra, India. Food grade AMP was procured from Sigma Aldrich Co. LLC (St. Louis, MO, USA). All the chemicals and reagents used for chemical analyses were of AR grade.

### 2.2. Cheddar cheese manufacturing

RSCC with approximately 75% sodium reduction and full sodium cheddar cheese (FSCC) were manufactured from 400 kg of fresh cows', standardised (casein/fat = 0.7) and pasteurised (72 °C, 15 s in plate heat exchanger) milk using the method described by Khetra et al. (2016). Cheese curd was divided into 2 blocks of 20 kg each before salting. To manufacture RSCC, one block had 2 g of a mixture of Saloni K and KCl (1:1) added per 100 g cheese curd, together with 0.2 g HVP per 100 g cheese curd and 300 mg AMP per kg cheese curd in dried form at the stage of salting. The other batch had 2 g NaCl added per 100 g cheese curd to manufacture the control Cheddar cheese. The salted curd was pressed overnight, vacuum packaged in low density polyethylene film and kept for ripening (8 °C) and monitored for a period of 180 d. Cheese samples were prepared in triplicate and all analyses were performed in triplicate. Samples of cheeses were analysed on 1, 15, 30, 60, 90, 120, 150 and 180 days of ripening.

### 2.3. Chemical analyses

Triplicate analysis of FSCC and RSCC were carried out for proximate composition, $a_w$, pH, lactate content and sensory attributes. Moisture, protein, fat, ash, sodium and potassium content of control and RSCC were determined using standard methods of AOAC (1990). The $a_w$ of the cheese samples was measured by using Aqua Lab $a_w$ meter (Decagon Devices Inc., Washington, USA). pH of the cheese was determined electrometrically with the mains operated pH meter (LAB INDIA microprocessor controlled pH Analyser). Ten grams of grated cheese sample was weighed into a 25 mL beaker and made into paste with the addition of 10 mL distilled water. The pH meter was first calibrated using the standard buffers of pH 4.0 and 9.2 and standardised using pH buffer of 7 at 20 ± 0.1 °C. The lactate content of cheese samples was determined by the method described in ISI (1984).

### 2.4. Sensory evaluation of Cheddar cheese

Samples of Cheddar cheese were subjected to sensory evaluation by a panel of 10 trained judges from different divisions of ICAR-National Dairy Research Institute, Karnal who had a basic knowledge of cheese technology. The mean scores of the judges were used for statistical analysis. Samples were subjected to sensory evaluation in triplicate by each judge. Samples of FSCC and RSCC were presented for sensory evaluation after tempering at 15 °C. Cheddar cheese samples in the form of cube weighing 5.0 ± 0.2 g were put in a closed plastic cup coded with a random three-digit code and served in a random order in an air-conditioned room (21 °C). The cheese samples were evaluated for sensory quality attributes, i.e., flavour, body and texture and colour and appearance, on a 10 point scale using a standard modified Cheddar cheese sensory analysis scorecard (Khetra et al., 2016). Since the study pertained to the reduction of sodium, which has a direct impact on perceptible saltiness and bitterness of the product, saltiness and bitterness parameters were also included in the standard scorecard. Similar to other sensory attributes, saltiness and bitterness were scored on the basis of liking rather than intensity. A time interval of 90 s was provided between each sample during which panellists were asked to rinse their mouth with distilled water.

### 2.5. Statistical analysis

Statistical analysis was performed using SPSS statistical package (SPSSv.20, SPSS Inc., Chicago, IL, USA). Statistical analysis of data obtained through sensory evaluation was carried out using univariate analysis of variance wherein cheese samples and storage days were kept as fixed factors while sensory attributes and physico-chemical parameters were the dependent variables. A full factorial model was used and post-hoc analysis was carried out using the Tukey HSD test. Significant differences were reported for $p < 0.05$.

## 3. Results and discussion

### 3.1. Proximate analysis

Moisture (g 100 g$^{-1}$), ash (g 100 g$^{-1}$), protein (g 100 g$^{-1}$), fat (g 100 g$^{-1}$), sodium (mg 100 g$^{-1}$), potassium (mg 100 g$^{-1}$), pH and $a_w$ of FSCC and RSCC at 1st day of ripening are presented in Table 1.

### 3.2. Changes in the physico chemical parameters

Changes in the physico chemical parameters are presented in Tables 1 and 2. The moisture content of FSCC and RSCC decreased significantly ($p < 0.05$) during 180 d of ripening. Non-significant ($p > 0.05$) differences between FSCC and RSCC were observed in moisture content at all intervals of ripening. These findings are in agreement with the results of others (Aly, 1995; Ayyash & Shah, 2010; Fitzgerald & Buckley, 1985; Katsiari, Voutsinas, Alichanidis, & Roussis, 1998; Reddy & Marth, 1993; Thibaudeau, Roy, & St-Gelais, 2015) on the effect of partial substitution of NaCl by KCl in various cheese varieties. The significant decrease in moisture content during ripening might be due to the moisture permeability of the packaging material leading to moisture loss from the product. Ash content of both FSCC and RSCC increased significantly ($p < 0.05$) at the end of 180 d of ripening. A significant difference between ash content of FSCC and RSCC was observed during the entire ripening period; RSCC had a significantly higher ash content than FSCC at all ripening intervals. This higher ash content in RSCC is proposed to be due to the addition of HVP and AMP contributing significantly to the total ash content. In FSCC and RSCC, initial fat and protein content was observed to increase significantly ($p < 0.05$) during 180 d of ripening. A significant difference between fat and protein content of FSCC and RSCC was observed at each interval of ripening over the 180 d period; however, the fat content of RSCC was consistently less than that of FSCC throughout the ripening duration. The significant differences between protein and fat content of FSCC and RSCC may be due to the different moisture content of the two samples; moisture content varies depending on the water holding capacity of casein (casein hydration) which varies because of the NaCl and KCl addition (El-Bakry, Duggan, O'Riordan, & O'Sullivan, 2011).

The sodium content of both FSCC and RSCC was observed to increase significantly during the ripening period ($p < 0.05$) (Table 2), and a significant difference ($p < 0.05$) between the sodium contents of FSCC and RSCC was observed at each ripening interval, this being consistently higher in FSCC due to the higher amount of NaCl addition.

The potassium content of FSCC samples increased non-significantly ($p > 0.05$) during 180 d of ripening, whereas that of RSCC samples increased significantly ($p < 0.05$) (Table 2). Within FSCC and RSCC samples, potassium content differed significantly ($p < 0.05$) during entire ripening period, being higher in RSCC samples due to the considerable substitution of NaCl with KCl.

The increases in ash, fat, protein, sodium and potassium content during ripening were due to the concomitant decrease in the moisture content of cheeses.

**Table 2**
Changes in sodium and potassium during ripening of full sodium Cheddar cheese (FSCC) and reduced sodium Cheddar cheese (RSCC).[a]

| Days | Sodium | | Potassium | |
|---|---|---|---|---|
| | FSCC | RSCC | FSCC | RSCC |
| 1 | 748 ± 5$^{dX}$ | 165 ± 3$^{bY}$ | 111 ± 3$^{cX}$ | 731 ± 4$^{dY}$ |
| 15 | 750 ± 4$^{dX}$ | 165 ± 3$^{bY}$ | 111 ± 3$^{cX}$ | 731 ± 4$^{dY}$ |
| 30 | 764 ± 8$^{cdX}$ | 167 ± 3$^{bY}$ | 112 ± 3$^{bcX}$ | 732 ± 4$^{dY}$ |
| 60 | 785 ± 6$^{bcY}$ | 173 ± 3$^{abY}$ | 115 ± 3$^{abcX}$ | 739 ± 5$^{dY}$ |
| 90 | 795 ± 8$^{bX}$ | 175 ± 3$^{abY}$ | 118 ± 3$^{abcX}$ | 762 ± 2$^{cY}$ |
| 120 | 799 ± 7$^{bX}$ | 176 ± 3$^{abY}$ | 119 ± 2$^{abcX}$ | 772 ± 2$^{bcY}$ |
| 150 | 824 ± 10$^{aX}$ | 180 ± 5$^{aY}$ | 121 ± 4$^{abX}$ | 780 ± 4$^{bY}$ |
| 180 | 824 ± 10$^{aX}$ | 181 ± 5$^{aY}$ | 122 ± 3$^{aX}$ | 797 ± 3$^{aY}$ |

[a] Values (in mg 100 g$^{-1}$) are the mean ± SE (n = 9); means with different superscript lowercase letters in a column and different superscript uppercase letters in a row with differ significantly ($p < 0.05$).

#### 3.2.1. Changes in $a_w$

The $a_w$ of FSCC and RSCC changed significantly ($p < 0.05$) with ripening and the $a_w$ of RSCC remained significantly higher ($p < 0.05$) than that of FSCC at all ripening days (Table 3). A higher $a_w$ in Cheddar cheese prepared with low levels of NaCl has also been reported by Ozturk, Govindasamy-Lucey, Jaeggi, Johnson, and Lucey (2015) and Rulikowska et al. (2013). McMahon et al. (2014) reported that the $a_w$ of Cheddar cheese decreased by 0.01 unit from 1 d to 9 months in low salt and high salt cheeses. However, it was also reported that there was no significant difference in the $a_w$ of Cheddar cheese made by substitution of sodium with potassium on molar basis. The difference in $a_w$ of FSCC and RSCC could be for two reasons: either the difference in molecular weight of the compounds or the difference in hydration of proteins caused by NaCl or KCl. The $a_w$ lowering by addition of NaCl or KCl varies because at the equivalent mass, lower molecular weight compounds contain more molecules than higher molecular weight compounds, which results in a greater $a_w$ lowering effect; this could be the reason why KCl causes less lowering of $a_w$ than NaCl (Grummer & Schoenfuss, 2011). NaCl causes less casein hydration or water holding than the potassium based salts and thus the bound water in potassium substituted cheese is higher than the sodium based cheese and therefore $a_w$ of the potassium based cheese is higher (El-Bakry et al., 2011).

**Table 1**
Changes in moisture, ash, protein and fat during ripening of full sodium Cheddar cheese (FSCC) and reduced sodium Cheddar cheese (RSCC).[a]

| Days | Moisture (g 100 g$^{-1}$) | | Ash (g 100 g$^{-1}$) | | Protein (g 100 g$^{-1}$) | | Fat (g 100 g$^{-1}$) | |
|---|---|---|---|---|---|---|---|---|
| | FSCC | RSCC | FSCC | RSCC | FSCC | RSCC | FSCC | RSCC |
| 1 | 42.03 ± 0.47$^{aX}$ | 42.31 ± 0.18$^{aX}$ | 2.97 ± 0.00$^{deX}$ | 3.50 ± 0.06$^{cdY}$ | 20.60 ± 0.18$^{dX}$ | 19.64 ± 0.13$^{fY}$ | 27.13 ± 0.54$^{cX}$ | 26.14 ± 0.18$^{dX}$ |
| 15 | 41.87 ± 0.44$^{abX}$ | 42.31 ± 0.13$^{aX}$ | 2.94 ± 0.02$^{eX}$ | 3.40 ± 0.01$^{eY}$ | 20.87 ± 0.17$^{dX}$ | 20.19 ± 0.06$^{eY}$ | 27.32 ± 0.21$^{cX}$ | 26.19 ± 0.17$^{dY}$ |
| 30 | 40.80 ± 0.31$^{bX}$ | 41.62 ± 0.18$^{aX}$ | 2.99 ± 0.02$^{dX}$ | 3.44 ± 0.01$^{deY}$ | 20.93 ± 0.16$^{cdX}$ | 20.37 ± 0.13$^{eY}$ | 27.82 ± 0.15$^{cX}$ | 26.57 ± 0.21$^{dY}$ |
| 60 | 39.11 ± 0.08$^{cX}$ | 39.78 ± 0.27$^{bX}$ | 3.08$^{cX}$ ± 0.00 | 3.55 ± 0.02$^{bcY}$ | 21.31 ± 0.11$^{cX}$ | 20.67 ± 0.17$^{dY}$ | 28.62 ± 0.04$^{bX}$ | 27.40 ± 0.05$^{cY}$ |
| 90 | 38.32 ± 0.19$^{cX}$ | 38.97 ± 0.33$^{bcX}$ | 3.12 ± 0.01$^{bcX}$ | 3.60 ± 0.02$^{bY}$ | 21.92 ± 0.03$^{bX}$ | 21.31 ± 0.04$^{cY}$ | 28.99 ± 0.09$^{bX}$ | 27.76 ± 0.05$^{bcY}$ |
| 120 | 38.05 ± 0.41$^{cX}$ | 38.36 ± 0.32$^{cX}$ | 3.13 ± 0.02$^{bX}$ | 3.64 ± 0.02$^{abY}$ | 22.20 ± 0.07$^{bX}$ | 21.59 ± 0.04$^{bcY}$ | 29.12 ± 0.19$^{bX}$ | 27.89 ± 0.01$^{bY}$ |
| 150 | 36.12 ± 0.47$^{dX}$ | 37.00 ± 0.51$^{dX}$ | 3.23 ± 0.02$^{aX}$ | 3.72 ± 0.03$^{aY}$ | 22.30 ± 0.15$^{bX}$ | 21.69 ± 0.01$^{bY}$ | 30.02 ± 0.22$^{aX}$ | 28.50 ± 0.13$^{aY}$ |
| 180 | 36.11 ± 0.46$^{dX}$ | 37.00 ± 0.51$^{dX}$ | 3.23 ± 0.02$^{aX}$ | 3.72 ± 0.03$^{aY}$ | 23.00 ± 0.17$^{aX}$ | 22.17 ± 0.10$^{aY}$ | 30.03 ± 0.22$^{aX}$ | 28.35 ± 0.23$^{aY}$ |

[a] Values (in g 100 g$^{-1}$) are means ± SE (n = 9); means with different superscript lowercase letters in a column and with different superscript uppercase letters in a row differ significantly ($p < 0.05$).

**Table 3**
Changes in pH, water activity and lactate content during ripening of full sodium Cheddar cheese (FSCC) and reduced sodium Cheddar cheese.[a]

| Days | pH | | Water Activity | | Lactate (g 100 $g^{-1}$) | |
|---|---|---|---|---|---|---|
| | FSCC | RSCC | FSCC | RSCC | FSCC | RSCC |
| 1 | 5.21 ± 0.00$^{eX}$ | 5.20 ± 0.00$^{efX}$ | 0.983 ± 0.000$^{aX}$ | 0.985 ± 0.000$^{aY}$ | 0.92 ± 0.00$^{eX}$ | 0.92 ± 0.01$^{eX}$ |
| 15 | 5.18 ± 0.00$^{fX}$ | 5.19 ± 0.00$^{fX}$ | 0.984 ± 0.000$^{aX}$ | 0.985 ± 0.000$^{bY}$ | 0.94 ± 0.01$^{deX}$ | 0.94 ± 0.00$^{eX}$ |
| 30 | 5.17 ± 0.00$^{gX}$ | 5.18 ± 0.00$^{gX}$ | 0.983 ± 0.000$^{bX}$ | 0.983 ± 0.000$^{cY}$ | 0.98 ± 0.01$^{cdX}$ | 0.99 ± 0.00$^{dX}$ |
| 60 | 5.20 ± 0.00$^{efX}$ | 5.21 ± 0.00$^{eY}$ | 0.982 ± 0.000$^{bX}$ | 0.983 ± 0.000$^{cY}$ | 0.99 ± 0.00$^{cX}$ | 1.02 ± 0.01$^{dY}$ |
| 90 | 5.26 ± 0.00$^{dX}$ | 5.28 ± 0.00$^{dY}$ | 0.979 ± 0.000$^{cX}$ | 0.980 ± 0.000$^{dY}$ | 1.04 ± 0.00$^{bX}$ | 1.07 ± 0.01$^{cX}$ |
| 120 | 5.31 ± 0.00$^{cY}$ | 5.36 ± 0.00$^{cY}$ | 0.978 ± 0.000$^{cX}$ | 0.979 ± 0.000$^{dY}$ | 1.18 ± 0.02$^{aX}$ | 1.19 ± 0.02$^{bX}$ |
| 150 | 5.38 ± 0.01$^{bX}$ | 5.46 ± 0.00$^{bY}$ | 0.977 ± 0.000$^{cX}$ | 0.978 ± 0.000$^{dY}$ | 1.20 ± 0.03$^{aX}$ | 1.28 ± 0.01$^{aX}$ |
| 180 | 5.43 ± 0.01$^{aX}$ | 5.48 ± 0.01$^{aY}$ | 0.975 ± 0.000$^{cX}$ | 0.977 ± 0.000$^{dY}$ | 1.21 ± 0.02$^{aX}$ | 1.28 ± 0.01$^{aY}$ |

[a] Values are the mean ± SE (n = 9); means with different superscript lowercase letters in a column and different superscript uppercase letters in a row with differ significantly ($p < 0.05$).

### 3.2.2. Changes in pH

It can be observed from Table 3 that the pH of FSCC samples increased significantly ($p < 0.05$) from an initial value of 5.21–5.43 after 180 d of ripening. In RSCC samples, the pH increased significantly ($p < 0.05$) from 5.20 to 5.48 at the end of 180 d of ripening. However, both the cheeses showed an initial decrease in pH up to 30 d ripening. There was no significant difference observed between the two until 30 d of ripening. After 30 d, both FSCC and RSCC showed increase in pH up to 180 d of ripening. Both FSCC and RSCC samples were observed to have significantly ($p < 0.05$) different pH values after 30 d of ripening.

The pH of Cheddar cheese is controlled by combined effect of salting and buffering capacity. Salt content, or more accurately salt in moisture (S/M), is an important parameter that effects the change in pH during ripening. The pH of Cheddar cheese is little affected at S/M in the range from 1 to 5% (w/w); however, a further increase in S/M levels affects change in pH as it drastically decreases the starter activity and thus lactose metabolism is impeded (Guinee & Fox, 2004).

The decrease in the pH in both the cheese samples during first 30 d of ripening was presumably because of the continued starter growth leading to the conversion of lactose to lactic acid and thus decreasing the pH. There was non-significant difference in pH of the two cheeses up to 30 d of ripening possibly because of similar S/M levels that did not affect the survival of the starter organisms. There may be difference in the sensitivity of starter microorganisms towards sodium or potassium that may cause difference in pH (McMahon et al., 2014), but as reported by Guinee and Fox (2004), S/M ≤ 4%, which was used in the present study, has little inhibitory effect on the starter lactococci in Cheddar cheese. Thus, pH of the two cheeses had non-significant difference up to 30 d of ripening.

After 30 d, increasing trends in pH of both the samples were observed and at the end of ripening period of 6 months, pH was higher than the pH at 1 d in both cheese samples. This increase in pH may be attributed to the extensive solubilisation of colloidal calcium phosphate (CCP) (Guinee & Fox, 2004; McMahon et al., 2014). Hassan, Johnson, and Lucey (2004) reported that approximately 20% of the insoluble calcium in cheese becomes soluble after 3 months of ripening. Solubilisation of calcium also releases a corresponding amount of phosphate ions from the proteins. The pH of cheese increases as the concentration of $H^+$ ions decreases because the protons are absorbed by the phosphate ions as they get dissolved into the cheese serum.

It has been reported that the pH of the high-salt cheeses decreased during the first week of storage. Lactose content in Cheddar cheese before salting varies from 0.8 to 1.0% and get metabolised quickly through the continued activity of the starter culture lactococci and thus pH is reduced (McSweeney & Fox, 2004). Oh et al. (2014) also reported significantly different pH in reduced sodium cheese (prepared by using NaCl and KCl in a 1:1 ratio) and full sodium liquid Cheddar cheese extract. McMahon et al. (2014) studied the effect of sodium, potassium, magnesium, and calcium salt cations on pH, proteolysis, organic acids, and microbial populations during storage of full-fat Cheddar cheese and reported a faster initial decrease in cheese pH manufactured either with low levels of NaCl or with potassium substitution and it remained lower throughout storage.

### 3.2.3. Changes in lactate content

Ripening was observed to have significant ($p > 0.05$) effect on the lactate content of FSCC samples (Table 3). Similarly, significant ($p < 0.05$) effect of ripening was observed on the lactate content of RSCC. Both the cheese were observed to have significant ($p > 0.05$) difference in the lactate content only after ripening interval of 60 and 150 d.

The continuous increase in lactate content was possibly due to lactose fermentation by the action of starter and non-starter microorganisms throughout the ripening period. However, during ripening at any particular day, lactate content did not vary between FSCC and RSCC; this could be attributed to the similar S/M content of the two cheeses and, hence, similar microbial action on the lactose.

The relationship of lactate content or residual lactose with S/M content of cheese has been studied by several researchers. Møller, Rattray, Bredie, Høier, and Ardö (2013) reported lower concentrations of lactose in high salt cheese than in low salt and reduced salt cheeses. Low lactate and high residual lactose in high salt cheese was reported to be because of the salt sensitivity of the starter culture. Upreti, McKay, and Metzger (2006) also reported higher lactic acid content in cheeses with low S/M than in those with a higher S/M. These differences can be explained by the influence of S/M on $a_w$; a reduction of $a_w$ leads to a decrease in the growth of lactic acid bacteria (LAB) and concomitant decrease in the lactic acid production (Bassit, Cochet, & Lebeault, 1993).

## 3.3. Sensorial changes

### 3.3.1. Changes in flavour score

The flavour score (Table 4) of RSCC and FSCC increased significantly ($p < 0.05$) during 180 d of ripening. Comparing FSCC with RSCC, the flavour score of the different types of cheese was not significantly ($p > 0.05$) different over the entire ripening period, except for cheese ripened to 180 d that could possibly be due to the excessive development of bitterness in RSCC at the end of ripening.

The flavour components of Cheddar cheese are mainly small molecules derived from the enzymatic breakdown of proteins and lipids during cheese ripening (Fox & Wallace, 1997). Production of flavour components and development of cheese flavour are strongly associated with metabolism by adventitious LAB. Activity of these LAB is directly related to the amount of salt added to the

**Table 4**
Changes in flavour, body and texture and colour and appearance scores during ripening of full sodium Cheddar cheese (FSCC) and reduced sodium Cheddar cheese (RSCC).[a]

| Days | Flavour | | Body and texture | | Colour and appearance | |
|---|---|---|---|---|---|---|
| | FSCC | RSCC | FSCC | RSCC | FSCC | RSCC |
| 1 | $6.4 \pm 0.19^{dX}$ | $6.5 \pm 0.22^{dX}$ | $8.2 \pm 0.12^{abX}$ | $8.2 \pm 0.12^{aX}$ | $8.8 \pm 0.12^{aX}$ | $8.4 \pm 0.19^{bX}$ |
| 15 | $7.2 \pm 0.12^{cX}$ | $7.1 \pm 0.19^{cX}$ | $8.5 \pm 0.22^{aX}$ | $8.3 \pm 0.12^{aX}$ | $8.8 \pm 0.12^{aX}$ | $8.8 \pm 0.12^{abX}$ |
| 30 | $7.3 \pm 0.12^{cX}$ | $7.2 \pm 0.12^{cX}$ | $8.3 \pm 0.12^{aX}$ | $8.2 \pm 0.12^{aX}$ | $8.6 \pm 0.10^{aX}$ | $8.9 \pm 0.10^{aX}$ |
| 60 | $7.5 \pm 0.21^{cX}$ | $7.2 \pm 0.12^{cX}$ | $8.2 \pm 0.12^{abX}$ | $8.1 \pm 0.10^{aX}$ | $8.9 \pm 0.10^{aX}$ | $8.8 \pm 0.12^{abX}$ |
| 90 | $8.1 \pm 0.10^{bX}$ | $7.8 \pm 0.12^{bX}$ | $8.3 \pm 0.12^{aX}$ | $7.9 \pm 0.10^{aY}$ | $8.7 \pm 0.12^{aX}$ | $8.8 \pm 0.12^{abY}$ |
| 120 | $8.3 \pm 0.12^{bX}$ | $7.1 \pm 0.12^{abX}$ | $7.8 \pm 0.12^{bcX}$ | $7.2 \pm 0.20^{bY}$ | $8.6 \pm 0.19^{aX}$ | $8.8 \pm 0.12^{abX}$ |
| 150 | $8.8 \pm 0.12^{aX}$ | $8.4 \pm 0.19^{aX}$ | $7.7 \pm 0.12^{cX}$ | $7.2 \pm 0.20^{bX}$ | $8.5 \pm 0.16^{aX}$ | $8.7 \pm 0.122^{abX}$ |
| 180 | $8.8 \pm 0.12^{aX}$ | $8.4 \pm 0.10^{aY}$ | $7.3 \pm 0.12^{cX}$ | $6.7 \pm 0.12^{cY}$ | $8.8 \pm 0.12^{aX}$ | $8.6 \pm 0.19^{abX}$ |

[a] Values are the mean ± SE (n = 9); means with different superscript lowercase letters in a column and different superscript uppercase letters in a row with differ significantly ($p < 0.05$).

cheese. Any deviation, particularly reduction, leads to the variations in bacterial metabolism and thus alters flavour development (Ganesan & Brown, 2013).

In the present study, no significant differences were observed between FSCC and RSCC up to 5 months of ripening period. However, at the end of ripening, the flavour of RSCC became more bitter. This could be explained by the fact that potassium addition to cheese spurs flavour development via early induction and acceleration of amino acid metabolism (Ganesan & Brown, 2013; Ganesan & Weimer, 2007). Potassium addition to cheese also increases the rate of glycolysis and leads to more lactic acid production and thus alters or regulates the glutamate biosynthesis. This glutamate synthesis is considered vital for the amino acid metabolism in cheese (Ganesan & Weimer, 2007). The flavour of FSCC and RSCC did not vary significantly possibly because of the combined effect of HVP and AMP that improved the saltiness perception of Cheddar cheese. Improvement in the saltiness perception has been reported to be linked with better flavour and overall acceptability scores of products.

### 3.3.2. Changes in body and texture score

Body and texture scores (Table 4) of FSCC and RSCC decreased significantly ($p < 0.05$) during 180 d of ripening and a significant ($p < 0.05$) difference in the body and texture score between FSCC and RSCC was observed after 60 d of ripening. Cheddar cheese texture is affected by its composition and extent of proteolysis. The casein molecules interact to form a continuous network that is further supported by CCP and occludes the fat globules and serum phase. Such structural change with ripening leads to an altered texture of Cheddar cheese (Walstra, Wouters, & Geurts, 2006). The higher pH of high-salt cheese would appear to favour casein hydration and aggregate integrity, whereas CCP solubilisation and casein dissociation proceeded in the lower pH cheeses, creating smaller and more compact casein aggregates. Such changes, along with parallel enzymatic degradation of the casein network, are responsible for the short texture of Cheddar cheese (Lawrence et al., 2004). Decrease in the texture scores during ripening can also be attributed to an altered casein hydration. Casein hydration increases during the ripening phase that results in decreasing the hardness of cheese, thus making the cheese softer (Guinee, 2004).

Reduction in the amount of salt added to the cheese has been associated with textural defects that include soft, weak, pasty body and also leads to excessive proteolysis. However, replacement of NaCl with KCl has been reported to have no significant effect on body and texture of the cheese. The literature reports many studies on the impact of replacing NaCl with KCl on the production and quality of some cheeses, including halloumi (Ayyash & Shah, 2010), kefalograviera (Katsiari, Alichanidis, Voutsinas, & Roussis, 2001), Feta (Aly, 1995; Katsiari, Voutsinas, Alichanidis, & Roussis, 1997), Cheddar (Fitzgerald & Buckley, 1985; Grummer et al., 2013), processed mozzarella (Chavhan, Kanawjia, Khetra, & Puri, 2015) and nabulsi (Ayyash & Shah, 2011). In general, these studies reported that the partial replacement of NaCl with KCl did not modify cheese composition, proteolysis, texture, and sensory properties. Contrary to this, there are several findings that report that more than 50% substitution of NaCl with KCl alters the sensory properties of the cheese.

Aly (1995) prepared Feta-type cheese containing NaCl and KCl. Cheeses containing 0.5 g KCl per 100 g cheese and 1.5 g NaCl per 100 g or equal quantities (1 g per 100 g of each) had similar flavour and body and texture characteristics as that containing NaCl alone; while the flavour, body and texture scores for cheeses containing a combination of KC1 and NaCl in a 3:1 ratio were significantly lower ($p < 0.01$) than those for cheese from the other treatments. Similarly, Chavhan et al. (2015) prepared processed mozzarella cheese by substituting sodium with potassium ions both in salt and emulsifying salt and reported a decrease in the body and texture scores with increasing substitution. Increased KCl content impacted negatively on body and texture of the cheese and it was reported to be softer with pasty body. Cruz et al. (2011) also reported that replacement of NaCl with KCl must be carefully studied as high concentrations (>1 g per 100 g) tends to decrease cheese firmness.

The present study also reports lower scores for body and texture of RSCC throughout the ripening period of 180 d. These findings corroborate with those of Aly (1995) and Chavhan et al. (2015). Increased casein hydration due to the substitution of sodium by potassium could be the reason for lower scores as it has been reported that potassium leads to lesser cation binding to the protein and causes a lower hydrogen ion displacement effect and eventually result in a higher pH. This increased pH leads to the increased electrostatic repulsion between the casein molecules and facilitates higher protein hydration (El-Bakry et al., 2011). Increased casein hydration thus causes the product to become soft and pasty.

### 3.3.3. Changes in colour and appearance score

In FSCC and RSCC, colour and appearance scores (Table 4) did not vary significantly ($p > 0.05$) during ripening. A non-significant ($p > 0.05$) difference between FSCC and RSCC was observed in colour and appearance scores during entire ripening period. These results corroborates with the finding of Chavhan et al. (2015) who reported no significant difference in the colour and appearance of low sodium mozzarella cheese and low sodium processed mozzarella cheese during storage. Contrary to this, Felicio et al. (2016) reported lower scores for appearance of low sodium probiotic Minas cheese containing added arginine, possibly due to the water retention in the cheese matrix caused by arginine, which negatively affected the visual appearance of the product. The arginine (0.2 g per 100 g) was added to mask the bitterness of KCl used to manufacture low sodium Minas cheese. In our study, we added AMP to mask the bitterness of KCl. However, the level of AMP was too low to produce any significant effect on water retention and thus on colour and appearance of RSCC.

### 3.3.4. Changes in saltiness score

Saltiness score (Table 5) of FSCC and RSCC increased significantly ($p < 0.05$) after 180 d of ripening. When FSCC and RSCC were compared, the saltiness score of both types of cheese was not significantly ($p > 0.05$) different during entire ripening period.

Change in saltiness scores in FSCC and RSCC during ripening can be attributed to the simultaneous change in flavour and body and texture characteristics of cheese as influenced by the biochemical changes taking place during ripening. Many researchers have stressed the relationship of overall flavour and saltiness or sweetness of products. As a consequence of taste–taste or odour–taste interaction, saltiness scores might have increased during the course of ripening because of the generation of flavour compounds and textural changes in the product. These changes probably caused higher saltiness perception in the product.

FSCC and RSCC obtained at par saltiness scores throughout the ripening period of 180 d. This was probably the result of addition of HVP as FE and AMP as BB. The increased saltiness and decreased bitterness of RSCC made it equivalent to FSCC in perception of saltiness.

The effect of inclusion of aromas has been studied comprehensively in past few years primarily to reduce sodium in foods. Lawrence et al. (2009) have studied the effect of inclusion of odours on saltiness perception of salt solutions and concluded that salt-associated odours can enhance saltiness perception of the solutions. Anchovy, sardine, bacon, chicken, comté cheese, concentrated cheese, goat cheese, ham, Roquefort cheese and tuna among others were some of the odours studied. The results revealed a significant effect of odour intensity on saltiness perception. Higher saltiness was perceived in solutions containing odours of higher intensity. Thus, odour intensity could be used as an indicator of the potential to induce increased saltiness perception. Nasri, Septier, Beno, Salles, and Thomas-Danguin (2013) studied the influence of odour intensity and the nature of salty tastants to determine whether odour could enhance saltiness in salty solutions containing KCl alone or mixed with NaCl. It was observed that higher odour induced saltiness enhancement occurred when the salty taste was more reliant on KCl as compared with the odour-induced saltiness enhancement elicited by NaCl.

These findings validate that cross-modal odour(s)-taste(s) interactions may be an efficient strategy, in combination with the use of salt replacers, to compensate for sodium reduction in the complex food systems. Nasri, Beno, Septier, Salles, and Thomas-Danguin (2011) also studied the effect of level of salt on induced saltiness of odours and reported that salty odours resulted in higher odour-induced saltiness enhancement when the solution had lower salt content. This could again be advantageously used for eliciting saltiness of low sodium solutions using odours. From the above discussion, it can be concluded that the equivalent saltiness of FSCC and RSCC might have been the result of inclusion of HVP as FE in combination of AMP as BB.

**Table 5**
Changes in saltiness and bitterness scores during ripening of full sodium Cheddar cheese (FSCC) and reduced sodium Cheddar cheese (RSCC).[a]

| Days | Saltiness | | Bitterness | |
|---|---|---|---|---|
| | FSCC | RSCC | FSCC | RSCC |
| 1 | 7.1 ± 0.10$^{eX}$ | 7.0 ± 0.16$^{fX}$ | 9.2 ± 0.12$^{aX}$ | 9.1 ± 0.10$^{aX}$ |
| 15 | 7.3 ± 0.12$^{eX}$ | 7.2 ± 0.12$^{efX}$ | 9.2 ± 0.12$^{aX}$ | 9.0 ± 0.16$^{aX}$ |
| 30 | 7.7 ± 0.12$^{dX}$ | 7.5 ± 0.16$^{deX}$ | 8.8 ± 0.12$^{aX}$ | 8.6 ± 0.19$^{aX}$ |
| 60 | 8.1 ± 0.10$^{cX}$ | 7.9 ± 0.10$^{cdX}$ | 8.2 ± 0.12$^{bX}$ | 8.1 ± 0.10$^{bX}$ |
| 90 | 8.3 ± 0.12$^{cX}$ | 8.2 ± 0.12$^{bcX}$ | 7.8 ± 0.12$^{bcX}$ | 7.6 ± 0.25$^{cX}$ |
| 120 | 8.8 ± 0.12$^{bX}$ | 8.6 ± 0.19$^{abX}$ | 7.6 ± 0.25$^{cX}$ | 7.2 ± 0.20$^{cX}$ |
| 150 | 9.1 ± 0.10$^{abX}$ | 8.9 ± 0.25$^{aX}$ | 6.8 ± 0.12$^{dX}$ | 6.4 ± 0.19$^{dX}$ |
| 180 | 9.2 ± 0.12$^{aX}$ | 9.0 ± 0.16$^{aX}$ | 6.1 ± 0.10$^{eX}$ | 5.8 ± 0.12$^{eX}$ |

[a] Values are the mean ± SE (n = 9); means with different superscript lowercase letters in a column and different superscript uppercase letters in a row with differ significantly ($p < 0.05$).

### 3.3.5. Changes in bitterness score

Bitterness scores (Table 5) of FSCC and RSCC decreased significantly ($p < 0.05$) during 180 d of ripening. A non-significant ($p > 0.05$) difference between bitterness score of FSCC and RSCC was observed during entire ripening period. Change in bitterness of FSCC and RSCC could be attributed to the simultaneous generation of bitter peptides as a consequence of proteolysis.

Bitterness of RSCC and FSCC did not vary significantly because of the presence of AMP as a bitterness blocker. As RSCC has considerably higher KCl, it could be expected to be more bitter than FSCC; however, bitterness was not significantly different, which could be the effect of addition of AMP that has been used successfully for its potency to reduce bitterness in low sodium products, particularly where NaCl is replaced with KCl salt. Linguagen, a US company, received patent protection and regulatory approval for this BB. AMP works by blocking the activation of the gustducin in taste receptor cells and thereby preventing taste nerve simulation (McGregor, 2004). This BB, marketed under the name Betra™, can be used to improve the taste of NaCl/KCl mixtures.

When NaCl is replaced with KCl, bitterness has been reported to be the most potent problem. Contrary to this, it was observed during the investigation that even 75% replacement of NaCl did not make the product extremely bitter. This was probably the combined effect of AMP that masked the bitterness and the increased saltiness intensity. It has been reported that increase in the saltiness intensity of the product improves other sensory attributes also such as mouthfeel, fullness, and overall flavour profile, while at the same time, intensity of bitterness and metallic notes are reduced (Gillette, 1985).

## 4. Conclusion

Taste–taste interactions were successfully exploited to manufacture RSCC. HVP was used as a flavour enhancer and AMP as a bitterness blocker. Addition of these ingredients significantly improved the flavour, saltiness and bitterness characteristics of RSCC. The study returned significant reduction in sodium content of Cheddar cheese and thus offers an attractive alternative to manufacture low or reduced sodium cheese without jeopardising sensory attributes, particularly flavour and including saltiness. Higher saltiness was observed in Cheddar cheese with reduced sodium content. The study validated the effect of taste–taste interaction for eliciting saltiness and masking bitterness in low or reduced sodium cheese. The research results can further be exploited to reduce sodium in other cheese varieties as well. Further research efforts are needed to improve the body and texture characteristics score of the low or reduced sodium cheese.

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## References


Aly, M. E. (1995). An attempt for producing low-sodium Feta-type cheese. *Food Chemistry, 52*, 295–299.

AOAC. (1990). *Official methods of analysis*. Washington, DC, USA: Association of Official Analytical Chemists.

Ayyash, M. M., & Shah, N. P. (2010). Effect of partial substitution of NaCl with KCl on Halloumi cheese during storage: Chemical composition, lactic bacterial count, and organic acids production. *Journal of Food Science, 75*, C525–C529.

Ayyash, M. M., & Shah, N. P. (2011). The effect of substituting NaCl with KCl on Nabulsi cheese: Chemical composition, total viable count, and texture profile. *Journal of Dairy Science, 94*, 2741–2751.

Bassit, N., Cochet, N., & Lebeault, J. M. (1993). Influence of water activity on *Streptococcus diacetylactis* metabolism. *Applied Microbiology and Biotechnology, 40*, 399–401.

Beardsley, R. J. (2017). *Growth of E. coli in reduced salt cheddar cheese*. Doctoral dissertation. Pretoria, South Africa: University of Pretoria.

Busch, J. L., Yong, F. Y. S., & Goh, S. M. (2013). Sodium reduction: Optimizing product composition and structure towards increasing saltiness perception. *Trends in Food Science and Technology, 29*, 21–34.

Chavhan, G. B., Kanawjia, S. K., Khetra, Y., & Puri, R. (2015). Effect of potassium-based emulsifying salts on sensory, textural, and functional attributes of low-sodium processed Mozzarella cheese. *Dairy Science and Technology, 95*, 265–278.

Cruz, A. G., Faria, J. A., Pollonio, M. A., Bolini, H., Celeghini, R., Granato, D., et al. (2011). Cheeses with reduced sodium content: Effects on functionality, public health benefits and sensory properties. *Trends in Food Science and Technology, 22*, 276–291.

Desmond, E. (2006). Reducing salt: A challenge for the meat industry. *Meat Science, 74*, 188–196.

Dötsch, M., Busch, J., Batenburg, M., Liem, G., Tareilus, E., Mueller, R., et al. (2009). Strategies to reduce sodium consumption: A food industry perspective. *Critical Reviews in Food Science and Nutrition, 49*, 841–851.

El-Bakry, M., Duggan, E., O'Riordan, E. D., & O'Sullivan, M. (2011). Effect of cation, sodium or potassium, on casein hydration and fat emulsification during imitation cheese manufacture and post-manufacture functionality. *LWT Food Science and Technology, 44*, 2012–2018.

Felicio, T. L., Esmerino, E. A., Vidal, V. A. S., Cappato, L. P., Garcia, R. K. A., Cavalcanti, R. N., et al. (2016). Physico-chemical changes during storage and sensory acceptance of low sodium probiotic Minas cheese added with arginine. *Food Chemistry, 196*, 628–637.

Fitzgerald, E., & Buckley, J. (1985). Effect of total and partial substitution of sodium chloride on the quality of Cheddar cheese. *Journal of Dairy Research, 68*, 3127–3134.

Fox, P. F., & Wallace, J. M. (1997). Formation of flavour compounds in cheese. *Advances in Applied Microbiology, 45*, 17–86.

Ganesan, B., & Brown, K. (2013). Informatic prediction of Cheddar cheese flavor pathway changes due to sodium substitution. *Microbiology Letters, 350*, 231–238.

Ganesan, B., & Weimer, B. C. (2007). Amino acid metabolism in relationship to cheese flavor development. In B. C. Weimer (Ed.), *Improving the flavour of cheese*. Cambridge, UK: Woodhead CRC Press.

Gillette, M. (1985). Flavor effects of sodium chloride. *Food Technology, 39*, 47–52.

Grummer, J., & Schoenfuss, T. C. (2011). Determining salt concentrations for equivalent water activity in reduced-sodium cheese by use of a model system. *Journal of Dairy Science, 94*, 4360–4365.

Grummer, J., Bobowski, N., Karalus, M., Vickers, Z., & Schoenfuss, T. (2013). Use of KCl and flavour enhancers in low sodium Cheddar cheese. *Journal of Dairy Science, 96*, 1401–1418.

Guinee, T. P. (2004). Salting and the role of salt in cheese. *International Journal of Dairy Technology, 57*, 99–109.

Guinee, T. P., & Fox, P. F. (2004). Salt in cheese: Physical, chemical and biological aspects. In P. F. Fox, P. L. H. McSweeney, T. M. Cogan, & T. P. Guinee (Eds.), *Cheese: Chemistry, physics and microbiology* (pp. 207–259). Oxford, UK: Elsevier Academic Press.

Hassan, A., Johnson, M. E., & Lucey, J. A. (2004). Changes in the proportions of soluble and insoluble calcium during the ripening of Cheddar cheese. *Journal of Dairy Science, 87*, 854–862.

ISI. (1984). *Method for determination of lactic acid and lactates in milk powder and similar products. IS 11202. Manak Bhavan*. New Delhi, India: Indian Standards Institution.

Katsiari, M. C., Alichanidis, E., Voutsinas, L. P., & Roussis, I. G. (2001). Proteolysis in reduced sodium Kefalograviera cheese made by partial replacement of NaCl with KCl. *Food Chemistry, 73*, 31–43.

Katsiari, M. C., Voutsinas, L. P., Alichanidis, E., & Roussis, I. G. (1997). Reduction of sodium content in Feta cheese by partial substitution of NaCl by KCl. *International Dairy Journal, 7*, 465–472.

Katsiari, M. C., Voutsinas, L. P., Alichanidis, E., & Roussis, I. G. (1998). Manufacture of Kefalograviera cheese with less sodium by partial replacement of NaCl with KCl. *Food Chemistry, 61*, 63–70.

Keast, R. S. J., & Breslin, P. A. S. (2002). Cross-adaptation and bitterness inhibition of l-tryptophan, l-phenylalanine and urea: Further support for shared peripheral physiology. *Chemical Senses, 27*, 123–131.

Khetra, Y., Kanawjia, S. K., & Puri, R. (2016). Selection and optimization of salt replacer, flavour enhancer and bitter blocker for manufacturing low sodium Cheddar cheese using response surface methodology. *LWT Food Science and Technology, 72*, 99–106.

Kremer, S., Mojet, J., & Shimojo, R. (2009). Salt reduction in foods using naturally brewed soy sauce. *Journal of Food Science, 74*, S255–S262.

Lawrence, R. C., Gilles, J., Creamer, L. K., Crow, V. L., Heap, H. A., & Honoré, C. G. (2004). Cheddar cheese and related dry-salted cheese varieties. In P. F. Fox, P. L. H. McSweeney, T. M. Cogan, & T. P. Guinee (Eds.), *Cheese: Chemistry, physics and microbiology* (pp. 71–102). Oxford, UK: Elsevier Academic Press.

Lawrence, G., Salles, C., Palicki, O., Septier, C., Busch, J., & Thomas-Danguin, T. (2011). Using cross-modal interactions to counterbalance salt reduction in solid foods. *International Dairy Journal, 21*, 103–110.

Lawrence, G., Salles, C., Septier, C., Busch, J., & Thomas-Danguin, T. (2009). Odour–taste interactions: A way to enhance saltiness in low-salt content solutions. *Food Quality and Preference, 20*, 241–248.

McGough, M. M., Sato, T., Rankin, S. A., & Sindelar, J. J. (2012). Reducing sodium levels in frankfurters using a natural flavour enhancer. *Meat Science, 91*, 185–194.

McGregor, R. (2004). Taste modification in the biotech era. *Food Technology, 58*, 24–30.

McMahon, D. J., Oberg, C. J., Drake, M. A., Farkye, N., Moyes, L. V., Arnold, M. R., et al. (2014). Effect of sodium, potassium, magnesium, and calcium salt cations on pH, proteolysis, organic acids, and microbial populations during storage of full-fat Cheddar cheese. *Journal of Dairy Science, 97*, 4780–4798.

McSweeney, P. L. H., & Fox, P. F. (2004). Metabolism of residual lactose and of lactate and citrate. In P. F. Fox, P. L. H. McSweeney, T. M. Cogan, & T. P. Guinee (Eds.), *Cheese: Chemistry, physics and microbiology* (pp. 361–371). Oxford, UK: Elsevier Academic Press.

Møller, K. K., Rattray, F. P., Bredie, W. L. P., Høier, E., & Ardö, Y. (2013). Physico-chemical and sensory characterization of Cheddar cheese with variable NaCl levels and equal moisture content. *Journal of Dairy Science, 96*, 1953–1971.

Nasri, N., Beno, N., Septier, C., Salles, C., & Thomas-Danguin, T. (2011). Cross-modal interactions between taste and smell: Odour-induced saltiness enhancement depends on salt level. *Food Quality and Preference, 22*, 678–682.

Nasri, N., Septier, C., Beno, N., Salles, C., & Thomas-Danguin, T. (2013). Enhancing salty taste through odour–taste–taste interactions: Influence of odour intensity and salty tastants' nature. *Food Quality and Preference, 28*, 134–140.

Oh, J. H., Vinay-Lara, E., McMinn, R., Glass, K. A., Johnson, M. E., & Steele, J. L. (2014). Evaluation of NaCl, pH, and lactic acid on the growth of Shiga toxin-producing *Escherichia coli* in a liquid Cheddar cheese extract. *Journal of Dairy Science, 97*, 6671–6679.

Ozturk, M., Govindasamy-Lucey, S., Jaeggi, J. J., Johnson, M. E., & Lucey, J. A. (2015). Low-sodium Cheddar cheese: Effect of fortification of cheese milk with ultrafiltration retentate and high-hydrostatic pressure treatment of cheese. *Journal of Dairy Science, 98*, 6713–6726.

Reddy, K. A., & Marth, E. H. (1993). Proteolysis in Cheddar cheese made with sodium chloride, potassium chloride or mixtures of sodium and potassium chloride. *LWT Food Science and Technology, 26*, 434–442.

Rulikowska, A., Kilcawley, K. N., Doolan, I. A., Alonso-Gomez, M., Nongonierma, A. B., Hannon, J. A., et al. (2013). The impact of reduced sodium chloride content on Cheddar cheese quality. *International Dairy Journal, 28*, 45–55.

Thibaudeau, E., Roy, D., & St-Gelais, D. (2015). Production of brine-salted Mozzarella cheese with different ratios of NaCl/KCl. *International Dairy Journal, 40*, 54–61.

Upreti, P., McKay, L. L., & Metzger, L. E. (2006). Influence of calcium and phosphorus, lactose, and salt-to-moisture ratio on Cheddar cheese quality: Changes in residual sugars and water-soluble organic acids during ripening. *Journal of Dairy Science, 89*, 429–443.

Walstra, P., Wouters, J. T. M., & Geurts, T. J. (2006). *Dairy science and technology* (2nd edn.). Boca Raton, FL, USA: CRC Press, Taylor & Francis Group.

WHO. (2012). *Guideline: Sodium intake for adults and children*. Geneva, Switzerland: World Health Organization.