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The use of colour parameters derived from an online fibre-optic sensor to monitor curd syneresis during cheese making

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ABSTRACT

Syneresis follows the cutting of milk coagulum into cubes and is promoted by stirring. Important cheese properties such as moisture, mineral and lactose content and texture are affected by rate and extent of syneresis. The objective of this study was to monitor syneresis indices and whey composition over the course of syneresis using colour parameters derived from a fibre-optic sensor, with a view to achieving higher levels of process control and thus improved cheese quality. A full factorial design consisting of three levels of milk fat content, three levels of gel cutting firmness and three replicates was used in this study to give a wide range of syneresis conditions. It was found that the technology can be used to predict curd moisture ($R^2 = 0.91$, $P < 0.001$) and fat content of whey ($R^2 = 0.89$, $P < 0.001$) during syneresis. The results obtained show that the sensor has potential to monitor syneresis using colour parameters and therefore allow improved control of curd moisture content before ripening, which would decrease the production of down-graded cheese.

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1. Introduction

During the syneresis phase in cheese manufacture, shrinkage of the casein micelle network expel whey from the curd grains (Everard et al., 2007), to a rate and extent which play a fundamental role in determining the quality of the final cheese (Castillo et al., 2006; Walstra, 2004). Curd particles are usually stirred in the increasing volume of expelled whey to promote syneresis (Everard et al., 2008). One-dimensional flow of whey from the curd is governed by Darcy's law (Castillo et al., 2006; Lucey, 2002; Van Dijk and Walstra, 1986) therefore flow rate is directly proportional to the pressure gradient of the liquid in the direction of flow $\Delta P/\Delta x$ (Pa m^{-1}), the curd permeability coefficient B (m^2) and inversely proportional to whey viscosity η (Pa s).

Syneresis rate and extent can be affected by indirect factors, i.e. milk pre-treatment, milk coagulation conditions and rheological and microstructural gel properties at cutting (Lucey, 2001; Marshall, 1982; Walstra et al., 2001), and direct factors, i.e., after cutting conditions, e.g. time, temperature, agitation, size of curd particles and volume of liquid surrounding the curd particles (Lawrence, 1959a, b). Walstra et al. (1985) reviewed factors affecting syneresis. Many authors agree that syneresis can be empirically described by first order kinetics (Castillo et al., 2006). Increasing milk fat content on average decreases syneresis rate (Dejmek and Walstra, 2004; Walstra et al., 1985). The increased fat content results in an increase in the number of interstices within the reticulum occupied by fat, impeding whey drainage (Pearse and Mackinlay, 1989). Weber (1984) reported that if the curd is cut very late syneresis may be decreased somewhat due to increased firmness of curd. Likewise, Van Dijk (1982) found that syneresis became progressively slower when the gel was left for longer times after setting before cutting or wetting. However, a number of studies reported that the rate of syneresis was independent of cutting time and therefore curd firmness (Pearse et al., 1984; Stroll, 1966; Storry and Ford, 1982).

Various off-line methods have been reported for monitoring syneresis (Talens et al., in press; Walstra et al., 1985; Walstra, 2004), mainly based on measurement of the shrinkage of various curd dimensions (Dejmek and Walstra, 2004). On-line non-destructive techniques need to be developed for measurement of syneresis since syneresis conditions used in the reported off-line techniques are often too far removed from conditions in an industrial cheese vat. Walstra et al. (1985) reviewed methods for off-line monitoring of syneresis and highlighted problems associated with these methods. Off-line measurements are subject to sampling errors. Removing a slice of curd four times from whey for 30 s reduced the curd weight by 13% more than by removing it just once (Walstra et al., 1985). Methods that involve the separation of curd and whey may also be subject to the issue of curd collapsing due to pressure caused by handling (Pearse and Mackinlay, 1989). This will result in rapid release of whey from the collapsed

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curd grains. Removing whey from the curd/whey mixture during syneresis under stirred conditions increases syneresis rate due to the resultant increase in pressure on the curd particles caused by increased collisions between the particles themselves and between the particles and the stirrers and the vat wall (Everard et al., 2008). Draining of whey from curd can be problematic as whey never completely drains off (Walstra et al., 1985). Tracer methods to measure syneresis might interfere with syneresis and/or diffuse into curd particles (Pearse and Mackinlay, 1989). Association of the tracer with the curd would result in the overestimation of syneresis (Walstra et al., 1985). In addition, tracer methods are only useful for research because they are destructive, i.e. the curd cannot be used to make consumable cheese. Walstra et al. (1985) concluded that for off-line syneresis measurement several combinations of in-vat conditions can be made but not all combinations are easy to perform or even feasible.

Optical methods have recently been developed for on-line monitoring of syneresis. Guillemin et al. (2006) used an optical method based on near-infrared technology to monitor casein particle size distribution in whey in the cheese vat. Castillo et al. (2005) and Fagan et al. (2007a) presented a large field of view optical sensor based on near infrared backscatter to monitor milk coagulation and whey separation in cheese making. Fagan et al. (2007b) developed equations using parameters derived form this sensor's response to predict syneresis indices. Renault et al. (1997) used computer vision to monitor the shrinkage of curd grains during syneresis; however this was not carried out in a cheese vat. Everard et al. (2007) used a computer vision system mounted above a cheese vat, based on colour distinction between curd and whey near the surface of the curd/whey mixture, to monitor syneresis. The study found that a computer vision system had potential for monitoring syneresis over a range of stirring speeds and milk pH using colour parameters. The study concluded that one limitation of the computer vision system was that measurements were taken at the top surface of the curd/whey mixture and at low stirring speeds the sinking curd was a confounding factor on syneresis monitoring.

Colour is an important measure of quality in the agricultural and food industries because it is considered by consumers to be related to product freshness, ripeness, desirability and food safety (Jeliński et al., 2007; McCraig, 2002). Colour analysis and, in particular, computer vision analysis has recently been reported as a viable method to monitor various food processes, e.g. cheese ripening process, (Dufossé et al., 2005; Everard et al., 2007; Olson et al., 2006). Colour measurement instruments, in accordance with the standards developed by the CIE (Commission Internationale de l'Éclairage) transform or filter reflected spectra to produce reproducible colour values (McCraig, 2002). CIE *Lab* and *Whiteness* values originally defined by the CIE in 1976 (CIE, 1986) constitute the most widely used numerical colour-space system (McCraig, 2002).

The objective of the present study was to monitor syneresis in a cheese vat using colour parameters derived from a fibre-optic sensor, with a view to achieving higher levels of process control and thus improved cheese quality. Colour parameters derived from the sensor were used to predict known syneresis and whey indices.

2. Materials and methods

2.1. Experimental design

In this study cheese curd was made from recombined milk in an 11 L vat, following a typical cheese making recipe. A randomised factorial design with two experimental factors, i.e. milk fat level and cutting firmness, and three replicates was used to investigate colour changes over syneresis. The levels of milk fat and cutting firmness investigated were 0, 2.5 and 5%, and 5, 35 and 65 Pa, respectively, giving a total of 27 trials ($nab = 3^3$). Constant coagulation temperature, milk pH, rennet, calcium chloride concentrations, cutting procedure and stirring speeds were used throughout the study.

2.2. Milk recombination and gel preparation

Whole milk was recombined in an 11 L cheese vat (Pierre Guerin Technologies, Mauze, France), as described in Everard et al. (2008) from low-heat skim milk powder (Irish Dairy Board, Dublin), distilled water and cream (Dairygold, Cork) at 42 ± 0.1 °C while being stirred at 44 rpm. Temperature was controlled by a water bath (Grant Instruments Ltd., Cambridge, England) connected to a heating jacket on the vat. The milk was formulated for the three milk fat levels with a constant protein level of 3.3% using least squares optimisation with the Solver tool in Microsoft Excel (V. 10 Microsoft® Excel).

The cheese vat had twin overlapping counter-rotating stirrers. The stirring blades (80 × 50 mm) were set at an angle of 30°, with a clearance of 8–10 mm from the bottom of the vat, which resulted in a 3-dimensional flow of curd/whey mixture during stirring. Calcium chloride ($CaCl_2 \cdot 2H_2O$) was added to the milk to 2.04 mM, which was then cooled to ~8 °C and stirred constantly at 10 rpm overnight.

On the day of analysis the milk was heated to 32 ± 0.1 °C and pH was adjusted to 6.5 using HCl (1 M). The milk coagulant used was 100% recombinant chymosin (CHY-MAX extra, EC 3.4.23.4, isozyme B, 600 IMCU mL^{-1}; Chr Hansen Ireland Ltd., Ireland). The rennet was added to the milk (0.18 g of chymosin kg^{-1} of milk) in the vat while being stirred constantly at 31 rpm. Stirring was stopped after 3 min and the stirrers were replaced with twin overlapping cutting blades.

2.3. Rheological determination of cutting firmness

After the rennet addition procedure, 13 mL of milk was removed from the vat and placed in a small amplitude oscillatory rheometer (Bohlin CVO Rheometer, Bohlin, Cirencester, UK), which was pre-warmed to 32 ± 0.1 °C, to determine the gel cutting time (t_{cut}). The rheometer geometry consisted of a cylindrical bob and cup used in oscillation mode at a shear strain of 0.01 and a frequency of 1 Hz, within the linear viscoelastic region (<0.03) reported for rennet milk gels (Mishra et al., 2005). The milk coagulum was cut at three different firmness levels (*Firm*) according to the experimental design, i.e. when the elastic modulus (G') reached 5, 35 or 65 Pa. Cutting was carried out using the twin sets of cutting blades. The moment of initiating gel cutting, i.e. t_{cut}, was taken as the reference time ($t = 0$) for all subsequent syneresis-related measurements. The cutting procedure consisted of three cutting and healing cycles of 1 min duration (Everard et al., 2008; Johnston et al., 1998). The curd was cut at 10 rpm for 40 s, allowed to rest for 20 s, cut at 22 rpm for 40 s, rested for 20 s, and finally cut again at 22 rpm for 40 s and rested again for 20 s.

After gel cutting, the cutting blades were replaced by the stirrers and stirring at 16 rpm commenced at $t = 4$ min and continued over syneresis up to $\sim t = 85$ min.

2.4. Colour sensor

The syneresis sensor was a prototype designed by Castillo et al. (2005) at the University of Kentucky (Fig. 1) with a large field of view (LFV), i.e. the sensor glass window was 20 mm in diameter.

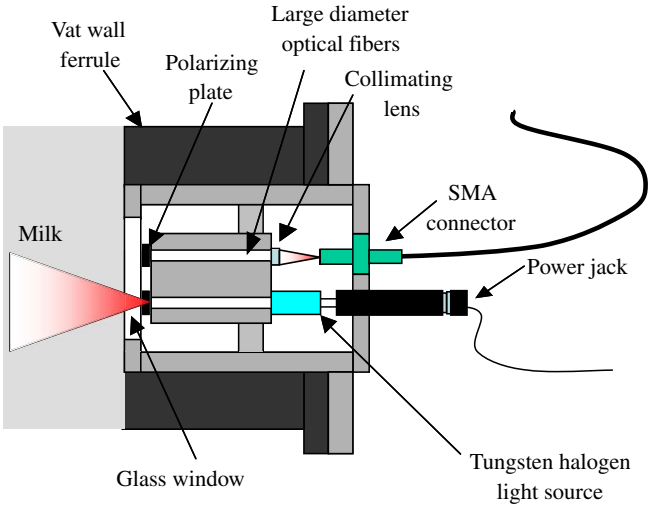

Fig. 1. Schematic of the novel large field of view (LFV) colour sensor and optical configuration employed for monitoring curd syneresis.

Light from a tungsten halogen source (model LS1B, Ocean Optics, Inc., Dunedin, FL, USA; spectral range of 360–2000 nm) was transmitted through a large diameter (5 mm) optical fiber (Fiberoptics Technology, Inc., Pomfret, CT, USA), a vertical polarizer (Edmund Optics, Inc., Barrington, NJ, USA) and a glass window (Melles Griot Inc., Rochester, NY, USA) to the sample. The large-diameter glass window allows scattered light to be collected from a large area. Another polarizing plate allows for the selective detection of horizontally polarized light. Reflected light is transmitted through another optical fiber and a collimating lens (Edmund Optics Inc.) that focuses the scattered light onto a ~800 μm diameter fiber optic cable (Spectran Specialty Optics, Avon, CN, USA) to the master unit of a miniature fibre optic spectrometer (model HR2000CG-UV-NIR, Ocean Optics B.V., Duiven, Netherlands) (Fig. 1). CIE *L*, *a*, *b* and *Whiteness* colour parameters were averaged and recorded every ~7 s using SpectraSuite software (SpectraSuite v. 5.1, Ocean Optics B.V.); these recorded values were an average of 35 scans. CIE *L*, *a*, *b* and *Whiteness* values were averaged over 2 min intervals around the sampling points to be compared with syneresis and whey indices at the respective times. CIE *Lab* and *Whiteness* values are as defined by CIE (1986).

Table 1
Analysis of variance (ANOVA) and F statistic showing the effects of milk fat, gel cutting firmness and time on CIE colour values, along with their interactive effects[a].

Source of variation	DF	*L*		*a*		*b*		*Whiteness*	
		F-value	Significance[b]	*F*-value	Significance[b]	*F*-value	Significance[b]	*F*-value	Significance[b]
Fat_M	2	167	***	876	***	519	***	102	***
Firm	2	1.44	ns	1.32	ns	1.65	ns	1.31	ns
t	7	148	***	73.4	***	72.9	***	151	***
$Fat_M \times Firm$	4	0.49	ns	4.02	*	1.76	ns	0.5	ns
$Fat_M \times$ t	14	28.7	***	28.9	***	36.1	***	21.0	***
$Firm \times$ t	14	0.29	ns	0.24	ns	0.30	ns	0.15	ns
$Fat_M \times Firm \times$ t	28	0.44	ns	0.68	ns	0.56	ns	0.32	ns
Residual	144								
Total	215								

[a] Key for parameters: *L*, *a*, *b* and *Whiteness*, CIE colour values; DF, degrees of freedom; Fat_M, milk fat level; *Firm*, gel cutting firmness level; *t*, time.
[b] Model significance: ns, not significant; *, $P < 0.05$; ***, $P < 0.001$.

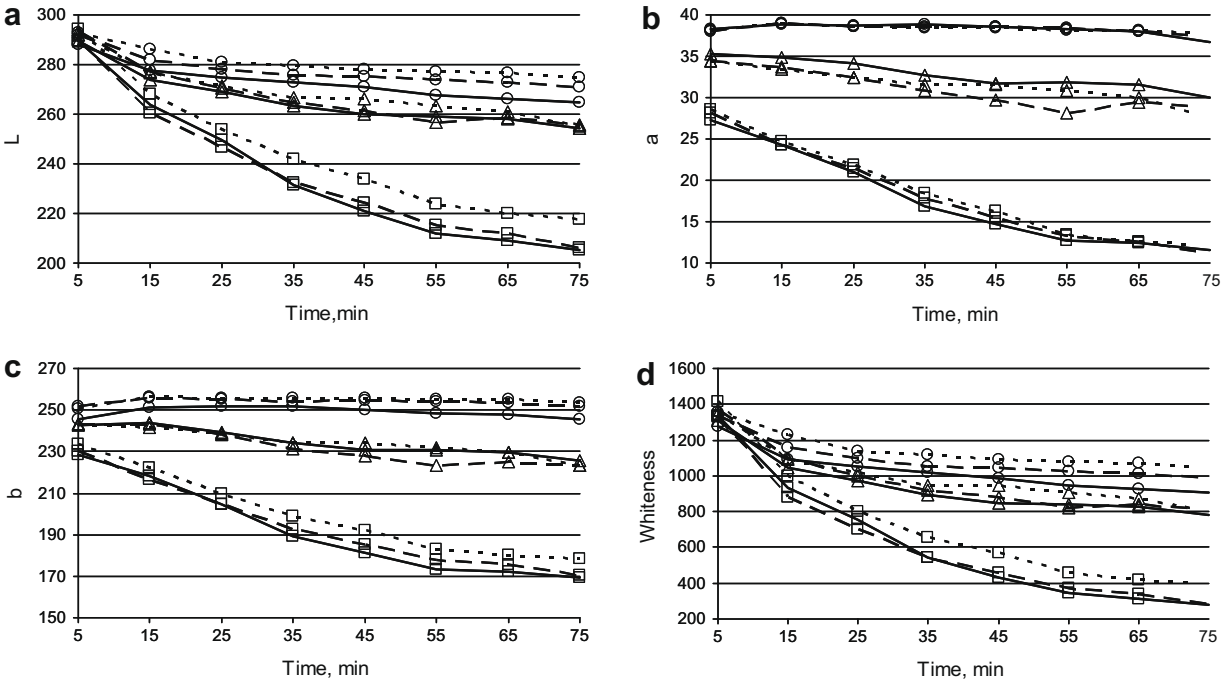

Fig. 2. Changes in CIE (a) *L*, (b) *a*, (c) *b* and (d) *Whiteness* colour values over the course of syneresis. 0% $Milk_F$ (□); 2.5% $Milk_F$ (Δ); 5% $Milk_F$ (○); 5 Pa cutting firmness (– – –); 35 Pa cutting firmness (— — —); 65 Pa cutting firmness (– – – –).

2.5. Measurements of syneresis indices and whey solids

Samples of curd/whey mixture were removed from the vat, using a specially-designed sampler, manufactured at the University of Kentucky in collaboration with Teagasc and University College Dublin (Everard et al., 2008). Samples of ~180 mL were drawn at 5, 25, 45 and 65 min and ~270 mL samples were drawn at 15, 35, 55 and 75 for analysis. Fines in whey ($Fines_W$), fat in whey (Fat_W) and protein in whey ($Protein_W$) were determined at 15, 35, 55, and 75 min only, hence the increased volume of sample taken at these times. Curd and whey were immediately separated, following the procedure proposed by Everard et al. (2007, 2008), using a 75 μm numerical aperture stainless steel sieve (AGB, Dublin, Ireland). The sieve characteristics were selected to ensure that whey fat globules were not retained. The two phases were weighed without delay using a precision balance for whey yield (Y_W) calculation. Y_W was calculated as the weight of whey in the sample expressed as a percentage of the total weight of curd and whey. Samples of ~3 g of curd and ~5 g of whey were then accurately weighed into pre-weighed aluminium dishes for determination of curd moisture (M_C) and whey total solids (S_W), respectively, by drying in triplicate in a convection oven at 102 °C for 16 h (Everard et al., 2007, 2008). Y_W, M_C and S_W were determined at all sample points, i.e. 5–75 min at 10 min intervals. The final whey yield (FY_W) was determined at ~85 min. It was calculated as the total weight of whey expressed as a percentage of the total weight of whey and curd in the vat. Fat_W was measured using the Rose–Gottlieb method (IDF, 1987). $Protein_W$ was determined by the Kjeldahl method (AOAC, 1984). $Fines_W$ were determined using a procedure adapted from Johnston et al. (1991). A 45 mL sample was centrifuged for 15 min at 1500*g*. The fat layer was removed using a spatula. Then the supernatant phase was poured off without disturbing the pellet of suspended solids and any fat residue was wiped from the side of the tubes with a tissue. A volume of ~45 mL of distilled water was added to the centrifuge tubes and this sample was centrifuged at 1500*g* for a further 15 min, to remove any remaining fat. The supernatant phase was poured off without disturbing the pellet. The pellet was washed onto GF/R filter paper in a Buckner funnel attached to a vacuum pump, using 50 mL of 40 °C distilled water. The filter paper with fines was dried in an oven at 102 °C for 1 h and then allowed to cool to room temperature in a desiccator for 30 min. $Fines_W$ was expressed as the weight of fines in the whey sample divided by the weight of whey.

2.6. Data analysis

Analysis of variance (*ANOVA*) was carried out, using the Proc Mixed procedure in SAS 9.1 (SAS Institute Inc., Cary, NC, USA) to determine the effects of the experimental design on colour readings. Pearson's correlations were carried out to show relationships between syneresis indices and whey solids, and colour values using SigmaStat V 3.1 (Systat Software UK Ltd., London, England). Linear regression was carried out to predict Y_W, M_C, Fat_W and $Fines_W$ from colour values using SigmaStat V 3.1. *L* and *Whiteness* were fitted to a first order equation, i.e. Eq. (1), as a function of time during syneresis (Castillo et al, 2005; Fagan et al., 2007a) using the Proc NLIN procedure in SAS.

$$x_t = x_\infty + (x_0 - x_\infty)e^{-k_x t} \quad (1)$$

where x_t represents the fitted *L* or *Whiteness* at time *t* (min), x_∞ is *L* or *Whiteness* predicted at an infinite time, x_0 is *L* or *Whiteness* for the milk before renneting and k_x is the kinetic rate constant (min^{-1}) for *L* or *Whiteness* changes over the course of syneresis. Procedure NLIN in SAS was used to estimate L_∞, k_L, $Whiteness_\infty$ and $k_{Whiteness}$.

3. Results

Colour parameters *L*, *a*, *b* and *Whiteness* significantly ($P < 0.001$) distinguished the effects of Fat_M and *t* but did not detect the effect of levels of *Firm* (Table 1). Fat_M and *t* had interactive effects on *L*, *a*, *b* and *Whiteness*, while Fat_M and *Firm* had an interactive effect on *a* (Table 1).

It was observed that *L* and *Whiteness* followed a first order reaction over the duration of syneresis (Fig. 2). *L* and *Whiteness* were fitted to a first order equation, i.e. Eq. (1), and subsequent two-way ANOVA showed that k_L, L_∞, $k_{Whiteness}$ and $Whiteness_\infty$ were affected by Fat_M level but were not affected by gel cutting firmness

Table 3
Pearson's correlation coefficients and implied significance between syneresis indices and CIE colour parameters obtained for the *LFV* (large field view) colour sensor[a].

	L	*a*	*b*	*Whiteness*	L_∞	$Whiteness_\infty$
Y_W[c]	−0.77***	−0.62***	−0.61***	−0.81***	–	–
M_C[c]	−0.33***	−0.70***	−0.64***	−0.25***	–	–
S_W[c]	0.53***	0.71***	0.69***	0.49***	–	–
Fat_W[d]	0.68***	0.84***	0.86***	0.64***	–	–
$Fines_W$[e]	0.33***	0.03ns	0.17ns	0.37***	–	–
$Protein_W$[e]	0.50***	0.65***	0.63***	0.48***	–	–
FY_W[f]	–	–	–	–	0.67***	0.71***

[ba] A key for parameters: *L*, *a*, *b* and *Whiteness*, CIE colour values; L_∞ and $Whiteness_\infty$, *L* or *Whiteness* predicted at an infinite time, cf. Eq. (1); Y_W, yield of whey; M_C, curd moisture; S_W, total solids in whey; Fat_W, fat in whey; $Fines_W$, fines in whey; $Protein_W$, protein in whey; FY_W, final whey yield.
[a] Significance: ***, $P < 0.001$; ns, not significant.
[c] $n = 216$.
[d] $n = 72$.
[e] $n = 108$.
[f] $n = 27$.

Table 2
Least square means of kinetic values for *L* and *Whiteness*, derived from fitting to first order equations, cf. Eq. (1) with respect to milk fat and gel cutting firmness levels [a,b].

Main effects	Colour kinetic parameters over the course of syneresis			
	k_L (min^{-1})	L_∞ (%, w/w)	$k_{Whiteness}$ (min^{-1})	$Whiteness_\infty$ (%, w/w)
$Milk_F$				
0%	0.0232c	187c	0.0338c	201c
2.5%	0.0394d	254d	0.0487d	799d
5%	0.0575e	271e	0.0660e	994e
Firm				
5 Pa	0.0348f	230f	0.0441f	599f
35 Pa	0.0440f	238f	0.0535f	664f
65 Pa	0.0413f	244f	0.0509f	732f

[a] Key for parameters: k_L, kinetic rate constant for *L* changes over the course of syneresis; L_∞, *L* predicted at an infinite time, $k_{Whiteness}$, kinetic rate constant for *Whiteness* changes over the course of syneresis; $Whiteness_\infty$, *Whiteness* at an infinite time; Fat_M, milk fat level; *Firm*, gel cutting firmness level.
[b] Least square means in same column followed by same letters are not significantly different.

Table 4
Multiple linear regression models showing the independent variables and colour parameters which significantly contribute to the prediction of syneresis indices [a].

	Standardised coefficients						R^2	Adjusted R^2	SEP g/100 g	Range g/100 g	Residual DF
	Fat_M	$Firm_{Cut}$	L	a	b	*Whiteness*					
Y_W	–	–	1.36	−1.24	1.61	−2.63	0.85	0.85	5.01	63.7	211
M_C[b]	−0.740	–	–	0.243	−1.07	1.00	0.91	0.91	0.514	15.8	211
Fat_W	0.760	–	0.292	–	–	–	0.89	0.89	0.0458	0.502	69
Fat_W	Omitted	Omitted	–	0.438	0.51	–	0.81	0.81	0.0597	0.502	69
$Fines_W$[c]	−0.521	0.536	−1.584	–	–	2.238	0.68	0.67	0.200	1.524	103

[a] Key for parameters: Fat_M, milk fat level; *Firm*, gel firmness level at cutting time; *L*, *a*, *b* and *Whiteness*, CIE colour values; Y_W, yield of whey; M_C, curd moisture; S_W, total solids in whey; Fat_W, fat in whey; $Fines_W$, fines in whey; $Protein_W$, protein in whey; SEP, standard error of prediction; DF, degrees of freedom.
[b] Mc was modelled using a transformation, i.e. M_C values were transformed to $100/(100-M_C)$. This ensured that the assumptions behind regression were satisfied.
[c] $Fines_W$ was modelled using a transformation, i.e. $Fines_W$ values are transformed to $\log(Fines_W)$. This ensured that the assumptions behind regression were satisfied.

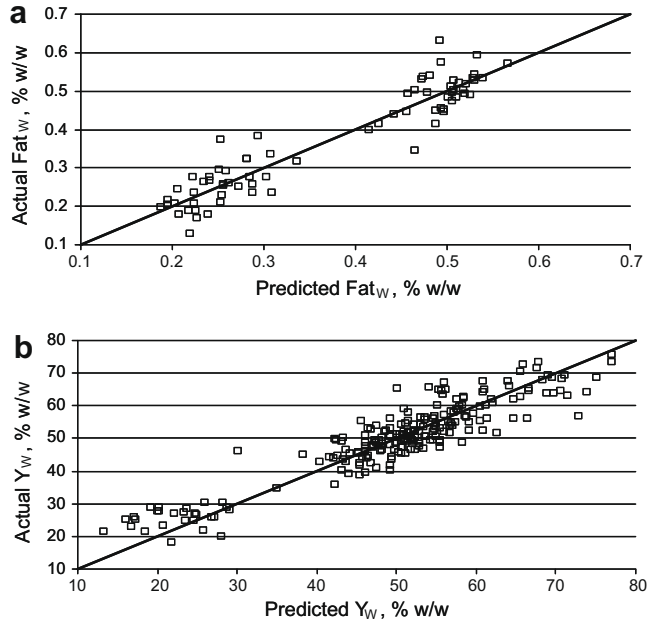

Fig. 3. Linear regression prediction models for (a) fat in whey, Fat_W ($R^2 = 0.89$, $P < 0.001$) and (b) whey yield, Y_W ($R^2 = 0.85$, $P < 0.001$), cf. Table 4.

(Table 2). Predicted L_∞ ($R^2 = 0.67$, $P < 0.001$) and $Whiteness_\infty$ ($R^2 = 0.71$, $P < 0.001$) correlated with FY_W (Table 3).

Table 3 shows that colour parameters correlated significantly with all syneresis indices and whey solids measured in this study. Most notable were the high significant correlations between colour parameters and Y_W, M_C and Fat_W, respectively (Table 3).

Best predictions using colour sensor readings were achieved for M_C, Fat_W, and Y_W, with R^2 values of 0.91, 0.89 and 0.85, respectively (Table 4 and Fig. 3). It was found that Fat_M or *Firm* did not significantly add to the ability of colour parameters to predict Y_W (Table 4). Fat_W was predicted from colour values *a* and *b* alone with a R^2 of 0.81 (Table 4). Two thirds of the variance in $Fines_W$ was also explained (Table 4).

4. Discussion

The LFV sensor used in this study can monitor colour changes over a relatively large area submerged in the curd/whey mixture midway on the wall of the cheese vat. Colour changes are due to the decreasing volume of white curd particles and the increasing volume of greenish yellow whey in the mixture which are intrinsic to syneresis. The effect of curd particle sedimentation, i.e. the settling of curd particles to the bottom of the cheese vat due to their increasing density over the course of syneresis will also affect the colour measurement.

The sensor in the present study is a non-destructive real time device that has potential to monitor several key syneresis indices, i.e. Y_W, M_C, Fat_W and $Fines_W$. The sensor was able to distinguish effects of Fat_M on syneresis in this study. The colour sensor predicted yield of whey, Y_W, (and hence, yield of curd) from cheese milk, during stirring in the vat, with *SEP* of 5 g/100 g over a range 20–75 g/100 g in our study. It predicted fat in whey, Fat_W, with *SEP* of 0.05 g/100 g over a range 0.15–0.65 g/100 g (Fig. 3 and Table 4). *L* and *Whiteness* followed a first order equation over syneresis. Several authors have reported that syneresis follows a first order equation over time (Castillo et al., 2006; Marshall, 1982; Peri et al., 1985).

Improved control of the syneresis phase in cheesemaking will allow the cheese maker to produce a more consistent cheese and will give a more accurate determination of time for draining of the cheese vat, thus improving cheese vat efficiency.

5. Conclusions

A novel large field of view online fibre-optic sensor installed in a cheese vat was used to monitor curd syneresis. Colour values derived from this sensor were able to predict syneresis indices such as whey yield, curd moisture and losses of fat to whey. The sensor shows potential for the use of colour monitoring techniques to track syneresis, however further developments, possibly involving further spectral analysis techniques, would be required to reduce the error of prediction to a level that is useful for industrial application.

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