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Computer Vision and Color Measurement Techniques for Inline Monitoring of Cheese Curd Syneresis

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ABSTRACT

Optical characteristics of stirred curd were simultaneously monitored during syneresis in a 10-L cheese vat using computer vision and colorimetric measurements. Curd syneresis kinetic conditions were varied using 2 levels of milk pH (6.0 and 6.5) and 2 agitation speeds (12.1 and 27.2 rpm). Measured optical parameters were compared with gravimetric measurements of syneresis, taken simultaneously. The results showed that computer vision and colorimeter measurements have potential for monitoring syneresis. The 2 different phases, curd and whey, were distinguished by means of color differences. As syneresis progressed, the backscattered light became increasingly yellow in hue for circa 20 min for the higher stirring speed and circa 30 min for the lower stirring speed. Syneresis-related gravimetric measurements of importance to cheese making (e.g., curd moisture content, total solids in whey, and yield of whey) correlated significantly with computer vision and colorimetric measurements.
Key words: syneresis, cheese, computer vision, color

INTRODUCTION

During syneresis, the curd matrix shrinks due to rearrangement of casein micelles, resulting in expulsion of whey from the curd grains (Walstra et al., 1985; Dejmek and Walstra, 2004; Castillo et al., 2006). Syneresis follows the cutting of milk coagulum into cubes and is generally promoted by thermal or mechanical treatments, or both.

Moisture is removed from cheese curd in a number of stages in cheese making. Most of the moisture and lactose are removed during syneresis in the cheese vat. Further moisture is removed during "complementary syneresis" [i.e., during postvat curd-handling (draining, salting, molding, pressing), and evaporation, which is a function of the ripening environment]. Moisture control of all these stages has implications for final cheese quality and yield (Weber, 1989; Castillo, 2001). In particular, control of curd moisture in the vat is essential for control of lactose and curd pH and also affects the removal of moisture in subsequent steps, and in turn, enables the cheese manufacturer to improve control of the biochemical processes during ripening. Syneresis also influences protein and fat losses in whey, which in turn affects cheese yield. At present, in the cheese industry worldwide, syneresis is empirically controlled, and there are no technologies available for online monitoring of curd syneresis to assist the cheesemaker.

Various empirical techniques have been developed to study the kinetics of syneresis as reviewed by Walstra, van Dijk and Geurts (1985), and Walstra (1993). First order kinetics has been reported by many authors to describe the rate of syneresis (Marshall, 1982; Peri et al., 1985; Castillo et al., 2006). Previous techniques developed to monitor syneresis include determination of the moisture content of curd, estimation of volume of shrunken curd by liquid displacement, and measuring the volume of whey drained from the curd directly (Lawrence, 1959a; Marshall, 1982; Daviau et al., 2000) or by determining the degree of dilution of added tracers (Beeby, 1959; Grundelius et al., 2000). Renault et al. (1997) developed an original off-line method to monitor curd shrinkage based on image analysis. The method did not submerse the curd in whey nor did it use stirring during syneresis and thus deviates from standard industrial conditions. In general, the instantaneous measurement of curd moisture during syneresis is challenging, which limits precision and accuracy of all reported methods (Zviedrans and Graham, 1981). Indeed, the experimental conditions are often too distant from industrial practice to extrapolate results.

Factors affecting syneresis rate and extent, including milk composition and pretreatment, coagulation factors, rheological properties of the gel at cutting, curd surface area, external pressure, and curd temperature

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and pH, have been widely reviewed (Marshall, 1982; Walstra et al., 1985; Pearse and Mackinlay, 1989; Weber, 1989; van Vliet et al., 1991; Lucey, 2001; Walstra et al., 2001). In this study the kinetics of syneresis were changed by altering milk pH and stirring speed during syneresis.

It is clear from observation during cheese manufacturing that the color of milk proceeds from a continuous white mass before cutting to a mixture of white particles in a mostly clear yellowish whey. Direct observation also reveals that light scattered by whey becomes increasingly yellow in hue as syneresis progresses. Based on those 2 empirical observations, it was hypothesized that a) a ratio of the white and yellow areas calculated by processing the images obtained after gel cutting would provide valuable information about syneresis kinetics; and b) the overall color of the curd/whey mixture would also change during syneresis and would carry useful syneresis kinetic information.

The objectives of this study were 1) to propose and test 2 original methods for syneresis monitoring in a cheese vat based on color measurement, 2) to evaluate the color parameters obtained from these methods to predict important indices of curd production, and 3) to assess the capability of these methods to respond to the effects of milk pH and stirring speed on syneresis. The 2 approaches being evaluated here are 1) the use of computer vision to distinguish curd from whey and 2) the monitoring of color changes in a cheese vat during syneresis.

MATERIALS AND METHODS

Experimental Design

A randomized factorial experimental design with 2 factors, 2 levels per factor, and 3 replicates was used in this study to evaluate the use of computer vision and a colorimeter for monitoring curd syneresis in a 10-L double-O cheese vat (Pierre Guerin Technologies, Mauze, France). Milk was coagulated using a fixed concentration of calcium chloride and rennet. A broad range of syneresis reaction rates was ensured by coagulating the milk at 2 different levels of pH (i.e., 6.0 and 6.5) and by stirring the curd/whey mixture at 2 different speeds (i.e., 12.1 and 27.2 rpm) after cutting the gels. A total of 12 trials ($nab = 3{\cdot}2^2$) were performed using this design. The double-O cheese vat had twin corotating stirrers (Figure 1). The stirring blades (80×50 mm) were set at an angle of 30°, with a clearance of 8 to 10 mm from the bottom, which resulted in a 3-dimensional flow of curd/whey mixture during stirring.

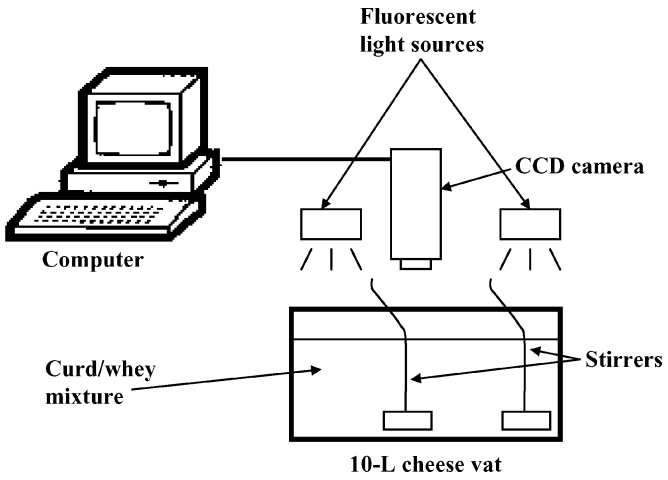

Figure 1. Schematic of computer vision system coupled to the cheese vat with twin corotating stirrers. CCD = charge-coupled device.

Milk Gel Preparation

Commercial pasteurized low-fat milk (Avonmore Slimline Milk, Glanbia, Ireland) was used in this study.

The low-fat milk had protein and fat concentrations of 38 and 3 g/L, respectively, and contained 1.36 g/L of calcium. Calcium chloride ($CaCl_2{\cdot}2H_2O$) was added (0.156 g/kg of milk), and milk was left to equilibrate for 1 h at 4°C before initial pH adjustment. Initial pH adjustment was carried out on the milk at 4°C using HCl (1.0 *M*) 1 or 2 d before analysis, and the milk was stored at 4°C until day of analysis. On the day of analysis, 10 kg of milk was added to the cheese vat for each trial, and the milk was heated to 32°C via the vat's heating jacket while being stirred at 27.2 rpm. The milk was held at this temperature and final pH adjustments were carried out using HCl (1.0 *M*) and NaOH (1.0 *M*) at 32°C. The milk coagulant used was 100% recombinant chymosin (CHY-MAX extra, EC 3.4.23.4, isozyme B, 600 IMCU/mL; Chr Hansen Ireland Ltd., Cork, Ireland). The rennet was added to the milk (0.18 g of chymosin/kg of milk) in the vat while being stirred constantly at 55 rpm. Stirring was stopped after 3 min, and the stirrers were replaced with twin cutting blades.

Rheological Assays and Cutting of the Gel

Small amplitude oscillatory rheometry was used to determine the gel cutting time (t_{cut}). At 3 min after rennet addition, ~3.5 mL aliquot of milk was removed from the vat and inserted in a controlled stress rheometer (Carri-med CSL^2-100, TA Instruments, Crawley, UK). The instrument was operated at 32°C in oscillation mode at a shear strain of 0.02 and a frequency of

1 Hz using double-gap concentric cylinder geometry. Cutting time was determined by the rheometer as the time at which milk gel reached storage modulus (**G′**) = 43 Pa. At t_{cut} the twin cutting blades were activated and the gel was cut at a constant speed of 6 rpm for 15 s, then allowed to heal for 1 min, cut a second time at a speed of 16 rpm for 15 s, allowed to heal for 1 min, and cut a third time at speed 16 rpm for 10 s and allowed to heal for 1 min (Johnston et al., 1998). The moment of initiating gel cutting was taken as the reference time (t = 0) for all subsequent measurements.

Curd and Whey Analysis

Samples of curd/whey mixture (~180 mL) were removed from the vat using a ladle at t = 5 min and at 10-min intervals thereafter up to t = 85 min. Curd and whey were immediately separated using a 75-μm numerical aperture stainless-steel sieve (AGB, Dublin, Ireland), and the 2 phases were weighed without delay using a precision balance for curd and whey yield calculation. The sieve characteristics were selected to ensure that whey fat globules were not retained. Approximately 3 g of curd and 5 g of whey were then accurately weighed into preweighed aluminum dishes for determination of total solids of curd and whey, respectively, by drying in triplicate in a convection oven at 102°C for 16 h (Fagan et al., 2007). The yield of whey was expressed as a percentage of the initial weight of milk used in each trial.

Computer Vision Analysis

A computer vision system was coupled to a 10-L cheese vat, as shown in Figure 1, to measure color changes in the curd/whey mixture during syneresis (Figure 2).

The computer vision system used in this study consisted of a high-quality 3-CCD Sony XC-003P camera (Sony Corporation, Tokyo, Japan) connected to a computer for image analysis with an IC-RGB frame grabber (Imaging Technology, Billerica, MA). Images were captured under 2 fluorescent lamps (Imaging Technology) with plastic light diffusers. The camera captured images (~100 mm^2) of the surface of the curd/whey mixture during syneresis while the mixture was being stirred. Images were captured at t = 5 or 6 min and at 1-min intervals thereafter up to t = 85 min. Care was taken to capture each image at the same stirrer position. Each image was subdivided into areas of curd or whey, respectively, according to a color threshold. This was achieved by converting each image into a greyscale image, de-noising it using a 2-dimensional adaptive noise-removal filter (Lim, 1990), enhancing the image contrast-limited adaptive histogram equalization (MathWorks, 1998), and defining a threshold value between curd and whey based on human perception to ensure clear separation of the curd and whey, using Matlab V 6.5.1 (The Mathworks Inc., Natick, MA). The areas of white ($\boldsymbol{A_w}$) and yellow ($\boldsymbol{A_y}$) in each image were determined mathematically, and their ratio ($\boldsymbol{a_{wy}} = A_w/A_y$) was calculated and used as a parameter to follow syneresis.

Red, green, and blue (***RGB***) values averaged across the images were also recorded using Matlab V 6.5.1 and used to follow syneresis. These *RGB* values were used to calculate $\boldsymbol{\Delta E_{RGB}}$ using the Euclidean formula Eq. [1], to give a computer vision metric as a function of time with respect to the initial image captured at t = 5 min or 6 min

$$\Delta E_{RGB} = \sqrt{(\Delta R)^2 + (\Delta G)^2 + (\Delta B)^2}, \quad [1]$$

where ΔR is the change in the R value, ΔG is the change in the G value, and ΔB is the change in the B value. A typical profile for ΔE_{RGB} as a function of syneresis time is shown in Figure 3a. A 4-parameter nonlinear model (***ΔEm***; Eq. 2) was fitted to ΔE_{RGB} as a function of time, t, after cutting the coagulum, using the Solver add-in with Microsoft Excel (Version 10.6789.6735).

$$\Delta E_m = \Delta E_0\,[1 - e^{-k_1(t-\tau)}] + k_2 t \quad [2]$$

The coefficients ΔE_0, k_1, τ, and k_2 were optimized to give a least squares fit to ΔE_{RGB} as shown in Figure 3b.

Measurement of Color Using a Colorimeter

Color measurements of the surface of the curd/whey mixture were taken at t = 5.5 min and at 1-min intervals thereafter up to t = 85.5 min, using a handheld tristimulus colorimeter (CR-300, Minolta Limited, Milton Keynes, UK). Color measurements were performed using a CIE standard C illuminate, an angle of observation of 0° and an 8-mm diameter field of view. The colorimeter was calibrated for light source index setting C before color measurements were taken. Measurements were recorded in Hunter Lab format [i.e., lightness variable **L** and chromaticity coordinates **a** (redness/greenness) and **b** (yellowness/blueness)].

The Lab color data for the colorimeter were filtered using an algorithm that took a weighted average over 5-min intervals, weighted in favor of the smallest values; i.e., weights 4, 4, 2, 1, and 0 were applied to the 5 values, having been ranked in ascending order. A graph of a Lab metric (***D***; Eq. [3]) was then fitted with a 4-parameter model ($\boldsymbol{D_m}$; Eq. [4]) vs. time

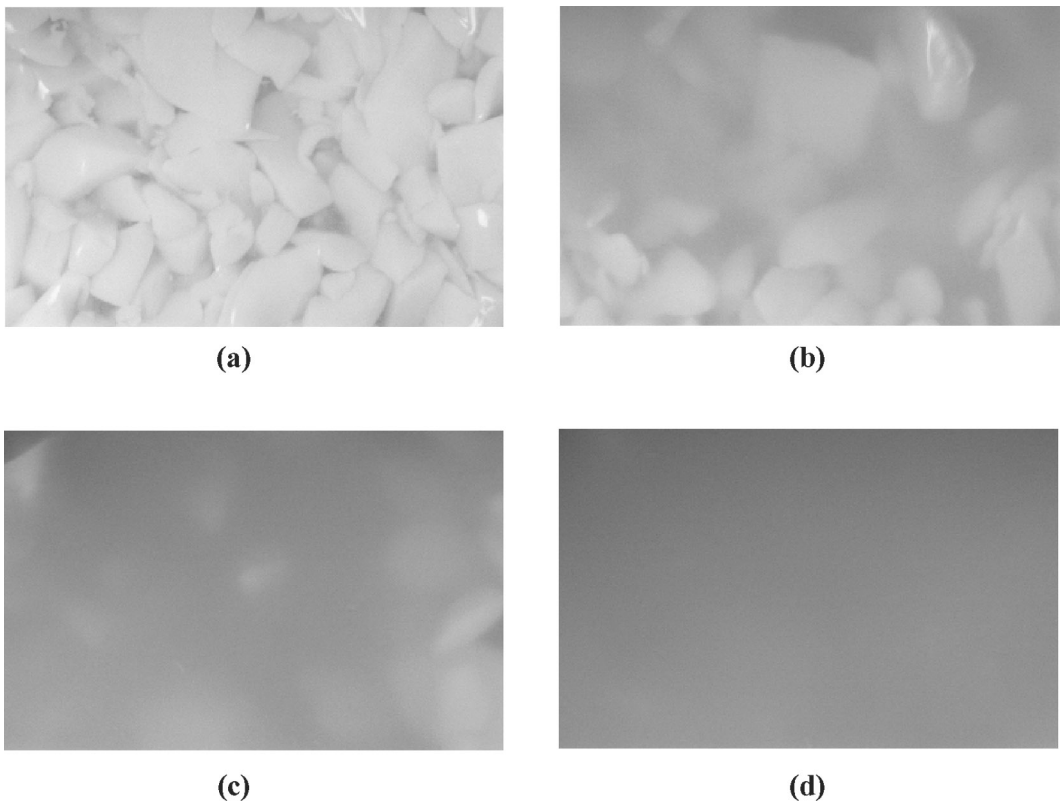

Figure 2. Computer vision images of the curd/whey mixture at a) 5 min, b) 15 min, c) 35 min, and d) 85 min after cutting, in the 10-L vat. The curd/whey mixture is being stirred by twin stirrers (Figure 1).

$$D = \sqrt{(L_0 - L_t)^2 + (a_0 - a_t)^2 + (b_0 - b_t)^2}, \quad [3]$$

where D was calculated relative to the initial image ($\boldsymbol{L_0 a_0 b_0}$) captured at t = 5 or 6 min for each image capture from t = 15 min to t = 75 min.

$$D_m = D_0[1 - e^{-k_3(t-\tau)}] + k_4 t, \quad [4]$$

where the coefficients D_0, k_3, τ, and k_4 were estimated using the Excel Solver tool to give a least squares fit to D values at time t after cutting the coagulum.

Statistical Analysis

Analysis of variance was carried out using SigmaStat V 3.1 (Systat Software UK Ltd., London, UK) to determine the factors affecting gravimetric measurements and optical parameters during syneresis. Pearson correlations were carried out, using SigmaStat, to show interdependencies between parameters. Multiple linear regression (***MLR***) was utilized, using Maximum R^2 Improvement and GLM procedures of the Statistical Analysis System (SAS 2002-2003, Rel. 9.1, SAS Institute Inc., Cary, NC) to generate equations for prediction of curd moisture from computer vision parameters.

RESULTS

Effects of pH, Stirring Speed, and Time on Syneresis

The experimental variables (i.e., pH and stirring speed) in addition to time, caused significant variation to the gravimetric measurements over the course of syneresis; i.e., t = 5 min to t = 85 min (Table 1). The pH significantly affected curd moisture ($\boldsymbol{M_C}$), yield of whey ($\boldsymbol{W_M}$), solids in curd per kilogram of milk ($\boldsymbol{S_{CM}}$, g/kg), and solids in whey per kilogram of milk ($\boldsymbol{S_{WM}}$, g/kg) during syneresis, whereas stirring speed significantly affected M_C, whey total solids ($\boldsymbol{S_W}$), W_M, and S_{WM} (Table 2, Figure 4). The M_C significantly correlated positively with S_{CM} and negatively with W_M and S_{WM}.

Computer Vision Analysis: a_{wy}

It was found that the graph of *log* a_{wy} vs. time had 2 distinct regions (Figure 5). The first region showed a linear decrease in *log* a_{wy} with time ending at $\boldsymbol{t_{linear}}$.

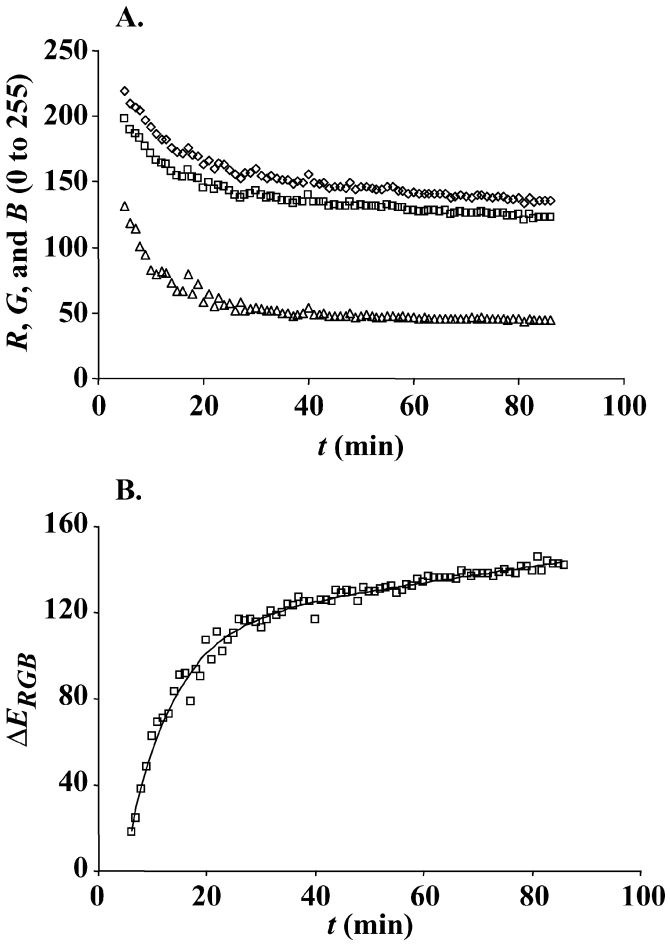

Figure 3. a) Red (◇), green (□), and blue (△) (i.e., *RGB*, values on a scale of 0 – 255 for a trial) and b) the corresponding ΔE_m values (———; RGB model) fitted to ΔE_{RGB} values (□) vs. time. $\Delta E_m = \Delta E_0\,[1 - e^{-k_1(t-\tau)}] + k_2 t$. $\Delta E_{RGB} = \sqrt{(\Delta R)^2 + (\Delta G)^2 + (\Delta B)^2}$.

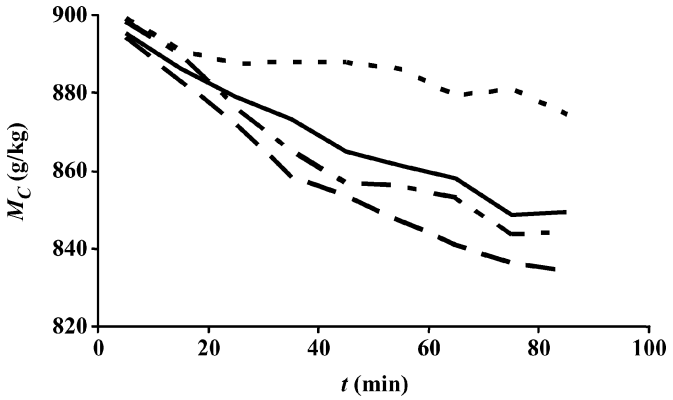

Figure 4. Changes in M_C (curd moisture) over the course of syneresis (t = 5 min to t = 85 min) for different treatments: pH, 6 and stirring speed, 12.1 rpm (average of 3 replicates, ——); pH, 6 and stirring speed, 27.2 rpm (average of 3 replicates, — — —); pH, 6.5 and stirring speed, 12.1 revolutions per minute (average of 3 replicates, – – –); pH, 6.5 and stirring speed, 27.2 (average of 3 replicates, — – — – —).

This linear period of time, t_{linear}, decreased by ~25 to 35% due to increased stirring speed (i.e., more rapid stirring implies increased shear velocities on curd surfaces, preventing formation of sediment on the curd layer) and also increased collisions between curd particles, speeding up syneresis. The second linear region of the graph showed a less-defined change in *log* a_{wy} over time and also showed considerable data scatter. Thus, log a_{wy} could be modeled in the form

$$y = mt + d,\ t = 5 \text{ min to } t_{linear}; \quad [5]$$

$$y = c,\ t = t_{linear} \text{ to } 85 \text{ min}, \quad [6]$$

where ***d*** and ***c*** are constants, ***m*** is the slope of log a_{wy} vs. time up to t_{linear} during the syneresis phase, and c is the average of log a_{wy} from t_{linear} during syneresis. The ANOVA for the main treatments on m and c is shown in Table 1.

An algorithm was developed to determine t_{linear} as follows: The standard error of the slope, m, of *log* a_{wy} vs. time (SE_m) was determined over 10-min periods (i.e., ±5 min) around any time. The t_{linear} value was defined as the line when SE_m had magnitude of one-half of the difference between the initial and maximum *log* a_{wy} values.

Various parameters describing the first and second regions of the graph were determined (Table 1). The effects of pH and stirring speed on syneresis were evident on the first and second regions of the *log* a_{wy} vs. time graph (Table 1). The slope parameter, m, of the

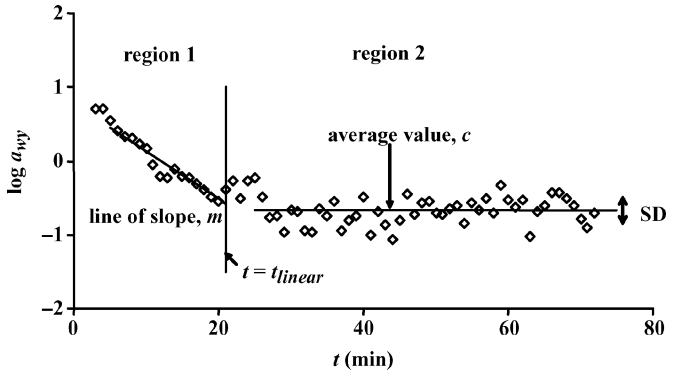

Figure 5. Graph of *log* a_{wy} (log of ratio between white and yellow areas) vs. time after cutting the coagulum for a typical trial, using the computer vision system. It is apparent that *log* a_{wy} decreases in a linear manner up to t_{linear}, the vertical bar indicating the point of departure from this first linear section.

Table 1. ANOVA and F-statistic showing the effects of pH, stirring speed (*SS*), and time (*t*) and their interactive effects on gravimetric measurements; computer vision parameters; red, green, and blue (*RGB*) computer vision model (ΔE_m); and Lab [lightness variable *L* and chromaticity coordinates *a* (redness/greenness) and *b* (yellowness/blueness)] colorimeter model (D_m) during the course of syneresis[1,2]

	n = 108[3]						n = 12[3]			n = 96[3]		n = 84[3]	
		F-value					F-value				F-value		F-value
Source	DF	M_C	S_W	W_M	S_{CM}	S_{WM}	DF	t_{linear}	m	c	DF	ΔE_m	DF	D_m
pH	1	133***	1.5^{NS}	35***	14***	37***	1	0.06^{NS}	12**	8.5*	1	10**	1	3.0^{NS}
SS	1	227***	6.2*	5.9*	0.04^{NS}	8.0**	1	6.4*	12**	162***	1	489***	1	0.45^{NS}
Time	8	99***	0.3^{NS}	81***	35***	82***	—	—	—	—	7	26***	6	2.9*
pH × SS	1	23***	7.6**	0.36^{NS}	0.21^{NS}	1.1^{NS}	1	0.71^{NS}	1.2^{NS}	0.46^{NS}	1	2.8^{NS}	1	7.0*
pH × Time	8	3.4***	0.11^{NS}	1.0^{NS}	0.94^{NS}	1.0^{NS}	—	—	—	—	7	0.14^{NS}	6	0.093^{NS}
SS × Time	8	8.8***	0.11^{NS}	0.99^{NS}	0.66^{NS}	1.0^{NS}	—	—	—	—	7	6.2***	6	0.40^{NS}
pH × SS × Time	8	2.0^{NS}	0.09^{NS}	0.82^{NS}	0.82^{NS}	0.81^{NS}	—	—	—	—	7	0.086^{NS}	6	0.012*
Error	72						8				64		56	
Model	107						11				95		83	

[1]Key for parameters: M_C = curd moisture; S_W = whey total solids; W_M = yield of whey; S_{CM} = solids in curd per kilogram of milk; S_{WM} = solids in whey per kilogram of milk; t_{linear} = time from gel cutting to the end of the of the first linear section of log a_{wy} over syneresis; m = slope of the log a_{wy} vs. time up to t_{linear}; c = average of log a_{wy} from t_{linear}; ΔE_m = *RGB* computer vision model; D_m = Lab colorimeter model.

[2]ANOVA: F-value, ANOVA F-statistics.

[3]Number of trials, 12. Number of observations during the course of syneresis for gravimetric variables M_C, S_W, W_M, S_{CM}, and S_{WM}, n = 108 (t = 5 to t = 85); and for parameters t_{linear}, m and c, n = 12 (one parameter per trial), ΔE_m, n = 96 (t = 5 to t = 85), D_m, n = 84 (t = 5 to t = 75). Further details for variation in the number of observations are provided in the text (results section).

***$P < 0.001$; **$P < 0.01$; *$P < 0.05$.

first region was significantly decreased in magnitude by increasing pH and stirring speed, indicating that the effects of these sources of variation were detected by the computer vision system. The pH and stirring speed also significantly decreased the *c* parameter, average *log* a_{wy}, in the second region (Table 1 and Figure 5). The large standard deviation around the average value in the second region decreased with increased stirring speed. Additionally it was found that there was a decrease a_{wy} with increasing W_M, which is shown in

Table 2. Effects of main experimental factors, pH, stirring speed and time, on gravimetric and optically derived variables for monitoring syneresis during cheese making[1,2]

Item	M_C (%, wt/wt)	S_W (%, wt/wt)	W_M (%, wt/wt)	S_{CM} (g/g)	S_{WM} (g/g)	t_{linear} (min)	m (min^{-1})	c (dimensionless)	ΔE_m (*RGB* units)	D_m (Lab units)
pH										
6.5	87.5^{a}	7.16^{a}	65.2^{a}	4.13^{a}	4.67^{a}	30.3^{a}	–0.049^{a}	–0.77^{a}	91.0^{a}	39.7^{a}
6.0	86.3^{b}	7.17^{a}	72.8^{b}	3.49^{b}	5.23^{b}	22.7^{a}	–0.068^{b}	–1.02^{b}	97.2^{b}	35.8^{a}
Stirring speed (rpm)										
27.2	86.1^{a}	7.20^{a}	70.5^{a}	3.79^{a}	5.08^{a}	22.0^{a}	–0.068^{a}	–0.34^{a}	73.5^{a}	37.0^{a}
12.1	87.7^{b}	7.15^{b}	67.4^{b}	3.83^{a}	4.82^{b}	31.0^{b}	–0.049^{b}	–1.45^{b}	114.7^{b}	38.5^{a}
Time (min)										
5	89.7^{a}	7.19^{a}	54.6^{a}	4.99^{a}	3.90^{a}	—	—	—	—	—
15	88.7^{b}	7.18^{a}	65.0^{b}	4.02^{bc}	4.64^{b}	—	—	—	27.1^{a}	65.1^{a}
25	87.9^{c}	7.14^{a}	70.9^{bc}	3.49^{b}	5.06^{bc}	—	—	—	36.1^{a}	85.6^{b}
35	87.1^{d}	7.15^{a}	74.3^{c}	3.20^{b}	5.31^{c}	—	—	—	39.6^{a}	93.5^{b}
45	86.6^{de}	7.17^{a}	74.4^{c}	3.32^{b}	5.32^{c}	—	—	—	40.8^{b}	97.4^{c}
55	86.2^{ef}	7.17^{a}	74.6^{c}	3.36^{b}	5.34^{c}	—	—	—	40.9^{b}	99.9^{c}
65	85.8^{f}	7.19^{a}	78.3^{c}	3.01^{b}	5.60^{c}	—	—	—	40.4^{b}	102.0^{c}
75	85.2^{g}	7.18^{a}	72.1^{bcd}	4.13^{ab}	5.33^{bc}	—	—	—	39.5^{a}	103.8^{c}
85	85.0^{g}	7.19^{a}	56.5^{ad}	4.80^{ac}	4.02^{a}	—	—	—	—	105.5^{c}

[a–g]Means within a column with the same superscript letters are not different ($P < 0.05$).

[1]Key for parameters: M_C = curd moisture; S_W = whey total solids; W_M = yield of whey; S_{CM} = solids in curd per kilogram of milk; S_{WM} = solids in whey per kilogram of milk; t_{linear} = time from gel cutting to the end of the of the first linear section of log a_{wy} over syneresis; m = slope of the log a_{wy} vs. time up to t_{linear}; c = average of log a_{wy} from t_{linear}; ΔE_m = red, green, and blue (*RGB*) computer vision model; D_m = Lab [lightness variable *L* and chromaticity coordinates *a* (redness/greenness) and *b* (yellowness/blueness)] colorimeter model.

[2]Number of trials, 12. Number of observations during the course of syneresis for gravimetric variables M_C, S_W, W_M, S_{CM}, and S_{WM}, n = 108 (t = 5 to t = 85); and for parameters t_{linear}, m and c, n = 12 (one parameter per trial), ΔE_m, n = 96 (t = 5 to t = 85), D_m, n = 84 (t = 5 to t = 75). Further details for variation in the number of observations are provided in the text (results section).

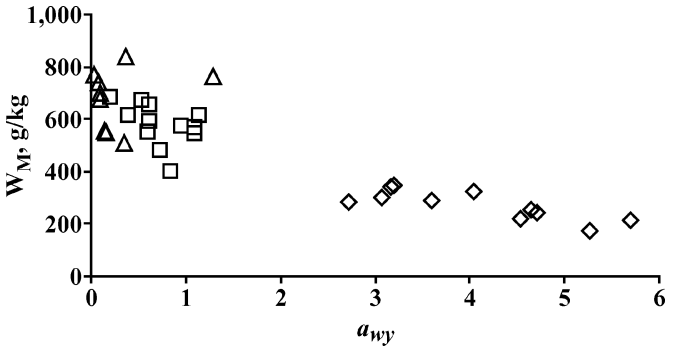

Figure 6. Plot showing trend of W_M (yield of whey) vs. a_{wy} (ratio between white and yellow area): t = 5 (◇); t = 15 (□); t = 25 (△).

Figure 6 (Table 3). It was found that an equation of the form

$$M_C = b_0 + b_1\, t + b_2\, t^2 + b_3\, m + b_4\, t_{linear} \qquad [7]$$

predicted curd moisture at high stirring speed, where b_0, b_1, b_2, b_3, and b_4 are constants. It was found that the low stirring speed confounded the prediction of curd moisture content (Figure 7a). However, this prediction equation fitted well at the high stirring speed gave a correlation coefficient of 0.96 (Figure 7b and 7c).

Computer Vision Analysis: RGB

The model of color change with respect to freshly cut coagulum, ΔE_m, which was generated at times corresponding with gravimetric measurements, was significantly affected by pH, stirring speed, and time over the duration of syneresis (Table 1). The ΔE_m decreased with S_{CM} and increased with W_M and S_{WM} (Table 3). A significant improvement in fit between the color change model, ΔE_m, and gravimetric parameters, M_C, W_M, S_{CM}, and S_{WM}, occurred when each stirring speed was considered separately (Table 3).

The change in ΔE_m during syneresis decreased with increased stirring speed ($P < 0.001$) between t = 7 min and t = 60 min (Table 2). Using MLR with ΔE_m, pH, and stirring speed as predictors over the course of syneresis (t = 7 min to t = 85 min) it was found that M_C was predicted with standard error of prediction (***SEy***) = 18% of range (R = 0.78), W_M was predicted with *SEy* = 14% of range (R = 0.73), and S_{WM} was predicted with *SEy* = 14% of range (R = 0.73).

Colorimetric Analysis

The D_m decreased significantly with S_{CM} and increased significantly with W_M and S_{WM} over the course

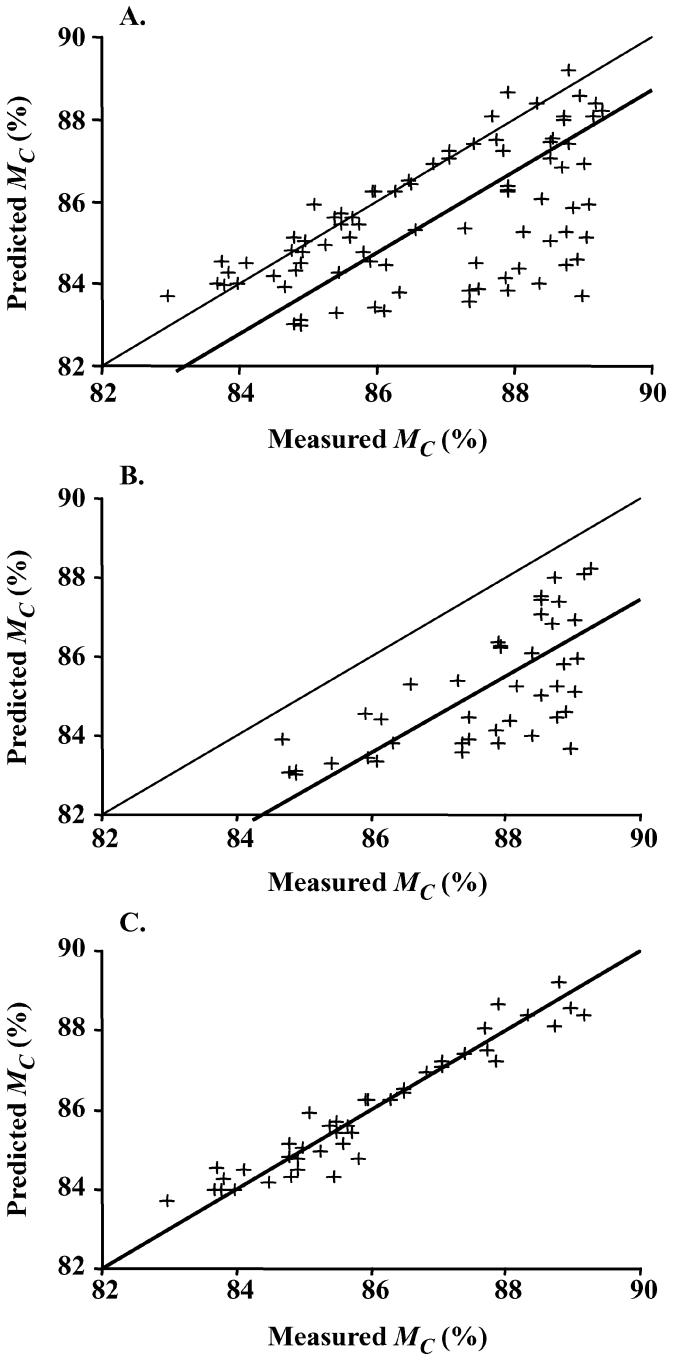

Figure 7. Fit of Eq. [7] to the experimental values of M_C (curd moisture content) at time t showing the effect of stirring speed on prediction consistency. Two different stirring speeds (12.1 and 27.2 rpm) were used to promote syneresis. Thin line, diagonal line; thick line, regression line. a) Fit for the 12 tests, which constituted the 3 whole replications of the experiment; Regression line: Predicted M_C = 0.985 × Measured M_C; b) Fit for the 6 tests at low stirring speed; Regression line: Predicted M_C = 0.972 × Measured M_C; c) Fit for the 6 tests at high stirring speed. Regression line: Predicted M_C = 1.000 × Measured M_C. Prediction equation coefficients were: b_0 = 92.63, b_1 = –0.150, b_2 = 0.000851, b_3 = 33.2, b_4 = –0.0171.

Table 3. Pearson correlation coefficients (R) and implied significance[1] between gravimetric variables and computer vision (a_{wy}, ΔE_m) and color (D_m) derived parameters,[2] as a function of the stirring speed (SS)

Item	M_C	S_W	W_M	S_{CM}	S_{WM}
a_{wy}					
All SS	0.024^{NS}	0.105^{NS}	–0.286**	0.287**	–0.269*
Low SS	0.443**	$–0.0351^{NS}$	–0.647***	0.561***	–0.640***
High SS	0.597***	$–0.135^{NS}$	–0.453**	0.309*	–0.455**
ΔE_m					
All SS	0.058^{NS}	$–0.141^{NS}$	0.281*	–0.320**	0.260*
Low SS	–0.652***	0.031^{NS}	0.716***	–0.582***	0.706***
High SS	–0.599***	0.215^{NS}	0.678***	–0.590***	0.682***
D_m					
All SS	$–0.013^{NS}$	–0.323**	0.381***	–0.435***	0.341**
Low SS	0.110^{NS}	–0.684***	0.286^{NS}	–0.372*	0.203^{NS}
High SS	$–0.289^{NS}$	0.436**	0.608***	–0.584***	0.628***

[1]n = 84; for low and high SS, n = 42.

[2]Key for parameters: M_C = curd moisture; S_W = whey total solids; W_M = yield of whey; S_{CM} = solids in curd per kilogram of milk; S_{WM} = solids in whey per kilogram of milk; a_{wy} ratio of white to yellow areas of surface of curd/whey mixture; ΔE_m = red, green, and blue (RGB) computer vision model; D_m = Lab [lightness variable L and chromaticity coordinates a (redness/greenness) and b (yellowness/blueness)] colorimeter model.

***$P < 0.001$, **$P < 0.01$, *$P < 0.05$.

of syneresis (Table 3). The D_m did not, however, distinguish between the different treatments over this period (Table 2).

Using MLR with D_m, pH, and stirring speed values as predictors, over the length of syneresis (t = 15 min to t = 75 min), M_C was predicted with standard error of prediction (SEy) = 22% of range (R = 0.63), W_M was predicted with SEy = 16% of range (R = 0.63), and S_{WM} was predicted with SEy = 17% of range (R = 0.61).

DISCUSSION

Two principal fundamental measures of syneresis, W_M and M_C, show that the majority of whey expression under the conditions of this study occurred in the first 35 min after t_{cut}. Such first-order behavior is consistent with the findings of Beeby (1959), Lawrence (1959a,b), Marshall (1982), and Renault et al. (1997). The W_M did not increase significantly after t = 35 min for any of the treatments applied in this study. However, that statistical observation may obscure the fact that small changes in whey yield after t = 35 min are important in reaching an end point. The decreases in M_C during syneresis were highly dependent on pH and stirring speed (Figure 4). The increase in syneresis, and the evidently faster leveling off due to stirring speed, were in accord with the findings of Lawrence (1959b) and Patel et al. (1972). The decrease in syneresis rate with increased pH was in accord with that found by Marshall (1982), Walstra et al. (1985), Daviau et al. (2000), and Dejmek and Walstra (2004). Our findings were consistent with those of Lodaite et al. (2000) who reported an increase in syneresis rate of about 50% with decreased pH from 6.4 to 6.0 for rennet-induced skim milk gels. Grundelius et al. (2000) found curd shrinkage to be more pronounced at lower pH with syneresis of single curd grains submerged in ultrafiltered milk permeate. Likewise, our findings were consistent with Patel et al. (1972) who reported that increasing agitation from 35 to 70 rpm, in a 5-L vat containing 2 L of milk, increased syneresis slightly.

Decreased white/yellow area ratio (a_{wy}) and increased RGB metric (ΔE_m) and Lab metric (D_m) were caused by 3 factors: 1) the shrinkage of curd particles during syneresis, 2) the expulsion of whey from the curd during syneresis, and 3) the sinking of curd particles to the bottom of the vat during constant stirring. All 3 factors are intrinsic to curd syneresis.

The computer vision system detected changes in M_C, W_M, S_{CM}, and S_{WM} from t = 5 min to t_{linear} and distinguished the different treatments of this study over the course of syneresis (t = 5 min to t = 85 min) using a defined color threshold to distinguish the areas of curd and whey at the surface. Stirring speed was found to be important for keeping curd particles in suspension, which assists a computer vision system in more accurately monitoring syneresis at the curd/whey mixture's surface. The lowest speed used in this study was not ideal for measurements at the surface, in that the heavier curd particles tended to sink easier. This is why prediction from computer vision and color measurements did not easily incorporate the effect of speed.

The computer vision parameters were also shown to correlate with W_M, S_{CM}, S_{WM}, and the different treatments of this study during syneresis (t = 5 or 6 min to t = 85 min) on the basis of RGB values averaged over

~100 mm^2 of surface of the curd/whey mixture. Although the hand-held colorimeter detected changes in S_W, W_M, S_{CM}, and S_{WM} during syneresis (t = 15 min to t = 75 min), it did not significantly distinguish the effects of pH and stirring speeds. The use of colorimeter measurements in this study was limited by practical considerations around a handheld instrument (i.e., the small time frame in which to take readings to avoid interference with the stirrers and possible human error in controlling the contact level between the curd/whey mixture and the colorimeter probe during this small time frame). However, the main limitation of the colorimeter is its small field of view compared with the computer vision system.

These computer vision and colorimetric techniques offer a potentially relatively inexpensive online means of monitoring syneresis during cheese manufacture.

CONCLUSIONS

Computer vision and colorimetric techniques were investigated as potential means of monitoring gravimetric measurements of curd and whey during the syneresis phase of cheese manufacture in a stirred-curd context. Computer vision techniques distinguished the effects of pH and stirring speeds, and it was shown that, with the inclusion of known factors and calibration to a range of operating conditions, there is potential for predicting an end point of syneresis. It was found that accuracy of a computer vision system for monitoring syneresis improves with size of field of view. One limitation of this study was that optical measurements were taken at the surface, and it was found that low stirring speeds were not effective in resuspending sinking curd and this confounded the prediction of curd moisture. This suggests that the use of submerged optical probes, installed on the vat wall, may be worthy of investigation for this application.

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