Practicability of TTI application to yogurt quality prediction in plausible scenarios of a distribution system with temperature variations

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Abstract Yogurt has high temperature sensitivity, resulting in the temperature variations from production to consumption. Cooling capacity of cold chain facilities and product storage height are regarded as factors contributing to temperature variations in this study. To find an effective method to monitor temperature history of every yogurt product, three measurements were used: the set point of a cold chamber, a data logger, and a time–temperature integrator (TTI). The mean measured yogurt quality factor (acidity, °T) of 30 samples was 92.1 °T, and predicted values were 91.8 °T from the set point, 93.3 °T from the data logger, and 92.4 °T from the TTI. In terms of individual prediction, the *SSE* of the TTI showed the smallest difference (5.76) followed by 81.5 of the set point and 118.9 of the data logger. Thus, the TTI showed the best performance and can be used to monitor the time–temperature history of yogurt in the cold chain system.

Keywords Microbial TTI · Microencapsulation · Quality monitoring · Temperature abuse · Yogurt

Introduction

Food quality and safety level are directly related to people's health, and therefore should be strictly controlled and monitored. There are external and internal factors that influence food quality during harvesting, processing, storage, distribution, and consumption. Environmental variables such as temperature, humidity, light exposure, and cross contamination are regarded as external factors, and existing variables in food such as initial contamination and vulnerable chemical components are internal factors (Blixt and Borch, 2002; Han et al., 2012). The external factors can be controlled, while internal factors are influenced only by the raw materials. Therefore, external factors would be of concern to food processors. In general, temperature is a prime variable that determines freshness and shelf life of foods (Kim et al., 2016). For the purposes of control, prediction of food quality should be considered more important than evaluation of current food quality status, because any quality problems that occur are irreversible and untreatable. To predict food quality, mathematical functions describing kinetics of food quality changes are utilized (Im and Lee, 2007). Dairy products which are usually transported via cold chain have attracted more attention due to their perishable property and temperature sensitivity. With increasing concern among the public, precise quality prediction has become necessary (Ozer, 2010).

The global dairy industry is of enormous scale, in which yogurt is a popular product due to its good mouthfeel and healthy probiotics (Ledenbach and Marshall, 2009). Yogurt is a fermented milk product with homofermentative lactic acid bacteria *Streptococcus salivarius* ssp. *thermophilus* and *Lactobacillus delbrueckii* ssp. *bulgaricus*, and the metabolites of these viable probiotics contribute to the

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healthy characteristics of yogurt significantly (Aghababaie et al., 2014; Kristo et al., 2003; Suriyarachchi and Fleet, 1981). The viability and activity of the micro-organisms change with time and temperature during storage or distribution, which needs meticulous management to maintain high quality. Yogurt should be stored and transported at approximately 5 °C to avoid undesirable deterioration. Practically, this temperature cannot be strictly maintained throughout the distribution process from production to consumption.

During the storage and transportation of yogurt, the cooling capacity of cold chain facilities plays an important role in temperature control. Large amounts of products could lead to a higher temperature than the set temperature in the cold chain, which might cause yogurt quality variation. In addition, the storage height also could result in variation of experienced temperature of yogurt products (Kang et al., 2014). If yogurt quality is predicted using only the set temperature of temperature controllers despite the presence of such temperature variation, there would be a significant error between true quality levels and the predicted ones. Thus, the impact of refrigeration capacity and storage height should be considered in the predictions. Recently, a novel method to measure temperature of individual food items has become available. This method uses time–temperature integrators (TTIs), which change color with time–temperature history. TTI application to individual food items would resolve large error-related problems in food quality prediction.

TTIs are small, inexpensive labels that can show users the food quality through color or other visual changes, which are easily measurable and irreversible (Taoukis and Labuza, 1989). These simple TTIs can be attached to the food package, and furthermore, the time–temperature history experienced by food can be monitored individually (Kang et al., 2014). According to their reaction mechanisms, TTIs are classified as biological, chemical, or physical systems (Hendrickx et al., 1993). The color-changing principles of TTIs are based on kinetics with temperature dependency. Any type of TTI can be used for food quality prediction. When choosing a TTI which has the best compatibility with a particular food, two factors should be considered—TTI end points and Arrhenius activation energy, corresponding to food shelf life and temperature dependency, respectively. Therefore, matching of a TTI with corresponding foods is non-trivial. Microbial TTI endpoints are based on a reaction between selected strains and substrates, which can change the pH of the system and lead to a color change through certain pH indicators (Taoukis, 2008). Because quality change and spoilage of food are mostly caused by the growth of microorganisms, the response of microbial TTI can represent food quality better than others and was chosen in this

study. Another option, the temperature data logger, measures individual temperatures as TTI functions. The data logger is a small, portable, electronic device, and has been used in the field to record time temperature history (Giannakourou et al., 2005). However, the price of a data logger ranges from \$15 to \$250 (https://en.wikipedia.org/wiki/Data_logger), which is too high to be used for individual yogurt packages. On the other hand, it is applicable for large-scale use including storage chambers and cold chain vehicles.

In this study, kinetic parameters and temperature dependency of yogurt quality and TTI were first analyzed. Second, cooling capacity of cold chain facilities and product storage height were taken into consideration for accurate prediction of yogurt quality. In the experimental setup, machine performance capacity was assessed by extra loading of the incubator, and product storage height was assessed by the location of yogurt samples in the incubator. The change of incubator loading resulted in temperature fluctuation. Third, use of the temperature set point, the data logger, and the microbial TTI to record time–temperature history for quality prediction were compared. The most precise method for yogurt quality prediction was thus identified.

Materials and methods

Materials

Pasteurized milk (1 L, Namyang Co., Ltd, Seoul, Korea), and a yogurt starter product (Yogurberry Life Co., Ltd, Seoul, Korea) were used. Yogurt was made as follows: a pack of yogurt starter was dissolved into 900 mL milk, which was preheated to 80 °C and cooled down to 40 °C. After stirring evenly, the mixture was fermented at 40 °C for 8 h, and then cooled at 5 °C for 40 h.

Microorganisms used in the TTI were lactic acid bacteria, *Weissella cibaria* CIPF 009 (maintained in MRS broth with 50% glycerol), isolated by the Center for Intelligent Agro-Food Packaging (Seoul, Korea). Before use, the microorganisms were sub-cultured at least three times.

Preparation of microbial TTI

The TTI was created as a microbead type rather than as a conventional broth. The Shiraus porous glass (SPG) membrane was applied for microencapsulation of the microorganisms for a new type of microbial TTI (Akamatsu et al., 2011; Choi et al., 2014; You et al., 2001). An internal pressure-type micro-kit (IMK-40M1; SPG Techno Co., Ltd., Miyazaki, Japan) equipped with an hydrophobic SPG membrane (SPG Techno Co., Ltd) was used.

The microorganisms were centrifuged (5050×g for 10 min, 4 °C) and washed with sterile buffered peptone water three times. Then, 5 mL of the cell suspension was mixed with 100 mL of sodium alginate solution (2%, w/v). A volume of 98 mL paraffin oil was mixed with 2 g of span 80. The alginate solution was dispersed into the paraffin oil through the membrane applying 15 kPa of pressure for emulsification. The mixture was stirred gently for 30 min to develop a stable W/O emulsion. Then, the emulsion was added into 400 mL calcium chloride solution (0.1 N) for solidification. The mixture was transferred into a separating funnel. After shaking for 10 min in a shaker (C-SKR, ChangShin Co., Ltd., Seoul, Korea) at 350 rpm, the funnel was kept upright until phase separation occurred. The microbeads could be collected from the lower phase. Finally, the microbeads were washed with sterile distilled water 5 times (2000×g for 5 min, 4 °C) and stored at 4 °C.

To prepare the microbial TTI, MRS (de Man, Rogosa and Sharpe, Difco, Detroit, MI, USA) agar was used as the growth substrate. Glucose (4%, w/v) and glycerol (15%, w/v) were added into the MRS agar, and a 10% (v/v) dye mixture was also added. The dye mixture solution was prepared by adding bromocresol purple (0.04%, w/v) in ethyl alcohol (95%, v/v), bromocresol green (0.05%, w/v) in ethyl alcohol (95%, v/v), and methyl orange (0.1%, w/v) in ethyl alcohol (95%, v/v) in a ratio of 1:1:1. Before mixing, the dye mixture and growth substrate were sterilized at 121 °C for 15 min separately. The pH of the substrate system was adjusted to 7.0 with 0.1N NaOH. Five grams of prepared microspheres were added into 10 mL substrate to obtain the TTI mixture. For individual monitoring of products, the TTI was designed as a sticker type. A PVC sticker was used as the base and custom made double-sided tape was pasted on it. A TTI mixture of 0.5 mL was pipetted into the center of the tape and a cover film (LDPE) was used to seal the TTI system.

Storage test

The yogurt and TTI were stored under several isothermal conditions in the temperature-controlled incubator (NEX-202S; Nexus Technologies Co., Ltd., Seoul, Korea). Individual TTI and yogurt samples were periodically taken out of the incubator, and their response variables were directly measured. The variables of TTI response and yogurt quality change were assessed by color of the TTI and lactic acid bacteria (LAB) count and acidity of yogurt, respectively.

The color of the TTI was measured with a colorimeter (CE-300; Minolta Co., Ltd., Osaka, Japan), and the color index was expressed by the color difference ΔE using CIE $L^*a^*b^*$ as follows.

$$\Delta E = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2} \quad (1)$$

where ΔL^* , Δa^* , and Δb^* are the differences in lightness, red/green, and yellow/blue, respectively.

The lactic acid bacteria (LAB) were counted using a spiral plating method (easySpiral, Interscience Co., Ltd., Saint Nom, France) (Gurtler and Beuchat, 2005). A yogurt sample of 1 mL was diluted in 9 mL buffered peptone water and the dilution process was repeated four times. The diluted solution was plated on MRS agar and stored at 30 °C for 5 days, and then the colonies were counted and recorded.

Based on the Chinese National Standard (2010), yogurt acidity (A) was measured as follows. Twenty milliliters of distilled water was added into 10 g of yogurt in a 150 mL Erlenmeyer flask, and then 2 mL of 0.5% (w/v) phenolphthalein solution was pipetted into the mixture. The titration was implemented using 0.1N standard sodium hydroxide solution until the color became reddish and was maintained over 30 s. The calculation of A (°T) is shown in Eq. (2).

$$A = \frac{c \times V \times 100}{m \times 0.1} \quad (2)$$

where c is the molarity of standard sodium hydroxide solution (mol/L), V is the volume of sodium hydroxide used in the titration (mL), m is the mass of sample (g) and 0.1 is the ideal defined molarity of sodium hydroxide (mol/L). The value of A has the multiple relationship with the standard value of titratable acidity (%), and the two values just have the coefficient difference without any fundamental difference. All the experiments were conducted with three replicates.

Kinetic studies

Kinetic and temperature dependent properties of both TTI color and yogurt quality changes were used to predict yogurt quality from TTI color.

The microbial TTI color change was examined in a zero-order reaction as follows (Taoukis and Labuza, 1989).

$$F(X) = kt + F(X_0) \quad (3)$$

where $F(X)$ is a TTI color variable, k is the reaction rate (h^{-1}), t is the time (h), and $F(X_0)$ is the initial level. The temperature dependency of reaction rate k is described by the Arrhenius Equation as follows (Taoukis and Labuza, 1989).

$$k = k_A \exp\left(-\frac{E_A}{RT}\right) \quad (4)$$

where E_A is the Arrhenius activation energy (kJ/mol), R is the universal gas constant (0.008314 kJ/mol·K), T is the temperature (K), and k_A is the pre-exponential factor (h^{-1}).

The yogurt quality variables were also analyzed kinetically. According to Zwietering (1990) and Kim (2016), microorganism kinetics and activity were described as a logistic function as follows.

$$\frac{dN}{dt} = kN \cdot \left(1 - \frac{N}{N_{max}}\right) \quad (5)$$

where N is the value of quality factors (acidity in °T or LAB count in log CFU/mL), t is the reaction time (h), N_{max} is the maximum quality value, and k is the reaction rate (h^{-1}). The temperature dependency of k was examined using Eq. (4).

Prediction of yogurt quality variables from TTI response

Under dynamic conditions, the constant T_{eff} defined as effective temperature can be regarded as the same as variable temperature. The T_{eff} estimated from TTI color was used to estimate the degree of food quality variables. T_{eff} was estimated using (6) (Shim et al., 2013; Taoukis and Labuza, 1989).

$$T_{eff} = -\frac{E_A}{R \ln \left[\frac{F(X) - F(X_0)}{k_A t} \right]} \quad (6)$$

Then, T_{eff} was substituted into Eq. (4) to calculate the reaction rate k of food. Finally, the target quality variable was estimated using Eq. (5).

Time-temperature history monitoring under plausible scenarios of a distribution system

The distribution system of yogurt products was assumed to be vulnerable to temperature control due to variations in cooling capacity of cold chain facilities and product storage height in cold chambers. It was reasoned that the amount and position of yogurt products in the cold chambers could be different at different stages of the distribution system. As shown in Fig. 1A, the yogurt products are produced and stored in the factory, and then transported to the distribution center through a cold chain truck. After storage in the distribution center, the products are transferred to retailers using a cold chain truck again.

The distribution system was simulated through a laboratory experiment using a temperature-controlled incubator (Fig. 1A). The possible alteration in cooling capacity of cold chain facilities was simulated by loading extra water in the incubator. Simulation of product storage height in the cold chambers was performed by positioning yogurt samples at different heights in the incubator. In total, 30 yogurt samples with individually attached TTIs were

placed into the incubator. A data logger was placed at the center of the incubator wall.

Results and discussion

The prediction model of quality changes of yogurt samples

The quality changes of yogurt were measured at temperatures of 9, 15, 20, and 25 °C. The LAB count did not change noticeably over time and temperature. Therefore, this quality factor could not be used in the quality prediction model. In terms of the acidity, it was found the logistic function could be used to fit the relationship over time (Fig. 2A). The reaction rates also varied with temperature. This suggested that the LAB level was maintained the same but its fermentation progressed to produce lactic acid, which finally resulted in increase of acidity of the yogurt. Because the acidity of yogurt is directly related to the mouthfeel experienced by consumers, the acidity of yogurt was chosen for the establishment of a prediction model of yogurt quality. The corresponding kinetics were represented using Eq. (5).

$$\frac{dA}{dt} = kA \cdot \left(1 - \frac{A}{A_{max}}\right) \quad (7)$$

Linear regression was performed on a logistic function, and the parameters in Eq. (7) were computed (Table 1).

The temperature dependence of reaction rate k was obtained using Eq. (4). Obtaining the logarithm of Eq. (4), the Arrhenius activation energy of k and related parameters were estimated through a linear regression between $\ln k$ and $1/T$, and the results were shown in Table 1. The other two parameters A_{max} and λ were estimated by calculating the average.

The prediction model of yogurt quality change over time was obtained subsequently by combining Eqs. (4) and (7) as follows.

$$A = \frac{113.5}{1 + e^{-1.75 - kt}} \quad (8)$$

where the reaction rate k was estimated as

$$k = 1.88 \times 10^{10} \times \exp\left(-\frac{67.5}{8.13 \times 10^{-3} \times T_{eff}}\right) \quad (9)$$

The kinetics and temperature dependency of the microbial TTI

The response of the microbial TTI was assessed by color variables. There are several variables in the CIE $L^*a^*b^*$ color system, the primary variables L^* , a^* , b^* and the

Fig. 1 Plausible scenarios of a distribution system. (A) Experimental simulation of the cold chain; (B) Time–temperature history recorded by the data logger during the simulation

secondary variable ΔE . To find the optimal color parameter of the TTI response, the relationships between the color variables and time at 25 °C were plotted. It was found that the CIE b^* value had the best linear relationship with time (correlation coefficient $R^2 = 0.9729$), followed by 0.7426 of ΔE , 0.7244 of L^* value and 0.6719 of a^* value. Therefore, the b^* value was chosen as the color response $F(X)$ of the microbial TTI. A kinetic study of the microbial TTI was conducted at temperatures of 5, 15 and 25 °C using Eq. (3), and plotted (Fig. 2B). The kinetic parameters obtained are

shown in Table 1. The TTIs at the same $F(X)$ showed the same visual color, regardless of the storage temperature.

The initial level of the color response $F(X_0)$ was obtained as 1.45 by calculating the average. Temperature dependency of the microbial TTI was estimated using Eq. (4). Obtaining the logarithm of Eq. (4), the Arrhenius activation energy of k was estimated using linear regression between $\ln k$ and $1/T$. The relevant parameters are shown in Table 1.

Fig. 2 Changes of parameters over time at different temperatures. **(A)** Yogurt acidity; **(B)** Color response of microbial TTI

Finally, the color change function of the TTI was represented using the following equation.

$$F(X) = kt + 1.45 \quad (10)$$

where the reaction rate k was estimated as

$$k = 1.23 \times 10^8 \times \exp\left(-\frac{50.2}{8.13 \times 10^{-3} \times T_{eff}}\right). \quad (11)$$

Compared with the E_A of yogurt acidity (67.5 kJ/mol), the E_A value of the TTI was 50.2 kJ/mol, which met the matching requirement (± 25 kJ/mol) (Taoukis, 2001). This demonstrated that the TTI can be used in prediction of yogurt acidity during distribution.

The end point of the microbial TTI was also determined as shown in Fig. 2B. When the TTI color response $F(X)$ reached a value of 7 at 30 h, the color response was maintained at that level over time. Thus, the color response value of 7 was determined as the end point of the microbial TTI. The color change of the TTI from the start point to the end point is also shown in Fig. 2B.

Yogurt quality predicted from temperature set point of cold chamber, data logger measurement, and TTI reading, respectively

Laboratory simulation (Fig. 1A) was performed for the comparison of effects on yogurt quality management using

Table 1 The parameters of kinetics and temperature dependency of the yogurt acidity and the microbial TTI

Kinetics					Temperature dependency		
Temperature (K)	k (h ⁻¹)	A _{max} (°T)	λ	R ²	E _A (kJ/mol)	k _A (h ⁻¹)	R ²
<i>Yogurt acidity</i>							
282	0.0064	105.5	-2.4139	0.953	67.5	1.88 × 10 ¹⁰	0.977
288	0.0098	110.4	-2.0198	0.938			
293	0.0160	116	-1.4455	0.974			
298	0.0304	122	-1.1384	0.978			
Kinetics					Temperature dependency		
Temperature (K)	k (h ⁻¹)	F(X ₀)	R ²		E _A (kJ/mol)	k _A (h ⁻¹)	R ²
<i>Microbial TTI</i>							
278	0.046	1.1925	0.942	50.2		1.23 × 10 ⁸	0.999
288	0.102	1.7086	0.938				
298	0.197	1.4432	0.967				

the three methods of prediction from temperature set point on the control panel of the cold chaer, prediction from time-temperature measured by the data logger, and prediction from the TTI color in the distribution system.

Simulation of yogurt quality based on temperature set points on control panel of cold chamber

The prediction of yogurt quality from the temperature set point of 5 °C on the control panel of the cold chamber was performed using Eqs. (8) and (9), and the results are shown in Table 2.

Simulation of yogurt quality based on time-temperature recorded by data-logger

The time-temperature history was recorded by the data logger during the plausible simulated distribution system (Fig. 1B). There were four large temperature fluctuations during the distribution steps, due to loading of different amounts of water. The different loadings resulted in different temperature profiles even under the same temperature set point of 5 °C. When 15 L or 25 L water was added into the incubator to simulate extra loading of cold chain facilities in the field, the temperature showed some obvious fluctuations. When 10 L water was added, the temperature showed good consistency without any obvious temperature fluctuations. This indicated that loading of cooling facilities influenced the actual temperature. Therefore, when food quality is estimated simply based on the temperature set points on the control panel of the equipment, the prediction is likely to be highly risky. The actual time-

temperature data would be more accurate if obtained using other means such as the data logger or the TTI.

The prediction of yogurt quality using the time-temperature history recorded by the data logger was performed using Eqs. (8) and (9), and the results are shown in Table 2. Variation in the final predicted values of the 30 yogurt samples even though the same time-temperature history was applied in the simulation, was due to variation in the initial quality levels of the samples.

Simulation of yogurt quality based on TTI color

For more accurate prediction, the TTI was employed for individual sample monitoring. The color responses $F(X)$ of 30 TTIs were measured after the simulated distribution system test and the corresponding T_{eff} values were estimated using Eq. (6). The results are shown in Table 3. The prediction of yogt quality using the individual T_{eff} values was performed using Eqs. (8) and (9), and the results are shown in Table 2.

Effectiveness of TTI use in the prediction of yogurt quality in the distribution system

The final quality levels (acidity) of 30 yogurt samples were experimentally measured to evaluate prediction accuracy (Table 2). To examine the values graphically, the values were plotted in Fig. 3. The measured and TTI-predicted acidity of yogurt were very similar both in tendency and magnitude. Unexpectedly, differences with data logger-predicted acidity were higher than those with set point-predicted ones. This might have been because the data

Table 2 Measured acidity and predicted acidity at the end of the plausible simulated distribution system test

No.	A ₀ ^a (°T)	A _m ^b (°T)	A _{Set} ^c (°T)	A _{Data} ^d (°T)	A _{TTI} ^e (°T)
1	91.5	91.0	94.7	96.1	91.7
2	89.0	91.5	92.4	94.0	91.9
3	88.5	91.5	92.0	93.6	91.9
4	90.0	91.0	93.3	94.8	91.6
5	88.5	93.0	92.0	93.6	93.0
6	88.5	92.0	92.0	93.6	92.0
7	88.0	92.5	91.5	93.1	92.5
8	87.5	91.5	91.1	92.7	91.9
9	88.0	92.0	91.5	93.1	92.2
10	88.0	92.0	91.5	93.1	92.1
11	88.0	93.5	91.5	93.1	93.5
12	88.5	93.0	92.0	93.6	92.9
13	88.0	92.0	91.5	93.1	92.1
14	86.5	92.5	90.2	91.9	92.6
15	85.0	94.0	88.8	90.6	93.8
16	88.5	91.0	92.0	93.6	91.7
17	88.5	93.0	92.0	93.6	93.1
18	87.5	92.0	91.1	92.7	92.4
19	88.5	92.0	92.0	93.6	92.2
20	88.5	92.5	92.0	93.6	92.4
21	86.0	91.0	89.7	91.4	91.8
22	87.5	94.5	91.1	92.7	93.9
23	88.0	92.5	91.5	93.1	92.7
24	88.0	91.5	91.5	93.1	92.0
25	88.5	91.0	92.0	93.6	91.8
26	88.5	91.0	92.0	93.6	91.8
27	88.5	91.0	92.0	93.6	91.8
28	88.5	91.5	92.0	93.6	92.0
29	89.0	93.5	92.4	94.0	93.2
30	90.0	92.5	93.3	94.8	92.5
Mean	88.3	92.1	91.8	93.3	92.4
SSE ^f	—	—	81.5	118.9	5.76

^aThe initial value of yogurt acidity in the simulated distribution system test

^bThe measured value of yogurt acidity at the end of the simulated distribution system test

^cYogurt acidity predicted using the temperature set point on the incubator at the end of the simulated distribution system test

^dYogurt acidity predicted using the time–temperature history recorded by the data logger at the end of the simulated distribution system test

^eYogurt acidity predicted using the time–temperature history recorded individually by the TTIs at the end of the simulated distribution system test

^fThe sum of squares for error between the predicted values and the measured values: $SSE = \sum_{i=1}^{30} (A_{X,i} - A_{m,i})^2$, where X is A_{Set}, A_{Data}, or A_{TTI}, and i is the sample number

Table 3 The color responses F(X) of 30 TTIs and the estimated corresponding T_{eff} values

No.	F(X)	T _{eff} (K)	No.	F(X)	T _{eff} (K)	No.	F(X)	T _{eff} (K)
1	3.81	257.87	11	4.72	280.05	21	3.85	280.93
2	3.91	276.40	12	4.44	278.89	22	4.95	277.00
3	3.89	276.29	13	4.03	278.05	23	4.32	278.36
4	3.75	275.55	14	4.25	280.59	24	3.95	276.60
5	4.48	279.06	15	4.86	275.87	25	3.84	276.03
6	3.96	276.65	16	3.81	279.27	26	3.84	276.03
7	4.21	277.86	17	4.53	277.68	27	3.84	276.03
8	3.92	276.45	18	4.17	277.05	28	3.94	276.55
9	4.08	277.25	19	4.04	277.58	29	4.59	279.52
10	4.02	276.95	20	4.15	276.09	30	4.23	277.95

loggers were located on the wall of incubator, and therefore could be influenced by heat transfer to the surroundings through the walls.

The mean values of the 30 samples were also compared. The mean differences between measured values and TTI-predicted or set point-predicted values were lower than those between measured values and data logger-predicted values. In terms of the *SSE* (sum of squares for error of prediction) between measured and predicted values, TTI at 5.76 showed the best agreement with the measured value, followed by set point at 81.5 and data logger at 118.9. This was in agreement with the graphical analysis above, confirming that the use of TTI could predict yogurt quality most accurately.

In conclusion, a microbial TTI created using a microencapsulation technique was used to monitor the quality of yogurt in a distribution system. In reality, the temperature of a cold chain is mostly monitored through a data logger. Considering the temperature set point on the cold chamber as the true temperature experienced by food is not advisable, and such a method places excessive trust in machine performance. This study showed that product positioning and loading influences machine performance and the temperature experienced by products, resulting in temperature variation during distribution.

Therefore, the TTI, small inexpensive device with intelligent packaging was applied for individual monitoring of yogurt products. The results showed that yogurt quality predicted by the TTI was closest to the actual levels than those predicted by conventional methods using a data logger or a temperature set point. Thus, the use of TTI was shown to be the best way to monitor quality of yogurt products. The benefits of TTI may ultimately contribute to creation of optimal distribution plans and measures of yogurt products, leading to economic value addition.

Fig. 3 Measured yogurt acidity and predicted yogurt acidity from set point, data logger, and TTI (column: measured acidity; solid line: acidity from TTI-predicted values; dashed line: acidity from data logger-predicted values; dashed-dotted line: acidity from set point-predicted values)

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