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Influence of extrusion conditions on the colour of millet-legume extrudates using digital imagery

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Colour acts as one of the triggers for acceptance of snack foods. Digital imaging in conjunction with Adobe Photoshop can help identification of variations in the colour of extruded products. Response surface methodology-based central composite rotatable designed experiments were conducted to understand the colour components and overall acceptability (OAA) of extruded snacks made from millet–legume blends, 12–28% legume, at different moisture content (MC) of 12–24% wet basis (w.b.), extruded at varying die head temperatures (DHT) from 160–200 °C, barrel temperatures from 100–140 °C and screw speeds of 100–140 rpm. A simple digital camera was used for capturing the images of the extrudates. An $L^*a^*b^*$ colour model (where L^* is the black/white element, a^* is green/red and b^* is blue/yellow) was used for colour characterisation and OAA was determined by a hedonic scale. It was inferred from the analysis of the resulting statistically valid second order models for the responses that all the colour components were significantly affected by the amount of legume in the extruder feed and by the DHT. It was also observed that DHT, synergistically with other processing parameters, had a significant effect on all the responses. The OAA was highest for the extrudates with higher L^* values. Optimum processing conditions were derived while the responses adhered to constraints. The responses of the extrudates prepared under optimum conditions exhibited no significant variation from model predicted values.

Keywords: colour; extrusion; legume; millet; optimisation

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Introduction

Extruded products are consumed as snack food throughout the world. Snacks can be a very potent vehicle for administering nutritionally important food components to consumers. Extruded snacks made from millet and legumes are rich in fibre and protein. These extrudates are also reported to have fairly good expansion indices (Chakraborty *et al*. 2009a) and textural properties (Chakraborty *et al*. 2009b). Use of fibres in food systems often results in a negative effect on the functional properties of the food (Brennan and Samyue 2004). Consumer attention to such foods can be drawn by manufacturing products of different composition, shapes, colour, etc.

Colour in many cases acts as a trigger for acceptance of products by the consumers, it plays an important role in visual recognition and assessment of the surface and the subsurface properties of the food (Nisha, Singhal and Pandit 2004). During extrusion cooking, the composition of the raw feed, and the temperature and residence time inside the extruder have been found to have significant effects on the colour of the extrudates as estimated by the International Commission on Illumination (CIE) Lab method (Bhattacharya, Sivakumar and Chakraborty 1997). This change in colour is primarily because of the non-enzymatic browning taking place as a result of the extrusion process. Again, such browning is not always an unwelcome feature, for example the golden colour of bread and biscuit crust (Berset 1989). Thus, colour has a very complicated relationship with the overall acceptability (OAA).

In understanding the colour of extrudates, it is necessary to analyse the surface colour qualitatively and quantitatively. Qualitative analysis involves visual inspection and comparison, which is reflected in the OAA scores. However, quantitative analysis requires measurement of colour. It is believed that measurement of surface colour is a much more complex phenomenon than the absorption by the stimuli pigments at specific wavelengths (Govindarajan, Rajalakshmi and Chand 1987).

The colour of pizza cooked by microwave has been measured and analysed by using a simple digital camera and the graphics software Photoshop (Adobe Systems Inc., San Jose, CA) (Yam and Papadakis 2004). The term "measure" means that the digital camera is used to obtain the colour values of the pixels on the extrudate surface. The term "analyse" means that Photoshop is used to judge those colour values. The principles of colour measurement have been very well reported by Clydesdale (1978), Hunt (1991) and Francis (1994).

The colour and OAA of millet and legume extrudates as affected by the changes in the extruder feed in terms of moisture content (MC), and blend ratio (BR), and the extruder system variables: die head temperature (DHT), barrel temperature (BT) and screw speed (SS) were studied in the present research work. Also, prediction models for the colour components and OAA which were used to derive the optimum processing conditions were developed.

Materials and Methods

Materials

The extrudates were manufactured with dehusked barnyard millet (*Echinochloa frumantacea* L.) and dehulled decorticated legume of pigeon pea or red gram (*Cajanus cajan* L.) as the key ingredients. The millet and legume were manually cleaned and ground into flour by a hammer mill, separately. The ground flour was then passed through an International Standard 200 mesh sieve, the under-flow was collected for further research work.

Plan of experiments

The experiments were designed using a central composite rotatable design (CCRD) comprising five independent processing parameters at five different levels. The CCRD was chosen for designing the experiments because it is a powerful tool for optimisation and it also reduces the number of experiments for studies involving more than two independent variables. The processing parameters were MC and BR of the raw feed; DHT, BT and SS of the extruder; each of the processing parameters had five levels. In all, thirty-two experiments (Table 1) were conducted with six experiments at centre point. The six centre point experiments were randomly conducted along with the other experiments so as to minimise the effects of unexplained variability in the observed responses due to extraneous factors (Nath and Chattopadhyay 2007).

Response surface methodology (RSM), which involves design of experiments, selection of levels of variables in experimental runs, fitting mathematical models and finally selecting the level of the variable by optimising the response, was employed in the study (Khuri and Cornell 1987). The processing parameters were coded using the following equations:

$$X_1 = \frac{\text{Moisture content} - 18}{3} \quad (1)$$

$$X_2 = \frac{\text{Blend ratio} - 20}{4} \quad (2)$$

Table 1. Experimental design for extrusion of millet-legume blends

	Values of processing parameters[a]				
	MC (% w.b.)	BR (% legume)	DHT (°C)	BT (°C)	SS (rpm)
Code[b]	Uncoded values				
–2	12	12	160	100	100
–1	15	16	170	110	110
0	18	20	180	120	120
+1	21	24	190	130	130
+2	24	28	200	140	140
Number of experiments	Plan of experiments				
16	±1	±1	±1	±1	±1
2	±2	0	0	0	0
2	0	±2	0	0	0
2	0	0	±2	0	0
2	0	0	0	±2	0
2	0	0	0	0	±2
6	0	0	0	0	0
32 = Total experiments					

[a]MC=moisture content, BR=blend ratio, DHT=die head temperature, BT=barrel temperature and SS=screw speed.

[b]Code '0' is for centre point value of the processing parameter, '±1' for factorial points and '±2' for the axial points.

$$X_3 = \frac{\text{Die head temperature} - 180}{10} \quad (3)$$

$$X_4 = \frac{\text{Barrel temperature} - 120}{10} \quad (4)$$

$$X_5 = \frac{\text{Screw speed} - 120}{10} \quad (5)$$

The experimental plan along with the levels of the processing parameters is detailed in Table 1.

Manufacture of extrudates

The millet and legume flours were blended as per the experimental design, i.e., 12, 16, 20, 24, and 28% legume. The MC of the blends was determined by the standard hot air oven method (Association of Official Analytical Chemists 1984), if required, an amount of water was added (American Association of Cereal Chemists 1983; Pelembe, Erasmus and Taylor 2002) to bring the MC on par with the requirements of the experimental design, i.e., 12, 15, 18, 21, and 24% wet basis (w.b.). The samples with specific BR–MC combinations were then fed into a single screw laboratory extruder (model Brabender D47055 Duisburg, Germany). The extruder had controls available to monitor the other processing parameters, like-DHT, BT, and SS as per the experimental design. There were certain variables of the extruder which were kept at a fixed value during the course of the experiments; feed rate, length-to-diameter ratio of barrel and compression ratio were fixed at 3.48 kg/h, 20 revolution per minute, 20:1 and 3:1, respectively.

Colour model

The colour of the extrudates was assessed by the $L^*a^*b^*$ model. The $L^*a^*b^*$ model is an international standard for colour measurement developed by the CIE in 1976. The $L^*a^*b^*$ colour model is device independent and provides consistent colour regardless of the input or output device such as digital camera, scanner, monitor, or printer. The $L^*a^*b^*$ values are often used in food research. The L^* is the lightness component and ranges from 0 (black) to 100 (white). The other two chromatic components are, a^* (–120, green to +120, red) and b^* (–120, blue to +120, yellow). The colour ($L^*a^*b^*$) and colour difference (ΔE) was measured using a simple digital imaging method (Yam and Papadakis 2004).

Colour measurement

The colour image of the extrudates was captured using a high resolution digital camera (Canon Power Shot A590 IS, 8.0 Mega Pixel, 4 × digital zoom) under two 40W fluorescent lights. Photoshop is commonly used by graphics producers and photographers for photo editing and retouching purposes (Adobe Systems 2002). This software has some striking features that make it useful for analysing the colour of food samples. The captured photo can be viewed in the Adobe Photoshop window and from the Info Palette and Histogram Window the L, a, and b values can be recorded. The use of Photoshop to examine food structure was also reported by Stanley and Baker (2002). These L, a and b values (mean of five replications) can be converted into standard colours, – L^*, a^* and b^* by using the following expressions:

$$L^* = \frac{\text{Lightness}}{255} \times 100 \quad (6)$$

$$a^* = \frac{240a}{255} - 120 \quad (7)$$

$$b^* = \frac{240b}{255} - 120. \quad (8)$$

The colour difference (ΔE) was measured by using the Hunter–Scotfield equation (Hunter 1975):

$$\Delta E = \sqrt{\left(L^* - L_i^*\right)^2 + \left(a^* - a_i^*\right)^2 + \left(b^* - b_i^*\right)^2}. \quad (9)$$

ΔE indicates the degree of overall colour change of a sample in comparison to colour values of L_i^*, a_i^* and b_i^*, which in the present case are those of the feed.

Overall acceptability

Sixty frequent consumers of extruded snack foods were recruited to carry out the sensory evaluation of the extrudates. The panel comprised graduate students, research fellows and researchers, the age group ranged between 20–45 years. The attributes evaluated were texture, appearance, mouth feel and overall acceptability. For each sample, panelists scored their liking of these characteristics using the nine-point hedonic scale (1=dislike extremely, 2=dislike very much, 3=dislike moderately, 4=dislike slightly, 5=neither like nor dislike, 6=like slightly, 7=like moderately, 8=like very much and 9=like extremely).

Data analysis

The experimental data were fitted to a second order polynomial model (10) for all the responses. The statistical validity of the models was assessed with the help of regression analysis and analysis of variance (ANOVA).

$$Y = \beta_o + \sum_{i=1}^{n} \beta_i X_i + \sum_{i=1}^{n} \beta_{ii} X_i^2 + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \beta_{ij} X_i X_j \quad (10)$$

where, Y is response, n is number of variables, X's are the variables, β_o, β_i, β_{ii} and β_{ij} are the regression coefficients.

The adequacy of the models was determined using model analysis, lack-of-fit test and R^2 (coefficient of determination) analysis (Wang *et al*. 2004). A model is said to be adequate in describing the response if the lack-of-fit is insignificant and the R^2 value for a model is more than 80% (Fillmore *et al*. 1976). The predominant effect of the processing parameters on the responses was determined by the method outlined by Alvarez–Martinez, Koundry and Harper (1988). The coefficient of variation (c.v.) is a measure of the reproducibility of the experiments and it indicates the relative dispersion of the experimental points from the prediction of the model. It is desirable for a model to have a c.v. of less than 10% (Nath and Chattopadhyay 2007). While the statistical validity of models was tested by analysis of variance (ANOVA), behaviour of the processing parameters was determined by the estimated regression coefficients of second order polynomial models for various responses. Numerical optimisation using RSM was carried out using Design-Expert 7.1.6 (2009) software. The effect of processing parameters on the colour and OAA was determined with the help of the generated response surfaces.

Results and Discussion

The experiments were conducted as per the plan reported in Table 1. The results of the application of RSM to the experimental data are presented in Table 2, perusal of this table establishes that all the models were significant ($P<0.01$), $R^2>0.8$, c.v. <0.10 and lack-of-fit was insignificant. Thus, all the models had the capability to be used to navigate the design space and to predict the responses correctly.

Colour of the extrudates

The significant decrease in L^* of the extrudates with an increase in the BR ($P<0.01$), BT ($P<0.01$) and DHT ($P<0.05$) can be attributed to the increased amount of

Table 2. Results of ANOVA for the second order polynomial models of the various responses

Predictor[a]	Regression coefficients (β)				
	L*	a*	b*	ΔE	OAA
Intercept	28.802***	–92.366***	–62.970***	50.265***	6.364***
X_1	0.100	0.863**	–0.576	0.927**	0.042
X_2	–2.868***	2.533***	–3.863***	0.802**	–0.350***
X_3	–0.613***	1.114***	–0.843**	1.083***	–0.058
X_4	–0.511**	0.345	1.110**	0.222	–0.158***
X_5	0.681***	0.180	–0.106	0.224	0.117**
$X_1 X_2$	0.096	–0.376	–0.465	0.333	–0.037
$X_1 X_3$	–0.066	0.588	0.076	–0.642	0.025
$X_1 X_4$	0.081	–0.859*	–0.324	0.763*	0.013
$X_1 X_5$	–0.434*	0.812*	–0.629	–0.815*	0.075
$X_2 X_3$	–0.708***	0.306	0.735	0.033	–0.350***
$X_2 X_4$	0.047	0.106	1.159**	–0.006	0.313***
$X_2 X_5$	0.199	–0.176	–1.194**	0.050	–0.050
$X_3 X_4$	–0.860***	–0.035	1.135**	0.410	–0.325***
$X_3 X_5$	0.125	0.953**	–0.018	–0.974**	0.062
$X_4 X_5$	0.105	–0.918**	0.218	0.852*	0.000
X_1^2	0.801***	–0.046	–1.148***	–0.290	0.049
X_2^2	0.041	1.589***	–1.018**	–1.448***	0.111**
X_3^2	–1.228***	1.178***	–0.818**	–1.058***	–0.114**
X_4^2	–0.919***	–0.034	–2.265***	–0.181	–0.026
X_5^2	0.012	0.330	–1.853***	–0.680**	–0.051
ANOVA					
Model (R^2)	0.975	0.929	0.954	0.882	0.945
Model (F-value)	21.9***	7.22***	11.44***	4.11***	9.46***
c.v. (%)	3.16	1.79	2.68	3.43	3.91
Lack of fit	n.s.	n.s.	n.s.	n.s.	n.s.

[a]L^* is the lightness component and ranges from 0 (black) to 100 (white), a^* is redness (–120, green to +120, red) and b^* is yellowness (–120, blue to +120, yellow); ΔE is colour difference.
n.s. = not significant.
X_1 = coded moisture content; X_2 = coded blend ratio; X_3 = coded die head temperature; X_4 = coded barrel temperature; X_5 = coded screw speed.

legume, resulting in a higher amount of amino acids in the melt and high working temperature during the extrusion process. Non-enzymatic browning, coupled with the colour of the legumes resulted in a darker product. L^* registered a significant ($P<0.01$) increase with an increase in SS. The residence time of the melt inside the extruder decreased sharply with an increase of SS leading to a product with higher L^* values. Similar findings were reported by Bhattacharya *et al*. (1997) in their study with green gram–rice extrudates. The a^* value was positively influenced at $P<0.05$ by MC and at $P<0.01$ by BR and DHT. Enhanced a^* was observed in the extrudates with an increase in the moisture and legume content in the feed and at higher working temperature. Higher a^* means the colour is traversing through the brown region towards red; this can be attributed to the formation of end products from the Maillard reaction. An increase in the levels of all the processing parameters except BT, resulted in a decrease in the b^* value. A decrease in b^* means that the colour of the product is towards the darker region of the b^* axis. The ΔE value increased invariably with increase in the levels of all the processing parameters. In other words, the colour of the extrudates departed from the colour of the melt, and it was observed that DHT ($P<0.01$) had a more pronounced effect followed by MC and BR at $P<0.05$.

Interactions of MC–SS, BR–DHT and DHT–BT significantly affected the lightness L^* value of the extrudates. However, the interaction of DHT–BT had the maximum (β=–0.860) effect on L^*. It was observed that L^* was maximum for the extrudates manufactured at values just more and just less than centre point for DHT and BT, respectively (Figure 1a). The a^* value of the extrudates was affected significantly by the interactions of SS with DHT and BT at $P<0.05$ and with MC at $P<0.1$. The a^* was most sensitive to the interactions of DHT and SS (β=0.953). At SS less than centre point and DHT between 180 to 190 °C, the extrudates had the highest values (Figure 1b). Owing to the reduced residence time at increased SS, a^* value markedly increased. The BT of the extruder contributed significantly to the b^* value of the extrudate at $P<0.05$ while interacting with BR and DHT. However, the b^* value was most sensitive to the interaction of BR with SS (β=–1.194, $P<0.05$). The extrudates were more towards the yellow colour when the BR was very low and SS was just above the centre point (Figure 1c). The interactions of MC of the melt and extrusion cooking variables (DHT, BT, and SS) had a significant effect on ΔE. It can be inferred that the extent of cooking (influenced by MC, DHT and BT) and residence time (influenced by SS) lead to departure of the colour of the extrudates from that of the melt. The interaction of MC–BT, MC–SS and BT–SS were all found to significantly affect ΔE at $P<0.1$. Furthermore, it was observed that the sensitivity of ΔE towards the interactions of DHT and SS was maximum (β=–0.974). The extrudates had colour values farthest from the melt when the SS was at centre point and DHT varied between factorial point and centre point (Figure 1d). The contribution of BR to the attainment of colour by the extrudates can be seen in Table 3. It can also be observed that temperature variables of the extruder DHT and BT had a noteworthy effect on the colour of the extrudates.

Overall acceptability. It can be observed from Table 2 that the OAA of the extrudates decreased significantly with the increase in BR and BT at $P<0.01$, while an increase in SS resulted in an increase in OAA at $P<0.05$. OAA exhibited almost the same trends with respect to processing parameters as L^*, i.e., OAA increased for all those reasons for which L^* increased. Perhaps darker extrudates were not popular amongst the panellists, hence the lower OAA at increased in BR and BT. This is supported by the antagonistic individual effects of processing parameters on OAA. The interactions of BR, DHT and BT had a significant ($P<0.01$) effect on OAA. Similar observations were also made from Table 3, that BR, DHT and BT, in that order, had a predominant effect on OAA. Most prominent was the BR–DHT (β=–0.350) interaction. The extrudates that found maximum acceptability amongst the consumers were manufactured at high DHT and low BR (Figure 1e).

Optimum conditions

The processing parameters were optimised with respect to the defined desirable constraints of the responses. The constraints and the optimum values are reported in Table 4.

Extrudates were manufactured at the optimum conditions obtained and the

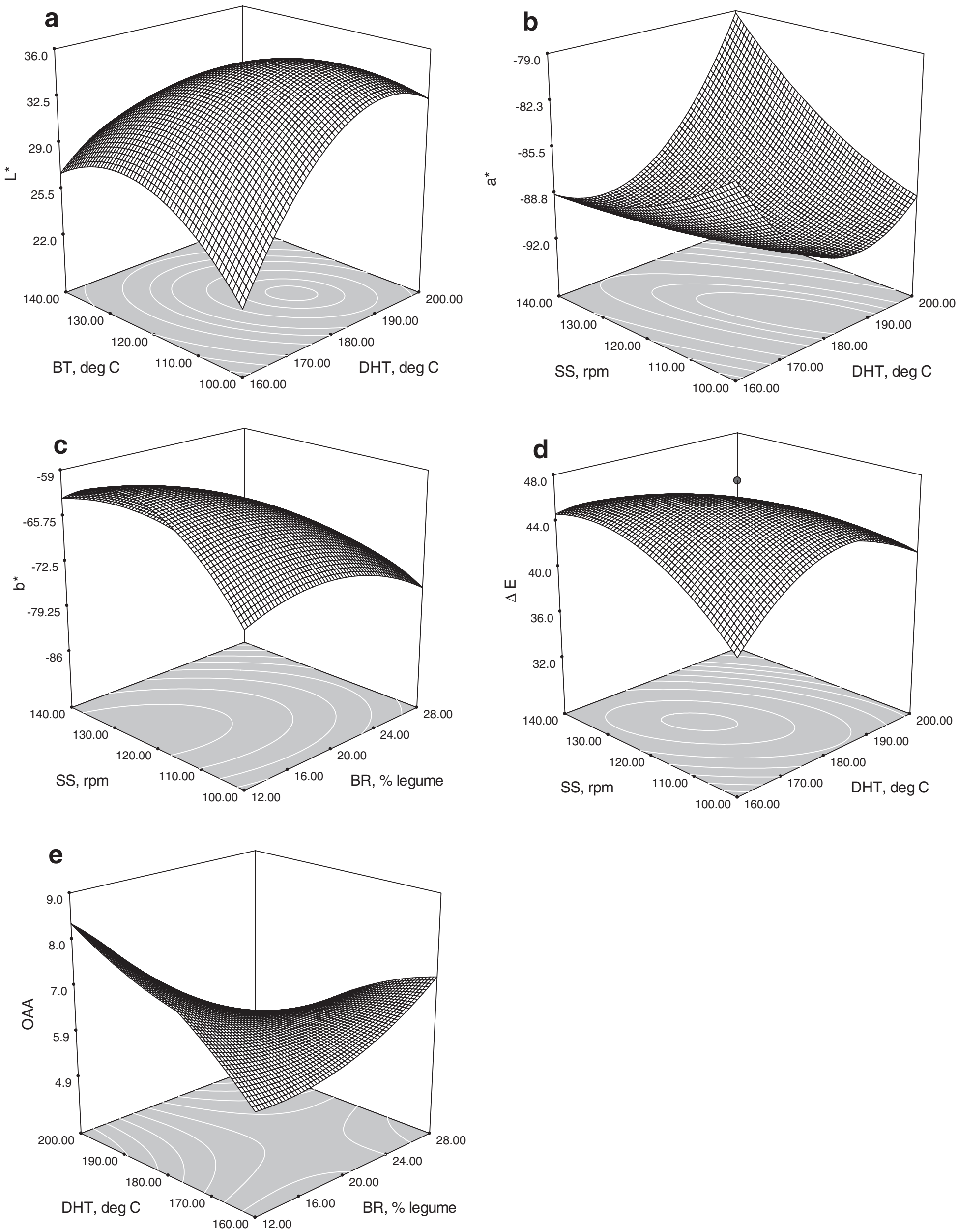

Figure 1. Response surfaces for L(1a), a*(1b), b*(1c), ΔE (1d) and OAA (1e) depicting interactive effects of processing parameters on the responses.*

responses were recorded (mean of 5 measurements). These responses were compared with the predicted values using a two-tailed, one sample t-test (Table 5). It was observed that there was no significant difference between the values of

Table 3. Contribution of the processing parameters to model R^2

Processing parameters	Responses				
	L*	a*	b*	ΔE	OAA
MC (% w.b.)	0.064	0.119	0.072	0.207	0.019
BR (% legume)	0.590	0.574	0.552	0.317	0.560
DHT (°C)	0.210	0.227	0.082	0.344	0.438
BT (°C)	0.123	0.070	0.279	0.104	0.413
SS (rpm)	0.043	0.106	0.162	0.210	0.048
Model (R^2)	0.975	0.929	0.954	0.882	0.945

See footnotes to Tables 1 and 2.

the predicted responses and the recorded response.

Conclusion

Statistically valid modelling of colour components (L^*, a^*, b^*, ΔE) and OAA for millet–legume based extrudates can be successfully carried out using RSM. The colour of millet–legume based extrudates can be measured by capturing colour images using a digital camera and analysing them using Photoshop software. The percent of legume in the feed, BR and the temperatures of the extruder DHT and BT were found to be the most prominent processing parameters having a substantial effect on the extrudates. It was also observed that darker coloured extrudates

Table 4. Constraints and goals applied to derive optimum conditions of processing parameters and responses

Processing parameters	Goal	Lower limit	Upper limit	Importance	Optimum value
MC (% w.b.)	in range	12	24	3	21.3
BR (% legume)	in range	12	28	3	13.4
DHT (°C)	in range	160	200	3	187.3
BT (°C)	in range	100	140	3	115.3
SS (rpm)	in range	100	140	3	137
Responses					
L^*	maximise	19.8	33.4	3	34.5
a^*	minimise	–95.4	–80.3	3	–83.6
b^*	minimise	–78.4	–57.3	3	–66.3
ΔE	minimise	39.6	52.3	3	37.4
OAA	maximise	5.2	8.4	3	8.6

See footnotes to Tables 1 and 2.

Table 5. Verifying the correctness of models by using two-tailed t-test

Response	Predicted value (μ_o)	Actual value@ (μ_1)±SD	Standard error	Mean difference	Percentage variation	t_{cal}
L*	34.5	32.6±3.24	1.447	1.9	5.76	1.30
a*	–83.6	–85.3±4.08	1.825	1.7	2.04	0.95
b*	–66.3	–64.7±2.64	1.179	1.6	2.47	1.36
ΔE	37.4	39.7±4.17	1.863	2.3	5.78	1.23
OAA	8.6	8.1±0.42	0.186	0.5	6.70	2.90

See footnotes to Table 2.
h_o: $\mu_o = \mu_1$, $t_{cal} < t_{table}$ at P<0.01, 'h_o' was accepted.
@mean of five replications.

had a decreased acceptance amongst the consumers. Second order models for the responses were found to predict the responses within the statistically acceptable range.

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