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The development and control of colour in extrusion cooked foods†

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Mixtures of wheat starch, glucose and lysine, 96:3:1 and 92:6:2 (m:m:m) of three moisture contents (13, 15 and 18%) were extrusion cooked using two target die temperatures (125 and 135°C). The colours of the extrudates were described and matched to standards, and CIELAB $L^*a^*b^*$ measurements were obtained for samples of the ground extrudates. In general, increasing the die temperature or the amounts of glucose and lysine, or decreasing the moisture content, increased the colour intensity of the extrudates, and resulted in decreased L^* and increased a^* and b^* values. In general, decreasing the moisture content from 18% to 13% had a greater influence on colour development than increasing the die temperature. Well-expanded products were obtained using moisture contents of 13 and 15%, but expansion was much poorer at 18% moisture.

INTRODUCTION

Food has been processed by extrusion cooking for more than 50 years (Harper, 1989). The process involves subjecting the feed material (of intermediate water activity) to elevated temperatures (e.g. 120–180°C) and pressures, as well as to shear stress. Advantages of extrusion cooking include the combination of a number of unit operations in one process, energy efficiency, the production of no effluent and the ability to process relatively dry viscous materials and unconventional ingredients (Harper, 1979, 1989). It is ideal for the processing of cereals, and is used for the manufacture of ready-to-eat cereals and expanded snack foods.

Both single- and twin-screw extrusion cookers are available. Twin-screw extruders began to be used for food processing in the 1970s, and possess greater operating flexibility than their single-screw counterparts. Harper (1979) has described the most important components of an extrusion cooker and their functions. The material may reach temperatures of, for example, 120–180°C during processing and the moisture content is typically in the region 12–18% (for cereal materials). Extrusion cooking is therefore a process involving the application of relatively high temperatures to materials of intermediate water activity, and such conditions favour the Maillard reaction.

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Extrusion cooking alters the nature of many food constituents, including starches and proteins, by changing their physical, chemical and nutritional properties (Harper, 1979). The resulting changes in conformation, together with the partial degradation of starch and protein, can result in increases in the availability of reactive groups which can go on to take part in reactions, including the Maillard reaction. In addition, reductions in low molecular weight carbohydrates during extrusion cooking have been reported by several authors. For example, Andersson *et al.* (1981) showed that a decrease in total sugar content (sucrose, glucose and fructose) of 70–80% occurred on extrusion cooking of a mixture of wheat starch, wheat gluten and wheat bran, using a final barrel temperature of 142–155°C. It was suggested that losses of glucose and fructose were at least partly due to these sugars taking part in the Maillard reaction, since higher recoveries were obtained when gluten was excluded from the feed mix. The effects of extrusion cooking on amino acids have usually concentrated on lysine. An increase in processing temperature results in a decrease in available lysine, and most reports conclude that an increase in moisture content (over the range 13–18%) gives an increase in lysine retention (Asp & Bjorck, 1989).

Very few studies have been reported on colour development, as a result of the Maillard reaction, during extrusion cooking. The most useful study is that of Noguchi *et al.* (1982), who monitored the effects of various processing variables on colour development in a mixture of wheat flour, corn starch, sucrose, soya protein isolate, sodium caseinate and sodium chloride.

At 13% moisture, the brown colour developed increased markedly with increasing die temperature over the range 170–210°C. Over the same temperature range, the product was much lighter in colour when the moisture content was 18%. It was shown that lysine losses paralleled colour development, and Noguchi *et al.* (1982) suggested that improved lysine retention at higher moisture content in the presence of carbonyl compounds, such as reducing sugars, could be explained by the law of mass action, since water is produced in the early stages of the Maillard reaction.

This paper reports a study on the development of colour, formed as a result of the Maillard reaction, in starch–glucose–lysine mixtures of varying moisture content and processed by extrusion cooking using two different target die temperatures.

MATERIALS AND METHODS

Materials

Experiments were performed using either wheat starch (Tenstar Products Ltd, Ashford, Kent, UK), or a mixture of wheat starch, D-(+)-glucose (AnalaR, BDH Chemicals Ltd, Poole, UK) and L-lysine monohydrochloride (minimum assay 99%, BDH Chemicals Ltd, Poole, UK).

Methods

Preparation and analysis of extruder feeds

Homogeneous starch–glucose–lysine extruder feeds were obtained using a Winkworth mixer (Winkworth Machines, Reading, UK) set at 50·2 rpm for 30 min. Extruder feeds were analysed immediately after mixing and extruded on the following day. Measurements of pH were carried out using the AOAC method for flour (AOAC, 1990). Moisture contents were determined using the Carter–Simon Rapid Moisture Tester (Henry Simon Ltd, Stockport, UK). A Protimeter dew point meter, Model DP.383R (Protimeter, Marlow, UK) was used to determine water activities.

Preparation of extrudates

All extruder runs were performed using an MPF50 twin-screw food extruder (APV Baker, Peterborough, UK), equipped with a water pump and a volumetric feed hopper, both of which were precalibrated. The feed rate was 30 kg h^{-1}. Extrudates with different colour intensities were prepared by varying the amounts of glucose and lysine in the extruder feed, the total moisture content of the material cooked (by adjusting the extruder water pump setting) and the die temperature. Two target die temperatures were chosen, i.e. 125 and 135°C, and reflected the final extrudate temperature. The screw configuration was 6·4 mm (¼ in) blank, 406 mm (16 in) blank, 356 mm (14 in) feed screw, 7 × 30° forward paddle, 76·2 mm (3 in) single lead screw, 3 × 60° reverse paddle, 76·2 mm (3 in) single lead screw, 4 × 60° forward paddle, 50·8 mm (2 in) single lead screw, 2 × 90° paddle, 3 × 45° reverse paddle, 50·8 mm (2 in) single lead screw. The die had two orifices, each with a diameter of 4 mm.

Median residence times were calculated using erythrosine dye, by measuring the time taken for the extrudate to achieve the strongest colour (as assessed visually). The target residence time was 25 s.

Analysis of extrudates

Triplicate samples of each extrudate were ground separately in a coffee grinder. Ground samples were placed in a glass cell (width 50 mm, height 54 mm, light path 10 mm) and CIELAB $L^*a^*b^*$ measurements were obtained using a HunterLab ColorQUEST spectrophotometer (Hunter Associates Laboratory Inc., Reston, VA, USA), in the reflectance mode. The illuminant was D65 and the observer angle was 10°. The colours of the extrudates in a light box (D65 illuminant) were described by two assessors, and matched to swatches in a Dulux Colour Dimensions Colour Fan Book (ICI Paints Division, Slough, UK).

The diameter of each extrudate was measured in at least triplicate, using a pair of callipers, to give an indication of the relative degree of expansion of each product.

RESULTS AND DISCUSSION

The aim of the study was to begin to understand and control the development of colour (caused by the Maillard reaction) in heat-treated foods, in particular those produced by extrusion cooking. Wheat starch was chosen as a relatively inert matrix which is readily available. Glucose and lysine were chosen as the reducing sugar and amino acid, respectively. Glucose occurs in the free form in a wide range of foods but, being a hexose, it takes part in the Maillard reaction more slowly than pentoses (Spark, 1969). Lysine possesses the greatest browning potential of all the amino acids commonly found in foods (Ames, 1986), and its free ε-amino group means that it can take part in the Maillard reaction, even when it is protein-bound. A glucose : lysine ratio of 3:1 was chosen, since it has been

Table 1. Moisture content, water activity and pH of extruder feeds

Feed composition[a]	Moisture content (%)[b]	Water activity[c]	pH[c]
Starch only	11·6 ± 0·1	0·48 ± 0·01	5·7 ± 0·1
S:G:L (96:3:1)	11·4 ± 0·1	0·43 ± 0·01	5·6 ± 0·1
S:G:L (92:6:2)	11·5 ± 0·1	0·41 ± 0·01	5·3 ± 0·1

[a] S, starch; G, glucose; L, lysine monohydrochloride. The ratio of the three components is given on a m:m:m basis.
[b] Average of at least triplicate measurements.
[c] Average of at least duplicate measurements.

Table 2. Conditions used for extrusion cooking and some properties of the extrudates

Run no.	Feed composition[a]	Barrel set temperature (°C)[b]	Torque (%)	Total moisture content (%)	Screw speed (rpm)	Pressure (psi)	Final barrel temperature (°C)	Target die temp. (°C)	Actual die temp. (°C)	Residence time[c]	CIELAB values[c]			Colour of extrudate[d]	Colour fan measurement	Diameter of extrudate (mm)[c]
											L^*	a^*	b^*			
C_0	S only	30/40/65/80/80	50	18	300	500	143	125	123	20	88·09	1·06	9·74	W (1)	0500-N	15·2
D_0	S only	30/40/65/80/80	60	13	300	600	157	135	136	25	87·54	1·29	9·22	off-W (2)	0000-N	18·8
A_1	S:G:L 96:3:1	25/30/45/50/50	80	13	300	400	151	125	132	25	73·77	5·80	21·78	G (6)	2030-Y20R	17·8
B_1	S:G:L 96:3:1	30/40/60/70/70	70–75	15	300	400	145	125	124	25	79·09	4·47	20·51	pG-Y (4)	1116-Y18R	20·0
C_1	S:G:L 96:3:1	30/50/70/90/90	75	18	300	400	142	125	125	25	86·40	1·39	13·99	pC (3)	0005-Y20R	15·5
D_1	S:G:L 96:3:1	30/50/70/90/90	65–70	13	300	400	156	135	136	23	73·93	6·34	22·84	G (6)	2030-Y20R	18·5
E_1	S:G:L 96:3:1	30/50/70/90/90	65	15	300	450	153	135	132	23	78·26	4·85	21·54	pG-Y (4)	1116-Y18R	18·3
F_1	S:G:L 96:3:1	30/50/85/120/120	75	18	230	300	154	135	136	30	81·86	3·00	18·50	pG-Y (4)	1116-Y18R	14·8
A_2	S:G:L 92:6:2	30/50/60/70/70	65	13	230	500	147	125	124	28	72·68	7·53	24·50	pG-B (7)	2040-Y20R	20·0
B_2	S:G:L 92:6:2	30/50/70/90/90	70	15	250	400	148	125	127	28	73·13	7·03	24·69	pG-B (7)	2040-Y20R	19·3
C_2	S:G:L 96:6:2	30/50/70/90/90	60	18	300	400	139	125	124	25	79·87	3·97	22·33	G-Y (5)	0020-Y20R	14·5
D_2	S:G:L 96:6:2	30/50/70/90/90	80	13	230	400	149	135	130	30	69·90	7·96	24·31	G-B (8)	3030-Y30R	16·3
E_2	S:G:L 96:6:2	30/50/70/90/90	70	15	300	400	148	135	131	25	72·56	7·53	25·25	pG-B (7)	2040-Y20R	17·3
F_2	S:G:L 96:6:2	50/70/90/120/120	75	18	210	350	153	135	135	35	72·88	6·88	24·94	pG-B (7)	2040-Y20R	10·3

[a] S, starch; G, glucose; L, lysine monohydrochloride. The ratio of the three components is given on a m:m:m basis.
[b] The set temperature for each of the five barrel zones is given.
[c] The mean values obtained from triplicate readings are given.
[d] p, pale; W, white; Y, yellow; C, cream; G, golden; B, brown. The numbers in brackets give the order of colour intensity; 1, least colour; 8, most colour.

shown that, at this ratio, glucose is not the limiting reactant (Lea & Hannan, 1950). Starch : glucose : lysine ratios of 96 : 3 : 1 and 92 : 6 : 2 (m : m : m) were arbitrary.

The moisture contents, water activities and pH values of all the extruder feeds were very similar (see Table 1). The data shown in Table 2 illustrate the effects of variations in die temperature and moisture content of the material processed and amounts of glucose and lysine on the colour properties of the extrudates. Other extrusion conditions were varied as required in order to achieve, as far as possible, the target residence time and die temperatures. Since the large number of processing variables are inter-dependent, some difficulty was experienced in attaining the desired settings.

Extrusion cooking starch alone always resulted in a white or off-white extrudate. In contrast, all the extrudates prepared from the starch–glucose–lysine mixtures showed the development of definite colour (ranging from pale cream to golden brown), which varied in intensity according to the die temperature, moisture content and amounts of glucose and lysine used. In general, *increases* in die temperature and amounts of glucose and lysine, and *decreases* in moisture content, each resulted in increased colour development. As the observed colour intensity of the extrudates increased, the CIELAB L^* value decreased (indicating a darker sample) and the a^* and b^* values generally increased (indicating increased redness and yellowness, respectively). As expected, increasing the levels of glucose and lysine (while maintaining the die temperature and moisture content constant) always gave an increase in colour development. Table 2 shows that, in general, decreasing the moisture content of the extruder feed from 18% to 13% has a greater effect on colour development than increasing the die temperature from 125°C to 135°C. This is in line with the data obtained by Noguchi *et al.* (1982), who showed that colour development paralleled lysine losses in their system and considered that the best means of minimising losses of available lysine (and minimising colour development) during extrusion cooking was to increase the moisture content of the material during processing. The data for the extrudates obtained using a starch : glucose : lysine ratio of 96 : 3 : 1 show this best, and it appears that the effect of temperature is negligible, especially at moisture contents of 15% or 13%. The effect of temperature on colour development seems most important at a moisture content of 18%, differences in colour intensity being noted between all samples processed at this moisture level.

Texture measurements were not of primary interest in this study; nevertheless, the diameter of the extrudates gave an indication of the degree of expansion of the products, and the data in Table 2 show that a moisture content of 18% resulted in a much lower degree of expansion than moisture levels of 13% or 15%.

CONCLUSION

This study illustrates the effects of varying the amounts of glucose and lysine in a starch–glucose–lysine mixture and modifying the moisture content and die temperature, on final product colour. Intensity of colour (as assessed visually and instrumentally) increased on raising the amounts of reducing sugar and amino acid in the extruder feed, increasing the die temperature and decreasing the moisture content. In general, decreasing the moisture content from 18% to 13% had a greater effect on colour intensity than increasing the die temperature from 125°C to 135°C.

Future work will involve looking at the effects of other processing variables on colour development and studying the chemistry underlying colour development in extrudates produced under selected conditions.

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