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Effect of extrusion barrel temperatures on residence time and physical properties of various flour extrudates

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Abstract

The aim of this study was to evaluate the effect of barrel temperature and flour types on the residence time and physical properties of various flour extrudates. Corn flour, rice flour, corn flour with potato starch (30% w/w, d.b), and rice flour with potato starch (30%w/w, d.b) were extruded at screw speed of 75rpm, feed moisture at 25% (w/w, w.b.), barrel temperature ranging from 80°C to 140°C and die size of 1.88mm. The extrudates were dried at 50°C overnight and further analysed. Results showed that an increase in extruder barrel temperature decreased the residence time of the flours in the extruder (from 4.11-11.32min to 2.24-6.76min), but increased the expansion ratio, rehydration ratio, water absorption index, water solubility index and b value of the extrudate ($p \leq 0.05$). The extrudates had the mean residence time and physical properties of rice flour<rice flour with potato starch<corn flour with potato starch<corn flour ($p \leq 0.05$). Results showed conclude that barrel temperature and flour types showed significant effect on the residence time and physical properties of the extrudates.

Introduction

Extrusion cooking is a thermal process that has been extensively used in food and non-food industries. In food industry, it is used for the production of different types of pasta, snacks, breakfast cereals and baby foods (Maskan and Altan, 2012). Extrusion cooking has advantages in the ability of handling a wide variety of raw materials in a low production cost (Deshpande and Poshadri, 2011). Flours and starches from rice, potato, and corn are commonly used in the industry as thickener or gelling agent. However, the lack of versatility to function properly in food process caused these flours to have limitations on food applications (Nakorn *et al*., 2009).

Using native flour in food industrial application often causes problems during pumping in processing pipeline. This is due to their thermal and shearing instability that cause poor end product quality as these flours retrograded during cooling and/or freezing (Arocas *et al*., 2009). After physical, enzymatic or chemical modification of these flours, they can be applied as ingredients in instant foods as they are easily dispersed in cold water (Nakorn *et al*., 2009; Kaur *et al*., 2012). Chemically modified starch is widely used in the industry, but due to an increase in consumers' awareness and negative perception on the labelling term "chemically modified", there are tendency towards producing clean label foods (Arocas *et al*., 2009).

Physically modified or pregelatinization of rice, corn, and potato starch flours can be achieved using extrusion cooking where complete cooking of starches can be done very fast. Mechanical shear which occurs during the extrusion cooking process causes starch gelatinization and protein denaturation, led to molecular transformation and chemical reactions where complete cooking can achieve (Singh *et al*., 2007; Yu *et al*., 2012). Types of flour, extruder barrel temperature and residence time are important contributors to different degree of starch gelatinization and protein denaturation that leads to the different physical properties of the extrudate (Singh *et al*., 2007; Mulla *et al*., 2011). Different researchers reported that different extruder barrel temperatures and flour types were found to affect physical properties of the extrudates, such as the expansion ratio (Hagenimana *et al*., 2006), rehydration ratio (Yu *et al*., 2012), colour (Sun and Muthukumarappan, 2002), water absorption index (Ding *et al*., 2006) and water solubility index (Kadan *et al*., 2003).

Besides physical properties, types of flour and extruder barrel temperature were also reported to

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affect residence time. Residence time distribution (RTD) is one of the fundamental parameter in extrusion process to understand the degree of cooking of the raw material (Ficarella *et al*., 2006) and nutrient retention for extrudates (Suparno *et al*., 2005). Iwe *et al.* (2001) reported that RTD was affected by different flour mixture ratio, where higher starch content caused longer mean residence time, while Kumar *et al.* (2006) reported that increase in barrel temperature decreased the mean residence time of the extrudates. However, these cited studies used single type of flour only, for example, Kumar *et al.* (2006) studied only on starch contains 25% amylose content. Although food industry normally used different types of flours such as rice, corn, and potato as thickening agent, comparison of the performance of extrudate from different types of flour has not been reported in literature. Different types of flour consists of different composition in starch (amylose: amylopectin content, granule size and shape), protein (rice protein and zein protein for corn), and fat contents, it is expected that these differences contribute to the different physical properties of the extrudate (Arocas *et al*., 2009). Potato starch but not flour, was added to the flour as the source of increasing starch content of the mixture due to its higher viscosity (Singh *et al.*, 2003b) as compared to the other two flours in this study.

Therefore, the objective of this research was to evaluate the effect of barrel temperature and flour types on the residence time distribution and physical properties of the extrudates, where this provides more fundamental understanding on these effects. The results will provide helpful information for the industries to understand the physical properties of the extrudates when selecting suitable processing condition to meet their processing needs. In addition, it could help to increase the interest of the industry on the usage of corn and rice flour as well as their blends with potato starch to produce more variety of food products from these ingredients.

Materials and Methods

Materials and sample preparation

Corn flour (Gemini, Malaysia), rice flour (Gemini, Malaysia) and potato starch (Windmill, Holland) were purchased from the local market around Seri Kembangan, Selangor. The samples used in the study were corn flour (CF), rice flour (RF), mixtures of corn flour to potato starch (CP; 70:30, w/w) and mixtures of rice flour to potato starch (RP; 70:30, w/w).

The samples were preconditioned to the moisture content of 25% w.b. The moisture contents of the samples were determined using a halogen moisture analyser (XM-120, Precisa Gravimetrics AG, Switzerland). Preconditioning of the samples were done by spraying the samples with water and homogeneously mixed by using a mixer (Alfa KB-502 Cake Mixer, Taiwan), then kept in the refrigerator at 4°C for 40h to ensure proper moisture distribution prior to extrusion process.

Extrusion process

The extrusion process was carried out by using a Brabender single screw stand-alone extruder (KE-19/25 D, Brabender, Germany). The screw used in the extrusion process was spiral screw with the compression ratio of 1:1, and round die diameter of 1.88mm. The screw speed during the extrusion process was held constant at 75 rpm. The flour samples were extruded under the same barrel temperature for all zones, and for each run the temperature was set constant at 80°C, 100°C, 120°C and 140°C, respectively. Each experiment set was conducted in triplicates. After extrusion process, the extrudates were dried in a cabinet dryer (SMA-112, Smoke Master, Japan) at 50°C for 16 h to remove additional moisture present in the extrudate after extrusion. The samples were packed in high density polyethylene (HDPE) plastic bag and kept at room temperature until further analysis.

Residence time distribution (RTD)

Red coloured flour for RTD determination was prepared by adding 2.5 g of red colorant (Artificial Cochineal Colour, Star Brand, Malaysia) to 10g of flour samples. In each extrusion process, red coloured flour sample of 0.25 g was introduced into the system after the extrudate exited the extruder smoothly. The time from the coloured sample to be fed in until the colour completely shaded off was recorded as the total collection time (t_c), and the time needed for dyed flour sample to appear at the die end was recorded as the minimum residence time (t_m) (Nwabueze and Iwe, 2010). The coloured extrudates were collected in interval defined time period (1min for corn flour and corn with potato starch, 30 s for rice flour and rice flour with potato starch) and it was grounded to particle size ≤425 µm (Chopper: Moulinette, Moulinex, France). The mean residence time (MRT) of the sample to exit the extruder was calculated using Trapezoidal rule, where the area below the graph of residence time distribution was estimated using the area of trapezium instead of rectangle.

Expansion ratio (ER)

The diameters of the samples were determined by using a vernier calliper (Model 530, Mitutoyo, Japan). Three readings were obtained for each extrudate. Expansion ratio was calculated by dividing the square of the sample diameter with the square of the die diameter as shown on Eq. 1 (Giri and Bandyopadhyay, 2000).

$$\text{Expansion ratio} = \frac{d_{sample}^{\,2}}{d_{die}^{\,2}} \qquad (1)$$

Rehydration ratio (RR)

RR was determined by referring to the method done by Yu *et al*. (2012) with slight modification. A known-weight (M_1) extrudate piece of 1 cm long was added into a test tube with 4mL of water and placed it in a water bath of 30°C. After 15min of hydration, the extrudate piece was drained, removed and weighed (M_2). Triplicates were done for each sample. The RR was calculated using Eq. 2.

$$RR = \frac{M_2 - M_1}{M_1} \times 100\% \qquad (2)$$

Water activity

Water activity of the ground samples was determined by using Aqualab water activity meter (Series 3, Decagon Inc., USA) and experiments were done in triplicate.

Colour

The colour of the ground extrudates were determined by using Minolta Chroma Meter CR-300 (Minolta, Japan). Each sample was analysed three times to produce triplicate results. The reading of *L*, *a* and *b* measures the lightness, redness and yellowness respectively. The colorimeter was calibrated with a standard white tile (L = 97.67, a = +0.09, b = +1.51) prior to analysis.

Water absorption index (WAI) and water solubility index (WSI)

Water absorption index (WAI) and water solubility index (WSI) were determined by the method mentioned by American Association of Cereal Chemists (AACC) International (2009) with slight modification. The extrudates were ground using Super-g Mixer Grinder (KM501, Premier, India) and 2.00 g of ground sample (particle size ≤425 µm) was weighed using Radwag balance (AS220/C/2, Poland) in a 50 mL centrifugal tube followed by adding 20 mL of distilled water. The sample was mixed well by vigorous manual shaking. Along the 10 min holding time, the tubes were shook in every 5 min interval. Then, the samples were centrifuged for 15 min at 3000 rpm in Kubota centrifuge (Kubota, Model 5800, Japan). The supernatant was decanted into an evaporating dish and the supernatant was dried in a universal oven (RD115, Binder, Germany) overnight at 105°C to obtain the data for WSI calculation. The sediments remained in the centrifugal tube were weighed and the data obtained were calculated for WAI determination. Triplicates were done for each sample. WAI and WSI were calculated in Eq. 3 and Eq. 4, respectively:

$$WAI = \frac{\text{Weight of Sediment}}{\text{Weight of Dry Sample}} \qquad (3)$$

$$WSI = \frac{\text{Weight of Dried Supernatant}}{\text{Weight of Dry Sample}} \qquad (4)$$

Statistical analysis

The data obtained were analysed statistically by SAS 9.2 (SAS Institute Inc., USA) using one way ANOVA at $p \leq 0.05$ significance level and post hoc tests were run by Tukey's Test.

Results and Discussion

Residence time distribution (RTD)

The RTD (a value from Hunter *L, a, b* versus time) for each sample were shown in Figures 1(A) – (D), while the effect of barrel temperature and different flour extrudates on the minimum residence time (t_m), mean residence time (MRT), and total collection time (t_c) were shown in Table 1. Tm is the breakthrough time or plug flow time which measure the time of appearance of the extrudate at the die (Iwe *et al*., 2001; Nwabueze and Iwe, 2010), MRT is the average time needed for the extrudate to exit the die whereas, tc of the extrudate is useful for scale-up operations by using the information to determine the optimal process conditions of the extruder, including mixing, dispersing and polymerization (Nwabueze and Iwe, 2010).

The results showed that tm for all extrudates ranged from 0.92 to 2.42 min. Barrel temperature showed significant decrease effect ($p \leq 0.05$) on the tm of the extrudates when temperature increased from 100°C to 140°C. The value of tc of the extrudates ranged from 2.76 to 11.73 min, which approximately four time larger than the t_m. Nwabueze and Iwe (2010) reported that the t_c of African breadfruit/soybean mixture doubled the tm recorded when working at screw speed range of 120-180 rpm. This study showed similarity on the effect of barrel temperature on the t_m and t_c of the extrudates, but the difference in raw material and screw speed caused different extend on the effect of extruder temperature on the t_c and the tm (Iwe *et al*., 2001; Nwabueze and Iwe, 2010)

The MRT for the extrudates decreased significantly when the extruder's barrel temperature increased ($p \leq 0.05$), with the lowest MRT value obtained at temperature of 140°C. Increased in barrel

Table 1. The minimum residence time (t_m), mean residence time (MRT) and total collection time (t_c) of various flour extrudates at barrel temperature (BT) of 80°C, 100°C, 120°C, and 140°C.

Raw Material	BT (°C)	t_m (min)	MRT (min)	t_c (min)
Corn Flour	80	2.42^{abA} ± 0.21	5.27^{abA} ± 0.01	10.42^{bA} ± 0.21
	100	2.73^{aA} ± 0.35	5.61^{aA} ± 0.68	11.73^{aA} ± 0.35
	120	1.91^{abA} ± 0.43	3.75^{bA} ± 0.72	9.92^{bA} ± 0.43
	140	1.64^{bA} ± 0.47	2.73^{cA} ± 0.65	6.64^{cA} ± 0.47
Rice Flour	80	1.44^{aB} ± 0.07	2.29^{aB} ± 0.28	4.11^{bC} ± 0.07
	100	1.27^{abB} ± 0.19	2.27^{aC} ± 0.42	5.27^{aC} ± 0.19
	120	0.92^{bB} ± 0.15	1.94^{abB} ± 0.11	4.92^{aC} ± 0.15
	140	1.09^{abAB} ± 0.01	1.31^{bB} ± 0.05	2.76^{cB} ± 0.01
Corn Flour and Potato Starch (70:30) Mixture	80	2.32^{aA} ± 0.19	5.47^{aA} ± 0.28	11.32^{aA} ± 0.19
	100	1.51^{bB} ± 0.15	4.08^{bB} ± 0.26	9.51^{bB} ± 0.15
	120	1.34^{bAB} ± 0.03	2.46^{cB} ± 0.28	6.34^{cB} ± 0.03
	140	1.30^{bAB} ± 0.12	2.45^{cA} ± 0.13	6.30^{cA} ± 0.12
Rice Flour and Potato Starch (70:30) Mixture	80	1.31^{aB} ± 0.09	2.45^{aB} ± 0.41	6.37^{aB} ± 1.26
	100	1.23^{aB} ± 0.08	2.42^{aC} ± 0.22	5.73^{aC} ± 0.08
	120	0.99^{bB} ± 0.13	1.81^{abB} ± 0.16	4.99^{aC} ± 0.13
	140	0.96^{bB} ± 0.01	1.49^{bB} ± 0.04	2.96^{bB} ± 0.01

*Data showed is mean ± standard deviation
*Different letters (a - d) after value indicates significant differences within the same flour type (p≤0.05) down the column.
*Different letters (A – D) after value indicates significant differences within the same extruder barrel temperature (p≤0.05) down the column.

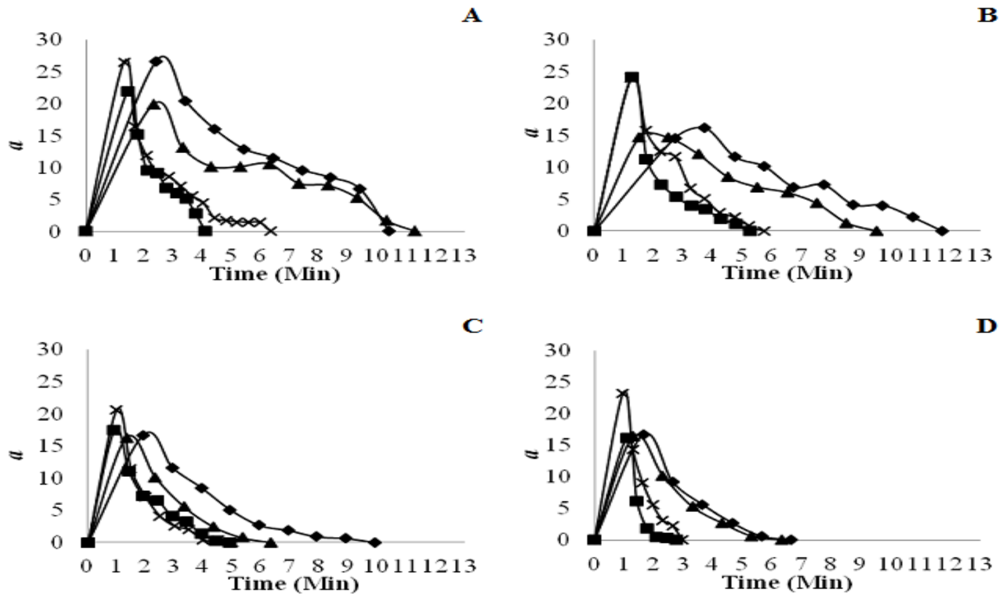

Figure 1. Residence time distribution (RTD) of corn flour (♦), rice flour (■), corn flour mixed with potato starch, 70:30 (▲), and rice flour mixed with potato starch, 70:30 (×) at extruder barrel temperature of: (A) 80°C, (B) 100°C, (C) 120°C, and (D) 140°C.

temperature supplied heat energy to the feed, causing decrease in the viscosity of the feed, and this resulted in a better flow of the material to move out from the barrel (Lee, 2012). This result agrees with the study of Kumar *et al.* (2006) in extruding starch.

Besides the barrel temperature of the extruder, the flour types used also showed a significant effect on the MRT of the extrusion process. CF and CP have significantly longer residence time than RF and RP (p≤0.05). Residence time distribution depends on the starch content of material, where higher starch content increased the viscosity of the mixture and caused difficulty during the exit of the material from extruder through the die (Iwe *et al.*, 2001; Wang and Wang, 2004). From previous researches, RF has the starch content of 45.70 to 82.00% (Luh, 1991) while CF has the starch content of 53.40 to 87.00% (Matz, 1991). Since different flour has different starch content and composition, as well as different protein types (rice protein and zein protein for corn),

Table 2. Physical properties of various flour extrudate at barrel temperature (BT) of 80°C, 100°C, 120°C, and 140°C

Raw material	BT (°C)	Expansion ratio, ER	Rehydration ratio, RR (%)	Water activity, a_w	Color *L*	Color *a*	Color *b*
Corn Flour	80	$2.38^{dCB} \pm 0.22$	$54.55^{bB} \pm 5.74$	0.47 ± 0.03	$92.88^{aA} \pm 1.32$	$-1.80^{abC} \pm 0.20$	$+9.41^{bA} \pm 1.09$
	100	$3.00^{cB} \pm 0.39$	$49.73^{bC} \pm 5.02$	0.43 ± 0.04	$92.28^{aA} \pm 2.01$	$-1.54^{aC} \pm 0.20$	$+8.79^{bB} \pm 1.17$
	120	$3.68^{bA} \pm 0.31$	$50.93^{bAB} \pm 4.51$	0.52 ± 0.01	$92.39^{aA} \pm 0.70$	$-1.84^{bC} \pm 0.21$	$+10.77^{aB} \pm 0.59$
	140	$4.48^{aA} \pm 0.38$	$80.12^{aB} \pm 19.55$	0.52 ± 0.01	$92.17^{aAB} \pm 0.84$	$-1.81^{bD} \pm 0.21$	$+11.67^{aB} \pm 0.93$
Rice Flour	80	$2.20^{cC} \pm 0.14$	$52.65^{bB} \pm 14.2$	0.42 ± 0.04	$90.27^{aB} \pm 0.93$	$+0.25^{aA} \pm 0.43$	$+8.92^{dA} \pm 0.56$
	100	$2.49^{cC} \pm 0.14$	$55.16^{bAB} \pm 8.12$	0.41 ± 0.04	$89.92^{aB} \pm 0.61$	$-0.03^{abA} \pm 0.12$	$+10.17^{cA} \pm 0.83$
	120	$3.09^{bB} \pm 0.51$	$52.24^{bA} \pm 4.32$	0.52 ± 0.00	$89.38^{aC} \pm 0.45$	$-0.21^{cAB} \pm 0.56$	$+11.56^{bA} \pm 0.29$
	140	$4.08^{aA} \pm 0.56$	$103.2^{aA} \pm 32.1$	0.53 ± 0.01	$89.16^{aC} \pm 3.10$	$+0.25^{aA} \pm 0.09$	$+15.35^{aA} \pm 0.88$
Corn Flour and Potato Starch (70:30) Mixture	80	$2.80^{cA} \pm 0.12$	$64.00^{aA} \pm 11.5$	0.44 ± 0.01	$93.88^{aA} \pm 0.51$	$-0.10^{bB} \pm 0.29$	$+7.28^{cB} \pm 0.76$
	100	$3.61^{bA} \pm 0.34$	$52.15^{bBC} \pm 10.3$	0.43 ± 0.02	$92.27^{bcA} \pm 1.69$	$-1.01^{bB} \pm 0.41$	$+7.68^{bcB} \pm 0.37$
	120	$3.88^{bA} \pm 0.39$	$50.45^{bAB} \pm 3.70$	0.46 ± 0.00	$91.57^{cB} \pm 0.69$	$-0.43^{aB.} \pm 0.37$	$+9.41^{aC} \pm 0.49$
	140	$4.60^{aA} \pm 0.57$	$65.97^{aB} \pm 20.9$	0.45 ± 0.01	$92.99^{aA} \pm 0.67$	$-1.19^{bC} \pm 0.33$	$+8.71^{abC} \pm 1.49$
Rice Flour and Potato Starch (70:30) Mixture	80	$2.51^{dB} \pm 0.12$	$58.26^{bAB} \pm 7.85$	0.41 ± 0.02	$90.86^{aB} \pm 1.04$	$-0.02^{aA} \pm 0.13$	$+7.71^{dB} \pm 0.60$
	100	$3.07^{cB} \pm 0.33$	$59.27^{bA} \pm 4.26$	0.43 ± 0.03	$91.13^{aAB} \pm 0.51$	$-0.02^{aA} \pm 0.17$	$+8.67^{cB} \pm 0.25$
	120	$3.68^{bA} \pm 0.31$	$48.05^{cB} \pm 6.76$	0.46 ± 0.00	$91.00^{aB} \pm 0.39$	$0.00^{aA} \pm 0.13$	$+9.40^{bC} \pm 0.51$
	140	$4.09^{aA} \pm 0.38$	$71.49^{aB} \pm 12.2$	0.42 ± 0.01	$90.60^{aBC} \pm 0.49$	$-0.04^{aB} \pm 0.12$	$+10.98^{aB} \pm 0.72$

*Data showed is mean ± standard deviation
*Different letters (a - d) after value indicates significant differences within the same flour type ($p \leq 0.05$) down the column.
*Different letters (A – D) after value indicates significant differences within the same extruder barrel temperature ($p \leq 0.05$) down the column.

this causes differences in MRT value for each type of flour. Potato starch with higher swelling power and viscosity tend to have longer residence time due to its increasing viscosity (Singh *et al.*, 2003b), whereas corn starch has shear thickening behaviour at high concentration (Steffe, 1996) causing longer residence time. However, there are no significant difference ($p > 0.05$) between RF and RP and between CF and CP (except at T=100°C and 120°C).

Expansion ratio (ER)

Extrudate expansion was caused by transformation of biopolymer structure, nucleation, swelling of extrudate, bubble growth in the melt and bubble collapse (Moraru and Kokini, 2003). The ER for the extrudates ranged from 2.20-4.60 as showed in Table 2. As extruder's barrel temperature increased, expansion ratio of the extrudate increased ($p \leq 0.05$). The ER ranges and the relationship between temperature and ER were supported research work published by few researchers as mentioned below. Hagenimana *et al.* (2006) also reported that and increase in barrel temperature caused an increase in the ER (ranging from 1.61-3.94) when the rice flour extrudate processed between 100°C to 160°C. Guha and Ali (2006) mentioned that the value of ER increases with an increase of extruder barrel temperature might happen due to the stretching of the molecules at higher temperature which causes higher degree of gelatinization.

Moraru and Kokini (2003) summarized that type of starch plays an important role in expansion of extrudates. In this study, different flour types showed different ER ($p \leq 0.05$), except at barrel temperature of 140°C. Different types of flour consists of different composition in starch (amylose: amylopectin content), protein and fat which contributes to the differences in ER. From the result, flour with additional potato starch has the highest expansion ratio ($p \leq 0.05$) compared to the other flour without potato starch at barrel temperature of 80-100°C. The expansion ratio of corn flour extrudate was also higher than the expansion ratio of rice flour extrudate ($p \leq 0.05$) due to the higher starch content of corn flour than rice flour. As expected, additional of potato starch which indicates an increase in starch content of the flour causes an increased in ER. Pure starches has the maximum expansion as much as 500% increase in the product diameter, and this contributed to higher ER of flour blend with pure potato starch (Moraru and Kokini, 2003). There was no significant difference in ER at barrel temperature of 140°C, where this might be the difference in the amount of expansion of different flour type, and they reach similar expansion ratio at 140°C. Further study at higher barrel temperature can be done to further understand the effect of barrel temperature on different flour type.

Rehydration ratio (RR)

For extruded products such as breakfast cereal and pasta which will be rehydrated before consuming, it is important to understand the rehydration ratio (Yu *et al*., 2012). The RR for all samples showed a maximum value at 140°C compared to other extruder's barrel temperatures (Table 2). It was found that at lower temperature (80°C), the RR for CF and RF has no significant differences (p>0.05), while CP and RP has the lowest RR at temperature of 120°C. The findings from Yu *et al*. (2012) showed that RR increase as the barrel temperature increases from 140°C to 180°C. RR has close relationship with ER, where higher ER indicates higher porosity of the extrudate and resulted in higher water absorbing capacity (Yu *et al*., 2012). Hence, from the ER result, extrudates process at barrel temperature of 140°C has the highest ER, which then contributes to the highest RR.

Water activity and colour

The water activity for all extrudates ranged from 0.41 – 0.52 (Table 2), despite the changes of barrel temperature and flour types used. Grant (2004) reported that below the water activity of 0.7, microorganism growth is inhibited. Mould growth was known to be inhibited at water activity below 0.6. From the result, the extrudates in this study were in the safety range in inhibiting microorganism and mould growth.

Colour of a food product is the first impression of consumers on the product. The colour of the products measured using Hunter *L, a, b* unit were shown in Table 2. Barrel temperature did not show effect on the *L* and a value of the extrudate (p>0.05), while b value increased when the temperature increased. Higher temperature enhanced better browning of extrudates, thus increase the yellowness of the extrudates as well as some difference in a value (redness) of the extrudates. There were some similarity between this result with the findings of Sun and Muthukumarappan (2002), where they reported that the *L* value did not affected by extruder barrel temperature, however it was the a value which increase with increasing barrel temperature for soy-based extrudates. The differences between the *L*, *a*, and *b* values of different extrudates can be related to the biological nature of the cereals and potato before they were processed into flour and starches as mention in the study of Singh *et al.* (2003a). Sacchetti *et al.* (2004) had earlier reported that extruder's barrel temperature showed little effect on the L^* and a^* values of their chestnut flour/corn flour extrudates, which agrees with the finding of this study.

Water absorption index (WAI) and water solubility index (WSI)

The value of WAI for extrudates in this study was shown in Figure 2. WAI measures the amount of water took up by the flour when immersed in excess water and was known to be indicator of starch gelatinization, as native starch did not imbibe water without elevation of temperature (Ding *et al*., 2005). It was noticed that increasing temperature increased the WAI of CF extrudate, while for RF, CP and RP extrudates, WAI increased when temperature increased from 80°C to 120°C, and dropped at temperature of 140°C. Several studies from different researchers found that WAI increased from 2.3 to 6.4 rice flour extrudate from 70-120°C (Kadan *et al*., 2003), which these results supported the findings for CF extrudate in this study.

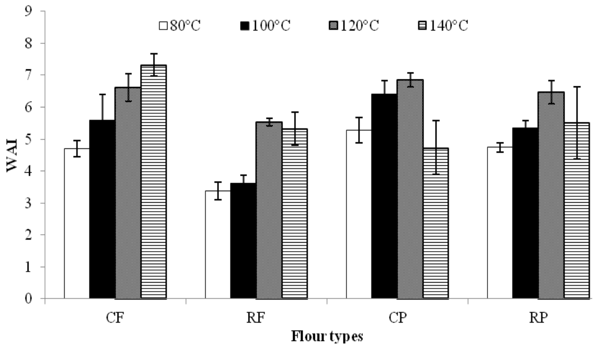

Figure 2. Water absorption index (WAI) of corn flour (CF), rice flour (RF), corn flour mixed with potato starch, 70:30 (CP), and rice flour mixed with potato starch, 70:30 (RP) at different barrel temperatures.

There were also studies showed that WAI increased with increasing temperature until the WAI reached its peak, and then decreased with further increase of temperature. Wu *et al.* (2010) reported that the WAI of flaxseed-maize extrudate increased from barrel temperature of 80-120°C, and decreased when barrel temperature reached 140°C. As in the study of Hagenimana *et al*. (2006) of rice flour extrudate, WAI increased when temperature of extrudate increase from 100°C to 130°C, and the WAI decreased after 130°C. These findings agree with the finding of RF, CP and RP in the current study. The main reason for the decrease of WAI after certain temperature was known to be caused by dextrinization of the starches, which is the depolymerisation of starch which breaks down the starch into shorter chain leading to higher

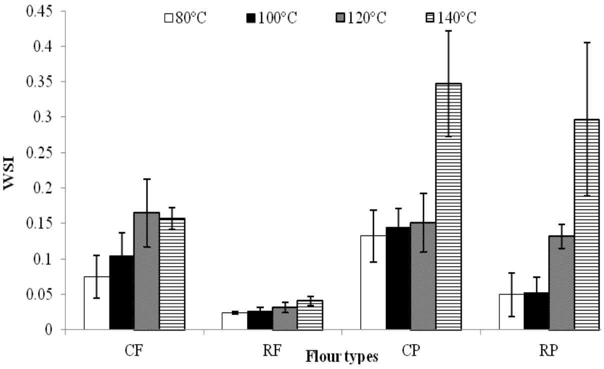

Figure 3. Water solubility index (WSI) of corn flour (CF), rice flour (RF), corn flour mixed with potato starch, 70:30 (CP), and rice flour mixed with potato starch, 70:30 (RP) at different barrel temperatures

solubility of the starches and cause losses of the dry extrudates into the water (Mcwilliams, 2007).

When comparing across the flour type, RF showed the lowest WAI at 80-120°C ($p \leq 0.05$). RF and RP have lower WAI compared to CF and CP. This result was similar with the finding of Adedokun and Itiola (2010), where pregelatinized CF has higher WAI value when compared to pregelatinized RF.

The value of WSI indicates the solubility of extrudates powder in water, which caused by starch conversion during extrusion (Ding *et al*., 2005). The WSI of extrudates produced from different extrusion condition were shown in Fig 3. In general, the data showed WSI increased with the increase of temperature, although some of the increases were not significant.

For CP and RP, there were drastic increases in WSI for both flour types from 120°C to 140°C. Extrusion of rice flour at 22% moisture content by Kadan *et al.* (2003) found that WSI increase drastically when temperature increased from 100-120°C. Their finding was similar with the result for CP and RP in this study. There were several findings by different researches showed that increasing temperature increased the WSI of the extrudates. Sacchetti *et al*. (2004) reported that WSI for chestnut and rice flour extrudates increased with increasing barrel temperature. The increase in temperature causes more damage on starch, and hence increases the solubility of the extrudate powder (Jyothi *et al*., 2009).

Different flour types showed different WSI value when processed under the same extruder barrel temperature. From the result showed in Figure 3. RF showed lowest WSI among all flour types while CP showed the highest WSI ($p \leq 0.05$). In addition, both CP and RP have higher WSI when compared with CF and RF. A research conducted by Yu *et al*. (2012) concluded that WSI depends on the nature of the major composition in the feed, which agrees with the result of this study. In this study, higher temperature showed higher value of WAI and WSI, and flour types as well showed effects on the WAI and WSI of the extrudate powder.

Conclusions

The physical properties of extrudates depend closely on the flour types and barrel temperature of the extrudates. An increase in barrel temperature reduced the MRT ($p<0.05$), where addition of potato starch showed no significant effect ($p>0.05$) on the MRT. The physical properties of the extrudates (ER, RR, WAI, WSI and b) increased with an increase in extruder barrel temperature ($p \leq 0.05$) except for L and a ($p>0.05$). The effect of flour type on the physical properties of the extrudate are rice flour<rice flour with potato starch<corn flour with potato starch<corn flour ($p \leq 0.05$). Further studies may include the effect of screw configuration, moisture content and screw speed to understand better the effect of flour types on the RTD and physical properties of the extrudates.

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