Influence of Extrusion-Cooking Conditions on Corn Pasta Quality

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Abstract—Gluten free products remain the cornerstone for celiac patients. Insufficiency, poverty and little offered about gluten free products (quality and quantity) represented a high obstacle for Egyptian celiac patients. Therefore, the purpose of this research is to modify a single screw extruder to produce gluten-free pasta (GFP) (tagliatelle type). The GFP was made from corn flour under screw rotation speed (N) of 10, 25 and 50 rpm at 40, 65, 90 and 115 °C of barrel temperature (BT). Extruder performance was evaluated as specific mechanical energy (SME) and expansion ratio (Er). The cooking quality of GFP as optimum cooking time (OCT), cooked yield (CY), swelling (Sw), cooking losses (CL) and sensory characteristics (appearance, colour, taste, mouth feel and overall acceptability) were evaluated. The better results of the GFP sensory evaluation were obtained at BT= 80 °C, N =25 rpm and Er ≈ 1.38 with OCT ≈ 3.3 min, CY= 196%, Sw = 210% and CL= 16.3%. All parameters were given a direct proportion with processing variables N and BT, except CL. Furthermore, it can be predicted cooking properties values for GFP by SME value using the following equation; $SME \approx 1.8675 (Er) + 0.8037 \approx 0.0608 (OCT)^{1.5984} \approx 8 \times 10^{-17} (CY)^{6.7878} \approx 2 \times 10^{-9} (Sw)^{3.494} \approx -0.0306 (CL) + 0.7877$.

Index Terms—Extruder Performance; Gluten Free Pasta; Corn Flour; Pasta Quality.

I. INTRODUCTION

The noodles were known as early as 300 B.C by Chinese [1]. However, noodle image was drawn first on the walls Egyptian tombs. Pasta is considered a type of noodle, and defined as an extruded product with consecutive drying of dough made from durum wheat semolina and water [2]. They are widely consumed throughout the world, and play an important role in human nutrition, due to its convenience (easy to cook, store and handle), palatability and low cost. Egypt occupies rank 17th and 7th in pasta export with 72, 13 Mg.year⁻¹ ≈ 63, 269,379 €, and production with up to 400 Gg.year⁻¹ [3].

Gluten-free diet (eliminate all food products containing gluten: wheat, rye and barley) require as a therapy to prevent celiac disease [4],[5]. Celiac patients (CP) or suffers chronic enteropathy is produced by gluten intolerance (prolamines

protein), which causes atrophy of intestinal villi, malabsorption and clinical symptoms [6].

On the other hand, corn is recommended as a safe food for CP. It contains 7–13 g/100 g of proteins, very low fats, phenolics, ferulic acid, flavonoid, carotenoid, rich in dietary fibre, vitamin B6 and magnesium [7], [8]. Thus, pasta production could be used other starchy raw materials to produce GFP to suit CP such as; corn, rice, sorghum, oats, and leguminous seeds [9]–[11]. Besides sweet potato, and the combination of amaranth flour with cassava starch can make GFP [12], [13].

Extrusion cooking technology has been widely used in cereal processing like snacks, baby foods, breakfast cereals, noodle and pasta [14], [15]. There are many advantages of extrusion cooking such as versatility, low costs, high production yields, good quality products, no effluents, reduce microbial contamination and inactivate enzymes [16]. The extrusion cooking process includes mechanical and thermal treatment of material under high pressure and high temperature. Workspace for single screw extruder is divided into three areas: dosing, mixing and compression. Screw used to move the material through barrel with significant increase in temperature and pressure occurs, makes the material plasticized and taking the form of pre-cooked viscous dough. High temperature generated during the extrusion cooking process is due to heat energy along the screw as a shearing effect, energy used for increased pressure of the viscous dough, the kinetic energy generated in the space between a screw and a barrel, also, the energy created during physiochemical changes of processed materials dependently on residence time distribution inside barrel [17], [5]. However, Low shear extruders with smooth barrels, deep flights and low screw speeds are used for product pastas, meats and cereals [18]. Raw material characteristics and operational conditions of the extruder are the main factors influencing extruded product characteristics. The main characteristics of the raw material as material type, pH, moisture content, physical state, and chemical composition (quantity and type of starch, proteins, fats and sugars). Temperature, pressure, die diameter, shear force, as well as, screw geometry and rotation speed are the main operational condition of extrusion machine [19]. Therefore, this paper aims to modify extrusion machine to produce GFP from corn flour with high quality specifications at optimum operating conditions.

II. MATERIALS AND METHODS

A. Extruder

All experiments were carried out in Bread and Pastries Research Dept., Food Technology Research Institute, Agriculture Research Center, Giza, Egypt. Semi-

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commercial laboratory extruder (DEMACO) was used to extrude GFP after modification by adding heating system. Extruder was equipped with single screw length 400 mm, a 45 mm of diameter, 8.9: 1 of length-diameter ratio, 8 mm of screw-channel depth, 29 mm of the screw-channel width, 5 mm of axial flight land width, 1mm of clearance between screw and barrel, and 34 mm of screw pitch.

The GFP was designed as a tagliatelle type (6.5 to 10 mm of width) and shaped by copper circle die head with 250 and 40 mm of diameter and thickness. Die head has two faces; one opposite the screw with 8 circular holes (20 mm of diameter) and the other face with 24 elliptic holes (product out face).

Heating system includes switcher (on/off), indicator lamp, thermostat and heater. Four heating units were connected together in parallel form to consist a heater. They made from Nichrome alloy (20% nickel, 25% chromium) wire, rolls on rectangular of mica core (67×10mm.). Heating units were put in a jacket of stainless steel sheet (0.5mm of thickness) and fixed on the outer wall of barrel (Fig. 1).

Fig.1. One - dimensional heat flow through multiple cylindrical sections and electrical analog.

Heater must be able to raise dough temperature into barrel over 200 °C. So, according Fourier's law (Fig .1)

$$T_3 = T_1 + \left[\frac{m^* (1.675 + 0.025 + D_{mc})(T_2 - T_1)}{2 \pi k_1 L} \left(\ln \frac{r_2}{r_1} + \ln \frac{r_3}{r_2} \right) \right],$$

where, T_3 is heater temperature (°C), T_1 is a dough temperature ≈ 25 °C (measured), m^* is a maximum of extrusion rate ≈ 0.004 kg s⁻¹ (calculated), D_{mc} is a dough water content $\approx 34\%$ [17], T_2 is a maximum dough temperature (Assuming 200 °C), k_1 is a stainless steel thermal conductivity (19 W m⁻¹ °C⁻¹), L is barrel length (0.27m), r_2 is outer barrel radius (45.5 mm), r_1 is inner barrel radius (42.5 mm), and r_3 is radius of stainless steel jacket opposite of heater (46 mm). Hence, $T_3 \approx 257.37$ °C

Coil wire length (L_c) and coils No. (n) at 1 mm coil wire diameter were expressed by,

$$L_c = \frac{X q}{\pi d k_2 (T_3 - T_i)} \text{ and } n = \frac{L_c}{C_{MC}}$$

Where, X is heater length, d is the cross section diameter of coil wire (0.001m), K_2 is Nichrome thermal conductivity (17 W m⁻¹ °C⁻¹), T_i is ambient temperature (25 °C), n is coils No., and C_{MC} is Mica core circumference (0.156 m). Hence, $L_c \approx 30.81$ m, and $n \approx 245$. Meanwhile, the critical radius value of isolation for heaters emerged by,

$$x = \frac{k_3}{h} - r_2$$

Where, x is the critical radius value of isolation (m), k_3 is a glass wool thermal conductivity (0.038 W m⁻¹ °C⁻¹), h is convection heat-transfer coefficient between glass wool and air (6.5 W m⁻² °C⁻¹). Hence, $x \approx 4$ cm. On the other hand, infrared thermometer (AG-42D model) with range -30 to +100 °C and ± 0.5 °C accuracy was used to calibrate thermostat scale with inner wall barrel temperature. The relation between thermostat scale and inner wall temperature of barrel (BT) was illustrated in Fig. 2.

Fig.2. Relationship between thermostat scale and average inner wall temperature of barrel (BT).

B. Raw materials

Both of yellow corn flour and corn starch were obtained from El-Masreya El-Italy Co., of corn products, and Egyptian starch and glucose Co., Egypt. Meanwhile, mono-diglycerides and sodium chloride were purchased from El-Gomhoreia Co., Cairo, Egypt.

C. Preparation of GFP

The GFP was prepared from a mixture of yellow corn flour 33%, corn starch 60%, corn oil 4%, mono-diglycerides 2% and NaCl 1%. The mixture was mixed by two stainless steel rotating augers at constant speed 75 rpm for 5 min. Hot distilled water (90 °C) was added stepwise and slowly to the mixture with constant agitation for 8 min to obtain the optimum consistency of dough. Thereafter, the trap door was opened and dough passed through the extruder.

The noodle was dried in an air drying oven (DHG-9140A, Shanghai Sanfa Scientific Instruments Co., LTD., China) at 100 °C for 15 min until a final moisture of 11% (w/w). And then, samples were cooled to room temperature.

D. Extruder performance

The extrusion was performed at a screw speed (N) of 10, 25 and 50 rpm, with 40, 65, 90 and 115 °C for inner wall temperature of barrel (BT). Data of GFP characteristics were analysed for each experiment using analysis of variance and the derived least significant difference. Extrusion rate (Er) and power requirement (Pr) at different conditions were measured for each sample. Product outputs were collected after 10 min of regular production to estimate Er. Whilst, super clamp meter-300k was used for measuring the current strength for extruder with and without load. Specific mechanical energy (SME) values were measured by

$$SME = \frac{\sqrt{3} \times V \times \cos \theta \times \eta}{1000} \times \frac{(I_2 - I_1)}{Er}$$

Where, $\sqrt{3}$ is resultant three phase current coefficient, V is a potential difference voltage (≈ 380 V), $\cos \theta$ is power factor (≈ 0.85), η is a mechanical efficiency (≈ 0.95), I_2 and

I_1 are line current strength (amperes) for extruder with and without load.

The dimensions mean of GFP strand was measured to calculate Er by;

$$Er = \frac{\text{Avg. of GFP strand dimensions (width} \times \text{thickness)}}{\text{Die hole dimentions (width} \times \text{thickness)}}.$$

E. Cooking properties

About 100 g of GFP from each sample was separately cooked in one litre of boiling water until the optimum cooking time (OCT). The OCT was determined using Approved Method 66-50 [20]. Two pieces of GFP were withdrawn every 20 Sec and squeezed gently between two glass plates until seeing the disappearance of the white central core of noodle. Then, it was rinsed in cold water and drained in a sieve at room temperature for 15 min. Thereafter, cooking water was collected and evaporated at 115 °C for 24 h to determine solid lost.

The volume of fresh and cooked noodle was determined by liquid (petroleum naphtha) displacement method. Cooked yield (CY) was calculated by;

$$CY (\%) = \frac{W_2 - W_1}{W_1} \times 100,$$

Where, W_1 is a weight of uncooked noodle and W_2 is a weight of cooked drained noodle at OCT [20]. Swelling (Sw) was determined by;

$$Sw (\%) = \frac{V_2 - V_1}{V_1} \times 100, \text{ where, } V_1 \text{ is a volume of}$$

uncooked noodle and V_2 is a volume of cooked drained noodle at OCT. Cooking loss (CL) was calculated by

$$CL (\%) = \frac{\text{Weight of drained water}}{W_1} \times 100 [20].$$

F. Sensory evaluation

Appearance, colour, taste, mouth feel (tenderness) and overall acceptability were considered for sensory evaluation. The samples were subjected to scoring to evaluate their attributes on a comparative basis. Sensory testing was done at room temperature. Ten trained panellists were selected from Food Technology Research Institute (FTRI) to evaluate the sensory attributes. For these tests, GFP samples were cooked at OCT and then drained for 2 min. The samples were coded and served at the same time. A five-point hedonic scale, Excellent (5), Good (4), Regular (3), Poor (2) and Unacceptable (1) was used.

III. RESULTS AND DISCUSSIONS

Specific mechanical energy (SME) measured energy consumption by extruder to produce one kilogram of GFP. The SME values ranged from 0.08 to 0.5 kWh/kg⁻¹ (Fig. 3). These values are larger than those mentioned by Wójtowicz and Mościcki [17] (0.07 to 0.13) during wheat starch extrusion – cooking. The difference between these results maybe due to use of a lower temperature for wheat starch gelatinization [21].

The minimum and maximum values of SME were obtained at screw rotation speed (N) 10 rpm with 40 °C and 50 rpm with 115 °C. The lowest value of SME, which refers to the weak dough properties was obtained as a result of decline both extrusion rate and mechanical energy required to

extrude. This caused by decreases in both of dough viscosity and friction between the dough and interior barrel surface (corn flour lipid reduces the friction between them). The critical level of friction was required to encourage the suitable movement of dough along the screw [22]. The SME transferred to the product was increased nearly from 0.05 to 0.13 by increasing N from 10 to 50 rpm and BT from 40 to 115 °C. These increases are due to energy added by heat energy which is generated along the screw like shearing, kinetic energy (created in the space between screw and barrel) and heater energy [23].

Fig.3: Effects of processing variables on specific mechanical energy (SME).

The expansion ratio (Er) of tagliatelle pasta ranged from 1 to 1.7 (Fig. 4). The values of extrusion variables were obtained lesser than those reported by Agama-Acevedo et al., [24], for producing pasta from unripe banana flour. Shear rate was increased by increasing N, extrusion temperature and expansion degree. Also, the increases of BT leads to create a high vapour pressure in the dough that's lead to greater expansion. These effects were in agreement with those of Fang and Hanna [14] and Wójtowicz [5]. The values of N were given a non-significant effect under 40 and 65 °C, and significant effect under 80 and 115 °C of BT at $P < 0.05$. On the other hand, the BT had more significant effects on Er under the same value of N. Moreover, the results were indicated to a positive correlation between Er and BT at different N. Where, $Er \approx 0.7778 e^{0.0057 BT} \approx 0.0087 BT + 0.6354 \approx 0.0091 BT + 0.6523$, with $R \approx 0.99, 0.98$, and 0.99 at $N \approx 10, 25$ and 50 rpm, respectively (data not shown). Eventually, the obtained results show a roughly linear positive correlation between SME and Er . Rather, $Er \approx 1.8675 SME + 0.8037$, with $R \approx 0.99$ (Data not shown).

Fig.4: Effects of processing variables on the expansion ratio (Er).

The relationship between OCT and processing variables N and BT was demonstrated in Fig.5. Generally, pasta made by extruder showed shorter OCT than other manufactures processing due to higher temperatures in the extrusion process and thus starch gelatinization [25]. The maximum

value of OCT (4.34 min) was obtained at BT= 105 °C with N= 50 rpm. This value is less than the one mentioned by Kosović et al. [25] and Manthey et al. [22] (6.2 ± 0.1 and 10.2 min) for pasta made from durum semolina. On the other hand, Iancu et al. [26] found OCT = 3 ± 0.5 min for GFP. This fact was compatible with (OCT= 3.3 min) BT= 80 °C and N = 25 rpm. In this respect, Oh et al. [27] has been mentioned the increases in flour protein correlated with increase cooking time. So, these results may be returned to a decrease in protein percentage (12%) of GFP from corn flour [28]. Beside, coagulation of proteins may be occurred with absence of gluten network (low gluten content) and protein not enough to cause a reaction to boil a GFP. Furthermore, overall high expansion ratio lead to a weak on gluten network, seems to facilitate and faster penetration of water diffusion through the spaghetti matrix. All these facts lead to reduce the time that water needs to reach the pasta centre during the cooking process, which resulted in short cooking time [29], [30].

Fig.5. The relation between optimum cooking time (OCT) and processing variables BT and N.

Results which derived from data revealed that, OCT had a direct proportion with BT and N. Wherever, by increase a BT from 40 to 115 °C the OCT increases about 2, 2.34, and 2.67 min at 10, 25 and 50 rpm of N, respectively. Meanwhile, the OCT increases about 0.34 min only by increasing N from 10 to 50 rpm at 40, 65 and 77 °C of BT and about 1 min at 115 °C of BT. These results are in agreement with Wang et al. [31], who noted that, cooking time increase with increasing BT or N. Otherwise, its led to increasing dough temperature and lessen dough moisture content. Subsequently, a small water amount in the pre-gelatinized flour reduces cooking time [32].

The highest (212%) and lowest (165%) values of cooked yield (CY) were obtained at 115 °C with 50 rpm and 40 °C with 10 rpm. Maximum value of CY was more than that obtained by Pamela et al. [33] (186.13%) for durum wheat semolina. This consequence may be due to strongly form of protein network that thwarts water diffuses into the starch granules. So, spaghetti with higher protein content absorbs water less than spaghetti with using corn flour as a raw material [21], [34]. There was a direct proportion between both (BT & N) and CY. Results which derived from Table (I), show that, CY increase about 19, 17, 21 and 14% at 40, 65, 80 and 115 °C by increasing N from 10 to 50 rpm, respectively. Meanwhile, it was increased from 165 to 198,

172 to 203 and 184 to 212% at 10, 25 and 50 rpm by increase BT from 40 to 115 °C, respectively. Therefore, both BT and N have significant effects ($P > 0.05$) on CY. These results have been dissimilar to those reported by Wang et al. [31]. Whereas, CY has been an inverse proportion with N. The increases of N due to increase in shear, which led to modify the structure of starch. As well as, BT had little effect on CY.

Swelling (Sw) has been a direct proportion with processing variables (Table I). Similar observations were found as Kim and Wiesenborn [35]. Moreover, Abecassis et al. [36] pointed out that N and BT have been a beneficial effect on increasing Sw at extrusion screw. Also, it has been positive correlations with N and T at all treatments. There was a positive power correlation among Sw and BT with 10 and 50 rpm. As well as N with 40 °C. Moreover, there were positive logarithmic correlations between Sw and other processing variables. As well as, previous relations were fitted to the following equations;

$$\begin{aligned} Sw &\approx 41.426 (BT)^{0.3379} && \text{at 10 rpm} && R^2= 0.9769 \\ Sw &\approx 63.871 \ln (BT) - 73.794 && \text{at 25 rpm} && R^2= 0.9896 \\ Sw &\approx 71.231 (BT)^{0.2553} && \text{at 50 rpm} && R^2= 0.9431 \\ Sw &\approx 104.45 (N)^{0.1402} && \text{at 40 °C} && R^2= 0.9912 \\ Sw &\approx 23.803 \ln (N) + 111.15 && \text{at 65 °C} && R^2= 0.9899 \\ Sw &\approx 24.866 \ln (N) + 129.81 && \text{at 80 °C} && R^2= 1 \\ Sw &\approx 18.978 \ln (N) + 162.99 && \text{at 115 °C} && R^2= 0.9529 \end{aligned}$$

The maximum augmentation of Sw (66 and 40%) was obtained at 25 rpm with increasing BT from 40 to 115 °C and at 80 °C with increasing N from 10 to 50 rpm. Furthermore, the results of Sw were affected significantly by both T and N ($P > 0.05$).

TABLE I: EFFECTS OF PROCESSING VARIABLES ON COOKING YIELD (CY) AND SWELLING (Sw).

BT, °C	Cooking yield (CY), %			Swelling (Sw), %		
	N, rpm			N, rpm		
	10	25	50	10	25	50
40	165	172	184	145	162	182
65	175	179	192	165	190	203
80	183	196	204	187	210	227
115	198	203	212	205	228	235

The results of cooking losses (CL) have been a direct and inverse proportion with N and BT (Fig. 6). The effects of extrusion variables on CL were similar to Mestres et al. [37] and Wang et al. [31]. On the other hand, the results obtained were differed considerably with Abecassis et al. [36]. Also, the CL was given a higher value (22.7%) at 40 °C with 50 rpm. Meanwhile, the lowest value (12.4%) was recorded at 115 °C with 10 rpm. However, CL for all treatments was given a higher significantly than those mentioned by Lu et al. [38] for noodles of wheat. On the other hand, it was more less than declared by Mestres et al. [37] that CL about 70% of extruded maize flour pasta. This increase might be due to soluble dietary fibre, where corn contains about 19.3% fibre with 6.53% soluble fibre [1], and weak starch-gluten network [22], [35]. The correlations of cooking properties OCT, CY, Sw and CL could be summarized as following equations;

$$\begin{aligned} CY &\approx 13.197 (OCT) + 152.66 \\ Sw &\approx 66.36 \ln (OCT) + 133.1 \approx 360.35 \ln (CY) - 1692.2 \\ CL &\approx -5.7292 \ln (OCT) + 22.787 \approx 56.032 e^{-0.0063 (CY)} \end{aligned}$$

$$CL \approx -0.0516 (Sw) + 27.509$$

From the results SME has been a positive power correlation with all cooking properties except CL. Whereas, it has been a negative linear correlation with cooking losses CL. Where, $SME \approx 0.0608 (OCT)^{1.5984}$

$$SME \approx 8 \times 10^{-17} (CY)^{6.7878}$$

$$SME \approx 2 \times 10^{-9} (Sw)^{3.494} \approx -0.0306 (CL) + 0.7877, \text{ (Data not shown).}$$

On the other hand, Er values have been an exponential correlation with cooking properties. It was given a positive correlation with OCT, CY and Sw and a negative correlation with CL. $Er \approx 0.766 e^{0.182} (OCT)$

$$Er \approx 0.1269 e^{0.0122} (CY)$$

$$Er \approx 0.3856 e^{0.0061} (Sw)$$

$$Er \approx 2.7952 e^{-0.0458} (CL) \text{ (Data not shown)}$$

Fig. 6. Effects of processing variables on cooking losses (CL).

Sensory attributes of GFP as appearance, colour, taste, mouth feel and overall acceptability were represented graphically as given in Fig.7. Sensory evaluation graph revealed that highest ranking scores in appearance and colour (4.6 ± 0.2 and 4.8 ± 0.09) were found at 80 °C with 25rpm. It was decreased dramatically to ruffle appearance and undesirable dull brown (1.4 ± 0.44 and 1.7 ± 0.28) at 115 °C with 50rpm. Meanwhile, there were a slight improvement in taste and mouth feel from (2.5 to 4.5) and (1.5 to 4.8) at (80 °C - 10 rpm) and (115 °C - 50 rpm). On the other hand, the lowest score of all sensory attributes; appearance (1.4), taste (2.5) and mouth feel (1.5) except colour was obtained at 40 °C with 10 rpm. The lowest score of colour (1.7) was found at 115 °C with 50 rpm. It is clearly seen that, all attributes were affected significantly by BT. While, only colour was affected significantly by N on attributes. The GFP colour was transformed slightly from light yellow at 65 °C with 10 rpm to pleasant yellow at 80 °C with 25 rpm. It was developed and decreased dramatically to undesirable dull brown at 80 °C with 25 rpm till 115 °C with 50 rpm. These results maybe return to a high carotene in corn, which oxidized by some substances at high temperature. So, high temperature has a negative effect on pasta colour. As well as, the increase of BT or N leads to change the colour from pleasant yellow to dull brown. These results consent and in harmony with Abecassis et al. [36]; Fang and Hanna [14]; Iancu et al. [26]; Kahlon et al. [1] and Kosović et al. [25].

The taste results of GFP return to the corn flour flavour and defined as "al dente" [34, 13]. The results highlighted that maximum value of overall acceptability (4.4 ± 0.3) was obtained at N= 25 rpm with BT= 80 °C. It was in the range (N of 22 – 25 rpm) recommended by DeFreacisci [39] for extruder operators. This behaviour ascribed to GFP dough

demand some heat to knead by extruder, which created by screw shear to malleable enough and squeeze through die.

Fig.7. Relation between processing variables behaviour and sensory evaluation of corn noodle.

IV. CONCLUSION

Electric heating system fixed on an extruder barrel to produce GFP from corn flour. The best sensory attributes of GFP produced at 80 °C and 25 rpm, with $SME = 0.28 \text{ kWhkg}^{-1}$, $Er = 1.38$, $OCT = 3.3 \text{ min}$, $CY = 196\%$, $Sw = 210\%$ and $CL = 16.3\%$. All parameters have a direct proportion with processing variables N and BT, except CL with BT. Further, cooking properties could be predicted from SME value using the following equation; $SME \approx 1.8675 (Er) + 0.8037 \approx 0.0608 (OCT)^{1.5984} \approx 8 \times 10^{-17} (CY)^{6.7878} \approx 2 \times 10^{-9} (Sw)^{3.494} \approx -0.0306 (CL) + 0.7877$.

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