Emirates Journal of Food and Agriculture. 2022. 34(5): 455-464
doi: xxxxx
http://www.ejfa.me/

SHORT COMMUNICATION

Impact of extrusion on swelling power and foam stability in mixtures of corn starch and whey protein isolate as a model system

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ABSTRACT

This study examines the impact of an extrusion process on the swelling power (SP) and the foaming stability (FS) of mixtures of corn starch (CS) and whey protein isolate (WPI). A single-screw extruder was operated with a speed of 200 rpm, feed rate of 100 g/min, extrusion temperature of 140°C, and initial moisture content of 20%. The results show that the extrusion process significantly increased the SP of the CS/WPI mixtures at each of the heating temperatures evaluated (60, 70, 80, and 90°C). Furthermore, a significant increase in SP was observed with the increase in temperature in most of the mixtures. The extrusion only slightly affected the foam stability of the mixtures. The results show the importance of extrusion on the interactions between CS and WPI.

Keywords: Extrusion; Foaming stability; Starch-Protein; Swelling power

INTRODUCTION

Extrusion cooking is becoming increasingly popular, and there is increasing use of raw materials containing protein, starch, and dietary fiber in the formulation and creation of snacks with high nutritional value (Hernandez-Santos et al., 2021). However, these raw materials could change the physicochemical and functional properties of food products during extrusion cooking, so there is a need to evaluate their effects on the quality of extruded products (Igual et al., 2020). The advantages of extrusion for food production include greater production efficiency and versatility, as well as the deactivation of some anti-nutritional factors, especially those present in legumes (Rodríguez-Miranda et al., 2014). Starch and proteins are two main components of food, and their interactions play an important role in their techno-functional and quality properties (Téllez-Morales et al., 2020; Téllez-Morales et al., 2021). Currently, products formulated with whey protein are commercially available as health foods, such as flavored shakes, flavored protein bars, and dietary supplements (Allen et al., 2007; Rivera-Mirón et al., 2020). Whey proteins have a high protein-efficiency ratio and are widely used in many foods products due to their nutritional and techno-functional properties, as well as to improve texture, flavor, color, and protein content (Amaya-Llano et al., 2007). When added to corn starch (CS), whey proteins improve the nutritional quality of extrudates, which is an economical way to enrich foods. Additionally, amylose extrudates can be used as binders to contain proteins due to their linear structure and their ability to form hydrogen bonds in extruded products (Amaya-Llano et al., 2007; Téllez-Morales et al., 2020). The swelling power (SP) reflects the properties of amylopectin, and it is assumed that a dense network of micelles in starch granules restricts swelling properties (Zhang et al., 2016). Extrudates with a high swelling value could be used to increase the viscosity and thickening property of food products (Cheng et al., 2020). Rodríguez-Miranda et al. (2021) found no foaming capacity or foam stability in flour made from *Muntingia calabura* and mentioned that the foaming capacity is governed by the content of lipids and proteins, as well as protein-fiber and protein-lipid interactions

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Received: 04 August 2021; **Accepted:** 03 April 2022

that decrease and affect foam stability. Therefore, the aim of the present work was to evaluate the impact of extrusion cooking on foaming stability (FS) and SP at different heating temperatures in mixtures of CS and whey protein isolate (WPI) as a model system.

MATERIALS AND METHODS

Materials

IMSA brand CS with 98% purity was purchased from Industrializadora de Maíz, S.A de C.V, Mexico. Its chemical composition (g/100 g dry basis (d.b)) is starch (98), ash (0.49), and lipids (0.62). Nature's Best brand whey protein isolate (WPI) was also used (Nature's Best, Inc., 195 Engineers Road, Hauppauge, NY 11788. USA), and its chemical composition (g/100 g d.b) is protein (86.2), ash (1.07), lipids (0.034), and carbohydrates (12.696).

Extrusion process

Extrusion cooking was carried out using a laboratory extruder (Model E19/25 D, Instruments Inc. South Hackensack, NJ USA), where CS/WPI mixtures (w/w) were processed according to a design of experiments. The operating conditions of the extruder were a screw speed of 200 rpm, compression force ratio of 1:1, 6-mm exit die, and feed rate of 100 g/min. The temperatures in the different zones of the extruder were 80, 100, 120, and 140°C, and the moisture content in the mixtures was 20% (Téllez-Morales et al., 2020). After processing, the extrudate was dried at 60°C for 2 h and ground to a particle size of 0.59 mm (No. 35 mesh screen).

Design of experiments

A simple lattice mixture design was generated with Design-Expert software (version 7.0, Godward St NE, Suite 6400, Minneapolis, MN 55413, USA). In the experiments, 5 CS/WPI formulations were evaluated (w/w): 100/0, 75/25, 50/50, 25/75, and 0/100 (Téllez-Morales et al., 2020).

Swelling power (SP)

The SP was determined according to the procedure of Sathe and Salunkhe (1981). Distilled water (10 mL) was added to a 1-g sample in centrifuge tubes, stirred gently for 2 min, and heated at 60, 70, 80 and 90ºC for 30 min (Fig. 1). The tubes were then centrifuged (Universal Compact Centrifuge HERMLE Labortechnik GmbH Mod Z 200A, Germany) at 1000 *x* g for 15 min, and the supernatant was removed. The resulting pellet with the tube was weighed, and the SP results were calculated as indicated by equation 1.

$$SP\ (\%) = \frac{Sediment\ weight\ (g)}{Sample\ weight\ (g)} * 100 \qquad (1)$$

Foam stability (FS)

FS was measured according to Bencini (1986) by mixing 2 g of sample with 100 mL of distilled water for 5 min at maximum speed in a blender (Oster, Model 465, LLC, 5200 Blue Lagoon Drive, Suite 470, Miami, FL 33126 USA) (Fig. 2). After this time, the final volume of the foam generated was measured, and the foam volumes were recorded at 10, 15, 30, 45, 60, and 120 min. To evaluate the FS of the samples in %, the volume of foam in the 250 mL graduated cylinder was measured (Equation 2).

$$FS\ (\%) = \frac{Foam\ level\ over\ time\,(mm)}{Initial\ water\ level\ with\ sample\ (mm)} * 100 \qquad (2)$$

Statistical analysis

The results were analyzed by multiple linear regression, and the significance of the coefficients was evaluated through a one-way analysis of variance (ANOVA) with a 95% confidence level using Statistica software version 10.0 (StatSoft, Inc., 1984-2008, USA).

RESULTS AND DISCUSSION

Swelling power (SP)

The SP at 60°C (Table 1) in the extruded CS/WPI mixtures was between 619.88 and 328.74%. The result decreased as the WPI concentration increased, but differences were only significant in the CS/WPI 100/0 and 75/25 mixtures ($p < 0.05$). In the raw mixtures, SP was between 540.53 and 38.92%, and there were statistically significant decreases with the increase in WPI ($p < 0.05$). The extrusion caused a significant increase in this property at 60°C as shown in Fig. 3a and 3b for the raw and extruded mixtures, respectively.

The regression models obtained (Table 2) showed R^2 values of 0.889 and 0.994 for the raw and extruded mixtures, respectively. That is, the models have great potential to predict the response because the coefficients of determination (R^2) obtained from the regressions were found to be greater than 0.70, indicating a high degree of correlation between the experimental results and those predicted by the model (Rodríguez-Miranda et al., 2021). The results also presented statistically significant differences ($p < 0.05$).

The ANOVA (Table 3) of the models presented statistical differences as well ($p < 0.05$) for all the terms of the raw and extruded mixtures. On the other hand, for the SP at 70ºC (Table 1), the extruded mixtures presented values between 692.84 and 335.47%, which also significantly decreased with the increase in WPI ($p < 0.05$). In the crude mixtures, this value's range was 665.53 to 49.86% and presented

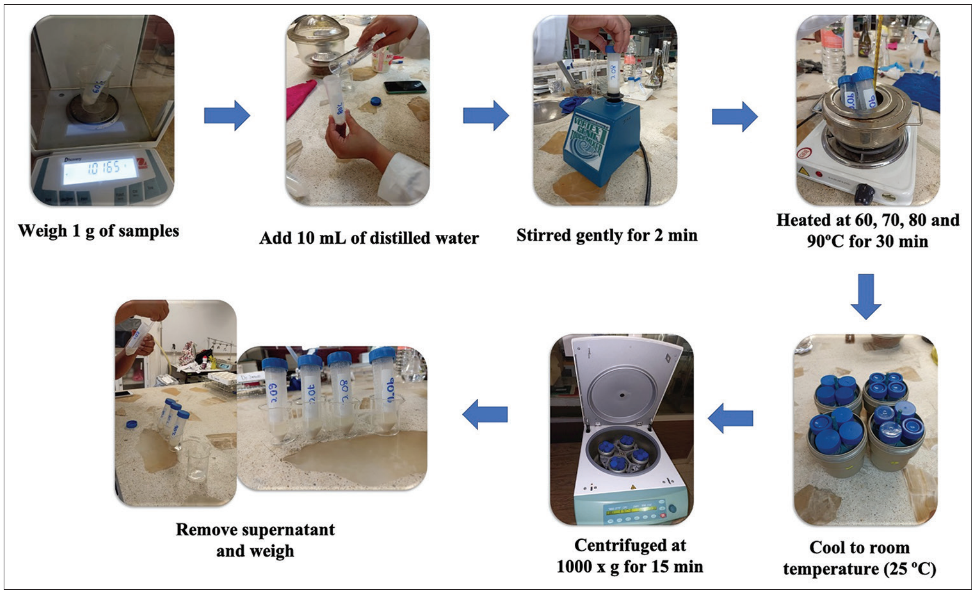

Fig 1. Diagram of determination of swelling power (SP).

Fig 2. Diagram of determination of foam stability (FS).

the same trend with statistically significant differences (p <0.05). Again, the extrusion influenced the increase in the SP evaluated at 70ºC, as shown in Fig. 3c and 3d for the raw and extruded mixtures, respectively. In the mathematical models obtained (Table 2), R^2 values of 0.962 and 1.000 were obtained for the raw and extruded mixtures, which means that the models were perfectly adjusted to predict this variable with a statistically significant difference (p <0.05). The ANOVA (Table 3) for all the terms of both models presented significant differences (p <0.05).

The SP of the extruded mixtures evaluated at 80°C (Table 1) was between 727.09 and 343.73%, presenting a significant downward trend with the increase in WPI (p <0.05). However, in the case of raw mixtures, this value ranged from 657.63 to 43.30%, and there was a significant and drastic drop in SP with the increase in WPI (p <0.05). As expected, extrusion induced an increase in this property at 80ºC, as shown in Fig. 4a and 4b for the raw and extruded mixtures, respectively. In the case of the regression models obtained (Table 2), it can be seen that in both cases, R^2 values of 0.995 and 0.999 were obtained for the raw and extruded mixtures, respectively, which indicates that they fit perfectly and that they are optimal for predicting this property with statistical significance (p <0.05). In the ANOVA (Table 3), for both cases, all their terms were also significant (p <0.05).

At 90°C, the SP values of the extruded mixtures (Table 1) were between 700.33 and 323.92%, and this statistically significant drop was influenced by the increase in WPI concentration (p <0.05). In the case of crude mixtures, the values were between 1053.22 and 680.29%, where the CS/WPI 100/0 mixture had a value of 680.29%. There was a downward trend as the concentration in WPI increased except when reaching 0/100 (only protein). In this case, an increase was registered until reaching a value of 1053.22%. This anomalous behavior is shown in Fig. 4c and 4d for the raw and extruded mixtures, respectively.

For the proposed mathematical models (Table 2), in both cases, R^2 values of 0.975 and 0.994 were obtained for the

Table 1: Swelling power and Foam stability in extruded mixtures

Param.	CS/WPI mixtures									
	100/0		75/25		50/50		25/75		0/100	
	Raw	Extruded	Raw	Extruded	Raw	Extruded	Raw	Extruded	Raw	Extruded
Swelling power (%)										
60°C	540.53±20.08^{d}	619.88±35.49^{c}	474.17±37.99^{c}	486.2±1.43^{b}	143.39±5.38^{a}	354.97±2.67^{a}	135.93±5.58^{a}	328.74±20.06^{a}	38.92±1.05^{b}	344.22±5.83^{a}
70°C	665.53±8.17^{e}	692.84±3.11^{e}	531.52±17.48^{d}	521.82±1.5^{d}	169.25±7.38^{c}	396.58±1.47^{c}	109.87±8.71^{b}	335.47±22.04^{a}	49.86±12.37^{a}	359.22±11.69^{b}
80°C	657.63±3.36^{e}	727.09±26.28^{e}	287.53±66.63^{d}	550.34±5.8^{d}	212.85±46.59^{c}	426.07±16.06^{c}	123.83±31.16^{b}	343.73±4.69^{a}	43.30±8.29^{a}	378.36±15.01^{b}
90°C	680.29±17.29^{d}	700.33±32.96^{e}	484±32.88^{c}	582.5±8.91^{d}	385.48±32.96^{b}	459.86±6.69^{c}	308.31±21.54^{a}	323.92±6.50^{a}	1053.22±22.51^{e}	382.07±21.06^{b}
Foam stability (%)										
10 min	3.08±0.38^{c}	2.46±3.48^{b}	16.82±3.71^{a}	14.24±0.94^{a}	16.33±1.57^{a}	14.48±0.66^{a}	10.84±1.40^{b}	15.98±0.40^{a}	12.73±0.91^{ab}	21.87±7.01^{a}
15 min	0^{b}	0^{c}	12.77±3.33^{a}	11.41±1.16^{a}	11.82±1.35^{a}	10.77±0.32^{a}	8.61±1.21^{a}	13.38±0.67^{ab}	9.85±0.68^{a}	18.34±4.52^{b}
30 min	0^{c}	0^{b}	11.06±2.69^{b}	8.56±1.23^{a}	8.56±1.99^{ab}	7.16±1.21^{ab}	7.13±0.79^{ab}	9.23±0.27^{a}	5.76±1.74^{a}	10.11±3.57^{a}
45 min	0^{b}	0^{a}	10.12±2.27^{c}	3.04±2.30^{a}	6.85±2.21^{ac}	0^{a}	4.46±0.87^{a}	6.04±0.25^{a}	3.94±1.73^{ab}	4.04±2.71^{a}
60 min	0^{b}	-	0.99±0.69^{c}	-	2.87±2.03^{ac}	-	0.23±0.16^{a}	-	0.44±0.31^{ab}	-
120 min	0^{a}	-	4.67±0.81^{a}	-	3.12±2.41^{a}	-	0^{a}	-	0^{a}	-

Values are the mean±standard deviation (n=minimum three replicas); The mean values in the same row followed by a different superscript are significantly different (*p*<0.05)

Table 2: Best-fit response surface models for extruded corn starch (CS)/whey protein isolate (WPI) mixtures

Parameters	Response surface model		R^2		F-Value		*p*-Value	
	Raw	Extruded	Raw	Extruded	Raw	Extruded	Raw	Extruded
Swelling power								
60°C	SP=517.49*A-3.55 *B	SP=623.69*A+343.66*B-475.80*A*B	0.889	0.994	48.08	158.69	0.000	< 0.000
70°C	SP=686.36*A+45.40*B-590.12*A*B	SP=692.82*A+359.20*B-518.27*A* B+104.21*A* B*(A-B)	0.962	1.000	8.93	6111.43	0.031	< 0.000
80°C	SP=654.37*A+40.04*B-615.67*A *B-765.15*A*B*(A-B)	SP=726.25*A+377.52*B-523.40* A*B+171.97*A* B*(A-B)	0.995	0.999	16.87	12.87	0.015	0.023
90°C	SP=671.69*A+1044.62*B-2097.09*A*B+1931.49 *A *B*(A-B)	SP=698.21*A+379.95*B-367.69* A*B+530.40*A* B*(A-B)	0.975	0.994	15.46	19.24	0.017	0.012
Foam stability								
10 min	FS=3.05*A+12.70*B+33.08 *A*B+57.63*A*B*(A-B)	FS=2.55*A+21.96*B+11.16* A*B+42.48*A*B*(A-B)	0.999	0.995	1066.78	61.51	< 0.000	0.001
15 min	FS=0.047*A+9.90*B+28.51* A*B+48.45*A*B*(A-B)	FS=0.16*A+18.50*B+9.58* A*B+38.40*A*B*(A-B)	0.998	0.985	331.67	17.91	< 0.000	0.013
30 min	FS=0.15*A+5.91*B+25.79*A*B+36.32*A*B*(A-B)	FS=1.97*A+11.11*B	0.957	0.763	17.19	19.27	0.014	0.005
45 min	FS=0.13*A+4.07*B+22.12*A* B+40.69*A*B*(A-B)	FS=0.016*A+4.27*B	0.959	0.491	29.93	5.78	0.005	0.053
60 min	FS = -0.016*A+0.21*B+8.09*A*B	-	0.645	-	8.99	-	0.030	-
120 min	FS = -3.922E-004*A-3.922E-004* B+12.47*A*B+24.91*A*B*(A-B)	-	1.000	-	1235837.67	-	< 0.000	-

FS (Foam stability); SP (Swelling power); A (Corn starch, %); B (Whey protein isolate, %)

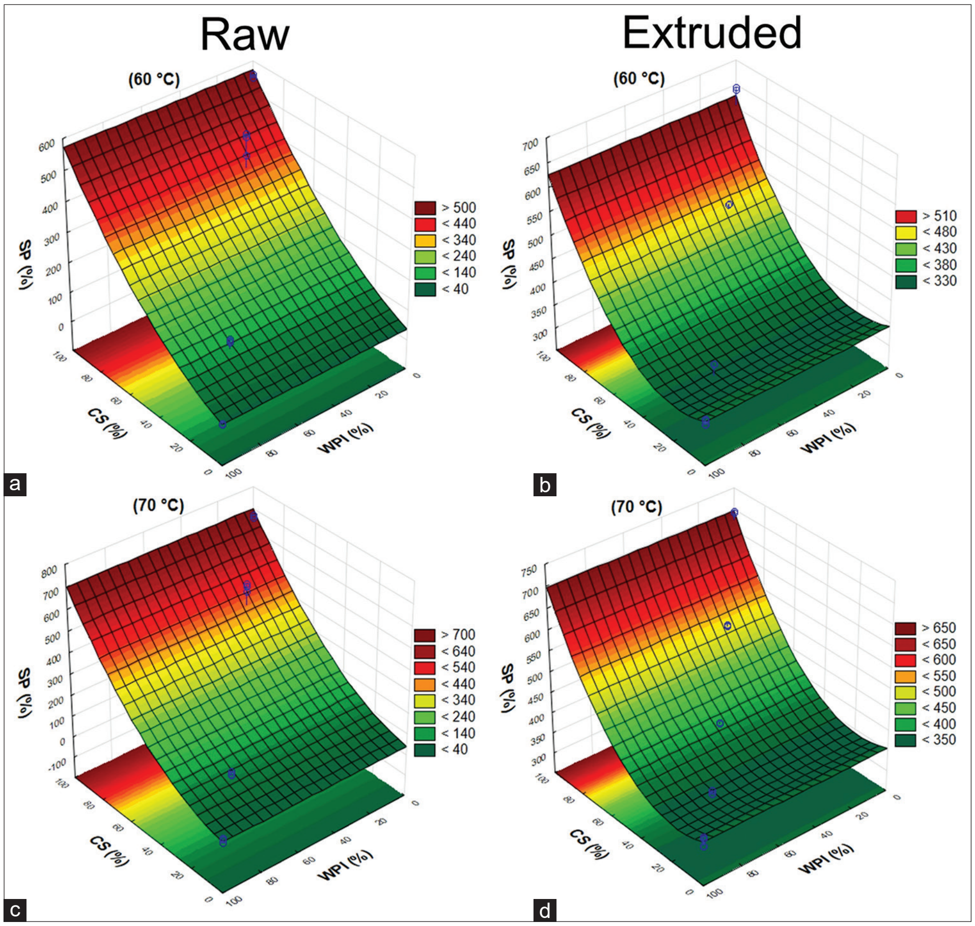

Fig 3. Response surface graphs of the impact on corn starch (CS)/whey protein isolate (WPI) blends on (a) swelling power of raw materials (SP 60°C); (b) extruded swelling power (SP 60°C); (c) raw swelling power (SP 70°C), and (d) extruded swelling power (SP 70°C).

raw and extruded mixtures, respectively, which indicates that they were also perfectly adjusted to predict this property with statistical differences ($p < 0.05$) in both cases. In the ANOVA (Table 3), statistically significant differences were obtained for all the terms in both mixtures ($p < 0.05$). When comparing all the results in general based on the heating temperatures evaluated, a significant increase in SP can be observed with the increase in temperature in most of the mixtures. To put this in perspective, the lowest SP of 38.92% was presented by the crude mixture 0/100 at 60ºC, and the highest value was obtained by the same crude mixture at 90ºC with a value of 1053.22%. The same trend in the increase of this property with the increase in temperature was reported by Harijono et al. (2013) in flours of two cultivars of aquatic yam (*Dioscorea alata*). Harijono et al. (2013) and Adams et al. (2019) commented that SP is the hydration capacity of the starch granules and is an indication of hydrogen bonds and association within the starch granules, while the water retention capacity is an indicator of the SP in the flours. Extrusion cooking may have had an impact on the degree of exposure of the internal structure of starch and gelling proteins present in extrudates, particularly due to the action of water (Kafilat, 2010). Ratnayake et al. (2002) explained that when starch is heated with an excess amount of water, the granules are progressively hydrated, the hydrogen bonds break, the crystalline regions become amorphous regions, and the granules continue to absorb water and swell. According to the results, extrusion improved the SP of the mixtures. This means that to incorporate any of the mixtures as a thickener or bulking agent in formulations or food products, it is recommended that they be subjected to an extrusion process before their application because gels are known to increase body, texture, and food cohesion (Ubbor and Akobundu, 2009; Adams et al., 2019).

Foam stability (FS)

The FS measured at 10 minutes (Table 1) in the extruded CS/WPI mixtures ranged from 2.46 to 21.87%. FS increased due to the increase in WPI, but only the 100/0 mixture presented a significant difference ($p < 0.05$). In the raw mixtures, this value was 3.08 to 16.82%, and the 100/0 mixture (only starch) had the lowest FS ($p < 0.05$). Fig. 5a and 5b show the trends for the raw and extruded mixtures, respectively. For the regression models obtained (Table 2), R^2 values of 0.999 and 0.995 were obtained from the raw and extruded

Table 3: Analysis of variance of the swelling power and foam stability in the extruded corn starch (CS)/whey protein isolate (WPI) mixtures

Param.	Source	Sum of Squares		df		Mean Square		F-Value		*p*-Value	
		Raw	Extruded	Raw	Extruded	Raw	Extruded	Raw	Extruded	Raw	Extruded
SP (60°C)	Model	305421.04	110764.36	1	2	305421.04	55382.18	48.08	389.72	0.000	< 0.000
	Linear Mixture	305421.04	88214.00	1	1	305421.04	88214.00	48.08	620.76	0.000	< 0.000
	AB	-	22550.36	-	1	-	22550.36	-	158.69	-	< 0.000
	AB (A-B)	-	-	-	-	-	-	-	-	-	-
	Residual	38114.60	710.53	6	5	6352.43	142.11	-	-	-	-
	Lack of Fit	38114.60	710.53	3	2	12704.87	355.27	-	-	-	-
	Pure Error	0.00	0.00	3	3	0.00	0.00	-	-	-	-
SP (70°C)	Model	496874.68	155420.58	2	3	248437.34	51806.86	63.97	1865793.25	0.000	< 0.000
	Linear Mixture	462186.64	128495.77	1	1	462186.64	128495.77	119.01	4627698.86	0.000	< 0.000
	AB	34688.04	26755.11	1	1	34688.04	26755.11	8.93	963569.45	0.031	< 0.000
	AB (A-B)	-	169.70	-	1	-	169.69	-	6111.43	-	< 0.000
	Residual	19417.54	0.11	5	4	3883.51	0.03	-	-	-	-
	Lack of Fit	19417.54	0.11	2	1	9708.77	0.11	-	-	-	-
	Pure Error	0.00	0.00	3	3	0.00	0.00	-	-	-	-
SP (80°C)	Model	428557.54	170244.45	3	3	142852.51	56748.15	263.45	1580.29	< 0.000	< 0.000
	Linear Mixture	381652.55	142494.35	1	1	381652.55	142494.35	703.85	3968.09	< 0.000	< 0.000
	AB	37757.35	27287.99	1	1	37757.35	27287.99	69.63	759.90	0.001	< 0.000
	AB (A-B)	9147.65	462.11	1	1	9147.65	462.11	16.87	12.87	0.015	0.023
	Residual	2168.94	143.64	4	4	542.24	35.91	-	-	-	-
	Lack of Fit	2168.94	143.64	1	1	2168.94	143.64	-	-	-	-
	Pure Error	0.00	0.00	3	3	0.00	0.00	-	-	-	-
SP (90°C)	Model	592571.12	148187.98	3	3	197523.71	49395.99	52.37	216.22	0.001	< 0.000
	Linear Mixture	96218.61	130325.55	1	1	96218.61	130325.55	25.51	570.47	0.007	< 0.000
	AB	438060.85	13466.74	1	1	438060.84	13466.74	116.15	58.95	0.000	0.002
	AB (A-B)	58291.66	4395.69	1	1	58291.66	4395.69	15.46	19.24	0.017	0.012
	Residual	15086.12	913.81	4	4	3771.53	228.45	-	-	-	-
	Lack of Fit	15086.12	913.81	1	1	15086.12	913.81	-	-	-	-
	Pure Error	0.00	0.00	3	3	0.00	0.00	-	-	-	-
FS (10 min)	Model	220.02	390.66	3	3	73.34	130.22	1507.82	284.09	< 0.000	< 0.000
	Linear Mixture	59.12	350.07	1	1	59.12	350.07	1215.36	763.71	< 0.000	< 0.000
	AB	109.02	12.40	1	1	109.02	12.40	2241.31	27.05	< 0.000	0.007
	AB (A-B)	51.89	28.20	1	1	51.89	28.20	1066.78	61.51	< 0.000	0.001
	Residual	0.20	1.83	4	4	0.05	0.46	-	-	-	-
	Lack of Fit	0.20	1.83	1	1	0.20	1.83	-	-	-	-
	Pure Error	0.00	0.00	3	3	0.00	0.00	-	-	-	-
FS (15 min)	Model	186.65	347.43	3	3	62.22	115.81	562.53	90.02	< 0.000	0.000
	Linear Mixture	68.99	315.26	1	1	68.99	315.26	623.80	245.06	< 0.000	< 0.000
	AB	80.97	9.14	1	1	80.97	9.14	732.12	7.10	< 0.000	0.056
	AB (A-B)	36.68	23.04	1	1	36.68	23.04	331.67	17.91	< 0.000	0.013
	Residual	0.44	5.15	4	4	0.11	1.29	-	-	-	-
	Lack of Fit	0.44	5.15	1	1	0.44	5.15	-	-	-	-
	Pure Error	0.00	0.00	3	3	0.00	0.00	-	-	-	-
FS (30 min)	Model	107.14	93.89	3	1	35.71	93.89	29.78	19.27	0.003	0.005
	Linear Mixture	20.29	93.89	1	1	20.29	93.89	16.92	19.27	0.015	0.005
	AB	66.24	-	1	-	66.24	-	55.24	-	0.002	-
	AB (A-B)	20.62	-	1	-	20.61	-	17.19	-	0.014	-
	Residual	4.80	29.23	4	6	1.20	4.87	-	-	-	-
	Lack of Fit	4.80	29.23	1	3	4.80	9.74	-	-	-	-
	Pure Error	0.00	0.00	3	3	0.00	0.00	-	-	-	-

(Contd...)

Table 3: *(Continued)*.

Param.	Source	Sum of Squares		df		Mean Square		F-Value		*p*-Value	
		Raw	Extruded	Raw	Extruded	Raw	Extruded	Raw	Extruded	Raw	Extruded
FS (45 min)	Model	80.30	20.40	3	1	26.77	20.40	30.96	5.78	0.003	0.053
	Linear Mixture	5.67	20.40	1	1	5.68	20.40	6.56	5.78	0.063	0.053
	AB	48.76	-	1	-	48.76	-	56.40	-	0.002	-
	AB (A-B)	25.87	-	1	-	25.87	-	29.93	-	0.005	-
	Residual	3.46	21.16	4	6	0.87	3.53	-	-	-	-
	Lack of Fit	3.46	21.16	1	3	3.46	7.06	-	-	-	-
	Pure Error	0	0.00	3	3	0.00	0.00	-	-	-	-
FS (60 min)	Model	6.58	-	2	-	3.29	-	4.53	-	0.075	-
	Linear Mixture	0.06	-	1	-	0.06	-	0.08	-	0.793	-
	AB	6.53	-	1	-	6.53	-	8.99	-	0.030	-
	AB (A-B)		-		-		-	-	-	-	-
	Residual	3.63	-	5	-	0.73	-	-	-	-	-
	Lack of Fit	3.63	-	2	-	1.82	-	-	-	-	-
	Pure Error	0.00	-	3	-	0.00	-	-	-	-	-
FS (120 min)	Model	26.40	-	3	-	8.80	-	1121964.14	-	< 0.000	-
	Linear Mixture	1.21	-	1	-	1.21	-	154479.71	-	< 0.000	-
	AB	15.50	-	1	-	15.50	-	1975575.03	-	< 0.000	-
	AB (A-B)	9.69	-	1	-	9.69	-	1235837.67	-	< 0.000	-
	Residual	0.00	-	4	-	0.00	-	-	-	-	-
	Lack of Fit	0.00	-	1	-	0.00	-	-	-	-	-
	Pure Error	0.00	-	3	-	0.00	-	-	-	-	-

A (Corn starch, %); B (Whey protein isolate, %); SP (Swelling power); FS (Foam stability); df (Degrees of freedom)

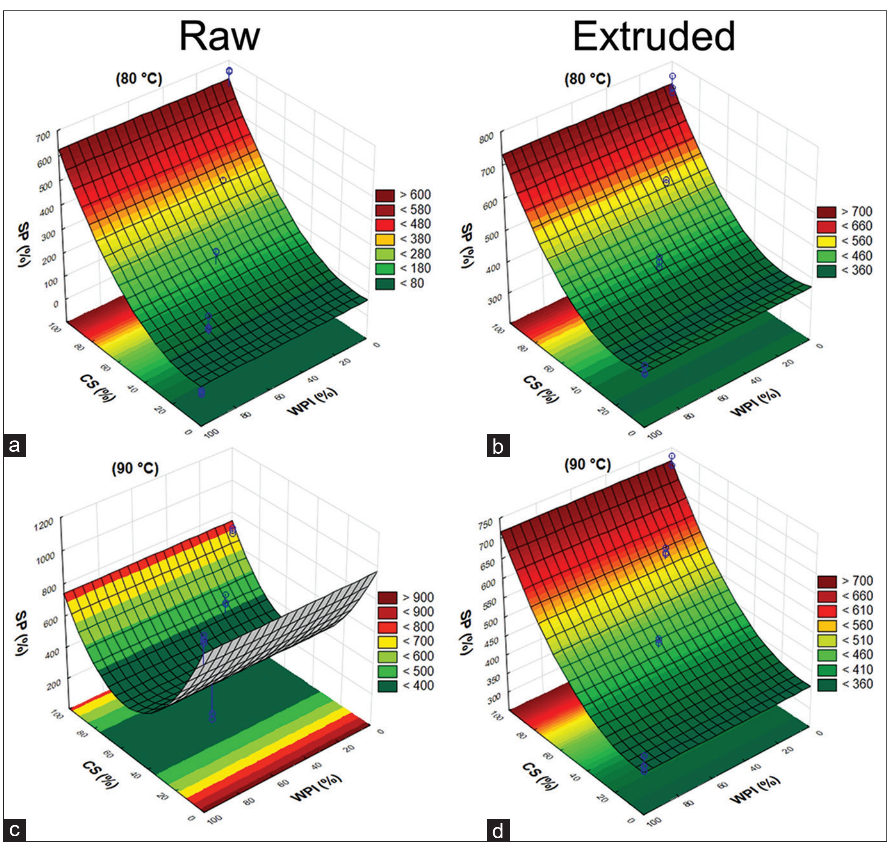

Fig 4. Response surface graphs of the impact on corn starch (CS)/whey protein isolate (WPI) blends on (a) raw swelling power (SP 80°C); (b) extruded swelling power (SP 80°C); (c) raw swelling power (SP 90°C), and (d) extruded swelling power (SP 90°C).

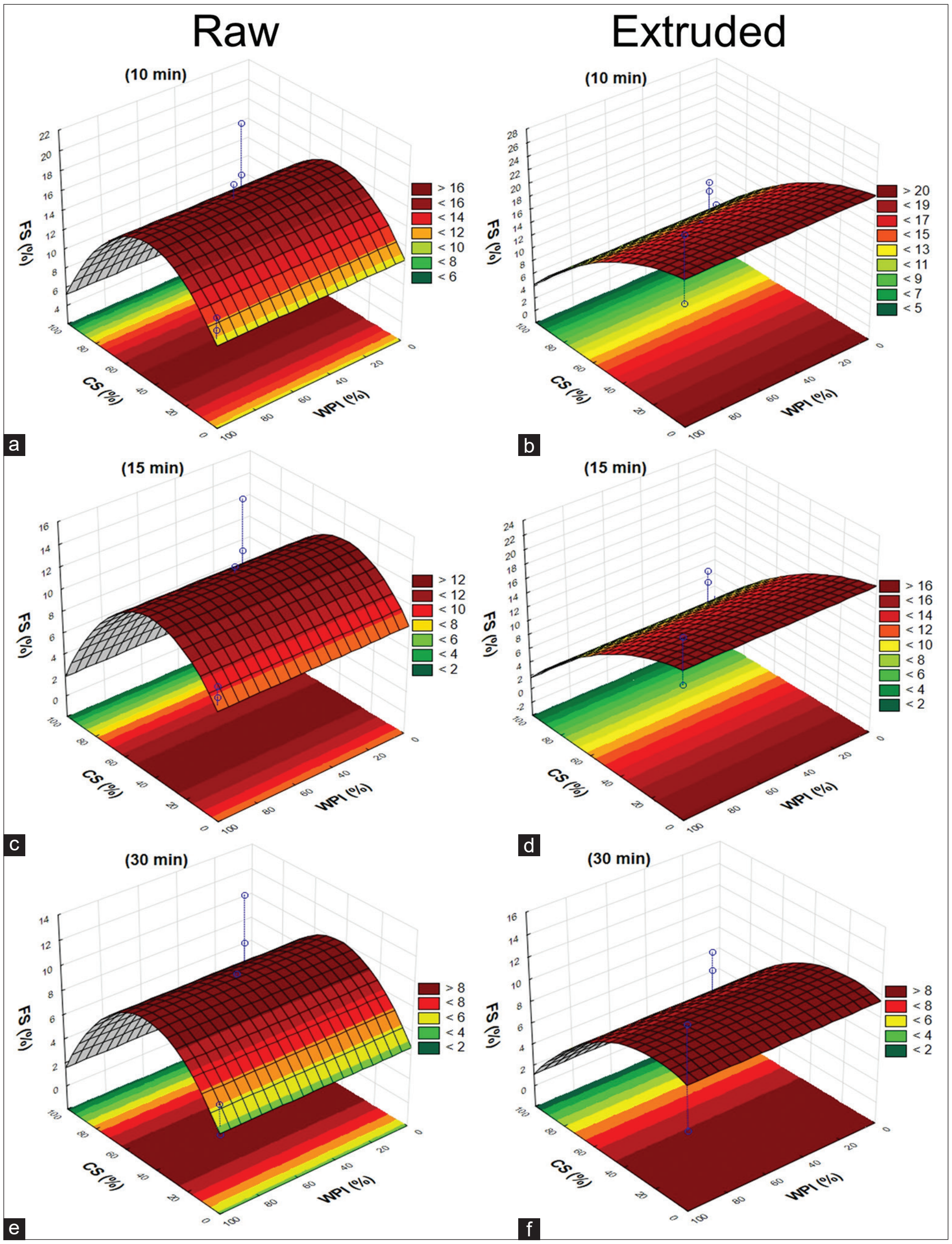

Fig 5. Response surface graphs illustrating the impact on corn starch (CS)/whey protein isolate (WPI) blends on (a) raw foam stability (FS 10 min) and (b) extruded; (c) raw foam stability (FS 15 min) and (d) extruded; (e) raw foam stability (FS 30 min) and (f) extruded.

mixtures, respectively, which means that they were perfectly adjusted and can predict this variable response (p <0.05). Table 3 presents the ANOVA results, which showed that all the terms of the models corresponding to both mixtures are statistically significant (p <0.05).

The FS measured at 15 min (Table 1) corresponding to the extruded mixtures varied between 0 and 18.34%. For the 100/0 mixture, the foam disappeared after this time. The 0/100 mixture generated more foam from the beginning, so the most foam remained after this time (Fig. 5d, p <0.05). In the raw mixtures, this value ranged between 0 and 12.77%. The 100/0 mixture lost all the foam after this time and was the only one that presented statistical differences (p <0.05, Fig. 5c). In the models (Table 2), R^2 values of 0.998 and 0.985 were obtained for the raw and extruded mixtures, respectively, which shows that they are useful for predicting FS at 15 min.

The ANOVA (Table 3) of the models showed that all the terms corresponding to both mixtures presented statistically significant differences (p <0.05). As time passed (30 and 46 min), the FS in all the mixtures decreased as expected, which can be seen in Fig. 5e (raw mixtures) and 5f (extruded mixtures) (30 min), as well as Fig. 6a (raw mixtures) and 6b

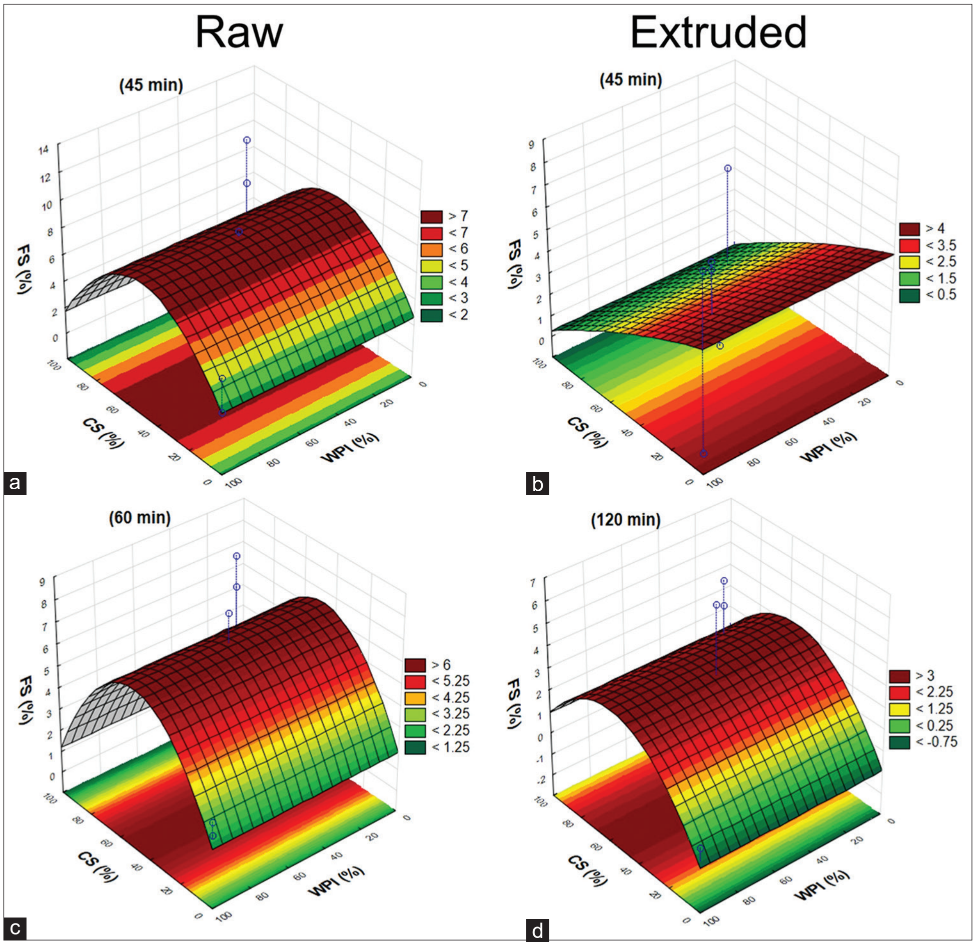

Fig 6. Response surface graphs illustrating the impact on corn starch (CS)/whey protein isolate (WPI) blends on (a) raw foam stability (FS 45 min) and (b) extruded; (c) raw foam stability (FS 60 min) and (d) raw foam stability (FS 120 min).

(extruded mixtures) (45 min). After 60 min, only the raw mixtures had a light layer of foam (Fig. 6c). In the last measurement taken at 120 min (Fig. 6d), only the 75/25 and 50/50 raw mixtures retained a slight foam layer.

In comparison, extrusion did not significantly affect FS in a previous study, but it did cause an increase in foaming capacity (Téllez-Morales et al., 2020). The R^2 values turned out to be quite low in the regression models obtained for the extruded mixtures evaluated at 30 and 45 min and the raw one at 60 min, which indicates that they were not adjusted enough to predict this property. In the ANOVA, some terms of the models corresponding to the raw and extruded mixtures at 45 min and 60 min for the raw mixtures were not statistically significant (p >0.05). Good foaming capacity and stability are desirable attributes for flours intended for the production of a variety of baked goods, such as cakes, muffins, cookies, fudges, etc., and they also act as functional agents in other food formulations (Ubbor and Akobundu, 2009). Harijono et al. (2013) explained that the capacity and stability of the foam are related to the protein content because some proteins have active surface properties to trap gas bubbles, which explains why the 100/0 mixtures presented low FS. Furthermore, they commented that proteins can also undergo rapid conformational change and rearrangement at the interface and form a cohesive viscoelastic film through intermolecular interactions to stabilize the foam (Harijono et al., 2013). Yuan et al. (2019) found that an increase in foaming capacity and FS could be due to the unfolding and aggregation of proteins induced by the extrusion process.

CONCLUSIONS

Extrusion cooking positively influenced the SP and FS of the mixtures analyzed. Furthermore, the results showed the importance of the components of CS and WPI in the extrusion process. In the case of the proposed mathematical models, for almost all the response variables, the results were significant (p <0.05) with high R^2 values in most cases. The ANOVA result was also statistically significant (p <0.05) in most of the mixtures, thus confirming its potential for use to predict the interactions generated by mixtures of CS and WPI.

ACKNOWLEDGMENTS

The authors appreciate of the National Council for Science and Technology (CONACYT) for the Master`s in Science scholarship of José A. Téllez-Morales.

Author's contributions

José A. Téllez-Morales: Data Curation-Equal, Formal Analysis-Equal, Investigation-Equal, Methodology-Equal, Software-Equal, Validation-Equal, Writing- original draft-Equal. Betsabé Hernandez-Santos, Carlos A. Gómez-Aldapa: Data Curation-Equal, Validation-Equal, Visualization-Equal, Writing-original draft-Equal. Jesus Rodriguez-Miranda: Conceptualization-Equal, Funding Acquisition-Equal, Investigation-Equal, Methodology-Equal, Project Administration-Equal, Validation-Equal, Visualization-Equal, Writing-original draft-Equal, Writing-review & editing-Equal

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