Color and texture of low-calorie peanuts as affected by a new oil extraction process named “Mechanical Expression Preserving Shape Integrity” (MEPSI)

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Abstract The current healthy life style pushed to develop and implement a novel efficient defatting process of high quality called “Mechanical Expression Preserving Shape Integrity” that conserved the sensory, color, textural, morphological and acceptability of partially defatted roasted peanuts. In this study, Response Surface Methodology was used to investigate the best extraction parameters (initial water content, pressure and pressing duration) based on the highest Color Consumer Evaluation scores, the best colorimetric parameters (L^* , a^* , b^* , ΔE^*) and the most appealing textural attributes (Fracturability, First Fracture Work Done, First Fracture Percentage of Deformation, Rupture Force, Percentage of Deformation at Rupture). Experimental results showed that defatting promotes a lighter and neutral grain color, higher fracturability and rupture force as well as higher deformation strength. Aiming to retain most of the colorimetric and textural properties after defatting and roasting, it was found that peanuts should be hydrated to 7 % d.b. and treated at 4.74 MPa for 14.22 min.

Keywords *Arachis hypogaea* · Oil extraction · Optimization · Roasting · Texture · Color

Introduction

Peanut (*Arachis hypogaea* L.) is a legume commonly known as groundnut because the seeds grow underground. This plant was cultivated as early as 2000–3000 BC (American peanut council 2015) and is native to South America. In recent years, China became the largest peanut producer, accounting for approximately 42.7 % of the overall world production, followed by India (14.2 %) and the United States of America (4.8 %) (USDA, Foreign Agricultural Service 2014).

Recent research studies have increasingly focused on peanut since this kernel represents a source of low-cost high quality protein with high essential amino acid content (Zhao et al. 2012). According to the USDA Nutrient Database for Standard References (2001), it has been verified that 100 g of peanuts have a caloric content of 567 Kcal and contain 26 % proteins and 49 % total fat. Fat and calorie contents of roasted nuts, being one of the major factors causing increased incidence of cardiovascular disease and obesity, are of great concern to health-conscious consumers. Hence, peanut oil extraction has gained remarkable attention since it factors into producing protein-rich products used to supplement human diets. Nevertheless, as can easily be detected through an intensive literature review, these aforementioned products are generally available as flakes, grits or partially defatted peanut flour (Evon et al. 2007) and not as roasted whole grain kernels. Thus, studying optimal methods of extraction and conceiving a new defatting process that preserves the characteristics of the peanuts while being eco-friendly and economical has become a necessity.

Several extraction techniques could be used to remove oil from nuts whether they are chemical (solvent (Sinha et al. 2015), enzymatic (Gaur et al. 2007), aqueous (Campbell and Glatz 2009), supercritical CO₂ extractions (Salea et al. 2014), etc.) or mechanical (hydraulic (Lanoisellé 1995), extrusion

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(Evon et al. 2007), etc.) methods. However, these techniques are often associated with major drawbacks restricting their wide application in the food industry. For instance, some of these techniques could adversely affect the sensory properties of the nuts (Zook 1992), their chemical composition (Gaur et al. 2007) and their shape and texture (Sriti et al. 2011), not to mention that they could be relatively low in efficiency, excessively costly (Venter et al. 2006) and sometimes non eco-friendly and polluting to the environment.

Moreover, high pressure treatments used in emerging technologies result in severe texture loss in legumes due to structure modification, rupture of cellular membranes and loss of turgor pressure (Aguilera 2005). Different microstructural features such as existing cracks, structural irregularities or anisotropy, and water/oil distribution, could affect the fracture and crack propagation through the material (Aguilera 2006). According to Vincent (1998), it was proven that crispness and crunchiness were directly related to the macro- and micro-structure of solid food materials, to the mechanical and fracture properties and to the way they are consumed. Texture is also highly affected by the different drying technologies (Orsat et al. 2007). Additionally, roasting provokes dehydration, browning, lipid oxidation and diverse structural snack changes that would induce changes in the appearance, color, flavor and several textural properties such as porosity, crispness, fracturability, grittiness, etc. (Varela et al. 2006). It is worth mentioning that fracturability is a defining textural characteristic of extruded and crunchy products such as puffed snacks and cereals (Idrus and Yang 2012).

Various techniques were used in the literature to define the products' textural properties: sensory tests, instrumental measurements, acoustic analysis (Liu and Tan 2000) and micro-structural observation (Aguilera 2006). Textural sensory evaluations can correlate as well with the physical and chemical attributes of food (Szczesniak 2002) and can describe the mouthfeel texture properties. However, the lack of an instrumental approach using a texture analyzer leads to a lack of control of all aspects of fracture.

Moreover, worth to mention that previous defatting techniques were abandoned as they were found to be economically non feasible since they were using very high pressures for relatively long pressing durations (Ammann 1935; Holloway and Wilkins 1982; Vix et al. 1966) and heating (60–65 °C) (Baxley 1972). Thus, introducing an efficient and innovative defatting process is the most important purpose of this study. As low fat food products are becoming more popular and as previously manufactured low fat snacks lack flavor, appealing color and seem harsh in texture, another objective of this study is to determine the color changes and textural profiles of differently treated kernels as affected by hydraulic pressure, processing time and initial water content through a new healthy defatting process that mostly preserves the organoleptic properties of peanuts with minimum structural damages in the

seeds (Louka and Nader 2014; Louka et al. 2014). Using sensory evaluation and instrumental color analysis, which results in the elimination of subjectivity, along with a tristimulus colorimeter that can view large areas of sample colors and simulate the eye-brain sensitivity to color, this research should result in a more comprehensive understanding of key reactions contributing to color development and texture of partially defatted roasted peanuts, and, in turn, allow a correlation between these properties that would be methodically optimized during the industrial defatting processes.

Material and methods

Sample preparation

Unshelled peanuts (*Arachis hypogaea* L.) of Virginia type with postharvest moisture content of 25.32 % d.b., were imported from China, were previously de-hulled and were naturally dried to a moisture content of 5.56 ± 0.24 % d.b. In the first step of this process, peanuts were harvested in October and the plants sat in the sun for two to three days to dry at ambient temperature then they were cleaned by removing all stones, soil, bits of vines and other foreign materials. The cleaned peanuts were forced through perforated grates of the shelling machines where they were de-hulled and then they passed through updraft air columns that separated the kernels from the hulls. Ten kilograms of these peanuts were randomly selected, manually cleaned to remove dirt, scraps, broken, deformed and immature seeds and then they were sieved twice using 9.5 and 8.5 mm square mesh sieves (Industrial Netting, Minneapolis, MN 55445) in order to select medium-sized and whole seeds with a geometric mean diameter (MD) of 12.41 ± 0.26 mm and a sphericity ratio (SR) of 0.59 ± 0.02 .

Pretreatments

Roasting and peeling

After several preliminary trials at the laboratory, a light initial air roasting (140 °C, 15 min) was performed in an oven (Memmert, Universalschrank, UFE700, Germany) in order to develop the flavor and color characterizing peanuts and to partially denature proteins in order to facilitate subsequent oil extraction (Zhang et al. 2011). Then, peanuts were manually peeled by hand rubbing.

Hydration and homogenization

Moisture content of peanuts after the initial light roasting was 2.48 ± 0.12 % d.b. A rehydration process before pressing was necessary to increase the grains compressibility and their

resistance to disintegration in order to minimize the rate of irreversible deformation and the percentage of broken seeds after pressing. Thus, peanuts were soaked in distilled water at 25 °C with a 1/5 (g/ml) grain to water ratio for a sufficient time to reach the recommended levels of moisture content (5, 7, 10, 13 and 15 % d.b.) (Eq. 1) that would be used afterwards in the experimental design.

$$Q = \frac{M_i (W_f - W_i)}{100 - W_f} \quad (1)$$

where Q (kg) is the mass of water added, M_i (kg) is the initial mass of the sample, W_i and W_f are respectively the initial and the final moisture content of the sample in % d.b.

Moreover, an equilibrium stage after rehydration was applied to let the grains withstand the rigors of mechanical pressing. Hence, peanuts were packed in tight PVC (Polyvinyl chloride) bags stored at 4 °C for 3 days to ensure a uniform distribution of water throughout the seeds.

All the above described pretreatments conditions (as well as post-treatments conditions discussed in the paragraphs below) were set after a series of trials that were carried out in LIPAI (Laboratoire d'Intensification des Procédés Agro-Industriels) laboratory.

Partial defatting by pressing

Experimental setup

A hydraulic press, weighing around 1000 kg and providing a maximum pressure of 26 MPa, was designed and operated at LIPAI laboratory. This press was mainly composed of (a) a hydraulic unit, (b) a steel frame provided with a plunger (stroke 40 cm, maximum downwards speed 13 mm/s) for uniaxial compression, (c) a stainless steel cylinder (internal diameter 20 cm, height 24.5 cm, capacity 6 kg of peanuts), all being run by (d) an automated system of control and measurement that was remotely operated (Fig. 1). A rotary pump was set to draw oil (12 L/min) to the piston and (e) an oil cooler was installed to avoid oil warming. A pressure regulator was set and calibrated to apply the desired amount of force. Pressure reading was performed by a pressure sensor with an accuracy of ± 0.1 MPa while piston speed was regulated by a speed control valve (± 0.5 mm/s). The press was also fitted with a position transducer (± 0.01 mm) and thermocouples (± 0.1 °C) to control oil and chamber temperatures.

Defatting process

The innovation was applied to the press machine, studied and recently patented ((LB-10,492 (Louka and

Nader 2014) and LB-10,493 (Louka et al. 2014)) as it yielded beneficial results to the industries. It aimed to enhance the efficiency and cost-effectiveness of the defatting process, to save energy during processing, to reduce wastes of highly distorted seeds with unrecoverable deformations, to reduce grains breakage at high pressures and to easily recover the extracted oil for multiple uses (Nader et al. 2014). The novelty of this defatting process lies in the distribution of a specific separation material (SSM) between the grains in the press chamber (Fig. 2a). Many types of food grade SSM were tested including cotton, sand, salt, polystyrene and peanut skins. It was found that elastic SSM yielded better results than the granular materials as such materials decreased the oil extraction yields by increasing the radial stress inside the pressing chamber. The choice of the appropriate food grade SSM was clearly justified in LB-10,492 (Louka and Nader 2014) and LB-10,493 (Louka et al. 2014) patents. The main roles of these SSM were to (a) limit the irreversible deformation of the grains during pressing by filling the voids between the peanuts while avoiding the fusion between the particles and eliminating the block effect and to (b) continually absorb the oil extracted during pressing in order to avoid the saturation of the inter-particle space with oil and thereby keeping a high concentration gradient between the inner and outside area of the seeds. This innovative mechanical oil extraction using SSM was named MEPSI “Mechanical Expression Preserving Shape Integrity” since peanuts were defatted without inducing any damages and the structure integrity of the grains was preserved.

Mechanical oil expression

Hydraulic pressing is generally influenced by the following independent operating parameters: the applied pressure, the peanuts initial water content, the compression speed, the pressing duration and the cake thickness (Lanoisellé 1995). For each experiment, 250 g of peanut seeds were spread uniformly at the base of the cylinder having an internal surface area of 314 cm² and were compressed with a piston displacement speed of 8 mm/s.

Further to several preliminary trials conducted at LIPAI laboratory, the ranges of variability of the selected process parameters were set as follows: pressure (4 to 10 MPa), pressing duration (10 to 30 min) and water content before pressing (7 to 13 % d.b.). Although temperature is a key factor that could positively affect the oil extraction yield; the temperature was not adopted as a variant parameter and was fixed at 25 °C $\pm$ 1 °C in order to preserve as much as possible the quality of the

Fig. 1 Hydraulic press with details of sieve plates (with small (12×250 wires/in.), medium (20×20 wires/in.) and large (14×14 wires/in.) pores) installed at the bottom of the cylinder

partially defatted peanuts and to prevent irreversible deformations at high temperatures.

Experimental design and statistical analysis

A Response Surface Methodology (RSM) was used to study the effect of the operating conditions on the following response parameters:

- (i) Colorimetric responses after defatting: Color Consumer Evaluation (CCE), Lightness color component (L^*),

Chromatic color components (a^* and b^*), Total color change (ΔE^*); and

- (ii) Textural responses after roasting: Fracturability (FRA), First Fracture Percentage of Deformation (FFPD), First Fracture Work Done (FFWD), Rupture Force (RF), Percentage of Deformation at Rupture (PDR).

The three studied independent variables affecting the defatting process were: initial moisture content (W), pressure (P) and pressing duration (t). These three independent variables (W , P , t) are shown in Table 1 in their coded and real

Fig. 2 **a** Hydraulic pressing of multi-layered product separated by the SSM, **b** Color and grain appearance after different stages of the defatting process: **a** raw peanuts, **b** after pressing, **c** after reconstitution, **d** after drying and roasting

Table 1 Response parameters values of raw and partially defatted peanuts differently treated according to the experimental design

RN	Process parameters[coded]			Response parameters										
	W[W]	P[P]	t[t]	DR ^a	CCE ^b	L ^{*c}	a ^{*c}	b ^{*c}	ΔE ^{*c}	FRA ^d	FFPD ^d	FFWD ^d	RF ^d	PDR ^d
Raw	5.56 ± 0.24	–	–	–	2.5 ± 0.2	66.17 ± 0.22	17.22 ± 0.57	–22.84 ± 0.36	–	9.57 ± 0.40	24.6 ± 1.63	14.86 ± 1.29	40.85 ± 0.92	18.23 ± 0.56
1	7[–1]	4[–1]	30[+1]	40.85	7.75	74.92	5.16	–12.1	76.06	7.022	7.18	3.5	28.244	4.75
2	13[+1]	4[–1]	10[–1]	13.92	8	68.47	14.86	–20.94	73.13	5.512	7.13	2.37	16.956	3.68
3	5[–α]	7[0]	20[0]	70.62	7.88	79.22	1.3	–2.47	79.27	8.758	7.41	3.35	22.762	4.7
4	7[–1]	4[–1]	10[–1]	34.15	8.25	73.25	8.41	–13.21	74.91	8.277	9.48	3.8	25.734	5.26
5	13[+1]	10[+1]	10[–1]	24.98	5	71.92	9.59	–16.86	74.49	4.286	6.38	1.66	12.582	2.92
6	13[+1]	10[+1]	30[+1]	27.07	6	72.83	9.42	–15.08	74.97	5.002	8.18	2.43	17.456	4.78
7	15[+α]	7[0]	20[0]	17.79	5.63	68.9	12.94	–20.76	73.11	4.462	5.76	0.92	15.642	3.85
8	10[0]	7[0]	3.2[–α]	22.97	6.56	69.38	10.27	–16.59	72.07	5.472	6.14	1.63	24.253	4.96
9	7[–1]	10[+1]	30[+1]	57.44	5.56	77.49	1.34	–6.82	77.8	12.563	9.29	5.98	33.020	4.48
10	10[0]	12[+α]	20[0]	32.68	5.25	73	8.55	–14.29	74.87	6.463	7.75	1.4	24.076	3.32
11	7[–1]	10[+1]	10[–1]	48.55	6	75.19	3.2	–8.62	75.75	6.953	6.9	1.63	25.753	5.6
12	10[0]	7[0]	36.8[+α]	24.77	5.63	70.72	9.65	–16.06	73.16	5.168	6.49	2.28	20.997	3.8
13	10[0]	1.95[–α]	20[0]	9.6	6.63	67.3	15.35	–22.13	72.49	4.080	8	1.38	18.957	2.58
14	13[+1]	4[–1]	30[+1]	14.29	5.13	68.48	13.86	–20.91	72.93	4.452	6.2	1.37	15.966	2.98
15	10[0]	7[0]	20[0]	23.6	6.38	69.71	9.73	–16.99	72.41	5.453	7.23	2.64	18.986	3.48
16	10[0]	7[0]	20[0]	24.61	6.25	70.55	9.24	–16.24	72.98	5.208	6.54	2.28	17.849	3.28
17	10[0]	7[0]	20[0]	23.34	6.13	69.55	9.7	–16.97	72.24	6.247	6.44	2.52	17.839	3.4
18	10[0]	7[0]	20[0]	24.6	6.5	70.41	9.61	–16.22	72.89	6.375	7.08	2.08	17.760	3.45
19	10[0]	7[0]	20[0]	21.34	6.38	69.32	10.26	–17.46	72.22	6.679	6.21	2.12	17.947	3.58
20	10[0]	7[0]	20[0]	22.94	6.63	69.31	10.13	–17.27	72.15	5.767	6.87	2.23	17.604	3.62

FRA of non defatted roasted peanuts: 3.6 N ± 0.2 N

RV Run Number, W Initial water content (% d.b.), P Pressure (MPa), t Processing duration (min), DR Defatting Ratio (%), CCE Color Consumer Evaluation (over 10), L* Lightness color component, a* and b* Chromatic color components, ΔE* Total color change, FRA Fracturability (N), FFPD First Fracture Percentage of Deformation (%), FFWD First Fracture Work Done (mJ), RF Rupture Force (N), PDR Percentage of Deformation at Rupture (%).

^a Values are represented as means of three repeated experiments with a mean standard deviation of 1.22 for DR

^b Values are represented as means of one-hundred and seven sensory results with a mean standard deviation of 0.18 for CCE

^c Values are represented as means of twenty repetitions with a mean standard deviation of 0.54 for L*, 0.37 for a*, 0.52 for b* and 0.36 for ΔE*

^d Values are represented as means of ten repeated experiments with a mean standard deviation of 0.57 for FRA, 0.4 for FFPD, 0.22 for FFWD, 0.5 for RF and 0.12 for PDR

values. A central composite rotatable design was adopted. Twenty experiments were completed with eight (2^3) factorial points, six axial points and six center points for replications. Statistical analyses as well as response surfaces were made by using the analysis design procedure of Statgraphics Plus (5.1 version, Windows software). A nonlinear second degree polynomial equation (Eq. 2) was fitted in each response to study the effect of operating parameters and to describe the process empirically:

$$Y = a_0 + \sum_{i=1}^3 a_i x_i + \sum_{i=1}^2 \sum_{j=2}^3 a_{ij} x_i x_j + \sum_{i=1}^3 a_{ii} x_i^2 \quad \text{with } j > i \quad (2)$$

Where Y is the predicted response, x_i and x_j are the coded values of the factors, a_0 is the mean value of responses at the central point of the experiment, and a_i , a_{ii} and a_{ij} are the linear, quadratic and interaction coefficients respectively.

The probability p -value (≤ 0.05) generated from the analysis of variance (ANOVA) and the coefficient of determination (R^2) represent the significance of independent variables and the percentage of experimental results explained by the model as fitted respectively.

Post-treatments: reconstitution and roasting

The compressed flattened peanuts were reconstituted by soaking in 0.6 dm³ of distilled water for 30 ± 2 min to achieve a full shape recovery and to reach a final moisture content of 20 % d.b. Then, samples were dried in an oven (Memmert, Universalschrank, UFE700, Germany) at 50 °C for a sufficient time in order to reach a water content of 7.5 to 11 % d.b. After drying, the samples were roasted at 180 °C for 210 s in a granular roaster using crystallized mineral salt as a heat conduction medium.

Physicochemical analysis

Moisture content

Moisture content (% d.b.) was determined gravimetrically by measuring the weight loss of 2 g of the sample upon convective drying in a dryer (Memmert, Universalschrank, UFE700, Germany) at 105 °C until reaching a stable weight for 60 min time frame (AOAC 2005).

Color measurement

Surface color of raw and partially defatted peanut samples after pressing was measured using a colorimeter (ADCI - 60 - C) after calibration against white and black glass standards.

Colors were expressed in CIE Lab color values (L^* , a^* , b^*). L^* value represents the lightness (100) to darkness (0) spectrum, a^* value represents the greenness (−120) to redness (+120) spectrum, while the b^* value represents the blueness (−120) to yellowness (+120) spectrum. For the two chromatic components (a^* and b^*), 0 value represents a neutral color. 20 readings for each sample were averaged in order to minimize measurement variation associated with non-uniform samples..

The total color change (ΔE^*) was then calculated as follows (Eq. 3) (Tran et al. 2007):

$$\Delta E^* = \sqrt{(L_0^* - L^*)^2 + (a_0^* - a^*)^2 + (b_0^* - b^*)^2} \quad (3)$$

where L_0 , a_0 and b_0 are color scores of raw untreated peanuts.

Textural analysis

Compression tests were performed using CT3 texture analyzer (Brookfield Engineering Labs. Inc.) with a 10 KN load cell in order to study the texture of the roasted partially defatted grains. First, the testing machine was fitted with a craft blade (TA3/100) that cut the sample at a speed of 2.0 mm/s to simulate the activity of the incisors during grain crushing, then, a second cylindrical probe (TA44) was used to simulate the force exerted by the molars during cracking. A software was connected to the texture analyzer and data was recorded and treated with a frequency of one measure per second, showing the force exerted on the grain versus the distance traveled by the probe. All textural measurements were performed in 10 replicates. Samples were placed onto the platform and the probe was allowed to penetrate 6 mm into the sample. Texture profile analysis enabled calculations for FRA, RF, FFPD, FFWD and PDR. The forces FRA at failure and RF at rupture which are an indication of the crisp's brittleness were determined at the first bite using TA3/100 and TA44 probes respectively. FFWD is the energy required at the first break to overcome the internal strength of bonds within the grain sample while FFPD and PDR are the percentage of deformation of the grain during compression just before failure and rupture respectively.

Consumer evaluation

One-hundred and seven consumers were selected from students, faculty, and staff at Saint Joseph University as well as customers of local and international industries of snack products. Consumers (62 males and 45 females, ages between 18 and 60, without reported case of peanut allergies) were chosen for their acuity in color, texture and flavor perception, their ability to verbalize and quantify sensory information. 20 peanut samples differently treated according to the experimental

design, packed in blind labeled tight transparent PVC bags, were randomly subject to consumer evaluation. The tests were carried out in a room illuminated with a fluorescent lamp. Consumers were asked to evaluate the color of defatted roasted grains, then they were instructed to place the peeled peanut between their incisors then between their molars with the core edge up for the initial bite so that biting was along a radial axis, since this was the orientation for the instrument tests.

A hybrid hedonic scale (Villanueva et al. 2005) was adopted to evaluate color and textural characteristics. Color was the visual evaluation of the browning degree after roasting and texture was evaluated in term of crunchiness acceptance of the roasted peanuts. Panelists were asked to rate how much they liked or disliked each sample with respect to overall acceptance, knowing that the scale has equidistant points and three verbal affective labels in the middle (5 refers to: “neither liked nor disliked”) and both ends (1 refers to “disliked extremely” and 10 refers to “liked extremely”) of the scale.

Results and discussion

Experimental results

The experimental matrix with actual factors levels of investigated process variables (W, P and t) along with the defatting ratio (DR) and the achieved sensory (CCE), colorimetric (L^* , a^* , b^* and ΔE^*) and textural (FRA, FFPD, FFWD, RF, PDR) responses are presented in Table 1. The variability among the experimental response parameters of the 20 runs shows the effect of operating variables on these responses during the defatting process. Major changes noticed during this process are explained as follows: Ammann (1935) has reported a 60–70 % oil yield when peanuts were pressed at 34.3 MPa for 45–60 min while an 80 % oil removal in 10 min at 35.1 MPa was reported by Wong and Sackenheim (1992). Compared to earlier defatting techniques, the biggest advantage obviously noticed from actual experimental results was that the use of a food grade SSM has enhanced the extraction yield without further need of high pressures and long pressing durations (Nader et al. 2014). In this efficient mechanical extraction process, and due to the SSM introduction in the press machine, pressure was reduced to an optimum level of 9.7 MPa during a cold pressing technique for 4 min (with 5 % d.b. as moisture content) resulting up to 70 % oil extraction yield (Louka and Nader 2014; Louka et al. 2014) and the structure integrity of the grains was well preserved. By comparing the 20 runs, it was noticed that a maximum DR (run3, Table 1) was observed when W (5 %) was at its lowest level ($-\alpha$) with a relatively high pressure (7 MPa) and long pressing duration (20 min). In fact, DR of peanut seeds decreased linearly with

increasing the water content because the water decreases the internal and intra-particle mobility of oil. On the other hand, DR increased with higher pressures and longer pressing durations since the proportion of oil extracted is higher in such conditions.

All sensory scores (CCE) granted by the consumers for color evaluation after defatting, reconstitution and roasting were higher than that of the raw peanuts (2.5/10) ranging between 5/10 and 8.25/10. It is obvious that the color of partially defatted nuts will be improved after roasting due to Maillard, browning and caramelization reactions (Cämmerer and Kroh 2009). On the other hand, color parameters (L^* , a^* , b^* and ΔE^*) evaluated by instrumental analysis varied differently after defatting compared to raw peanuts. Raw samples had a lightness L^* of 66.2. After maximum defatting (run 3 of Table 1), peanuts turned into whiter color acquiring an L^* value of 79.2 while a^* and b^* values tended to approach to the 0 level (neutral). This color change induced a ΔE^* of 79.3. The color change and the grain appearance during several stages of MEPSI defatting process were clearly shown in Fig. 2b.

As for the textural instrumental analysis, FRA values of defatted peanuts were most of the time lower than FRA of the raw ones (9.6 ± 0.4 N), same for RF values which ranged between 12.6 N and 33 N staying below RF value of raw peanuts (40.9 ± 0.9 N). Similarly, a significant decrease of FFWD (varying from 0.9 mJ to 6 mJ) was noticed after treatment compared to the FFWD of raw unextracted peanuts (14.9 ± 1.3 mJ). FRA, RF and FFWD values were positively correlated, with decreasing fracturability occurring in tandem with decreasing rupture force and work done. Moreover, compared to raw peanuts (having FFPD of $24.6 \% \pm 1.6$ and PDR of $18.2 \% \pm 0.56$), lower FFPD (varying from 5.8 % to 9.5 %) and PDR (ranging between 2.6 % and 5.3 %) were noticed after several defatting treatments. On the other hand, by comparing the roasted kernels of the 20 runs to the raw ones, after roasting peanuts have a lower water content rendering them less chewy thus less deformable. In fact, during compression of the seeds at their raw state, a force accumulation occurs as the product is chewier and as the contact area between the blade and peanuts increases with the duration of compression. Furthermore, by comparing the 20 runs between each others, the effect of oil content (defatting ratio) on textural attributes of the finished defatted and roasted peanuts could be deduced. The presence of the oil may increase the softness of the seeds; this could explain the fact that FRA increases with a progressive decrease in oil content which was confirmed by a simple comparison between the 20 trials where samples were differently defatted with a non treated roasted sample, the latter having the lowest fracturability ($3.6 \text{ N} \pm 0.2 \text{ N}$).

All the previously described textural results imply that after defatting, reconstitution and roasting, peanuts become less hard, more crumbly, less chewy, more fracture and crispier than the non-defatted roasted product.

Regression modeling

Experimentally obtained values of the responses were analyzed by the multiple regression method to fit the second-order polynomial equation. The obtained second-order polynomial equations showing the studied response parameter as a function of actual values of initial water content (W), pressure (P) and pressing duration (t) along with the coefficient of determination R^2 (%) indicating the significance of the model equation and measuring the degree of fitting are presented in Table 2. The operating parameters that had significant effects (linear, interaction and quadratic) on each response parameter at 95 % confidence level (p -value <0.05) were marked in bold face (Table 2).

The models can then be used to calculate any and all combinations of variables and their effects within the test range. For all the studied response parameters, correlation coefficients R^2 were mostly high (varying from 78.58 % to 97.62 %) which indicates that the second order models of multiple regressions can be used to explain the functional relationship between process and response parameters.

Effect of process variables on response parameters

In the following, significant linear, quadratic and interaction effects at 95 % confidence level (5 % risk level) will be clarified by the Pareto charts (Fig. 3a, d, g, j, m and Fig. 4a, d, g, j, m). On the other hand, response surfaces will be illustrated as three-dimensional (3D) plots by presenting the studied response as a function of the two significant variables while fixing the third at the central level. Response surfaces (Fig. 3b, e, h, k, n and Fig. 4b, e, h, k, n) will be used to visualize the quantitative variation of response parameters with process variables, to depict the significant interactions if any, and to predict responses within a chosen range of process parameters. Moreover, the projected response surface contour plots (isoresponse curves) (Fig. 3c, f, i, l, o) and Fig. 4c, f, i, l, o) will provide an adequate representation of most continuous surfaces over a relatively broad factor domain and the combinations of levels of factors necessary to achieve the optimal predicted value that will be indicated by a cross shown on this figure.

Sensory analysis: color consumer evaluation (CCE)

As it is shown in Table 1, the lowest CCE value (5/10) was obtained in run 5 where W and P were at their high level and t at its low level (+1, +1, -1 respectively) while the highest CCE values (8.25/10) corresponded to the fourth run where W, P and t were fixed at their low level (-1). These results demonstrated that CCE appeared to be negatively affected by

Table 2 Equations of the fitted models with coefficients of determination (R^2) for each response parameter

Response parameter	Equation of the fitted model	R^2 (%)
Color Consumer Evaluation	$CCE = 15.18 - 0.715*W - 0.691*P - 0.0851*t + 0.0196*W^2 + 0.0321*W*P - 0.0039*W*t - 0.0124*P^2 + 0.0164*P*t - 0.00057*t^2$	83.41
L^*	$L^* = 98.78 - 4.907*W - 0.665*P - 0.0092*t + 0.1975*W^2 + 0.0457*W*P - 0.0127*W*t + 0.0439*P^2 + 0.0064*P*t + 0.0036*t^2$	95.56
a^*	$a^* = -4.29 + 3.703*W - 1.549*P - 0.1866*t - 0.138*W^2 - 0.0094*W*P + 0.0164*W*t + 0.0515*P^2 + 0.0093*P*t - 0.0024*t^2$	96.84
b^*	$b^* = 15.76 - 6.047*W + 1.019*P - 0.1421*t + 0.229*W^2 + 0.00056*W*P - 0.0046*W*t - 0.0302*P^2 + 0.0102*P*t + 0.0039*t^2$	97.62
ΔE^*	$\Delta E^* = 94.26 - 3.57*W - 0.904*P + 0.033*t + 0.163*W^2 + 0.0114*W*P - 0.0122*W*t + 0.0645*P^2 + 0.0066*P*t + 0.002*t^2$	94.59
Fracturability	$FRA = 10.91 - 0.69*W + 0.179*P - 0.0284*t + 0.0501*W^2 - 0.068*W*P - 0.0196*W*t - 0.0025*P^2 + 0.036*P*t - 0.00005*t^2$	84.55
First Fracture Percentage of Deformation	$FFPD = 18.84 - 0.614*W - 1.692*P - 0.234*t + 0.0097*W^2 + 0.0236*W*P + 0.0033*W*t + 0.0604*P^2 + 0.0309*P*t - 0.00008*t^2$	85.34
First Fracture Work Done	$FFWD = 5.94 - 0.271*W - 0.36*P - 0.011*t + 0.0176*W^2 + 0.0006*W*P - 0.0178*W*t - 0.0117*P^2 + 0.0268*P*t + 0.0009*t^2$	78.73
Rupture Force	$RF = 44.79 - 1.526*W - 1.714*P - 0.7145*t + 0.063*W^2 - 0.1066*W*P - 0.0245*W*t + 0.1537*P^2 + 0.0442*P*t + 0.0177*t^2$	81.46
Percentage of Deformation at Rupture	$PDR = 14.82 - 1.329*W - 0.090*P - 0.3547*t + 0.0414*W^2 + 0.0135*W*P + 0.0116*W*t - 0.0107*P^2 + 0.0081*P*t + 0.0041*t^2$	78.58

The significant effects at 95 % confidence level are marked in bold face

Fig. 3 (a, d, g, j) Standardized Pareto chart, (b, e, h, k) Trend of the estimated response surface, (c, f, i, l) Contour plots of response surface and optimum values of operating parameters (W, P, t) on color parameters

(L^* , a^* , b^* , ΔE^*) and Color Consumer Evaluation (CCE) after peanuts defatting and roasting respectively

the linear effects of P, W and t and this was proven by the ANOVA test and the Pareto chart (Fig. 3a). CCE values decreased with increased pressures (Fig. 3b). In fact, high pressures exerted on the seeds or long durations contributed to high extraction yields that would considerably empty the oleosomes from their oil content (Lanoisellé 1995) and would negatively affect peanuts color after oil extraction,

reconstitution, drying and roasting. On the other hand, lower defatting ratios were observed at increased W (Table 1) as high water content prevents the elimination of oil by mechanical pressing since the water decreases the internal and intra-particle mobility of oil (Holloway and Wilkins 1982). Nevertheless, CCE decreased at high moisture contents due to the fact that after defatting, peanuts would

Fig. 4 (a, d, g, j, m) Standardized Pareto charts, (b, e, h, k, n) Trends of the estimated response surfaces, (c, f, i, l, o) Contour plots of response surfaces and optimum values of operating parameters (W, P, t) on roasted

partially defatted peanuts' Fracturability (FRA), Rupture Force (RF), First Fracture Work Done (FFWD), and Percentage of Deformation at first break (FFPD, PDR)

require extensive durations of drying and roasting which will contribute in darkening the finished product. Moreover, a significant effect of interaction between P and t was noticed (Fig. 3a, b). During relatively short pressing durations, CCE values decreased while increasing P due to a higher defatting ratio that would lighten

the color of the finished product. However, for longer t and by rising P, CCE showed a slight increase pattern that could be due to a cutback of the defatting process as a result of cellular interstices clogging at high pressures and for long durations. As a result, in order to achieve the highest color sensory scores by the

consumer, we have interest to work at relatively low W (4 to 7.5 % d.b.), short t (around 6 min) and low P (2 to 5 MPa) (optimal region shown in Fig. 3c).

Color parameters: L^* , a^* , b^* and ΔE^*

Regarding the colorimetric parameters, the linear effect of W has significantly affected L^* and b^* (p -values <0.01 % with negative effects) as well as a^* (p -value <0.01 % with a positive effect) (Fig. 3d, g, j). These results could be explained by the fact that mobility of oil throughout the seeds and therefore oil extraction yields were enhanced at low levels of moisture content (Table 1). Consequently, high defatting ratios at low W rendered the peanuts whiter (higher L^*) but slightly more neutral (lower a^* and higher b^* tending towards the zero value or neutral color) (Table 1 run 3, Table 2, Fig. 3e, h, k). Moreover, the linear effect of P and the quadratic effect of W were positively affecting L^* and b^* and negatively a^* (Fig. 3d, g, j). In fact, by increasing P exerted on peanuts, L^* increased and the chromatic parameters varied in the direction of the neutral color (zero point) since at these operating conditions, a significant defatting occurred resulting in a whiter and more grey product due to oil loss (Fig. 3e, h, k). On the other hand, at very high W, the trend of color variability (L^* , a^* and b^*) was attenuated which could be perceived by the significant effect of W^2 that is due to reduction of the defatting process at these treatment conditions (Table 2, Fig. 3e, h, k).

Regarding ΔE^* , its variability (Fig. 3n) was significantly affected by the negative linear effect of W and the positive linear effects of P and t and the quadratic effects of W and P. Same explanation as for L^* , low W, high P and long t induced high oil extraction yields leading to a high total color change mainly due to changes occurring in lightness (whiter) and slightly in chromatic parameters (neutral). However, the quadratic effects of P and W could be explained by the fact that at low pressures, low defatting ratios were observed and at high water contents a significant W^2 effect was noticed due to water reactions and rancidity inducing color changes in the defatted product (Fig. 3n). To conclude, by comparing the sensory color analysis after roasting to the instrumental results after pressing and in order to obtain the most acceptable color and appearance, it would be recommended to extract oil from peanuts at moderate W (~7 % d.b.), for medium t (~10 min) at relatively low P (~4 MPa) to optimize color changes (Fig. 3f, i, l, o).

Textural parameters: FRA, FFPD, FFWD, RF and PDR

As it is shown in Table 1, generally the required force to crack the sample between the molars (RF) is higher than the one exerted by the incisors (FRA) as the contact surface area is higher. Moreover, as the elimination of oil leads to hardening the product and rendering it more fracture (crumbly), FRA

and RF were significantly and negatively affected by high W (Fig. 4a, b, j, h). This negative effect was clearly shown in Table 1 (run 3 and run 9) where FRA and RF attained the highest values (8.758 N and 33 N respectively) when W was set at its low levels ($-\alpha$ and -1). On the other hand, the interaction between the two operating parameters (P-t) had a positive effect on FRA (Fig. 4a, b). At low pressing durations (t) and with pressure increase, FRA slightly decreased instead of increasing due to the fact that oil has not had enough time to migrate from inside to the surface of the seeds. Contrariwise, for long t and by increasing P exerted on the grains, the fracturability increased due to the elimination of a high percentage of oil and a cell wall collapse on the grain surface after reconstitution and roasting.

The most desirable and acceptable FRA (~5 N) and RF (~17.5 N) values were defined by a panel after several textural sensory analysis resulting in the best treatment conditions determined by the optimal region shown in Fig. 4c and l ($10.25 < W(\% \text{ d.b.}) < 12.25$; $5.5 < P(\text{N}) < 7$; $18.5 < t(\text{min}) < 19.5$).

FFWD varied same way as FRA (Fig. 4a and g) since more the grain structure is dense, greater is the FRA and more work is required to overcome the resistance of internal bonds within the grains. This parameter was influenced by the linear negative effect of W, and the positive interaction effect (P-t) with 0.18 % and 1 % p -values respectively (Fig. 4g, h).

At low initial water contents and/or by applying high pressures for long duration, greater defatting ratios occurred which resulted in hardening the product and consequently increasing the work required (Fig. 4g, h) to break the seed. The negative effect of P-t interaction on FRA and FFWD is clearly shown (Fig. 4b, h) by the reversed slope noticed at high pressures and/or high pressing durations where the decrease of these response parameters was converted to an increase pattern. In fact, the effect of P was added to that of t, resulting in an acute deceleration of the defatting process due to the clogging of pores at high P and high t and to the inhibition of oil drainage at high water contents. In conclusion, in order to obtain low calorie crunchy peanuts with a non-crumbly texture neither a very brittle one at the first fracture, FFWD required during crushing should be around 2.4 mJ. This could be achieved by pressing the grains initially moistened to 9.7 % d.b. at 7.1 MPa for 20.8 min (Fig. 4i).

Concerning the deformation strength, the interaction effect P-t on FFPD was the most significant followed by the linear effect of W and the quadratic effect of P with p -values ~0.3 % (Fig. 4d). Same for PDR, W had the highest significant effect on this response followed by the quadratic effects of t and W having p -values of 0.5 %, 1.6 % and 2.5 % respectively (Fig. 4m).

It was noted here that FFPD and PDR did not depend on P and t factors (Fig. 4d, m). Therefore, the effect of defatting (which often accompanies the increase in P and T) seemed to

Fig. 5 Contours plots and optimum value generated from multiple response analysis

be masked by the effect of initial water content. In this case, W had a very significant negative incidence on the deformation strength (Fig. 4d, m, n). Then, it is well known that soaking plays a key role in changing the rheological behavior of matter after drying (Yaacoub 2009). So, high water content caused an increase in the hardness of the finished dry-roasted product and thereafter made it less deformable at the first break applied whether by the incisors (FFPD) or by the molars (PDR).

Regarding the positive interaction effect P - t (Fig. 4d, e), it could be explained as follows: at low P and short t , defatting is limited (Table 1) and therefore the presence of the oil in the product made it more deformable. At high P and short t or at low P and long t , defatting was improved and the product contained less oil thus became less deformable. It was expected that while increasing P and t when defatting becomes very high, that the deformation goes lower. However, it was noticed that a reconstituted product emptied of the major part of its oil

content became much hygroscopic and rapidly absorbed moisture from the atmosphere especially at its surface making it more deformable (Fig. 4d, e, m). Same reasons were behind the quadratic positive effects of P (Fig. 4d) and t (Fig. 4m) on FFPD and PDR respectively. Regarding the significant positive effect of W^2 shown in Figs. 4m and n it was not really a quadratic effect but rather a deceleration towards an asymptotic value of PDR.

As a result, in order to achieve the most acceptable deformation strength after roasting of the defatted peanuts, it is recommended to work at low W (5 to 5.6 % d.b.) and relatively high P (8.5 to 9.5 MPa) for moderate t (22.5 to 29 min) (Fig. 4f, o).

Multiple optimization

The optimization of MEPSI defatting process using Response Surface Methodology was aimed at finding the levels of initial water content, pressure and pressing duration, which could maximize the textural and color sensory scores evaluated by the consumers (CCE) while optimizing the colorimetric parameters (L^* , a^* , b^* and ΔE^*) as well as the textural attributes covering fracturability, deformation strength, rupture force and work done (FRA, FFPD, FFWD, RF and PDR). A graphical multiple response optimization technique was used to determine the workable optimum conditions for the defatting process of peanuts. The contour plots for all responses were superimposed (Fig. 5) and regions that best satisfy all the constraints were selected as optimum conditions. The optimal

Table 3 Optimum values of response parameters resulting from separate and multiple optimization

	Response parameters	Operating parameters			Optimums
		W (% d.b.)	P (MPa)	t (min)	
Separate optimization	CCE (/10)	5.61	2.52	6.02	10
	L^*	6.89	4.12	10.2	73.3
	a^*	9.21	7.48	20.72	8.4
	b^*	8.48	7.94	20.93	-13.2
	ΔE^*	7.02	4.06	9.93	74.9
	FRA (N)	12.17	5.52	18.44	5
	FFPD (%)	5.05	8.45	28.91	8.2
	FFWD (mJ)	9.70	7.1	20.81	2.4
	RF (N)	10.29	6.9	19.47	17.5
	PDR (%)	5.72	9.45	22.6	4.8
Multiple optimization**	CCE (/10)	7.02	4.74	14.22	8.03
	ΔE^*				74.9
	FRA (N)				7.12
	FFPD (%)				8.2
	RF (N)				22.93
	PDR (%)				4.8

** In multiple optimization, colorimetric parameters (L^* , a^* and b^*) and FFWD were removed since they varied the same way as ΔE^* and FRA (N) respectively

responses (maximum CCE and optimum colorimetric and textural values that correspond to the runs having the highest sensory scores) with their relative operating conditions are shown in Table 3 and the most suitable combination of factors (W: 7 % d.b.; P: 4.74 MPa; t: 14.22 min) is designated in Fig. 5 after establishing a multiple response optimization resulting in a compromise between all studied response parameters..

Conclusion

A healthy and eco-friendly defatting process of peanut seeds using mechanical expression technique (MEPSI) was implemented and optimized by Response Surface Methodology. As a result, the above described defatting process should be carried out in the most efficient conditions: hydration to 5 % d.b., homogenization for 3 days at 4 °C, hydraulic pressing at 9.7 MPa for 4 min using SSM materials, reconstitution by soaking to 20 % d.b., drying and roasting at 180 °C for 210 s, noting that no chemicals were used during the whole process. MEPSI allowed the preparation of highly defatted peanuts (70 % defatting ratio) while preserving structure integrity and organoleptic properties (with 12.9 %, 42.6 % and 15.9 % final oil, protein and fiber contents respectively). This novel process has proven to be effective in preserving most of the textural properties of the treated kernels. The resulting treated peanuts appeared to be lighter in color, less deformable and crunchier. According to the empirical models generated from the experimental design, it was feasible to choose the best pressing parameters (P, W and t) leading to the production of partially defatted peanuts having the most appealing color (CCE = 8.03/10; ΔE^* = 74.9) and a crunchy non-hard texture (FRA = 7.12 N; FFPD = 8.2 %; RF = 22.93 N; PDR = 4.8 %).

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