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# Impact of instant controlled pressure drop (DIC) treatment on the technological quality of gluten-free bread based on rice-field bean formula using design of experiments

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This work aimed to investigate the impact of Instant Controlled Pressure Drop (DIC) treatment on the technological quality of Gluten-Free Bread (GFB) based on Rice-Field bean Formula (RFF). Two DIC factors were used as independent parameters of a Design of Experiments (DoE);  $X_1$ : DIC temperature ranged from 100 to 165°C which was rigorously correlated with the dry saturated steam pressure ranged between 0.1 and 0.7 MPa, and  $X_2$ : the processing time ranged from 20 to 60 s. The main response (Y) was the specific Volume (Vsp) of the GFB. The statistical analysis was performed using the Response Surface Methodology (MSR) to study and optimize the DIC treatment effect on technological quality (Vsp) of the GFB. The breads crumb was characterized by image analysis. The GFB optimum from RFF was obtained with DIC steam pressure of 0.3 MPa (temperature of 132.5°C) for a short treatment time of 20 s. It provided the highest Vsp of  $2.7 \pm 0.04 \text{ cm}^3/\text{g}$  with an improvement of 10.20% than the GFB control and a great total number of *alveoli*. Hence, DIC treatment was an effective improvement mean of technological quality of GFB based on RFF for celiac patients.

**Key words:** Instant controlled pressure drop (DIC), rice-field bean formula, gluten-free bread, design of experiments (DoE), specific volume, crumb structure.

## INTRODUCTION

Celiac disease (CD) is considered as one of the most widespread gastro-intestinal diseases. It is a state of

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autoimmune response to gluten proteins in a genetically predisposed subject, characterized by nutriment malabsorption caused by the atrophy of intestinal mucosa (Lionetti and Catassi, 2011; Lebowl et al., 2018). It touches approximately 1% of the world's population with a great variation between countries (Makharia et al., 2011; Do Nascimento et al., 2017). Currently, the only treatment for CD is exclusively dietetic: a lifetime strict gluten-free diet, which entails removing any source of gluten containing in wheat, barley and rye and to substitute them by other gluten-free cereals such as rice and corn (O'Shea et al., 2014).

Bread is the basic consumed food in the world. However, its manufacture based on gluten-free ingredients remains difficult with a lower quality than the conventional wheat bread (Benatallah et al., 2012), due to the absence of the gluten, which is a great challenge for cereal researchers on gluten-free bread making (Masure et al., 2016). Many studies carried out for answering this problem were based on substituting the gluten by adding specific ingredients and additives like starches (Bourekoua et al., 2016; Bourekoua et al., 2018), proteins (Phongthai et al., 2016), enzymes (Mohammadi et al., 2015; Calle et al., 2020) and hydrocolloids (Benatallah et al., 2012).

Furthermore, the National Council of Food (CNA) (2009) of France highlighted the interest of the use of physical treatments in food industry in which these treatments could modify the chemical, functional, molecular, and structural properties of the raw materials used in the production of various foods. Among these physical treatments, the Instant Controlled Pressure Drop (French: *Détente Instantanée Contrôlée*- DIC) technology, which was defined in 1988, as a high temperature-short time stage usually carried out by establishing high-pressure dry saturated steam-high temperature (usually between 0.1-0.7 MPa relating with 100-165°C) during 5-60 s. This ends by an instant pressure-drop towards a vacuum of about 0.005 MPa and an instant cooling, at a rate  $\Delta P/\Delta t$  higher than 0.5 MPa s<sup>-1</sup> (Allaf and Vidal, 1989).

This thermo-mechanical treatment method has been used in many industrial applications such as drying and texturing of plants (Louka and Allaf, 2002; Albitar et al., 2011; Nguyen, 2015), microbiological decontamination (Setyoprato et al., 2009), extraction volatile compounds and essential oils (Kristiawan et al., 2004; Besombes et al., 2010), and steam treatment of cereals (Habba and Allaf, 1997; Duong et al., 2008; Pilatowski et al., 2010).

However, the effect of Instant Controlled Pressure Drop (DIC) treatment on the quality of GFB has never been previously studied. Therefore, this study aimed to investigate and optimize the effect of DIC treatment on the technological quality (specific volume) of GFB based on RFF, with the objective of improving the situation of celiac patients.

## MATERIALS AND METHODS

### Raw materials

White long rice grain (*Oryza sativa*) from Basmati variety obtained from India and field bean seeds (*Vicia faba minor*) obtained from an Egyptian Company (Elamir Company, Egypt) were used in our study. Rice and field bean seeds were ground by a laboratory mill (Moulinex, France); thereafter, the flours obtained were sieved manually with 200- $\mu$ m seive. The Gluten-Free Formula (GFF) used was based on the mixture of rice and field bean flour with a ratio 2/1 (w/w). The soft wheat flour was used for the control bread. Additional ingredients were used such as bakery freeze-dried yeast, *Saccharomyces cerevisiae* (S.I. Lesaffre, France) and salt (ENASel, Algeria). All these raw materials were purchased from an Algerian local market.

### Chemical composition of flours

Chemical composition of rice and field bean flours was determined following the ISO methods for moisture (ISO 712: 2009) and ash content (ISO 2171: 2010), and the AACC methods (1995) for protein (AACC 46-10) and lipid content (AACC 30-10) in three replications. Total carbohydrates content was evaluated by subtracting the total percentage of the other components from one hundred.

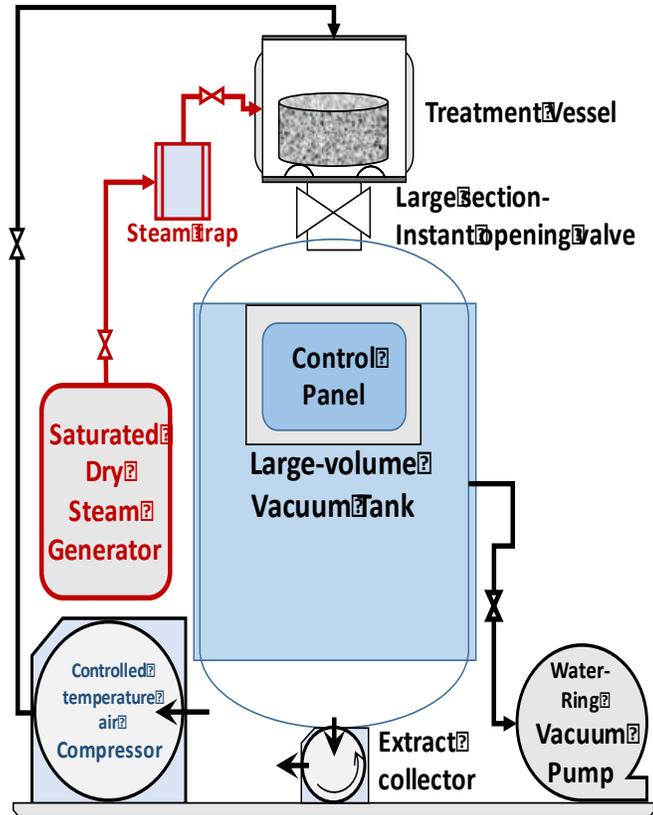
### Instant controlled pressure drop (DIC) treatment of gluten-free formula

In the present study, DIC equipment used for the GFF treatment was a laboratory scale DIC unit (manufactured and provided by ABCAR-DIC Process, La Rochelle, France) (Figure 1). It consists of 11-L processing vessel with heating jacket, where samples are set and treated, a 1.6 m<sup>3</sup>-vacuum tank with cooling water jacket, a water ring vacuum pump, a steam generator with a thermally isolated storage tank and a specific condensed steam trap; a large-section pneumatic valve that assures an "instant" connection between the vacuum tank and the processing vessel that can be opened in less than 40 ms (Allaf, 2013).

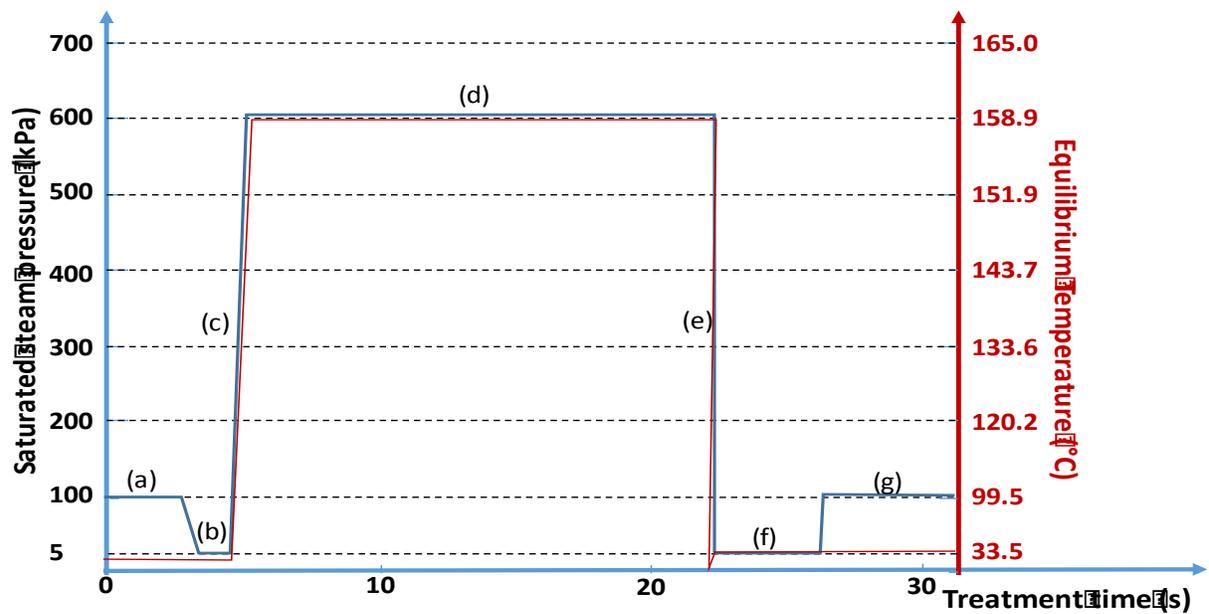
DIC treatment of the different GFF samples, starts by placing 180 g of sample within a bag of coffee-type filter and positioning it in the treatment vessel at atmospheric pressure (Figure 2-phase a). After closing it, an initial vacuum stage (about 5 kPa = 0.005 MPa) was established (Figure 2-phase b) in order to remove the air presented in the vessel and, thus to assure close contact between the surface of the sample and the saturated dry steam to be injected just after (Figure 2-phase c). As demonstrated by Allaf and Allaf (2014), the use of dry saturated steam allows a subsequent hugely-fast heating by condensation. In our case, dry saturated steam pressure ranged between 0.10 and 0.70 MPa according to a specific design of experiments (DoE) we adopted based on the know-how of the research team, the literature, and a preliminary series of trials. This allowed the treatment temperature to be between 100 and 165°C. This stage (Figure 2-phase d) of 20 to 60 s ends by an abrupt pressure-drop towards a vacuum (5 kPa = 0.005 MPa) (Figure 2-phase e) obtained by opening the pneumatic large-section instant valve. Finally, the atmospheric pressure was restored in the treatment vessel (Figure 2-phase g) and the sample was recovered.

### Design of experiments (DoE)

In order to study the effect of DIC operating parameters on the Vsp of GFB based on RFF, a specific DoE was carried out. It was a 5-level (- $\alpha$ , -1, 0, +1, + $\alpha$ ) DoE with two factors; X<sub>1</sub>: DIC temperature



**Figure 1.** Schematic diagram of the Instant Controlled Pressure Drop (DIC) apparatus. Source: Allaf (2013).



**Figure 2.** Temperature and pressure history of a DIC processing cycle: (a) Sample at atmospheric pressure; (b) Initial vacuum; (c) Saturated steam injection to reach the selected pressure and temperature; heating by condensation; (d) stage for almost homogenizing both temperature and water content within the product; (e) abrupt pressure-drop towards a vacuum of ~4-5 kPa coupled to an autovaporization; (f) vacuum of 4-5 kPa; (g) releasing to the atmospheric pressure. Source: Allaf (2013)

**Table 1.** Codes levels values of factors used in the Design of Experiments (DoE).

Code level		- $\alpha$	-1	0	+1	+ $\alpha$
X1: Temperature (T) coupled with the saturated dry steam pressure (P)	T (°C)	100.0	109.5	132.5	155.5	165.0
	P (MPa)	0.10	0.15	0.30	0.55	0.70
X2: Thermal treatment time (s)		20.0	25.9	40.0	54.1	60.0

**Table 2.** Run experimental values used in DIC treatment and added water to make dough of differently DIC treated rice-field bean formula.

Run	Coded variable	X1: Temperature (T) accorded to the steam pressure (P)		X2: Thermal treatment time (s)	Amount of water added (mL)
		T (°C)	P (MPa)		
1	(0, 0)	132.5	0.30	40	219.5
2	(+1.414, 0)	165.0	0.70	40	220.56
3	(0, +1.414)	132.5	0.30	60	221.9
4	(0, 0)	132.5	0.30	40	219.63
5	(+1, +1)	155.5	0.55	54	221.46
6	(+1, -1)	155.5	0.55	26	220.8
7	(0, 0)	132.5	0.30	40	221.03
8	(-1, -1)	109.5	0.15	26	219.93
9	(-1, +1)	109.5	0.15	54	219.83
10	(0, 0)	132.5	0.30	40	222.36
11	(-1.414, 0)	100.0	0.10	40	222.93
12	(0, -1.414)	132.5	0.30	20	222.5
13	(0, 0)	132.5	0.30	40	220.76

(T) coupled with the dry saturated steam pressure (P) and X<sub>2</sub>: the thermal treatment time (t) (Table 1). In this case, DoE included 13 trials: 2<sup>0</sup>=2<sup>2</sup>=4 factorial points (-1,-1), (-1,+1), (+1,-1) and (+1,+1); 2×n=2×2=4 star-points (- $\alpha$ ,0), (0,- $\alpha$ ), (0,+ $\alpha$ ), and (+ $\alpha$ ,0); and 5 replicates for the center-point (0,0) were added. DIC treatment experiments were carried out in random using the operating conditions done in Table 2. The saturated dry steam pressure (expressed in Pa) applied in the current DIC range was accorded to the temperature level (T) (expressed in K) following the Equation 1:

$$P (Pa) = 10^{\left(10.09938 - \frac{1681}{T - 43.037}\right)} \quad (1)$$

The mathematical model used with the DoE is a second order model, which allows the study of the linear, quadratic and interaction effects according to the following Equation 2:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \beta_{12} X_1 X_2 \quad (2)$$

Where Y is response variable; X<sub>1</sub>, X<sub>2</sub>: are independent variables, treatment temperature and time, respectively;  $\beta_0$  is the constant coefficient;  $\beta_1$  and  $\beta_2$  are regression linear coefficients;  $\beta_{11}$  and  $\beta_{22}$  are regression quadratic coefficients and  $\beta_{12}$  is interaction regression coefficient.

### Optimization

The DIC treatment optimization consisted of defining the highest value of the studied response (V<sub>sp</sub>). For that, the response surface of the V<sub>sp</sub> of GFB from RFF was represented versus DIC factors (X<sub>1</sub> and X<sub>2</sub>) of the couple (temperature-time). To confirm the optimized result computed by the MSR, a second experiment series

was performed including selected couples of temperature-time inside and outside the optimal delimited zone, in which the V<sub>sp</sub> of the obtained GFB was determined.

### Bread making process

In bread making test, the GFF used was based on rice and field bean flour with a ratio 2/1 (w/w) aimed to obtain a better nutritional balance of essential amino-acids (FAO, 1982; Benatallah et al., 2012).

For the 13 samples of treated DIC rice-field bean formula and the untreated formula, the amount of water added to each sample depended on its moisture content and it was calculated so that all the dough samples had the same final water content (70 g of water for 100 g of dough) (Table 2). So, preliminary tests allowed defining the hydration levels of manufacturing GFB as ranged between 219.5 and 222.93 mL of water for 100 g of rice/field bean flour. As for the control dough with soft wheat, preliminary tests based on obtaining the best V<sub>sp</sub> of bread helped to retain an optimal hydration level of 61 mL of water for 100 g of wheat flour.

The bread recipe used consisted of 66.66 g of rice flour, 33.33 g of field bean flour, 2 g of salt, 2 g of instant freeze-dried yeast (*Saccharomyces cerevisiae*) and the amount of water suitable for each sample (Table 2). These ingredients were mixed for 15 min twice, with a 5-min break, in a kneader (HEIDOLPH RZR 2020, Germany) at 25°C. The resulting dough was divided in lumps (45 g) and put into a silicon mold (9×4.7×3 cm<sup>3</sup>), and then proofed at 37°C in wet atmosphere for 45 min in a fermentation cabinet (MEMMERT, France). The baking tests were performed in an electric oven (SAMSUNG, Germany) at 230°C in wet atmosphere for 55 min for GFB based on DIC-treated rice-field bean formula, 22 min for the control GFB and 15 min for the control wheat bread.

**Table 3.** Chemical composition of rice flour, field bean flour, and gluten free formula (d.b).

Flour	Moisture (%)	Protein (%)	Fat (%)	Ash (%)	Carbohydrate <sup>a</sup> (%)
Rice flour (RF)	10.83% ± 0.01	6.37% ± 0.02	0.33% ± 0.01	0.59% ± 0.03	92.71
Field bean (FF)	10.54% ± 0.04	29.41% ± 0.03	1.99% ± 0.01	3.18% ± 0.02	65.42
RF/FF (2/1) <sup>b</sup>	10.73	14.05	0.88	1.45	83.61

<sup>a</sup>Carbohydrates content estimated by difference; <sup>b</sup>Results obtained by calculation (2:1).

**Table 4.** Statistical parameters of specific volume of gluten-free bread of treated DIC rice-field bean formula (Empirical Statistical Model:  $Y = \beta_0 + \beta_1X_1 + \beta_2X_2 + \beta_{11}X_1^2 + \beta_{22}X_2^2 + \beta_{12}X_1X_2$ ).

Regression coefficient	$\beta_0$	$\beta_1$	$\beta_2$	$\beta_{11}$	$\beta_{22}$	$\beta_{12}$
Value	-0.48	0.0567	-0.0301	-0.000159	0.001068	-0.000562
P- value	0.000	0.117	0.033	0.469	0.093	0.248

### Gluten-free bread quality evaluation

After 60 min post-baking, GFB characterization was carried out by the determination of Vsp and the image analysis of bread crumb structure.

Volume was determined by the rapeseed displacement method according to the AACC Approved Method 10.05 (AACC, 2000). Vsp of bread expressed in "cm<sup>3</sup>/g" was calculated by dividing its volume (V) by its mass (M).

According to Gonzales-Barron and Butler (2006), image analysis of bread crumb was performed using Image J software (version 1.43, National Institutes of Health, USA). Slices of bread (1 cm thick) were scanned using a flatbed scanner (Epson stylus SX 105) with a resolution of 300 dots per inch. The parameters recorded were the number of cells, the average surface and cells circularity (shape).

### Statistical analysis

Statistical analysis of the design of experiments (DoE) was performed with MINITAB 17 software (Minitab Inc., PA State College, USA) and the response surface was traced using STATISTICA version 10 software (Stat Soft, France). The K-means test was applied to classify (regroup) the different types of breads. A coefficient of determination ( $R^2$ ) was computed and the model adequacy was tested by separating the residual sum of squares into pure error and lack-of-fit. The significance level was set at 0.05.

## RESULTS AND DISCUSSION

### Chemical composition of raw materials

The chemical composition results of rice and field bean flour used, expressed in percentage (based on dry basis), are given in Table 3. Rice flour was characterized by high carbohydrates (92.71%), lower protein (6.37%), fat (0.33%) and ash (1.37%) contents compared to field bean flour. The calculation of GFF composition based on rice and field bean flour with a ratio 2/1 indicated improvement in protein (14.05%), fat (0.88%), and ash (1.45%) contents due to the incorporation of field bean

flour. The results obtained are in agreement with those reported for GFB made with rice/field bean flour with 2/1 (w/w) by Benatallah et al. (2012) and Bourekoua et al. (2016). Thus, the incorporation of legumes flours in gluten-free products enhances their nutritional quality (Lamacchia et al., 2014).

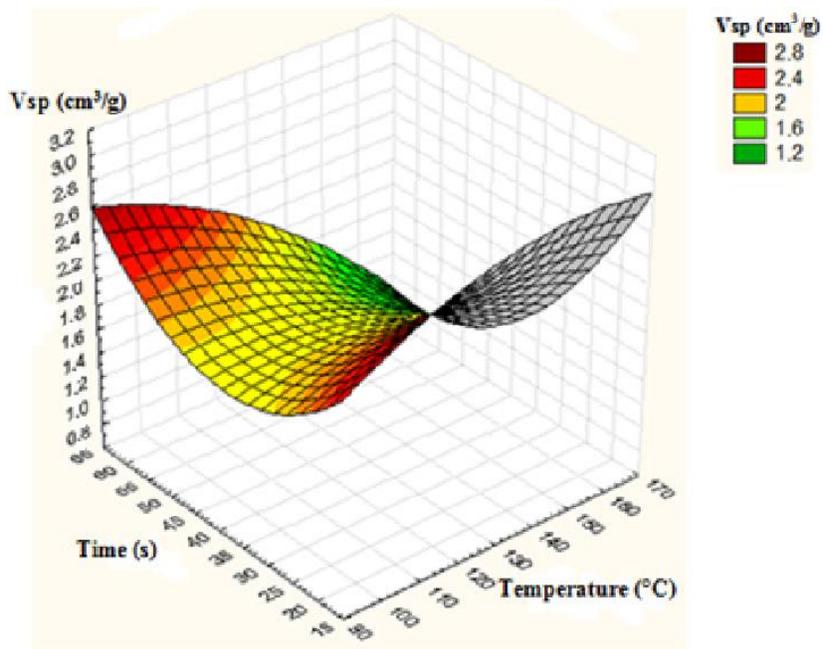
### Model fitting

According to Goupy (2013) and Granato and de Araújo Calado (2014), the calculation of  $R^2$  coefficient is used to measure the DoE empirical model quality and the lower lack-of-fit indicated the adequacy of the model. The statistical analysis of the effect of DIC operating parameters ( $X_1$ : the steam temperature coupled with the pressure, and  $X_2$ : the thermal treatment time) on the Vsp (Y) of GFB indicated that the fitting model was adequate due to the reasonable value of  $R^2$  (0.73) and a non-significant lack-of-fit test (0.55).

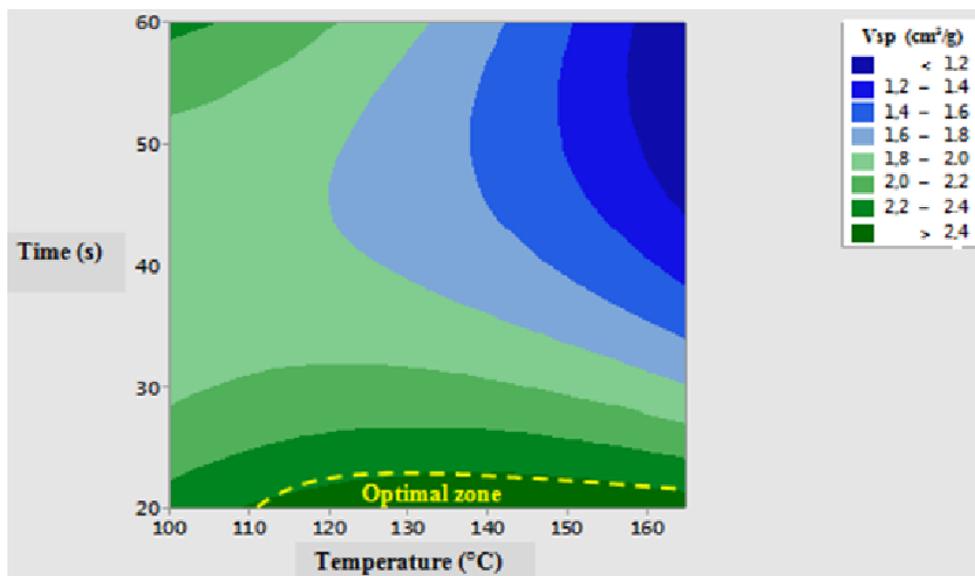
### Effect of DIC treatment on specific volume of gluten-free breads

The Vsp is one of the most important visual characteristics of bread, strongly influencing consumer choice, and it is the key-parameter for the bread quality evaluation (Hager and Arendt, 2013). The parameters of the statistical empirical model of the Vsp of GFB versus DIC factors are summarized in Table 4. It was observed that only the linear effect of DIC processing time  $X_2$  was significant with the value 0.033, based on the  $p$  value relative to 0.050 ( $p < 0.05$ ), whereas, the other terms were not significant ( $p > 0.05$ ).

The effect of DIC operating parameters  $X_1$  and  $X_2$  on Vsp of GFB based on RFF is shown as response surface in Figure 3. It shows that the Vsp values varied from 1.2 to 2.8 cm<sup>3</sup>/g. Moreover, the highest Vsp was lower than



**Figure 3.** Response surface of specific volume of gluten-free bread of DIC-textured rice-field bean formula according to DIC couple (temperature-time).

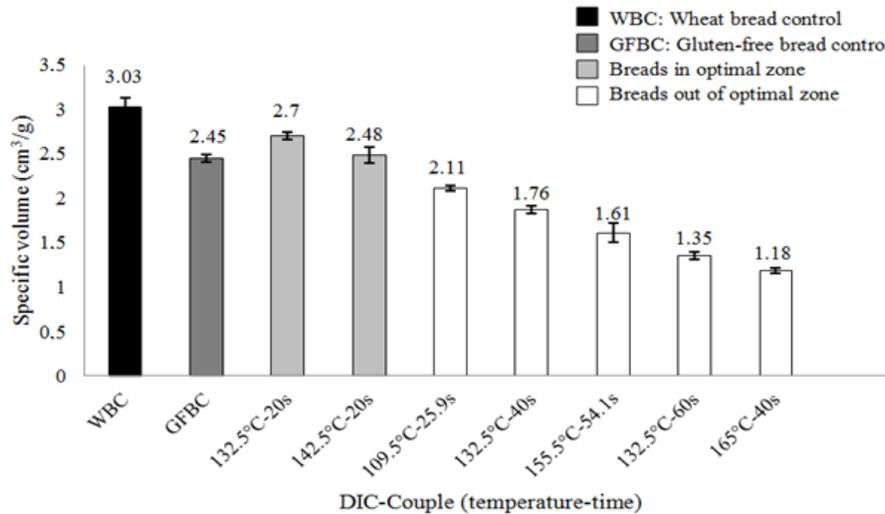


**Figure 4.** Level curve of specific volume of gluten-free bread of DIC-textured rice-field bean formula according to DIC couple (temperature-time).

that of the wheat bread control ( $3.03 \pm 0.10 \text{ cm}^3/\text{g}$ ), but it was higher than that of the GFB control from untreated formula ( $2.45 \pm 0.04 \text{ cm}^3/\text{g}$ ). The highest values of the Vsp were recorded for a wide range of temperature and steam pressure, coupled with a short treatment time, also for low temperature and steam pressure, and a long treatment time.

### Optimization results

The level curve of the Vsp of GFB of DIC-treated rice-field bean formula according to couple (temperature-time) is illustrated in Figure 4. It shows that the highest Vsp values of GFB situated in the optimal zone, in which the Vsp values were higher than  $2.4 \text{ cm}^3/\text{g}$ , include



**Figure 5.** Confirmation points of specific volume of gluten-free breads of DIC-treated rice-field bean formula according to DIC couple (temperature-time).

temperature that ranged from 110 to 165°C, steam pressure from 0.15 to 0.7 MPa, and low treatment time from 20 to 22 s.

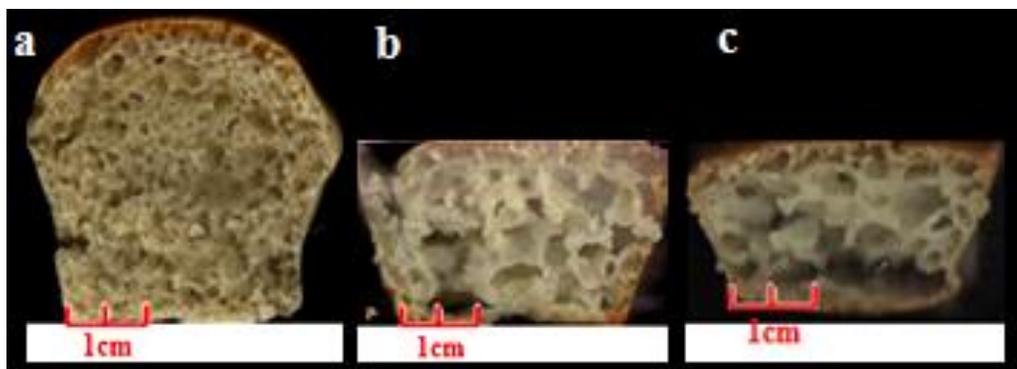
Figure 5 represents the confirmation points selected inside and outside the optimal delimited zone of the Vsp of GFB based on DIC-treated rice-field bean formula. All the GFB presented lower Vsp than that of the wheat control bread ( $3.03 \pm 0.10 \text{ cm}^3/\text{g}$ ). Obviously, this is due to the absence of structural protein "gluten" in the raw material used in our study (Gallagher et al., 2004). Kawamura-Konishi et al. (2013) demonstrated the inability of rice proteins to form a three-dimensional viscoelastic network similar to that of wheat gluten, which results in low gas retention thus giving bread with low Vsp.

The k-mean classification indicates that the GFB obtained from the treated DIC-rice-field bean formula at 132.5°C (steam pressure of 0.3 MPa) for 20 s giving the highest Vsp of  $2.7 \pm 0.04 \text{ cm}^3/\text{g}$  would belong in the same class of wheat bread control. In addition, this GFB showed an improvement of Vsp with a gain of 10.20% compared to the GFB control ( $2.45 \pm 0.04 \text{ cm}^3/\text{g}$ ). Therefore, it is considered as the optimum GFB of our present study. On the other hand, the GFB of DIC-treated rice-field bean formula at 142.5°C/0.39 MPa for 20 s gave a Vsp of  $2.48 \pm 0.09 \text{ cm}^3/\text{g}$ . This increase in Vsp of GFB of DIC-treated rice-field bean formula with these conditions compared to the GFB control, would probably be explained by the effect of DIC treatment on the properties of rice flour, which was the basic ingredient used in our GFF. According to Habba and Allaf (1997), Duong et al. (2008), and Pilatowski et al. (2010), the DIC treatment improved and controlled the rice quality compared to the untreated rice sample. Therefore, the Vsp improvement of GFB of DIC-treated rice-field bean formula could be explained by the DIC impacts in terms

of texturing, expanding, and instant cooling. Indeed, the instant pressure-drop towards a vacuum causes an abrupt water autovaporization of the treated sample, inducing a modification of its structure as well as a significant cooling. In addition, Delgado-Rosas et al. (2006) showed that the DIC treatment applied to a maltodextrin powder effectively generates a porous structure with alveoli in the treated sample compared to the untreated one.

According to Prameswari et al. (2018), there is a relationship between the amount of water added during bread making procedure and the ability of flour to absorb water; consequently, the characteristics of bread were affected. Therefore, in our present study, the increase in Vsp of GFB optimum compared to the GFB control could be related to the amount of water added during dough preparation, in which the DIC-treated rice-field bean formula required higher water quantity. Our results are corroborated by those of Setyoprato et al. (2009), who found that the water holding capacity of DIC-treated cassava flour was greater than that of untreated flour. They explain their results by the microstructure change of the treated sample, as the total pore volume and the specific surface. Therefore, the higher amount of water added had a positive effect on the Vsp of GFB based on DIC-treated Rice-Field bean Formula.

On the other hand, the structure of rice flour starch can be affected and modified by the DIC treatment as reported by Onyango (2016), for which this physical treatment (DIC) is one of the methods used to synthesize the physically modified starch. In addition, Onyango (2016) indicated that the damaged starch content of physically treated flours was higher than that of untreated flours, and therefore their water absorption capacity increased, which could be the reason of the Vsp improvement of the GFB optimum.



**Figure 6.** Cross section of bread slices obtained from (a) wheat bread control, (b) gluten-free bread control and (c) gluten-free bread optimum of DIC-treated rice-field bean formula.

Also, it should be noted that the field bean flour incorporated in our GFF has improved the protein content (14.05%) than that of rice flour (6.37%) as previously indicated. According to Verni et al. (2019), field bean flour is characterized by a high protein content (26-39%) of good quality, and its mixture with cereal proteins allows a good balanced amino acid composition. Therefore, we can explain the Vsp improvement of GFB by the positive effect of DIC treatment on protein structure and properties of field bean flour compared to that of untreated formula.

Concerning the points selected outside the optimal delimited zone, the Vsp values recorded are lower than the wheat control and also than the GFB control. They ranged from  $1.18 \pm 0.04 \text{ cm}^3/\text{g}$  to  $2.11 \pm 0.03 \text{ cm}^3/\text{g}$  for the couple temperature/pressure-time:  $165^\circ\text{C}/0.70 \text{ MPa} - 40 \text{ s}$  and  $109.5^\circ\text{C}/0.15 \text{ MPa} - 25.9 \text{ s}$ , respectively. Therefore, the increase in temperature (increase in steam pressure) and time of DIC treatment causes the decrease of Vsp of GFB of RFF. It is possible to observe that, for the same temperature (same steam pressure), the increase in treatment time causes the decrease of Vsp of GFB. For example, the Vsp was  $1.76 \pm 0.04 \text{ cm}^3/\text{g}$  for the conditions  $132.5^\circ\text{C}/0.3 \text{ MPa}$  and 40 s, whereas for 60 s it became  $1.35 \pm 0.03 \text{ cm}^3/\text{g}$ . In addition, the decrease of Vsp is generated by the increase in temperature (increase in steam pressure) for the same treatment time. For instance, for a treatment time of 40 s and a temperature of  $132.5^\circ\text{C}/0.3 \text{ MPa}$ , the Vsp was  $1.76 \pm 0.04 \text{ cm}^3/\text{g}$ , whereas at  $165^\circ\text{C}/0.7 \text{ MPa}$ , it decreases to  $1.18 \pm 0.03 \text{ cm}^3/\text{g}$ . These decrease in Vsp values could be explained by the intense negative effect of severe DIC conditions treatment (temperature/pressure-time) applied on the GFF of rice and field bean flour.

### Structural characteristics of bread crumb

The crumb appearance of the GFB optimum of DIC-treated rice-field bean formula compared to wheat bread

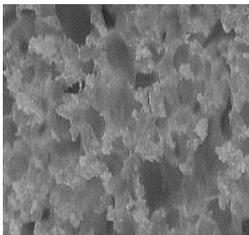
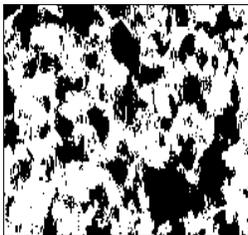
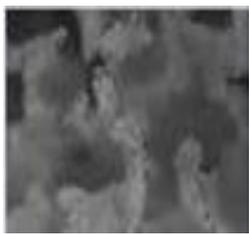
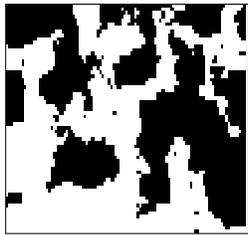
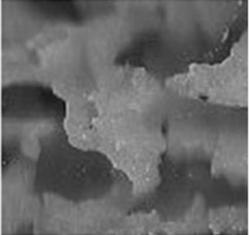
control and GFB control is shown in Figure 6. Our GFB optimum has a well-developed crumb and alveolar structure including a majority of large *alveoli* close to that of GFB control, in opposite, the wheat bread control presents a homogeneous alveolar distribution of small size.

Image analysis results of breads crumb revealed that the *alveoli* total number of GFB optimum of DIC treated rice-field bean formula (28 *alveoli*) was greater than that of GFB control (14 *alveoli*), but it remains inferior than the wheat control bread (110 *alveoli*). Concerning the average size, our breads presented the following values, 0.81, 0.19, and 0.096 for GFB optimum, GFB control and wheat bread control, respectively. In this case, the cells average size of GFB optimum was higher than that of the GFB control and the wheat bread control. Therefore, the DIC treatment of our GFF based on RFF facilitated the air bubbles creation and also favored their development during fermentation. This might be due to the water absorption capacity of treated formula during dough preparation as already mentioned above, as well as the sudden drop of pressure toward vacuum and the rapid autovaporisation of moisture sample during DIC treatment, which could modify the texture and the functional behavior of the material. Indeed, those breads have all a circular *alveoli* shape, with the values close to 1. Consequently, the DIC treatment did not affect the roundness values of the GFB optimum than the GFB control. According to Table 5, the crumb *alveoli* of our GFB optimum and that of GFB control are more open compared to the wheat bread control.

### Conclusion

Our study confirmed the considerable contribution of Instant Controlled Pressure Drop (DIC) treatment in the improvement of the technological quality of GFB based on RFF. After performing statistical validation of the obtained model, the effect of DIC operating parameters

**Table 5.** Crumb representation of the wheat bread control, gluten-free bread control and the gluten-free bread optimum of DIC treated rice-field bean formula.

Type of bread	Real image	Gray level image	Binary image
Wheat bread control			
Gluten-free bread control			
Gluten-free bread optimum of DIC- treated rice-field bean formula			

on the Vsp of GFB was analyzed. The optimization results obtained by the Response Surface Methodology showed the optimal zone including a wide range of temperature between 110 and 165°C corresponding to steam pressures of 0.15 and 0.7 MPa, respectively, and low treatment time ranging from 20 to 22 s. After bread making test, k-means classification indicated that the GFB obtained from DIC treated Rice-Field bean Formula at 132.5°C (steam pressure 0.3MPa) during 20 s is categorized in the same class of wheat bread control, and it is considered as the GFB optimum of DIC treated Rice-Field bean Formula, which gave the highest Vsp of  $2.7 \pm 0.04 \text{ cm}^3/\text{g}$  with a gain of 10.20% compared to the GFB control ( $2.45 \pm 0.04 \text{ cm}^3/\text{g}$ ). Based on the results of image analysis of bread crumb, the *alveoli* total number of our GFB optimum of RFF treated with DIC was greater than that of the GFB control. On the other hand, the field bean flour incorporation has improved the nutritional quality of our GFF used in bread making by increasing its protein content. This work carried out in the present study deserved to be completed by in-depth analyzes to have more comprehensive results.

#### CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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