J Food Sci Technol
https://doi.org/10.1007/s13197-019-03730-9

ORIGINAL ARTICLE

Effect of ingredients on the quality of gluten-free steamed bread based on potato flour

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Revised: 14 March 2019 / Accepted: 18 March 2019

Abstract Response surface methodology was used to analyze effects of the amounts of pregelatinized potato flour (PGPF), hydroxypropylmethylcellulose (HPMC), egg white protein (EWP), and water on the dough fermentation and physical properties of gluten-free (GF) steamed bread based on potato flour. The results showed that PGPF, HPMC, EWP, and water at the appropriate amounts improved the maximum dough height (H_m), specific volume (SV) and hardness, as well as H_m correlated with SV ($R^2 = 0.6993$) and hardness ($R^2 = 0.7273$). Moreover, the optimal formulation contained 4.84 g/100 g PGPF, 1.68 g/100 g HPMC, 5.87 g/100 g EWP, and 69.69 g/100 g water, potato flour basis. Furthermore, the dietary fiber, total polyphenol content, antioxidant activity, and estimated glycemic index of the steamed GF bread were, respectively, 3.17-, 1.56-, 1.44-, and 0.75-fold of those of steamed wheat bread. The optimized steamed GF bread was found to be acceptable according to the results of sensory analysis. Information collected within this study may provide further insight for optimizing the formulation of steamed GF bread based on potato flour.

Keywords Bread making · Food physical properties · Coeliac · Food process modeling · Texture

Introduction

Steamed bread is a traditional staple food of China, and it has been gaining considerable popularity in worldwide (Zhu et al. 2016). The reason may be that the acrylamide content and loss of soluble amino acids of steamed bread are less than those of baked bread. In the production of steamed bread, gluten is essential to the formation of a strong protein network required for retention of gas produced during fermentation, as well as the desired volume and structure. However, gluten intake can lead to coeliac disease (CD) or gluten sensitivity.

CD is related to the inflammation of the small intestine. It leads to malabsorption of several important nutrients and intestinal mucosal damage. The estimated prevalence of this disease is about 1% of the general population, affecting persons of any age, race, and ethnic group (Fasano and Catassi 2012). CD is not historically considered a condition that affects individuals of Chinese descent, largely because of a lack of data on the existence of CD. However, Tan et al. (2015) suggested that CD was more common than previously estimated in China. Therefore, interest in gluten-free (GF) products in the market has increased. At present, GF products mainly contain starch, rice flour, corn flour, which can lead to an excessive intake of carbohydrates and a reduced intake of protein, dietary fiber,

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Electronic supplementary material The online version of this article (https://doi.org/10.1007/s13197-019-03730-9) contains supplementary material, which is available to authorized users.

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vitamins, and minerals. To fulfill the expectations of CD sufferers, it is important to supplement GF ingredients to increase the nutritional and physiological properties of finished products (Kumar et al. 2019). Potato flour could be a good material for GF products as it is a rich source of essential amino acids, dietary fiber, and it contains several phytochemicals, such as phenolics, flavonoids, and carotenoids (Ezekiel et al. 2013). Consequently, the GF steamed bread based on potato flour enhances the nutritional and functional qualities of GF diets. Some researchers have added potato fiber, potato protein, as well as red or purple potato flour to formulations of bread in order to improve its quality (Gumul et al. 2017).

Most GF breads have physical and textural qualities poorer than those of traditional wheat bread because of the absence of gluten. To counteract these technological problems, several additives have been employed to mimic gluten properties. Witczak et al. (2019) found that addition of waxy starch has a positive impact on the texture characteristics of GF breadcrumb, reducing the hardness and chewiness in comparison with control and limiting the increase of these parameters during storage. For hydrocolloid application, cellulose and its modified forms can serve as dietary fiber to improve the product nutritional quality (Morreale et al. 2019). It is generally known that hydroxypropylmethylcellulose (HPMC) can increase the specific volume (SV) of bread up to a certain level (Mariotti et al. 2013; Hager and Arendt 2013; Liu et al. 2018). For protein, egg white protein (EWP) can be used as a functional ingredient to improve the rheological properties and bread-making performance of GF batter, which is related to its foam-stabilizing properties (Han et al. 2019). Moreover, de la Hera et al. (2014) and Cappa et al. (2013) found that the water amount significantly influences the bread SV and texture. Although some studies have discussed the improvement of GF food properties through the addition of pregelatinized flour, HPMC, and EWP individually in the appropriate amounts, most studies have focused on the production of baked bread and pasta. The interaction effects of these ingredients on the characteristics of GF steamed bread based on potato flour have rarely been reported. Because steamed bread dough can be considered a system, response surface methodology (RSM) can be used to evaluate the relative significance of a system affected by many factors, even in the presence of complex interactions.

Therefore, the main objective of this study was to optimize the formulation (pregelatinized potato flour (PGPF), HPMC, EWP, and water) of GF steamed bread based on potato flour. The relationships of steamed bread quality with fermentation properties were also studied.

Materials and methods

Materials

Potato flour (cultivar: Shepody) were kindly provided by the Institute of Vegetables and Flowers, Chinese Academy of Agricultural Sciences (Beijing, China). The protein, ash, fat, dietary fiber, starch, and amylose contents of the potato flour were 9.97 ± 0.11%, 1.43 ± 0.01%, 0.26 ± 0.01%, 6.08 ± 0.06%, 68.78 ± 0.32%, and 18.22 ± 0.31%, respectively. HPMC and EWP were obtained from Henan Zhongxin Chemical Co., Ltd. (Zhengzhou, Henan, China). The degrees of methoxyl and hydroxypropyl substitution of HPMC were 28.2% and 7.8%, respectively, and the protein content of EWP was 89.98%. PGPF was provided by Chifeng Lingzhi Food Co. Ltd. (Neimenggu, China). Instant dry yeast was obtained from Angel Yeast Co. Ltd. (Yichang, Hubei, China).

Experimental design for the optimization of GF steamed bread formulation

The formulation variables evaluated in this study were selected for their potential to influence GF bread quality based on findings of previous studies (Han et al. 2019; Morreale et al. 2019). Their lower and upper limits were chosen as extreme levels at which a steamed bread product can still be manufactured based on preliminary experiments by the authors. Specifically, each variable was tested individually according to the method of a single-factor experiment, as follows: PGPF, HPMC, EWP, and water were tested in the ranges of 2.0–10.0%, 1–5%, 2.5–12.5%, and 55–75%, respectively. Subsequently, three variation levels of the ingredients of the RSM were chosen on the basis of the result of the single-factor experiment (Supplementary Fig. 1).

RSM was applied to obtain the formulation of the GF potato steamed bread. The Box-Behnken design, the most common RSM, is used to estimate coefficients of quadratic models that can be used for accurate optimization. A Box-Behnken design with four independent factors (X_1, PGPF (2–6%); X_2, HPMC (1.5–2.5%); X_3, EWP (5–10%); X_4, water (60–70%)) set at three variation levels was implemented. The complete design consisted of 29 experiments (24 factorial experiments and 5 replicates) at the center point (Table 1).

Design-Expert Version 8 software (Stat-Ease Inc. Minneapolis, MN, USA) was used for model generation, tests of model adequacy, and contour plot generation. Pearson's correlation test was used for correlation of fermentation rheological parameters and steamed-bread physical

Table 1 Design approach and experimental result of response surface methodology

Run	Parameters				H_m (mm)	V_T (ml)	SV (ml/g)	Hardness (N)
	X_1	X_2	X_3	X_4				
1	4(0)	2.0(0)	10.0(1)	70(1)	31.4 ± 0.9	1836 ± 28	2.32 ± 0.08	23.57 ± 1.22
2	4(0)	2.5(1)	10.0(1)	65(0)	32.5 ± 1.2	1927 ± 19	2.39 ± 0.09	26.32 ± 1.59
3	4(0)	1.5(− 1)	10.0(1))	65(0)	32.9 ± 0.3	1937 ± 37	2.52 ± 0.06	22.21 ± 1.98
4	6(1)	2.0(0)	7.5(0)	60(− 1)	28.8 ± 0.1	1450 ± 44	2.34 ± 0.07	32.46 ± 1.58
5	4(0)	2.0(0)	7.5(0)	65(0)	37.2 ± 0.5	1867 ± 53	2.59 ± 0.11	22.08 ± 1.64
6	2(− 1)	2.0(0)	10.0(1)	65(0)	32.1 ± 1.1	1017 ± 20	2.55 ± 0.09	21.82 ± 2.25
7	6(1)	2.5(1)	7.5(0)	65(0)	28.2 ± 0.1	1544 ± 32	2.29 ± 0.12	33.06 ± 1.92
8	6(1)	2.0(0)	5.0(− 1)	65(0)	33.4 ± 0.4	1881 ± 16	2.57 ± 0.10	23.43 ± 2.14
9	2(− 1)	2.5(1)	7.5(0)	65(0)	34.9 ± 0.3	1598 ± 29	2.65 ± 0.05	18.67 ± 1.45
10	6(1)	1.5(− 1)	7.5(0)	65(0)	35.4 ± 1.5	1130 ± 31	2.66 ± 0.08	21.59 ± 1.01
11	4(0)	2.0(0)	10.0(1)	60(− 1)	31.2 ± 0.2	1588 ± 24	2.36 ± 0.07	25.19 ± 1.04
12	4(0)	1.5(− 1)	7.5(0)	70(1)	36.9 ± 0.4	1153 ± 33	2.62 ± 0.06	19.02 ± 1.42
13	4(0)	2.0(0)	7.5(0)	65(0)	36.8 ± 0.9	1272 ± 27	2.61 ± 0.12	19.38 ± 1.71
14	4(0)	2.5(1)	7.5(0)	70(1)	34.3 ± 0.1	1563 ± 10	2.49 ± 0.05	24.82 ± 2.32
15	4(0)	2.0(0)	5.0(− 1)	60(− 1)	30.5 ± 0.3	1492 ± 18	2.15 ± 0.08	34.23 ± 1.54
16	2(− 1)	2.0(0)	5.0(− 1)	65(0)	31.1 ± 0.5	1157 ± 34	2.20 ± 0.06	31.14 ± 1.48
17	2(− 1)	2.0(0)	7.5(0)	70(1)	34.0 ± 0.3	1489 ± 21	2.55 ± 0.10	21.23 ± 1.53
18	2(− 1)	1.5(− 1)	7.5(0)	65(0)	30.5 ± 0.1	1438 ± 14	2.30 ± 0.03	29.67 ± 1.70
19	4(0)	2.0(0)	7.5(0)	65(0)	36.7 ± 1.3	1348 ± 19	2.61 ± 0.11	19.39 ± 1.75
20	2(− 1)	2.0(0)	7.5(0)	60(− 1)	29.1 ± 0.1	1299 ± 38	2.19 ± 0.08	32.89 ± 1.99
21	4(0)	1.5(− 1)	7.5(0)	60(− 1)	32.7 ± 0.7	1884 ± 41	2.34 ± 0.09	30.22 ± 2.27
22	4(0)	2.0(0)	7.5(0)	65(0)	36.8 ± 0.2	1190 ± 20	2.62 ± 0.07	19.26 ± 0.98
23	4(0)	2.0(0)	7.5(0)	65(0)	37.4 ± 0.9	1190 ± 25	2.62 ± 0.10	19.45 ± 1.77
24	6(1)	2.0(0)	10.0(1)	65(0)	27.6 ± 0.1	1452 ± 16	2.17 ± 0.13	33.66 ± 2.32
25	4(0)	2.5(1)	7.5(0)	60(− 1)	31.6 ± 0.5	1276 ± 34	2.41 ± 0.04	27.24 ± 2.16
26	6(1)	2.0(0)	7.5(0)	70(1)	32.4 ± 0.5	1478 ± 42	2.39 ± 0.05	26.58 ± 1.94
27	4(0)	2.5(1)	5.0(− 1)	65(0)	32.6 ± 0.2	1492 ± 21	2.49 ± 0.05	25.53 ± 1.50
28	4(0)	1.5(− 1)	5.0(− 1)	65(0)	37.2 ± 0.6	1086 ± 39	2.43 ± 0.04	26.74 ± 1.88
29	4(0)	2.0(0)	5.0(− 1)	70(1)	36.8 ± 0.1	1896 ± 27	2.57 ± 0.11	21.02 ± 1.74

PGPF(X_1) pregelatinized potato flour, *HPMC*(X_2) hydroxypropylmethylcellulose, *EWP*(X_3) egg white protein; Water, X_4; H_m, the maximum dough height; V_T, total volume of gas; SV, specific volume

characteristics. Optimization was primarily based on generating a solution to give maximum SV and minimum hardness.

Rheofermentometer rheological measurements

Rheofermentometer F4 (Chopin Technologies, France) was used to check dough fermentation properties. The dough was prepared using 400 g of composite flour with water added at various combinations (Table 1), the yeast content was 1% (flour basis). The dough (315 g) was fermented in a bucket at 30 °C for 3 h, and 500 g was used as a restraint. The fermentation rheological parameters contained H_m, the maximum dough height at development time (mm), as well as V_T, the total volume of gas produced during the 3-h fermentation (ml) (Huang et al. 2008).

Steamed bread making

The steamed bread was manufactured according to Zhu et al. (2016) with slight modification. The flour (100 g), trehalose (0.5 g), salt (0.1 g), and water mixture based on the experimental design was blended at a rate of 80 rpm for 5 min using an A-120 Hobart mixer (The Hobart Manufacturing Company, Tory, OH). The dough was stored in a fermenting machine for 1 h at 30 °C and 85% relative humidity. The dough was mixed at a rate of 80 rpm for 3.5 min and thereafter cut into pieces of 100 g with a round shape. Finally, the dough pieces were placed in a steam cooker (Supor Co., Ltd., Hangzhou, Zhejiang, China) and cooked for 30 min under atmospheric pressure. The steamed bread was cooled 60 min at room temperature before quality evaluation and freeze-dried for compositional analysis.

Steamed bread quality evaluation

SV

The weight of steamed bread was measured to the nearest of 0.01 g. Its volume was determined using rapeseed displacement method. SV was calculated as the ratio of volume to weight of the loaf.

Textural properties

Texture profile analysis was performed using a TA-XT2i texture analyzer (Stable Micro Systems, Surrey, UK) equipped with a 5 kg load cell and a 50 mm aluminum cylindrical probe. The parameter was set at a pre-test speed of 1.0 mm/s, a test speed of 4.0 mm/s, and a post-test speed of 1.0 mm/s; the interval time between the first and second cycles was 1 s.

Chemical composition analysis

Starch, crude fat, crude protein, dietary fiber, and ash contents of steamed bread samples were determined by AOAC methods (AACC 2000).

Total polyphenol content (TPC) was measured using the Folin-Ciocalteu method with modifications. Chlorogenic acid was used as a standard, and the TPC of the steamed bread was represented as mg of chlorogenic acid equivalent per g of dry weight (mg CAE/g DW).

The antioxidant activity of steamed bread was determined by the oxygen radical absorption capacity assay, and the antioxidant activity was represented as milligrams of g Trolox equivalent (TE) per 100 mg of DW.

In vitro starch digestibility and expected glycemic index

The starch digestibility of the steamed bread was determined according to the method reported by Granfeldt et al. (1992) with slight modification. The starch hydrolyzed rapidly (within 20 min) was digestible starch, the starch hydrolyzed within 20 and 120 min was slowly digestible starch, and the remaining starch after 16 h was resistant starch (RS). The estimated glycemic index (eGI) was calculated according to the method of Granfeldt et al. (1992).

Sensory properties

Sensory analyses of the freshly GF steamed breads based on the potato flour (overall acceptability, flavor, color, appearance, and texture) were carried out by a panel of 20 consumers (10 females and 10 males, aged 20–40 years) (Jafari et al. 2018). Steamed bread samples were coded using random three-digit numbers and served randomly. A nine-point hedonic scale was used to evaluate the sensory properties of the steamed bread (Kiumarsi et al. 2019). The scores ranged from 1 (dislike extremely) to 9 (like extremely). The steamed bread was considered acceptable if its mean scores for overall acceptability were above 6.

Statistical analysis

All experiments were carried out in triplicate, and the results were expressed as mean ± SD (standard deviation). Statistical analyses were performed using Statistical Analysis System version 8.1 software (SAS Institute Inc., Cary, NC, USA). A value of $P < 0.05$ was considered statistically significant.

Results and discussion

Analysis of variance (ANOVA) of the response parameters

ANOVA of the quadratic model is required to test the significance and adequacy of the model. The results of ANOVA of model Y_1-Y_4 are shown in Table 2. The regression models of H_m, SV, and hardness were highly significant ($P < 0.01$), and the lack of fit was not significant ($P > 0.05$). For these quality parameters (H_m, SV, and hardness), second-order models were fitted and high coefficients of determination (R^2) were observed; R^2 values of the predicted model ranged between 0.8772 and 0.9905 (Table 2). The V_T model was not significant ($P > 0.05$), and R^2 of the predicted model was 0.3773. Therefore, the RSM is not suitable for predicting V_T, and this result is contrary to the findings of Gujral and Singh (1999), who reported that the models computed had high R^2 value, indicating that they are appropriate and can be a useful tool for predicting the effect of different parameters on wheat dough development and bread volume, which can be ascribed to different parameters and flour system.

Analysis of response surface

The interaction between the variables on H_m

H_m is an indirect estimation of yeast performance and overall microstructure formed in the studied system. A higher H_m suggests that the combination of gas produced and the microstructure present in that particular system was more favorable in sustaining the microstructure of the

Table 2 Regression equations for potato gluten-free steamed bread containing different formulations

Source	P value of H_m	P value of V_T	P value of SV	P value of hardness
Model	< 0.0001	0.8203	< 0.0001	< 0.0001
X_1	0.0002	0.4048	0.5976	0.0021
X_2	< 0.0001	0.4907	0.0007	0.1528
X_3	< 0.0001	0.5013	0.0172	0.0391
X_4	< 0.0001	0.7020	< 0.0001	< 0.0001
X_1X_2	< 0.0001	0.6928	< 0.0001	< 0.0001
X_1X_3	< 0.0001	0.6534	< 0.0001	< 0.0001
X_1X_4	0.0772	0.8007	< 0.0001	0.0283
X_2X_3	< 0.0001	0.5196	< 0.0001	0.0410
X_2X_4	0.0451	0.1283	< 0.0001	0.0023
X_3X_4	< 0.0001	0.8080	< 0.0001	0.0002
X_1^2	< 0.0001	0.5659	< 0.0001	< 0.0001
X_2^2	< 0.0001	0.6118	0.0001	0.0014
X_3^2	< 0.0001	0.2282	< 0.0001	< 0.0001
X_4^2	< 0.0001	0.3838	< 0.0001	< 0.0001
Lack of Fit	0.4090	0.4225	0.7258	0.5828
Predicted R^2	0.9685	0.3773	0.9905	0.8772

X_1, pregelatinized potato flour; X_2, hydroxypropylmethylcellulose; X_3, egg white protein; X_4, water; H_m, the maximum dough height; V_T, total volume of gas; SV, specific volume

proofed dough compared with another system with lower H_m (Huang et al. 2008).

PGPF had significant positive effect on H_m among the four factors and the most significant negative interaction effect with HPMC (Table 2 and Fig. 1a). When the PGPF level was in the lower region, the H_m increased as the amount of HPMC increased, while the reverse occurred at higher PGPF levels (Fig. 1a). This result is in accordance with the results of Cai et al. (2016), who reported that the hydrothermally treated polysaccharide mixtures of glutinous rice flour and xanthan gum increased the dough extensibility from 2.8 mm to 11.9 mm. Singh et al. (2005) also found that the addition of potato flour with lower amylose content and higher water absorption resulted in higher extensibility of *chapati*. Moreover, the dough should have enough strength to expand and hold CO_2 gas cells in order to achieve a high H_m, and to increase the substituted PGPF content to 6 g/100 g of the damaged structure of dough, thus leading to decreased strength and H_m.

The interaction of PGPF with EWP negatively affected H_m (Table 2 and Fig. 1b). When the PGPF level was 2–4 g/100 g, H_m increased as the amount of EWP increased, while a different trend was present at a higher level (> 4 g/100 g), similar to Fig. 1a. The interaction of PGPF with water had no significant effect on H_m (Table 2 and Fig. 1c).

HPMC had a positive effect on H_m in the linear term and had a negative effect in the quadratic term, and its interaction with EWP affected H_m positively (Table 2 and Fig. 1d). H_m increased with the increase in HPMC in the lower region, in agreement with the results of Zettel et al. (2015), who reported that hydrocolloids from chia increased the dough height of wheat flour. Mariotti et al. (2013) also stated a higher H_m was obtained upon HPMC addition to some commercial GF bread formulations. A possible explanation for the increased dough height was that hydrocolloids formed an additional layer of molecules around the bubbles in the dough. The other possible reason was that hydrocolloids improved the pasting properties of starch, thus improving the food-making properties (Kaur et al. 2015). However, the result disagreed with Rosell et al. (2001), who found that xanthan gum addition reduced the H_m of wheat dough. This behavior can be mainly ascribed to the previously described differences between the formulations. The reverse influence was observed at higher HPMC levels. This may be due to the interaction between hydrocolloids and protein, which was crucial for dough properties; strong interactions caused disaggregation and instability of the protein network (Li et al. 2019). The influence of EPW on H_m was similar to that of HPMC (Fig. 1d): H_m increased as the amount of EWP increased in the lower region (< 8.75 g/100 g), in accordance with the increase in H_m from 28.7 to 29.4 mm with addition of carrot concentrated protein to 6.2 g/1000 g (Zhang et al. 2007). The addition of protein at different levels significantly affected the viscoelastic properties of the composite flour dough, thus influencing the fermentation capability. A different trend was observed at higher EWP (> 8.75 g/100 g) because water absorption was significantly affected by the amount of protein (Marco and Rosell 2008). Han

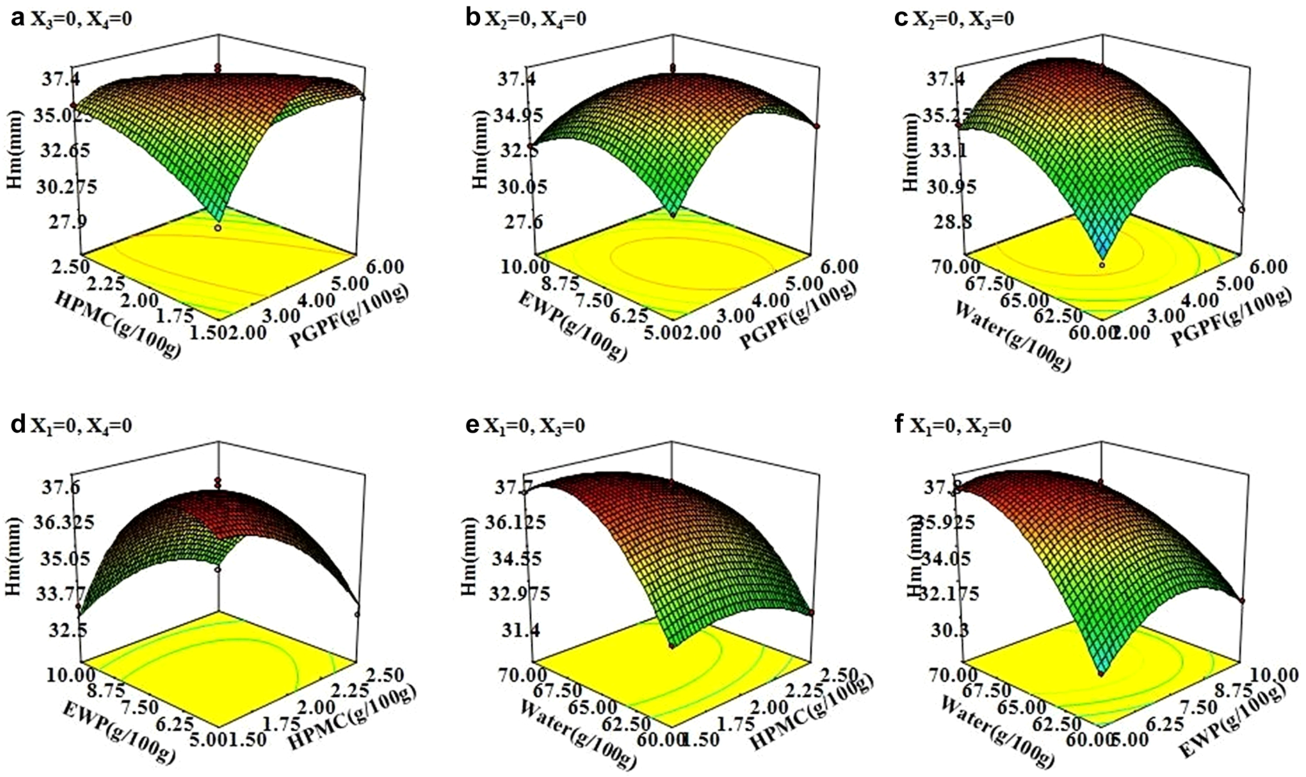

Fig. 1 Response surface and contour plots showing effects of the different formulations on H_m. **a** At varying HPMC and PGPF level, **b** at varying EWP and PGPF level, **c** at varying water and HPMC level, **d** at varying EWP and HPMC level, **e** at varying water and HPMC level, **f** at varying water and EWP level. *Note PGPF* pregelatinized potato flour, *HPMC* hydroxypropylmethylcellulose, *EWP* egg white protein, H_m the maximum dough height

et al. (2019) also reported that EWP prepared by different methods improved the SV, texture, and the staling process of GF bread because it possessed more capacity of lowering surface tension and a better stabilization of air bubbles in the water phase or GF batters.

Figure 1e shows the response surface plot of the effect of HPMC and water. The effects of HPMC and water were very significant to H_m (Table 2), but the interaction between them was mainly the effect of water level, probably because that the plasticizer effect of the water is crucial when making GF steamed bread since it contributes to the extensional properties of the dough during mixing (Marco and Rosell 2008). Increasing the water added significantly increased the H_m. This result coincides with that of Cappa et al. (2013), who reported that the appropriate amount of water caused adequate expansion during the bread-making process, resulting in large H_m and volume. This can be attributed to better dispersal of HPMC and its best thickening action in the presence of a higher amount of water, which create a structure able to sustain and develop itself during the fermentation process. Addition of low amounts of water slightly increased H_m during the fermentation process because of the high resistance to deformation (de la Hera et al. 2014).

The influence of the interaction between water and EWP is illustrated in Fig. 1f. The interaction effect was similar to that in Fig. 1e, which showed that the influence of water was more significant compared with that of EWP. This indicated that water was the principal "ingredient" that affected the fermentation behavior of the GF dough investigated. Generally, the more hydrocolloid was applied, the higher the was amount of water required to obtain a suitable dough for fermentation. However, if water is limited in the original mass, and many substances have to compete for it, both hydrocolloid and EWP ingredients cannot carry out their functionality at the best.

The interaction between the variables on SV

SV is one of the most important visual characteristics of steamed bread, strongly influencing consumers' preference. Hence, it is a key parameter when evaluating steamed bread quality.

The flour properties had strong relationship with bread properties; the effect of PGPF and HPMC (Fig. 2a) demonstrated that the SV increased rapidly with the increase in PGPF (< 5 g/100 g) and HPMC (< 2.25 g/100 g) in the lower region. Our result is in agreement with

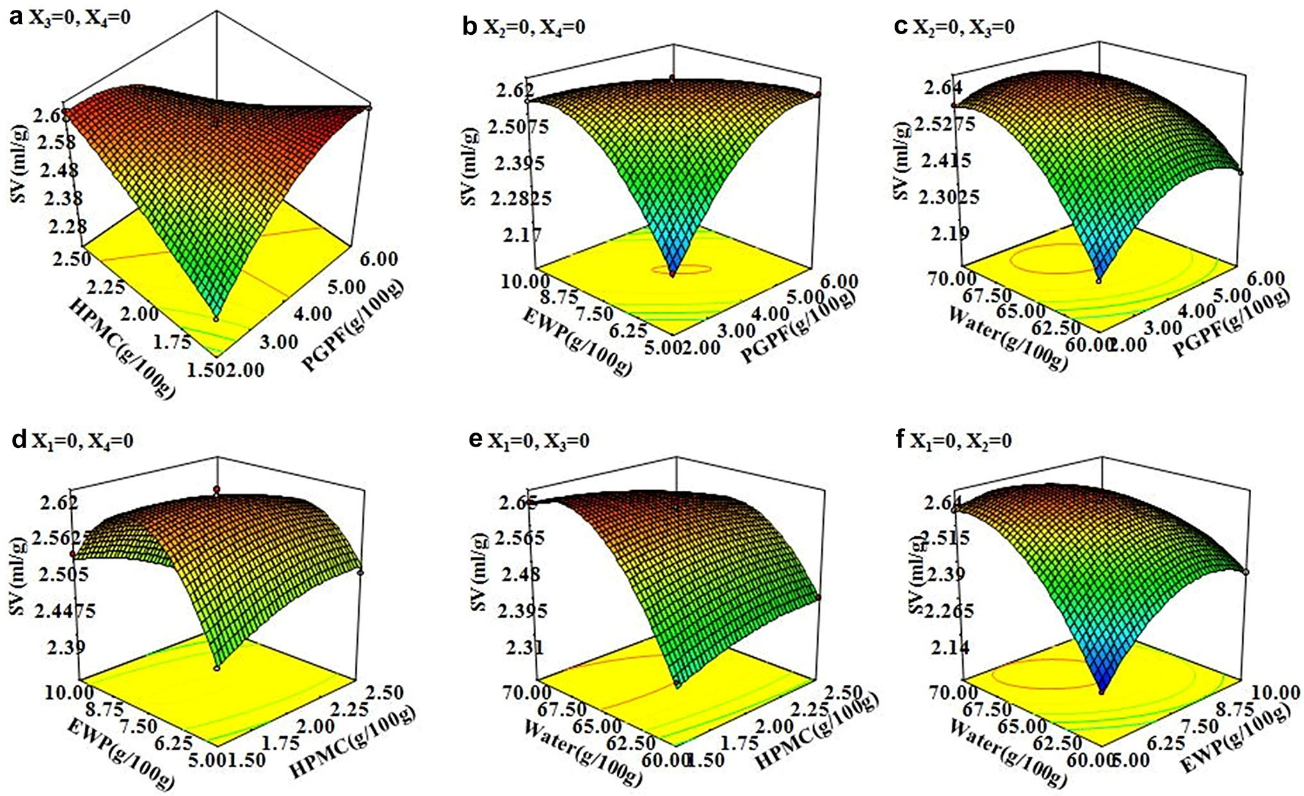

Fig. 2 Response surface and contour plots showing effects of the different formulations on specific volume (SV). **a** At varying HPMC and PGPF level, **b** at varying EWP and PGPF level, **c** at varying water and HPMC level, **d** at varying EWP and HPMC level, **e** at varying water and HPMC level, **f** at varying water and EWP level. *Note PGPF* pregelatinized potato flour, *HPMC* hydroxypropylmethylcellulose, *EWP* egg white protein, *SV* specific volume

that of Pongjaruvat et al. (2014), who observed that pregelatinized tapioca starch improved the SV of GF bread. The well-known effect of PGPF improvement of the viscoelastic property of the dough, which efficiently traps and retains carbon dioxide gas bubbles produced during fermentation, may result in an increase in SV. Similar effects on SV have been reported with the additions of HPMC to commercial GF bread mixtures (Mariotti et al. 2013), of HPMC to GF maize-teff bread (Hager and Arendt 2013), and of HPMC to GF bread based on rice flour and potato starch (McCarthy et al. 2005). The SV decreased at higher HPMC (> 2.25 g/100 g) and PGPF (> 5 g/100 g) levels when the EWP and water level were fixed because larger amounts of HPMC and PGPF added need more water to modify the dough. This result can be confirmed by the increased bread volume when the amount of substitution was less than 20%, which is due the replacement of the pregelatinized starch (Pongjaruvat et al. 2014).

Figure 2b shows the interactive effect of PGPF and EWP on SV. The interaction of PGPF and EWP was similar to that of PGPF and HPMC. The SV increased from 2.24 to 2.54 ml/g with the increase in EWP from 5.0 g/100 g to 8.2 g/100 g, likely because more gas was incorporated and retained during mixing and steaming. This may be due to significant modification of the gelatinization and gelling behavior of the flour by the protein. Our results were in accordance increase in SV of the muffins due to the EWP, increase in the SV of rice cake, lupine, and albumin due to wheat protein, which resulted in a significant increase in the SV of GF bread (Ronda et al. 2011).

The effects of water and PGPF on SV were significant (Table 2), but the interaction between them was mainly the effect of the amount of water. Water is necessary for solubilizing other ingredients and for developing the protein network. It also plays an important role in the changes associated with starch during making of steamed bread. With the increase in water from 60 to 68.5 g/100 g, the SV increased from 2.27 to 2.56 ml/g, in accordance with the result that the SV of GF bread was higher with less added water (Cappa et al. 2013; de la Hera et al. 2014).

The effect of different HPMC and EWP on the SV is illustrated in Fig. 2d. With the rise in HPMC (from 1.50 to 2.25 g/100 g) and EWP (5.0 to 6.5 g/100 g) concentration, the SV increased from 2.46 to 2.57 ml/g because of their ability to retain water and the formation of a gel network during steaming. This network improved dough strength and gas retention during fermentation. In contrast, the SV decreased as the HPMC and EWP continuously increased, in agreement with the very low SV level at the highest whey protein isolate and β-glucan levels (Kittisuban et al. 2014). The reason was probably the high resistance and consistency of the dough system, which caused a limited gas cell expansion during proofing.

The effects of the interaction between water and HPMC and EWP are illustrated in Fig. 2e, f. The interaction effect was similar to that in Fig. 1c, which showed that the influence of water was significant compared with those of HPMC and EWP.

The interaction between the variables on hardness

Another important quality characteristic of steamed bread is texture, with consumers desiring soft and flexible crumbs. The hardness of GF steamed bread ranged from 18.67 to 34.23 N, and the generated model showed linear, interactive, and quadratic associations with formulations (Table 2).

Figure 3a presents the response surface plot of the effects of the level of PGPF and HPMC. This plot demonstrated that there was a limited and specific combination of the amounts of PGPF flour (3.75 g/100 g) and HPMC (2.1 g/100 g) when the other independent variables were set at midpoint. This limited and specific combination was due to the quadratic effects of both the level of PGPF and HPMC incorporation and their interaction. Some researchers also found that HPMC, pregelatinized cassava starch, and heat-treated barley flour addition at low amount decreased this parameter of GF bread (Mariotti et al. 2013).

Hardness decreased as the PGPF increased from 2.0 to 4.0 g/100 g, and increased when PGPF > 4.0 g/100 g. At constant PGPF, the hardness decreased with the increase in EWP from 5.0 to 8.0 g/100 g, but it increased with higher EWP (Fig. 3b). These results might be due to the higher PGPF values (> 4.0 g/100 g) and EWP (> 8.0 g/100 g), which needed more water to form the ideal viscoelasticity of dough. The interaction of PGPF and water had a significant effect on the hardness (Fig. 3c), but the interaction between them was mainly the effect of the water level. The amount of water added to the mixture in order to obtain a coherent mass having a specific consistency strongly influenced the subsequent workability of the dough and thus affected the quality of the finished product. The increase in water levels had a negative linear effect on the

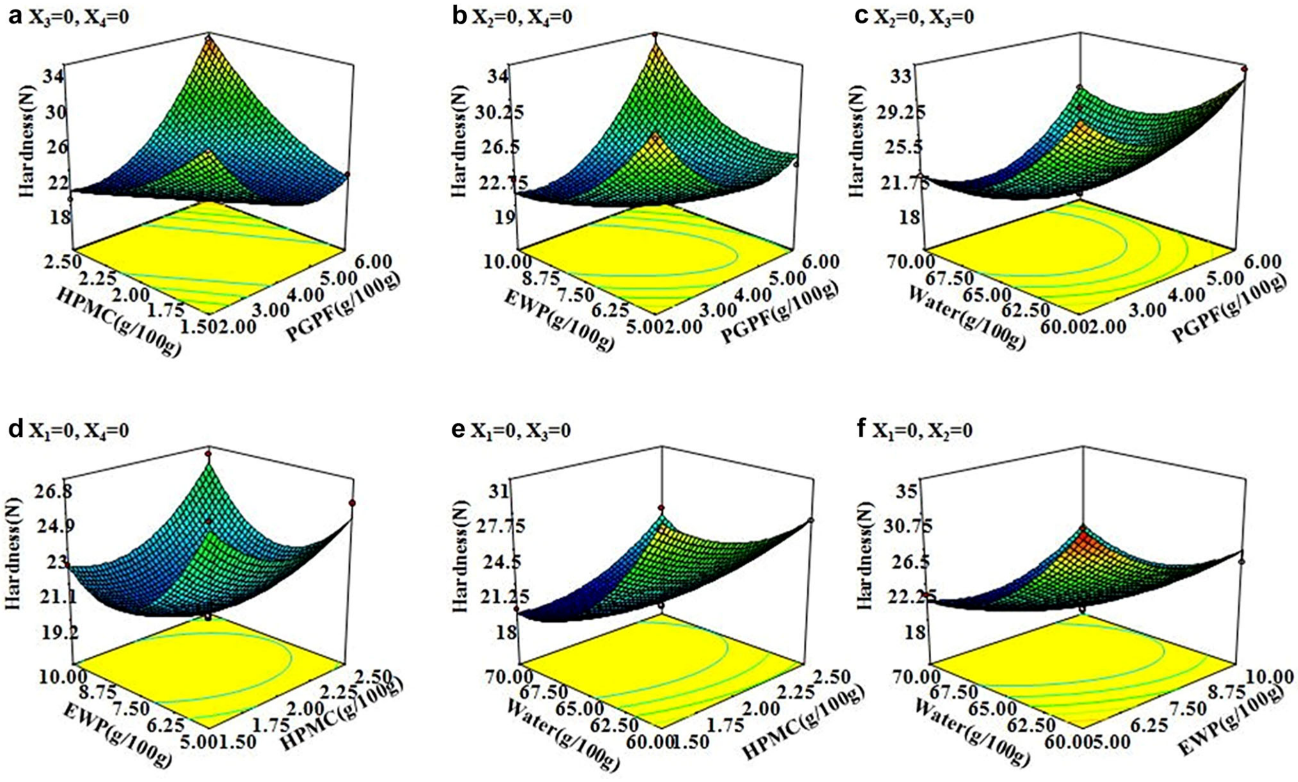

Fig. 3 Response surface and contour plots showing effects of the different formulations on hardness. **a** At varying HPMC and PGPF level, **b** at varying EWP and PGPF level, **c** at varying water and HPMC level, **d** at varying EWP and HPMC level, **e** at varying water and HPMC level, **f** at varying water and EWP level. *PGPF* pregelatinized potato flour, *HPMC* hydroxypropylmethylcellulose, *EWP* egg white protein

hardness; this result agreed with the finding of Cappa et al. (2013).

Figure 3d shows the effect of the interaction between HPMC and EWP. When the HPMC (< 2.0 g/100 g) and EWP (< 7.5 g/100 g) levels were in the lower region, the hardness decreased as the amounts of HPMC and EWP increased. It seems that hydrocolloids and protein have a weakening effect on the starch structure that leads to better water distribution and retention; the reverse was observed at higher HPMC (> 2.0 g/100 g) and EWP (> 7.5 g/100 g) levels.

The effects of the interactions between water and HPMC and PGPF are illustrated in Fig. 3e, f. The interaction effect was similar to that in Fig. 3c, which shows that the effect of water on hardness was significant compared with those of HPMC and PGPF. Therefore, we should control the water content strictly in the making process.

Verification

In order to obtain the maximum SV and to minimize hardness of steamed GF bread based on potato flour, the optimization of the model was performed by RSM using Design-Expert software. The determined optimal parameters were as follows; 4.84 g/100 g for PGPF, 1.68 g/100 g for HPMC, 5.87 g/100 g for EWP, and 69.69 g/100 g for water. Under the formulation, the experimental SV and hardness were 2.68 ml/g and 18.13 N, respectively, which were in good agreement with the values predicted by the model (2.67 ml/g and 18.17 N, respectively), and confirming that the model was powerful and suitable for the estimation of experimental values.

Relationships between quality of steamed bread and fermentation parameters

H_m correlated significantly with the SV and hardness of the steamed bread ($R^2 = 0.6993$, $R^2 = 0.7273$, respectively; Supplementary Fig. 2). CO_2 production had no significant correlation with these parameters, in accordance with the result that H_m correlated significantly with the bread SV ($R^2 = 0.75$), and that CO_2 production had no significant correlation with this parameter ($R^2 = 0.11$) (Huang et al. 2008). Interestingly, a negative correlation was obtained in the current study between hardness and SV ($R^2 = 0.9160$), which was confirmed by the results of Mezaize et al. (2009).

Chemical composition of GF steamed bread

The chemical composition of GF steamed bread is shown in Table 3. The starch and protein contents of the bread were similar to those of wheat steamed bread. Moreover, the ash, dietary fiber, TPC, and antioxidant activity of the bread were, respectively, 3.10-, 3.17-, 1.56-, and 1.44-fold of those of steamed wheat bread. The steamed GF potato steamed bread showed a RS content (38.46 g/100 g) higher than that of wheat steamed bread (16.26 g/100 g). Furthermore, the eGI of GF steamed bread (55.17) was significantly lower than that of wheat steamed bread (73.63) because the SV and the granule surface area of GF steamed bread were lower than those of wheat steamed bread. This result also agrees with the report that the eGI varies from 27 (barley bread with 75 g/100 g substitution) to 95 (extremely porous French baguette) (Segura and Rosell 2011).

Sensory analysis

Consumers evaluated the overall acceptability, flavor, color, appearance, and texture of GF and wheat steamed bread samples. The acceptability score of 6.0 in a 9-point hedonic scale has a commercial or quality limit (Kiumarsi et al. 2019). According to this criterion, the samples of GF steamed bread based on potato flour were acceptable, because its overall acceptability was higher than 6.0 (Table 3), and the overall acceptability of GF steamed bread (7.68) was lower than that of wheat steamed bread (8.21). In terms of flavor, GF steamed bread presented a higher mean and differed significantly ($P < 0.05$) from wheat steamed bread. This was due to the greater amount of substance produced by potato flour in relation to flavor. The results for texture indicated that the GF sample was lower than the wheat steamed bread, different from the results of Alvarez-Jubete et al. (2010), who showed that pseudo-cereal flours improves the crumb texture without adversely affecting other bread sensory properties. For the color attribute, steamed GF bread had higher score albeit it was not different from that of wheat steamed bread ($P > 0.05$). The mean scores for both samples were close to the "like extremely" answer, indicating that the GF breads presented a good acceptability in relation to color, and that the appearance of GF steamed bread was inferior than that of steamed wheat bread. However, the use of a small number of consumers was a limitation of this study. Nevertheless, it was able to show the feasibility of developing steamed GF bread based on potato flour with a good sensory acceptability.

The market for GF products is expected to rise significantly as consumers' demand increases in reaction to the increased levels of CD diagnosis. Masih (2018) reported that the market potential of GF products was estimated to be USD 7.59 billion in 2020. In this sense, there is a large potential consumer market for highly nutritious GF products. Commercially available GF breads cannot compete with traditional gluten containing samples in terms of quality and acceptability because of the poor mouth feel

Table 3 Chemical composition and sensory analysis of gluten-free potato steamed bread

Composition	Wheat steamed bread	Gluten-free potato steamed bread
Starch (%)	65.96 ± 0.18a	63.87 ± 0.45b
Protein (%)	14.49 ± 0.02a	14.99 ± 0.02a
Fat (%)	1.23 ± 0.01a	0.66 ± 0.01b
Dietary fiber(%)	2.65 ± 0.05b	8.41 ± 0.11a
Ash (%)	0.60 ± 0.05b	1.86 ± 0.05a
TPC[a]	1.57 ± 0.02b	2.45 ± 0.01a
Antioxidant activity[b]	1.52 ± 0.06b	2.19 ± 0.05a
RDS (%)	23.39 ± 0.12a	20.64 ± 0.04b
SDS (%)	60.35 ± 0.32a	40.90 ± 0.11b
RS (%)	16.26 ± 0.11a	38.46 ± 0.24b
eGI	73.63 ± 0.32a	55.17 ± 0.18b
Overall acceptability	8.21 ± 0.16a	7.68 ± 0.11b
Flavor	7.03 ± 0.20b	7.54 ± 0.18a
Color	8.05 ± 0.14a	8.14 ± 0.25a
Appearance	8.45 ± 0.18a	7.86 ± 0.19b
Texture	7.47 ± 0.08a	7.02 ± 0.13b

[a]Expressed as mg chlorogenic acid equivalent/g DW, [b] Expressed as mg trolox equivalents/mg DW, [a,b]Values labelled with a different letter in the same column are significantly different ($P < 0.05$)

and flavor, higher eGI, and fast staling. These disadvantages for GF bread may be due to inefficient gas expansion and retention during leavening, resulting in reduced volume with high hardness (Naqash et al. 2017). The results of this study showed that PGPF, HPMC, EWP, and water in appropriate amounts could improve H_m, SV, and hardness of GF steamed bread. Moreover, the optimized product can represent an innovative food with functionalities such as similar overall acceptability, higher dietary fiber, and lower eGI, which can improve the quality of GF products to some extent.

Conclusions

GF potato steamed bread, compatible with regular wheat bread in key physical properties, could be formulated based on PGPF, HPMC, EWP, and water. RSM is a useful tool for determining the optimal formulation of GF potato steamed bread. The optimal GF potato steamed bread could be produced by adding 4.84 g/100 g PGPF, 1.68 g/100 g HPMC, 5.87 g/100 g EWP, and 69.69 g/100 g water based on potato flour. Using the abovementioned formulation, the experimental SV and hardness were 2.68 ml/g and 18.13 N, respectively. In addition, compared with wheat steamed bread, the GF potato steamed bread had higher dietary fiber, TPC antioxidant activity, and lower eGI, suggesting that the studied GF potato steamed bread can improve the adequate nutritional level of steamed bread. Further studies should cover the influence of non-sensorial factors as shelf life and packaging design. Moreover, a systematic consumer study with people with no CD should also be performed.

Acknowledgements This scientific study was financed by the Natural Science Foundation of China (31801578), and the Central Public-interest Scientific Institution Basal Research Fund (Y2016PT21). We thank the University of Liège-Gembloux Agro-Bio Tech and more specifically the research platform AgricultureIsLife for the funding of the scientific stay in Belgium that made this paper possible.

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