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RESEARCH ARTICLE

Influence of potato flour on dough rheological properties and quality of steamed bread

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Abstract

It is a novel idea to make steamed bread by adding potato flour into wheat flour considering the production and nutritional factors of potato. In this study, the influence of potato flour (0–35%) on dough rheology and quality of steamed bread were investigated. Potato flour addition significantly influenced the dough rheological properties and steamed bread quality, such as increased water absorption, the maximum gaseous release height, total volume of CO_2 and hardness, while decreased dough stability and specific volume of steamed bread. Moreover, correlation analysis suggested that dough height at the maximum development time, dough stability, water absorption and the phase tangent can be used for predicting the technological quality of steamed bread. Potato-wheat steamed bread had higher dietary fibre, ash content and antioxidant activity than those of wheat steamed bread. The estimated glycemic index decreased from 73.63 (0%) to 60.01 (35%). Considering the sensory evaluation, the steamed bread with 20% potato flour is acceptable. In conclusion, adding appropriate quantity of potato flour to wheat flour for steamed bread production will not only maintain the technological quality, but also can improve the nutritional value of the steamed bread.

Keywords: potato flour, thermo-mechanical properties, viscoelasticity, rheofermentometer, texture properties, antioxidant activity

1. Introduction

Steamed bread is a staple food of China, and has been consumed for at least 2 000 years, taking up almost 40% of wheat consumption (Wu *et al.* 2010). Various studies in China (Zhang *et al.* 2007; Hao and Beta 2012; Lin *et al.* 2012; Zhu *et al.* 2014, 2016), South Africa (Lombard *et al.* 2000; Nkhabutlane *et al.* 2014), Ghana (Nout *et al.* 1995; Nche *et al.* 1996) and western countries (Sim *et al.* 2011) have been committed to develop steamed bread. Moreover, the acrylamide content and loss of soluble amino acids of steamed bread are less than baked bread (Becalski *et al.* 2003). However, lysine, mineral element, and vitamins content in only wheat steamed bread are not enough for human nutrition balance if not supplemented with vegetables, fruits or dairy products. It is necessary to add other flours or functional components to improve the nutrition and create varieties of steamed breads, such as potato, sweet potato, yam, oat, corn, wheat germ, barely, buckwheat, fibre, and polyphenols steamed breads (Ananingsih *et al.*

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2013; Shiau *et al.* 2015; Sun *et al.* 2015). However, the other ingredients will change dough properties, which are important for the quality of the end product. Many studies found that thermo-mechanical parameters, dynamic rheological properties, and fermentation characteristics had a remarkable influence on the volume, texture, and structure of products (Sensoy *et al*. 2006; Kahraman *et al.* 2008; Ozturk *et al.* 2008; Verheyen *et al.* 2015). Therefore, it is important to study these dough properties in order to get high quality steamed bread.

Potato (*Solanum tuberosum*) is one of the most widely planted vegetables worldwide, the total production of potatoes in the world is 0.37 billion tons in 2013, and China, the leading producer of potato, had an annual production of 89.0 million tons in 2013 (24.17% of the world's production) and is the only major food crop that belongs to tuber (FAOSAT 2015). One of the main commercial products is potato flour, which is convenient to store and circulate. Potato flour protein is characterized by balanced amino acid composition, which improves the deficiency of cereal proteins, and the dietary fibre (Bártová *et al.* 2015). Vitamin and mineral element content of potato flour are higher than wheat flour. Moreover, potato flour contains several phytochemicals such as polyphenolics and flavonoids, which have antioxidant, anticancer, anti-hypertension activity, and so on (Ezekiel *et al.* 2013). Thus, it is rational to incorporate potato flour into steamed food to enhance its nutritional and functional quality, along with novel eating properties.

However, the major study on potato was focused on the starch, which was also the main component of the gluten-free bread (Sarker *et al.* 2008; Onyango *et al.* 2011). Nowadays, little information is available on the potato flour addition in wheat steamed bread. Therefore, in this study, potato flour at various concentrations was incorporated into steamed bread, the dough rheological properties, technological qualities and the correlations between them were analyzed. In addition, the nutrition qualities including proximate components, antioxidant capacity, and *in vitro* starch digestibility of steamed bread were also evaluated. This study may stimulate further interest in the use of potato flour for novel product development.

2. Materials and methods

2.1. Materials

Wheat flour was obtained from Beijing Guchuan Food Ltd. (Beijing, China). Fresh potato (Shepody) was kindly provided by the Institute of Vegetables and Flowers, Chinese Academy of Agricultural Sciences (Beijing, China). Potato tubers were peeled, washed, then steamed for 30 min at 100°C, and dried in a dryer where the temperature varied between 170 and 200°C, then milled into flour by a hammer mill, sieved with a 100-μm screen in order to obtain smooth flour with a uniform particle size. Protein, ash, fat, dietary fibre, and starch content in wheat flour were 13.22, 0.48, 1.23, 1.88, and 60.58%, respectively, those of potato flour were 9.87, 1.86, 0.26, 6.28, and 68.78%, respectively.

Wheat flour with different percentages of potato flour (0, 10, 15, 20, 25, 30, and 35%) are formulated before being analyzed. Yeast was purchased from Angel Yeast Co., Ltd. (Hubei, China).

2.2. Thermo-mechanical rheological properties

Thermo-mechanical properties investigations were performed by Mixolab (Chopin, Tripetteet Renaud, Paris, France) which simultaneously determinates protein and starch characteristics during the process of mixing at a constant temperature, as well as during the period of heating and cooling. The Mixolab was set to follow the Chopin+ program: Firstly, mixed for 8 min at 30°C, secondly heated to 90°C at a speed of 4°C min^{-1}, then maintained at 90°C for 7 min and lastly decreased the temperature to 30°C at a speed of 4°C min^{-1} (Jensen *et al.* 2015).

2.3. Dynamic rheological properties

All dry samples (without yeast) were blended for 8 min with the appropriate content of water (80% of the water absorption according to Mixolab, 48.88, 58.80, 62.32, 66.16, 71.68, 75.28, and 77.20% for 0, 10, 15, 20, 25, 30, and 35%, respectively) using the mechanical stirrer (RW20, IKA Labortechnic, Germany). In order to prevent moisture loss, we used paraffin to seal the edges of the dough. Dynamic oscillatory tests were conducted in an Anton Par Physica MCR301 controlled stress oscillatory rheometer (Graz, Austria). The temperature was maintained at (25±0.1)°C, the gap between plates was 1 mm. Frequency sweeps (from 1–100 rad s^{-1}) were performed at a settled stress within the linear viscoelastic range. Experimental data were described according to the following equations (Korus *et al.* 2009):

$$G'(\omega)=K'\omega^{n'}$$

$$G''(\omega)=K''\omega^{n''}$$

Where, G', a storage modulus (Pa); G'', loss modulus (Pa); ω, angular frequency (rad s^{-1}); and K′, K′′, n′, n′′, experimental constants.

2.4. Rheofermentometer rheological measurements

Rheofermentometer F3 was used to check dough fermentation properties (Chopin Technologies, France). 300 g mixed flour, 3 g yeast and appropriate water (according to 2.3) were blended at a low rate (80 r min^{-1}) for 5 min using a Hobart mixer A-120 (The Hobart Manufacturing Company, Tory, Ohio). Dough was mixed and placed (315 g) in the bucket at constant temperature of 30°C for 3 h and 2 000 g was used as a restraint. The fermentation rheological parameters contained: dough development parameters (H_m, the maximum height at development time (mm)); h, dough height at the terminate (mm); $(H_m–h)H_m^{-1}$ that is reversely related to dough stability) and gas behavior (H_m', maximum height of gas production (mm)); V_T, total volume of gas produced during three hour fermentation; V_r, total volume of the gas saving at the end of time; R_C (V_r/V_T), the gas retention coefficient.

2.5. Scanning electron microscopy (SEM) of dough

Dough samples for SEM examination were prepared according to the method of dynamic rheological properties, then frozen (–45°C) and freeze dried. We fractured the freeze dried dough samples into small pieces of about 1 cm×1 cm×0.5 cm (length×width×height). Gold was sprayed on the interior surface of the samples (Bárcenas *et al.* 2010). Sample analysis was performed in a Hitachi S3400N (Japan) scanning electron microscope.

2.6. Steamed bread making

The steamed bread was manufactured according to Ma *et al.* (2014) with slight modification. 100 g mixed flour, 1 g yeast and appropriate water (according to 2.3) were blended at a low rate (80 r min^{-1}) for 5 min using a Hobart mixer A-120 (The Hobart Manufacturing Company, Tory, Ohio). Dough was putted in a fermenting machine for 1 h at 30°C and 85% relative humidity. The dough was mingled at a rate of 80 r min^{-1} for 3.5 min, and chipped into pieces of 100 g, forming 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. Steamed bread was cooled 60 min at room temperature before quality evaluation, and freeze dried for compositional analysis.

2.7. Steamed bread quality evaluation

Specific volume and height/Diameter ratio We measured the specific volume of steamed bread using rapeseed displacement method and the height/diameter ratio using a vernier caliper.

Texture profile analysis (TPA) TPA was conducted using a TA-XT2i texture analyser equipped with a 5-kg load cell (Stable Microsystems Ltd., Godalming, London). The measurement probe was used 50 mm diameter cylinder, before testing and after testing speed were 4.0 mm s^{-1}, testing speed was 1 mm s^{-1}; the compression degree was 50%, the interval time between the first and second cycles was 1 s. Hardness, adhesiveness, chewiness, and resilience were counted through the TPA graphic.

Colour Colour parameters were measured using a Hunter Lab colour flex model A60-1012-312 (Hunter Associates laboratory, Reston, VA). The equipment was standardized each time with white and black standards. Samples were scanned to determine lightness (L^*), red-green (a^*) and yellow-blue (b^*) colour components.

Chemical composition analysis Starch, crude fat, crude protein, dietary fibre, and ash of flour and steamed bread were determined by association of official analytical chemists (AOAC) methods (AAC 2000).

Total polyphenol content (TPC) was measured by using the Folin-Ciocalteu method with a modification (Singleton *et al.* 1999). Chlorogenic acid (CAE) was as standard, and TPC of steamed bread was represented as mg CAE g^{-1} DW (Sun *et al.* 2014).

Antioxidant activity of steamed bread was determined by the oxygen radical absorption capacity (ORAC) assay, as reported by Sun *et al.* (2014). The antioxidant activity was represented as mg Trolox equivalents (TE) 100 mg^{-1} DW.

***In vitro* starch digestibility and expected glycemic index** Starch digestibility of steamed bread was determined according to the method reported by Gularte and Rosell (2011) with slight modification. The starch hydrolysed within 30 min was rapidly digestible starch (RDS); the starch hydrolysed within 30 and 120 min was slowly digestible starch (SDS), and the remnant starch after 16 h was resistant starch (RS). We obtained the hydrolysis index (HI) through the equation (Granfeldt *et al.* 1992):

$$HI=S_{sample}/S_{glucose}$$

Where, S_{sample} was the area under the hydrolysis curve (0–180 min) of the sample and $S_{glucose}$ was the area under the hydrolysis curve of glucose (control) over 0–180 min. The estimated glycaemic index (eGI) was calculated according to the method of Granfeldt *et al.* (1992).

2.8. Sensory evaluation

Discriminative testing was performed by nine panelists in triplicate. All panelists were of Asian ethnicity with steamed bread as part of the diet. The evaluation forms with a list of line scales were given to each personnel. Panelists were given all seven samples with randomized numbers at the same time. The values of colour, adhesiveness, and firmness of the steamed bread were from 1 (the lowest) to 9 (the highest). The overall acceptability of each sample was counted from 1 (extremely the lowest) to 9 (extremely the highest).

2.9. Statistical analysis

All the experiments were conducted in triplicate, and the results were expressed as means±standard deviation. Statistical analysis was executed using the Statistical Analysis System (SAS) ver. 9.2 software (SAS Institute Inc., Cary, NC, USA), $P<0.05$ was considered statistically significant.

3. Results

3.1. Effect of potato flour on thermo-mechanical rheological properties

Table 1 showed the influence of potato flour on thermo-mechanical rheological properties of wheat flour. The Mixolab condition mixing for 8 min at 30°C refers to the protein characteristics of tested flour and it is characterized by the following parameters: water absorption, dough development time, dough stability and C2 (protein weakening due to mechanical and thermal constraints). Development time (the time required to obtain the maximum torque ((1.1±0.05) Nm) at 30°C) of different proportions potato flour was significantly reduced (Table 1). Increasing the content of potato flour from 10 to 35%, dough stability and C2 also diminished progressively.

The other Mixolab tested systems reveals the starch properties. The starch gelatinization (C3), the starch stability (C4) and starch retrogradation (C5) are important parameters for researches (Ozturk *et al.* 2008). The result of C3 suggested that the gelling ability of wheat was the highest, which was decreased significantly with potato flour addition (Table 1). Increasing the amount of potato flour, the starch stability (C4) and starch retrogradation (C5) also decreased.

3.2. Effect of potato flour on dynamic rheological properties

Appendix A represented the variations in storage modulus (G'), loss modulus (G''), and damping factor (tanδ, the ratio of G' and G'') for the samples. Table 2 contained parameters of power law model describing the dependence G', $G''=f(\omega)$. G' was larger than G'', which indicates that elastic properties are predominated, not the viscous features. The addition of potato flour resulted in more evident changes of dough rheology. Addition of potato flour increased the G' and G'' significantly which was also confirmed by the values of K' and K'' (Table 2). In the meantime, potato flour addition significantly reduced tanδ (from 0.404 to 0.283) compared to only wheat dough (Appendix A and Table 2).

3.3. Effect of potato flour on fermentation properties

Dough development and gassing power are two important parameters of the fermentation process. The maximum dough height (H_m) and dough stability ((H_m–h) H_m^{-1}) were

Table 1 Effect of potato flour on thermo-mechanical properties of wheat flour[1)]

Compositions (%)	Water absorption (%)	Dough development (min)	Thermal stability (min)	C2	C3	C4	C5
0	61.1±0.1 a	2.87±0.02 f	6.18±0.07 g	0.44±0.01 c	1.97±0.01 g	1.92±0.01 g	3.11±0.02 g
10	73.5±0.2 b	1.75±0.01 e	2.13±0.06 f	0.17±0.01 b	1.39±0.02 f	1.19±0.01 f	1.77±0.01 f
15	77.9±0.1 c	1.52±0.02 d	1.98±0.02 e	0.11±0.02 a	1.05±0.04 e	1.01±0.02 e	1.52±0.02 e
20	82.7±0.1 d	1.26±0.03 c	1.75±0.01 d	0.11±0.01 a	0.84±0.01 d	0.85±0.01 d	1.32±0.03 d
25	89.6±0.1 e	1.18±0.01 b	1.62±0.04 c	0.10±0.01 a	0.78±0.03 c	0.71±0.02 c	1.10±0.01 c
30	94.1±0.1 f	1.15±0.01 b	1.52±0.02 b	0.10±0.02 a	0.67±0.01 b	0.58±0.01 b	0.92±0.01 b
35	96.5±0.1 g	1.10±0.04 a	1.40±0.03 a	0.10±0.03 a	0.57±0.02 a	0.48±0.01 a	0.82±0.04 a

[1)] C2 represents the weakening of the protein based on the mechanical work and the increasing temperature; C3 expresses the starch gelatinization; C4 indicates the stability of the hot-formed gel; C5 represents starch retrogradation.
Different letters indicate significant difference at P<0.05. Values are means±SD. The same as below.

Table 2 Parameters of the power-law functions describing dependence of storage and loss moduli on angular frequency

Proportions (%)	$G'=K'\omega^{n'}$ [1)]		$G''=K''\omega^{n''}$ [2)]		tanδ (at 1 Hz)[3)]
	$K'\times10^{-3}$ (Pa $s^{n'}$)	n'	$K''\times10^{-3}$ (Pa $s^{n''}$)	n''	
0	18.79±0.52 e	0.239±0.002 a	7.93±0.21 f	0.288±0.006 a	0.404±0.001 a
10	33.15±0.23 d	0.199±0.003 b	11.61±0.19 c	0.275±0.004 b	0.342±0.006 b
15	39.87±0.12 b	0.205±0.006 b	13.50±0.08 b	0.269±0.005 bc	0.323±0.005 d
20	33.12±1.59 d	0.205±0.001 b	11.59±0.27 c	0.266±0.008 bc	0.331±0.001 c
25	44.04±0.67 a	0.189±0.004 c	14.04±0.19 a	0.258±0.005 cd	0.308±0.004 e
30	35.56±0.42 c	0.181±0.006 d	10.84±0.09 d	0.253±0.009 d	0.297±0.002 f
35	35.29±0.17 c	0.167±0.003 e	10.32±0.12 e	0.249±0.004 d	0.283±0.002 g

[1)] G', storage modulus (Pa); ω, angular frequency (rad s^{-1}); K', K'', n', n'', experimental constants.
[2)] G'', loss modulus (Pa).
[3)] tanδ, damping factor, the ratio of G' and G''.

significantly lowered by the potato flour addition (Table 3). While, potato flour increased the total volume of CO_2 (V_T) and H_m' (the maximum height of CO_2 production). V_T (2 650 mL) was the highest when the concentration was up to 15%.

3.4. Effect of potato flour on morphology structure by SEM

The microstructures of dough with different proportions of potato flour were evaluated by SEM (Fig. 1). The starch granules were totally embedded in gluten network (0%), which was the typical structure of wheat dough (Sun *et al.* 2015). The micrograph of the dough with 10 and 15% potato flour addition was similar to wheat dough, respectively. In addition, high proportions of potato flour increased the surface connectivity between starch granules and gluten, and the gluten strands in the dough cannot be clearly observed. While, voids among the gluten network and starch granules existed in all dough samples.

3.5. Effect of potato flour on steamed bread technological qualities

Specific volume and height/diameter ratio Photographs of front, side and section of steamed bread with different potato flour contents were displayed in Appendix B. With potato flour addition, a reduction in the specific volume (from 2.95 to 1.24 mL g^{-1}) was observed, which might be due to that potato flour diluted the gluten network, and the maximum dough height (H_m) was decreased (Table 3). On the other hand, an increase in height/diameter ratio (from 0.64 to 1.36) was observed (Table 4 and Appendix B), and the reason could be assumed that the expansibility of wheat dough was restrained and diameter was decreased by potato flour addition.

Colour Table 4 displayed the results of L^*, a^*, and b^* evaluated of the steamed bread samples. Steamed breads

Table 3 Effect of potato flour on fermentation rheological properties of wheat dough

Proportions (%)	Dough development[1)]			Gas behavior[2)]		
	H_m (mm)	H (mm)	$(H_m–h)/H_m$	H_m' (mm)	V_T (mL)	R_C
0	36.4±0.1 a	20.0±0.1 c	45.1±1.1 a	70.8±1.1 f	1 572±21 f	98.6±0.1 ab
10	29.1±0.1 b	22.8±0.1 a	21.6±0.8 d	122.9±0.8 c	2 303±19 c	98.1±0.1 c
15	28.1±0.1 b	20.8±0.1 b	26.0±0.6 c	133.3±0.6 a	2 650±15 a	98.7±0.1 a
20	23.4±0.2 c	16.7±0.2 f	28.6±1.2 b	132.7±1.2 a	2 538±23 b	98.7±0.2 a
25	24.0±0.3 cd	17.4±0.3 e	27.5±0.9 bc	125.4±0.9 b	2 317±14 c	98.1±0.1 c
30	19.7±0.1 de	18.5±0.1 d	6.1±0.3 f	114.0±1.3 e	1 990±15 e	98.4±0.1 b
35	17.0±0.1 e	15.0±0.1 e	11.8±1.3 e	118.6±1.3 d	2 100±15 d	98.5±0.1 ab

[1)] H_m, dough height at maximum development time; h, height of dough at the end of the test; $(H_m–h)/H_m$ that is inversely related to dough stability.
[2)] H_m', the maximum height of CO_2 production; V_T, total volume of CO_2 (mL); R_C, the CO_2 retention coefficience.

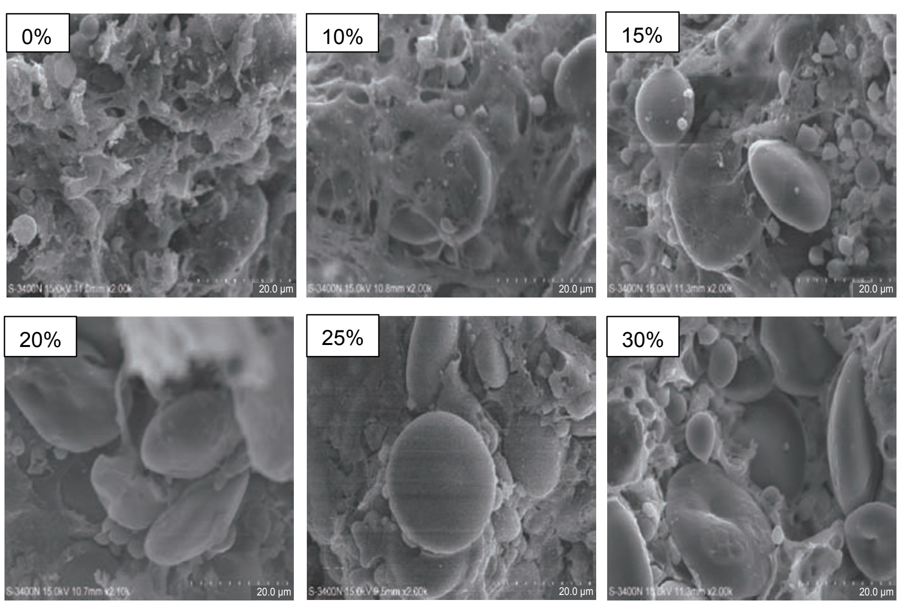

Fig. 1 Microstructure of wheat dough with different potato flour proportions (magnification ×2 000).

Table 4 Effect of potato flour on technological parameters of steamed bread

Proportions (%)	Height/Diameter ratio	Specific volume (mL g^{-1})	Colour[1]			Texture			
			L^*	a^*	b^*	Hardness (N)	Adhesiveness	Chewiness (N)	Resilience
0	0.64±0.056 d	2.95±0.182 a	61.06±1.01 a	−1.07±0.027 d	13.15±1.11 dc	17.43±1.70 f	230.9±25.72 a	9.96±0.57 de	0.53±0.043 a
10	0.67±0.033 d	2.45±0.394 b	59.67±1.74 b	−0.92±0.035 cd	12.42±1.99 d	18.67±1.81 f	198.93±10.04 b	8.84±0.75 de	0.50±0.029 ab
15	0.68±0.028 d	2.17±0.152 bc	59.16±1.02 bc	−1.13±0.030 d	13.99±0.47 bc	21.18±1.64 e	110.75±25.43 c	9.78±1.75 e	0.49±0.017 ab
20	0.72±0.047 c	2.02±0.058 c	57.39±0.08 d	−0.70±0.021 bc	13.34±0.11 c	25.26±0.68 d	82.48±4.11 c	11.17±0.45 d	0.52±0.038 a
25	0.75±0.033 c	1.92±0.050 c	59.29±0.13 bc	−0.60±0.024 b	14.32±0.09 b	28.13±0.94 c	57.63±1.56 cd	13.72±1.30 c	0.43±0.003 bc
30	1.29±0.029 b	1.28±0.028 d	59.94±0.13 b	0.025±0.043 a	16.24±0.15 a	32.99±1.26 b	0.73±0.11 d	16.68±0.60 b	0.43±0.006 bc
35	1.36±0.042 a	1.24±0.024 d	58.77±0.16 c	0.12±0.020 a	15.87±0.07 a	49.33±0.41 a	0.72±0.15 d	24.91±0.37 a	0.45±0.004 b

[1] L^*, determine lightness; a^*, red-green; b^*, yellow-blue.

containing potato flour had lower L^* values, higher a^* and b^* values compared to wheat steamed bread. This suggested that the steamed bread stained toward a darker colour, tending to yellow and red colour compared with only wheat steamed bread.

Texture properties Hardness, adhesiveness, chewiness and resilience were texture attributes of steamed bread. These textural properties showed significant difference between samples (Table 4). Hardness is often considered as the index of the total textural attributes. After addition of potato flour, the value of hardness was higher, which significantly ($P<0.05$) differed from wheat steamed bread (17.43 Newton), the hardness of potato-wheat compound steamed bread (35%) increased to 49.33 Newton. Resilience indicated the recovery of steamed bread to its original position. The resilience was not markedly influenced by the level of potato flour ($P>0.05$). Values of adhesiveness dropped sharply. Hardness had significantly related to chewiness, which was the highest when 35% potato flour supplemented. Similar to hardness, the addition of potato flour pronounced increased the value of chewiness.

3.6. Correlation analysis

The results for correlation between dough characters and technological parameters of steamed bread quality (height/diameter ratio, specific volume, L^*, hardness through the result of principal components analysis (data not shown)) are shown in Fig. 2. Dough characters had significant effect on the specific volume, especially water absorption (R^2, 0.9748), H_m (R^2, 0.9764) and n´´ (R^2, 0.9785), and for height/diameter ratio were $(H_m–h)/H_m$ (R^2, 0.8197), H_m (R^2, 0.8127), n´´ (R^2, 0.8023), respectively. With regard to hardness, the main dough characters were H_m (R^2, 0.8672), n´´ (R^2, 0.8578) and water absorption (R^2, 0.8410). However, the dough did not have significantly influenced on the L^*, which may be influenced by the material and making process. From these results, H_m, $(H_m–h)/H_m$, n´´ and water absorption can be used for predicting the quality of steamed bread.

3.7. Effect of potato flour on steamed bread nutritional qualities

Proximate composition Table 5 showed the results of incorporation of potato flour on the proximate composition of steamed bread. All the potato flour containing steamed bread had higher levels of ash, dietary fibre, and starch. The dietary fibre and ash in the 35% steamed bread were 68 and 330% greater than the only wheat steamed bread. The starch content increased from 60.49 to 64.38% as potato flour addition increased from 0 to 35%. Protein and fat content decreased significantly, but the amino acid composition of protein was more balance than the only wheat steamed bread (lack of lysine) with respect to a reference protein of FAO/WHO. The lysine content of wheat and potato flour was 20.6 and 39.71 mg g^{-1} protein, respectively.

***In vitro* starch digestibility and expected glycemic index** Rapidly digestible starch (RDS) ranged from 15.68 to 23.39%, and wheat steamed bread was found to have the highest RDS content (Table 5). Slowly digestible starch (SDS) can increase the levels of postprandial plasma glucose and insulin slowly (Englyst *et al.* 1996). Resistant starch (RS) refers to the sum of intact starch and retrograded starch, which passed into the large intestine. In this study, RS varied from 16.26 to 38.4%, RS contents of steamed breads containing potato flour were higher than the only wheat steamed bread.

The values of the estimated glycaemic index (eGI) ranged from 60.01 to 73.63, the eGI of steamed breads with potato flour were lower than the only wheat steamed bread (Table 5).

Total polyphenol contents (TPC) and antioxidant activity TPC and antioxidant activity of potato-wheat steamed bread samples were shown in Table 5. The TPC of steamed bread increased with the addition of potato flour. When the addition level

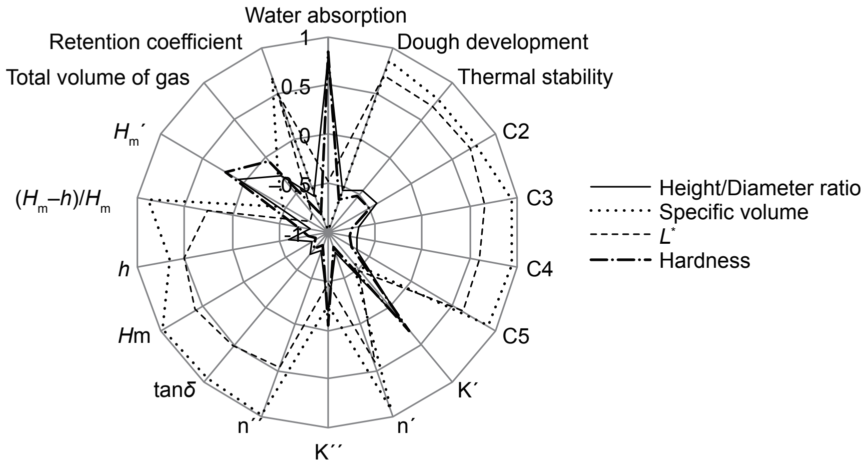

Fig. 2 Plot of correlation coefficientce between dough characters and technological parameters of steamed bread.

was 10%, the content of TPC was the highest compared to the other samples, especially an increase of polyphenol amount of approximately 20% compared to the steamed bread only using wheat flour. However, TPC did not increase proportionally with the potato flour increasing, which might be due to that not only the flour composition, but also the production process which can influence its content. For example, the fermentation process can generate some phenolics, and steaming process may induce some loss of antioxidant ingredients. Steamed bread samples contain bioactive polyphenols, which may have significant health promoting effect on human health.

Antioxidant activity was determined by the oxygen radical absorbance capacity (CRAC) method. The antioxidant activity of 30% potato-wheat compound steamed bread ((1 858.04±11.45) mg ACE 100 g^{-1} DW) was 1.2 times that of the wheat steamed bread ((1 542.18±6.12) mg ACE 100 g^{-1} DW). However, the correlation coefficience between antioxidant activity and TPC (R^2=0.276) was low, indicating that TPC was not the only factor influencing on antioxidant activity. This result could be attributed to that, steamed bread samples mentioned above might contain other contents, which possess synergistic effect or antagonistic effect on the antioxidant activity of polyphenol.

3.8. Sensory evaluation

Appendix C showed potato flour addition had a significant effect on colour. Steamed bread containing potato flour appeared higher firmness than wheat steamed bread. However, the trends about the cohesiveness and adhesiveness were opposite. The steamed bread containing 10–20% potato flour received the similar overall acceptability scores (Appendix C). These findings can conclude that using the potato flour up to 20% could obtain the analogous quality and pleasant appearance as regular wheat steamed bread.

4. Discussion

4.1. Potato flour addition affected the thermo-mechanical properties of dough

Mixolab is a new instrument to measure dough thermo-mechanical properties, which can analyze the protein network and starch behavior, and also can check the dough empirical rheological quality (Abdel-Samie *et al.* 2010; Huang *et al.* 2010; Rosell *et al.* 2010). Samples containing potato flour progressively decreased the dough development time, the reason may be attributed to that the pre-gelatinization of starch decreased the absorbed water time (Table 1). Dough stability diminished markedly due to the higher content of fibre and diluted gluten network (Fig. 1) caused by the potato flour addition. This might be due to that potato protein is not similar to the wheat protein from the technological point, and therefore the addition of potato flour alters the wheat properties, which are accountable for the qualities of the final product. The results were supported by the report of Rosell *et al.* (2010), who found that quinoa flour (12.5–25%) addition decreased the dough development time and dough stability.

Wheat flour had the highest starch gelatinization (C3), starch stability (C4) and starch retrogradation (C5), and potato flour addition decreased the values of C3, C4 and C5 (Table 1). Recently, Ozturk *et al.* (2008) also found that wheat flours with high C3, C4 and C5 values (2.45, 2.46 and 3.38 Nm, respectively), and the typical characters of flour were special suitable for getting higher cookies quality, for example, higher diameter and spread ratio. However, Kahraman *et al.* (2008) found that good cake flour should present low C2, C3, C4 and C5 values (0.39, 1.43, 1.36

Table 5 Chemical composition of steamed bread containing potato flour[1)]

Proportions (%)	Starch (%)	Protein (%)	Fat (%)	DF (%)	Ash (%)	TPC	Antioxidant activity	RDS (%)	SDS (%)	RS (%)	eGI
0	60.49±0.88 a	13.49±0.02 a	1.23±0.01 a	2.65±0.05 a	0.60±0.05 a	1.57±0.02 e	1 542.18±6.12 e	23.39±0.12 a	60.35±0.32 a	16.26±0.11 g	73.63±0.32 a
10	61.57±0.21 ab	12.61±0.02 b	1.13±0.01 b	3.23±0.10 b	0.92±0.11 b	1.81±0.01 a	1 663.05±5.78 d	18.90±0.04 e	48.99±0.11 c	32.12±0.24 d	65.09±0.18 b
15	62.91±0.52 b	12.21±0.12 b	1.08±0.02 b	3.79±0.12 b	1.08±0.21 b	1.80±0.02 ab	1 729.89±7.29 c	20.75±0.11 c	46.07±0.12 d	33.18±0.01 c	65.75±0.17 b
20	63.46±0.13 b	11.91±0.09 c	1.03±0.01 bc	4.29±0.09 bc	1.29±0.08 c	1.79±0.02 ab	1 787.26±11.23 b	20.98±0.21 b	49.46±0.42 c	29.56±0.08 f	65.02±0.24 b
25	63.74±0.23 b	11.77±0.15 c	0.98±0.01 c	4.31±0.15 c	1.74±0.07 d	1.73±0.03 c	1 787.96±12.78 b	15.68±0.14 g	53.55±0.52 b	30.77±0.06 e	65.79±0.25 b
30	63.57±0.96 b	11.24±0.05 cd	0.93±0.02 c	4.40±0.05 c	2.00±0.14 de	1.77±0.01 b	1 858.04±11.45 a	18.37±0.08 f	43.23±0.08 e	38.4±0.22 a	61.99±0.14 c
35	64.38±0.56 c	11.04±0.08 c	0.89±0.01 c	4.46±0.08 c	2.58±0.05 e	1.67±0.02 d	1 796.78±9.87 b	20.49±0.08 d	43.61±0.21 e	35.9±0.14 b	60.01±0.21 c

[1)] DF, dietary fiber; TPC, total polyphenol contents, expressed as mg chlorogenic acid g^{-1} DW; antioxidant activity, expressed as μg TE g^{-1} DW; RDS, rapidly digestible starch; SDS, slowly digestible starch; RS, resistant starch; eGI, estimated glycaemic index.

and 1.61 Nm, respectively). From this point, 35% potato flour could be fit for cakes, not for cookies. But it is still difficult to predict the effect of such on steamed bread, which is different from cookie and cake.

4.2. Potato flour addition influenced the dynamic rheological properties of dough

Analysis of dynamic rheological properties of dough can give more information about viscoelastic properties, which can affect the fermentation process and are important for the products production. The addition of potato flour significantly affected dough rheology (Table 2). It was manifested with the results of Balestra *et al.* (2011), ginger powder addition significantly changed the moduli values representing dough viscoelastic properties. In addition, the addition of potato flour caused a decrease of tanδ and an increase of G'. The increased G´ declared that it was tough to mound from the viewpoint of industrialization (Peressini and Sensidoni 2009). The different proportions of potato flour had different tanδ (Fig. 1), we speculate that the different cross-linking levels and structural changes may cause the change. Dreese *et al.* (1998) had already reported that the polymer system's cross-linking might exert the increase of storage modulus and the decrease of phase angle. In steamed bread production, dough rheology changed with the change of composition and gluten network, and then affected the starch gelatinization and viscoelasticity of the matrix. In this study, the alteration of wheat dough rheology was likely due to the diluting effect of potato flour on gluten network, and the interactions between the fibre structure and wheat proteins. While, a low dietary fibre content had minor changes in steamed bread quality because of the little change of dough viscoelastic properties (Balestra *et al.* 2011).

4.3. Potato flour addition influenced the fermentation rheological properties of dough

For the bread products, one of the most important processes is fermentation, which can produce gas through yeast activity, and enlarges the incorporated air bubbles during the mixing process (Ktenioudaki *et al.* 2009). Many factors can change the dough fermentation, and then modify the final product development, such as the new materials, the yeast, and the temperature. Dough development (H_m and h) was significantly decreased by the potato flour addition (Table 3). The reason might be speculated that potato flour restrained the extension of wheat dough during fermentation process (Penella *et al.* 2008). And the dough stability also progressively decreased with the potato flour addition, which was also confirmed by the Mixolab result (Table 1) and SEM (Fig. 1). The effect was likely to be the reason that potato flour impeded the normal formation, diluted the gluten structure, reduced the viscoelasticity (Table 2) and forced gas diffusion in all directions (Pomeranz *et al.* 1977). While, the total volume of gas was remarkably increased by the increasing of potato flour, the reason might be that potato starch was gelatinized by making potato flour process, the structure of potato starch was changed, active sites of starch were emerged, the enzyme could easily contact the starch active sites, and then catalyze it into sugars which can be utilized by yeast. If we continued to increase the potato flour concentration, the content of alpha-amylase decreased significantly and affected the total volume of gas.

4.4. Potato flour addition influenced the microstructural properties of dough

We further studied the microstructural properties to help explain the dough properties.

The SEM showed that the presence of potato flour disturbed the formation of gluten network (Fig. 1). The potato flour addition resulted in easy disruption of the gluten network, which also altered the dough viscoelasticity. This discovery was supported by the reports of Sun *et al.* (2015) who studied on wheat germ flour addition on Chinese steamed bread properties. The discontinuous gluten matrix implied that the resistance and extensibility of dough were disturbed, which could cause a poor dough stability (Table 2) and further influence the textural properties of steamed bread (Sim *et al.* 2003; Keeratipibul *et al.* 2010).

4.5. Correlation analysis between dough rheology and steamed bread quality

With the development of the new equipment, a great number of methods were used to check the quality of dough and product, which will contribute to get overall information of food. However, it will multiply the workload, and is difficult to choose which kind of method or parameter. Meanwhile, it has a high correlation between these parameters, indicating that it is possible to decrease the checked parameters through the analysis method (Verdú *et al.* 2015). Specific volume, L^* and hardness are important quality parameters of steamed bread (Principal components analysis, data not shown). From these result of correlation between dough characters and technological parameters, H_m, $(H_m–h)/H_m$, n´´ and water absorption can be used for predicting the quality of steamed bread, which will save time and reduce duplication of work in future.

4.6. *In vitro* starch digestibility and expected glycemic index were related to potato flour addition

Previous study found that it had high relationship between rapidly digestible starch and glycaemic response (Englyst *et al.* 2003). We noticed that wheat steamed bread had the highest rapidly digestible starch content (Table 5). This could be attributed to that it increased the possibility of α- amylase to starch and its hydrolysis if the product had higher specific volume and porous structure. Tahir *et al.* (2010) had found that the starch particle size, granules surface area and the ratio of amylopectin all affected the level of α-amylase hydrolysis. In this study, when addition potato flour, the specific volume and the surface area of granules decreased, physical structure compacted, the contact possibility between enzyme and starch reduced, therefore, the RDS content lowered, the contents of SDS and RS increased, the eGI decreased, which was in agreement with the results of Borczak *et al.* (2012) and Tahir *et al.* (2010).

5. Conclusion

Supplementation of wheat flour with potato flour significantly influences the dough rheological properties and steamed bread quality, such as increased the water absorption, the maximum gaseous release height, total volume of CO_2 and hardness, with decreased dough stability, dough development and specific volume. Moreover, correlation analysis suggested H_m, $(H_m–h)/H_m$, n´´ and water absorption can be used for predicting the quality of steamed bread, which will save time and reduce duplication of work. In addition, potato flour addition improved nutritional content of steamed bread, enhancing the dietary fibre, ash, total polyphenol content and antioxidant activity. It reduced the rapidly digestible starch and estimated glycemic index. These results showed that addition of 20% potato flour to steamed bread will enhance the breads functional components and offer diverse diet to steamed bread consumers.

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Appendix associated with this paper can be available on http://www.ChinaAgriSci.com/V2/En/appendix.htm

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