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Effects of apple pomace assisted by steam explosion on physicochemical performance of wheat starch, and sensory properties of bread

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Abstract

The present work aimed to develop a type of bread rich in dietary fibre (DF), and to investigate the effects of different amounts of steam-exploded apple pomace (AP) on the physicochemical properties of wheat flour and bread quality. The content of soluble dietary fibre (SDF) in apple pomace treated with steam explosion (SE-AP) increased, which could improve the quality of flour products and supplement dietary fibre. Adding 12% apple pomace powder resulted in maximum solubility (10.23 ± 0.25%) and swelling power (3.97 ± 0.14%). The relative viscosity of the mixed powder decreased with increasing SE-AP content. Moreover, the coagulation value of the mixed powder increased with the increase in SE-AP content. Based on the textural characteristics and sensory evaluation analysis of the bread, the quality of bread made with mixed powder was the best when 10% SE-AP was added to high-gluten flour. SE-AP can be utilised to produce bread rich in DF. The addition of 10% SE-AP resulted in the highest overall acceptance.

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Introduction

The milling of wheat into refined flour results in the loss of certain nutrients, particularly dietary fibre (DF), which is drastically reduced. DF helps prevent chronic diseases caused by sedentary lifestyles and metabolic disorders prevalent in modern society (Korczak and Slavin, 2020). A high-DF diet improves health since it is related to a lower incidence of several diseases. DF offers numerous beneficial effects such as increased faecal volume, reduced intestinal transit time, and lowered cholesterol and blood glucose levels. Furthermore, DF reduces potentially harmful substances to the human body (mutagens and carcinogens), and stimulates the proliferation of intestinal flora (Stephen *et al*., 2017). A recent survey by the Food Science and Nutrition Association indicates that global DF intake is lower than the recommended value (Barber *et al*., 2020). Bread is the ideal carrier for incorporating more DF.

DF is classified into soluble dietary fibre (SDF) and insoluble dietary fibre (IDF). The impact of SDF amount on physiological function of DF is more significant than that of IDF (Salleh *et al*., 2019). Apple pomace (AP), the main by-product of apple juice processing, is a potential source of DF (Bhushan *et al*., 2008). AP contains more than 70% of the total dietary fibre (TDF), and has been utilised as a potential source of SDF and other health-promoting compounds (Fernandes *et al*., 2019; Gumul *et al*., 2021). AP has been added to wheat flour to elevate the DF content of flour products. Curutchet *et al*. (2021) utilised AP as a DF supplement in cakes, and discovered that cakes with 31% AP addition were highly popular among consumers. Alongi *et al*. (2019) used AP to make an AP biscuit, and found that the replacement of AP not only increased the content of DF in the biscuit, but also reduced the glycaemic index of the finished biscuit. Although the DF content in AP is high, the SDF content is only 3 - 9%. Therefore, increasing the content of SDF in AP has important application value for apple processing.

Steam explosion (SE) is an effective physical treatment technology for biomass materials (Deepa *et al*., 2011), including orange peel (Wang *et al*., 2015) and wheat straw (Monschein and Nidetzky, 2016). SE technology aims to maintain raw materials in high-temperature pressurised steam for a few minutes before releasing the high pressure in a few

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milliseconds (Rocha *et al*., 2012; Singh *et al*., 2015). The rapid evaporation of internal water due to the sudden release of high-pressure results in a sharp rise in the volume and destruction of the cell structure. Moreover, chemical reactions such as thermal degradation and hydrogen bond cleavage during SE can significantly destroy the structure of fibre macromolecules, promoting the dissolution of SDF. Furthermore, SE triggers the modification reaction of insoluble macromolecular polymers with SDF by disrupting glycosidic bonds (Li *et al*., 2015). Preliminary studies have demonstrated that the total amount of SDF in AP increased by 4.76 times (6.27 - 29.85%) following SE treatment (Liang *et al*., 2017).

Currently, numerous DF-rich by-products, such as wheat bran, sweet potato pulp, rice bran or konjac mannan, inulin, and other biopolymers are incorporated into flour products to increase DF consumption (Saleh *et al*., 2019). However, with an increase in the amount added, the quality of flour products often varies, impacting both the dough system and the flour products. In general, adding more DF increases water absorption, degree of weakening, and tensile resistance, while decreasing stability and the extensibility of dough during mixing (Saleh *et al*., 2019; Iuga and Mironeasa, 2020). However, appropriate amounts of DF may improve the quality of steamed bread. Guo *et al*. (2022) added konjac glucomannan to the dough, and observed that when the addition amount of konjac glucomannan was 1.5%, the stability of the dough structure, and the specific volume of the steamed bread increased, whereas the hardness decreased. Li *et al*. (2016) added natural bran SDF and fermented bran SDF to the dough, and this improved the rheological properties and tensile properties of the dough. Ziobro *et al*. (2013) discovered that adding inulin increased the volume of bread while reducing the hardness of bread crumbs. Therefore, incorporating AP rich in SDF following SE to wheat flour for bread preparation may improve both the SDF content of bread as well as the added value of AP.

In the present work, SE-AP powder rich in SDF was added to high-gluten wheat flour for the first time. The effects of adding different SE-AP powders on the solubility, swelling power, viscosity, and retrogradation of wheat starch, and the texture and sensory quality of bread prepared with mixed powder, were investigated. The present work could serve as a reference for the development of high-SDF bread, and the effective utilisation of AP.

Materials and methods

Materials

AP was supplied in dried form by SDIC Zhonglu Fruit Juice Co., Ltd. (Beijing, China). High gluten flour was obtained from Suntory Flour Group Co. Ltd (Xinxiang China). The high gluten flour contained 24% carbohydrates, 20% protein, 3% fat, 13.5% moisture, and 0.31% ash. Instant dry yeast was produced by Angel Yeast Co, Ltd (Zhengzhou, China).

Preparation of SE-AP powders

Liang *et al*. (2017) outlined the detailed preparation process. The AP powder was subjected to SE using a QBS-80 steam explosion apparatus (Hebi Zhengdao Bioenergy Co., Ltd., Henan, China). Dry AP sieved with US-60 mesh was placed into an SE system cylinder (0.415 L of effective explosion chamber volume), and the pressure of the device was adjusted to 0.51 MPa. High-temperature and high-pressure steam entered the cylinder through the intake valve. The sample was held at a temperature for 168 s, after which the intake valve was closed, and the ball valve at the bottom of the reactor was quickly opened to release the pressure. The resulting steamed AP powder was sealed in plastic bags, and stored in the dark at -20°C before use.

Chemical analysis

The compositions of AP and SE-AP powders were analysed using the AOAC (2000) methodology. The contents of protein, fat, TDF, IDF, SDF, moisture, and ash were determined using the methods 955.04, 920.39, 991.43, 925.09, and 942.05, respectively.

Preparation of mixed powder

High gluten flour was mixed with SE-AP powder at mass ratios of 0, 2, 4, 6, 8, 10, 12, 14, and 16%.

Swelling power and solubility analysis of mixed powder

The swelling power and solubility of starch were determined as described by Wang *et al*. (2017). Following SE, approximately 25 mL of a 2% wheat flour suspension mixed with AP was obtained. After cooling, the suspension was heated at 90°C for 30 min, and centrifuged at 1,258 *g* for 20 min. The supernatant was transferred to the evaporator A1, which was then placed in a drying oven at 110°C until it attained constant weight A2. The quality of the dissolved starch was determined by subtracting the weight of the evaporating dish from the quality of the dried starch. *P* denotes the quality of the sediment after centrifugation, and *M* denotes the dry mass of the starch sample. The solubility (SOL) and swelling power (SP) were then calculated using Eqs. 1 and 2:

$$\mathrm{SOL} = \frac{A_2 - A_1}{M} \times 100\% \quad \text{(Eq. 1)}$$

$$\mathrm{SP} = \frac{P}{[M(1-\mathrm{SOL})]} \times 100\% \quad \text{(Eq. 2)}$$

Relative viscosity analysis of mixed powder

A rapid viscosity analyser (RVA-Super3, Newport Scientific Pty. Ltd., Warriewood, Australia) was used to assess the relative viscosity of the mixed powder during gelatinisation. An emulsion of wheat flour and SE-AP with an 8% mass fraction was prepared and gelatinised in a boiling water bath for 20 min. After cooling, 25 mL of the gelatinised emulsion was placed in an aluminium box to determine the relative viscosity (Majzoobi *et al*., 2011).

Coagulation properties analysis of wheat powder

Following the method described by Majzoobi *et al*. (2011), the coagulability of the mixed powder (wheat flour + SE-AP) was evaluated. At room temperature, 20 mL of wheat flour + SE-AP paste was added to a calibration tube, and the volume of the supernatant was recorded every 1 h. The sedimentation time was plotted against the volume percentage of the sedimentation solution which served as the retrogradation curve for the starch paste. The volume of wheat flour + SE-AP after 24 h of sedimentation represented the sedimentation volume.

Breadmaking and bread characteristics

The method described by Curti *et al*. (2016) was applied, with minor modifications. Mixed powder (150 g), sugar (12 g), yeast (1.5 g), egg white (15 g), water (85 g), and milk powder (6 g) were blended in a mixer bowl. Butter (15 g, flour base) was then added and mixed with all ingredients. The dough was kneaded for about 30 min until it rolled into a film shape. After fermentation at 37°C for 60 min, the dough was shaped into a mould, and placed in a fermentation cabinet for further fermentation until the volume doubled. The samples were then baked at 180°C for 20 min. Next, the egg liquid was spread out on the dough surface, and baked in an oven until it turned golden.

Texture profile analysis of bread

The texture properties of the bread were analysed using the TA-XT plus texture analyser (Stable Micro System Ltd., Surry, UK) equipped with a P/36R cylindrical probe as per the method reported by Świeca *et al*. (2014). The instrument's test parameters were set to 2.0 mm/s for both pre-test and test speeds, 4.0 mm/s for post-test speed, 5 g for threshold, 50% compression, and 200 pps for recording rate. The computed textural parameters included hardness, springiness, chewiness, and resilience. The measurements for each group of samples were performed thrice, and the average value was calculated.

Determination of bread-specific volume

The specific volume of bread was determined with reference to the AACC Method 10-05.01 (AACC, 2010). Little rapeseed grains were loaded into a cleaned large beaker until reaching the marked level, and then unloaded back. Then, the rapeseed was poured into the measuring cylinder to measure the volume V_1. The bread sample was placed into the beaker, and measured rapeseed was added to reach the marked level. The volume V_2 of the remaining rapeseed grains left outside the beaker was measured using a measuring cylinder. The volume of the bread was calculated as V_1 - V_2. Following the procedure already described, the mass of each loaf sample and the loaf-specific volumes were obtained using Eq. 3:

$$\text{Specific volume} = \frac{\text{Bread volume(ml)}}{\text{Bread weight(g)}} \quad \text{(Eq. 3)}$$

Sensory evaluation of bread

The sensory properties of the bread were scored using a nine-point hedonic scale (1 for 'very disliked' and 9 for 'very liked'), as described by Bouaziz *et al*. (2020) with slight modifications. A total of 25-panel members were selected, comprising 12 males and 13 females, aged 22 - 50 years. Each bread sample was represented by three different numbers. The bread was prepared into a bread block with dimensions of 15 × 15 × 15 mm, and randomly presented to the evaluator along with water. Nine different SE-AP bread samples were used to assess the structure, colour, crumb colour, elasticity, taste, aroma, and overall acceptability of bread.

Statistical analysis

All statistical analyses were performed and plotted using SPSS Software 22.0 (Version 22.0, SPSS Inc., USA) and Origin Software 2021. Data were represented as mean ± standard deviation (SD) of three replicates. One-way analysis of variance (ANOVA) was used to evaluate the statistical differences between groups, and the differences were considered significant at $p < 0.05$.

Results and discussion

Analysis of main components of untreated AP and SE-AP

As shown in Table 1, there was no significant change in the protein, fat, and ash contents between AP and SE-AP ($p > 0.05$). However, the IDF content decreased from 68.68 ± 1.54% to 41.84 ± 1.36%, while the SDF content increased by 4.76 times, from 5.51 ± 0.32% to 31.72 ± 0.53%. This shift could have been due to the shear stress generated by thermal explosion decomposition during SE that destroyed the macromolecular polysaccharides (including cellulose and lignin) in AP, thus disrupting the original dense structure, and increasing the surface area. Consequently, the lignocellulose structure was severely damaged, resulting in higher SDF content (Wang *et al*., 2023). Liang *et al*. (2017) found that compared to untreated AP, the fibre of SE-AP became more poriferous, the structure became more loose and dilatant, and the water-holding capacity and swelling capacity of SDF increased by 40.64 and 37.79%, respectively. The physicochemical properties of AP were greatly improved.

Table 1. Basic components of untreated AP and SE-AP.

Parameter (%)	Untreated AP	SE-AP
Fat	7.51 ± 0.16^a	7.17 ± 0.21^a
Protein	6.34 ± 0.28^a	6.68 ± 0.25^a
Ash	2.25 ± 0.14^a	2.39 ± 0.26^a
TDF	74.35 ± 2.79^a	73.63 ± 1.98^a
IDF	68.68 ± 1.54^a	41.84 ± 1.36^b
SDF	5.51 ± 0.32^a	31.72 ± 0.53^b

Means followed by different lowercase superscripts in similar row are significantly different ($p < 0.05$).

Effect of SE-AP addition on solubility and swelling power of wheat starch

Figure 1A shows that adding 0 - 12% SE-AP gradually increased the solubility of the mixtures. Increasing the amount of SE-AP 12% resulted in a significant improvement of 4.17% in solubility (10.23 ± 0.25%) compared to the control sample (Figure 1A). However, as the SE-AP powder content exceeded 12%, the solubility of wheat starch gradually decreased. Statistical analysis indicated that solubility differed remarkably between the mixtures containing 12 and 14% of SE-AP. This difference could have been due to an increase in the DF content of SE-AP, which increased the water-holding capacity (Wang *et al*., 2015). Moreover, the increase in solubility with the addition of SE-AP could have been due to an increase in SDF content. However, when the addition of SE-AP powder exceeded 12%, it caused excessive dilution of wheat starch, resulting in a decrease in the solubility of the mixed powder. This could have been due to a combination of excess fibre, resulting in increased water-holding capacity, and less available soluble starch (Hou *et al*., 2020).

As depicted in Figure 1B, when 12% SE-AP was added, the swelling power of mixed powders increased from (2.64 ± 0.08%) to (3.97 ± 0.14%), representing a 1.33% increase compared to the control group. However, when the amount of SE-AP exceeded 12%, the swelling power rapidly decreased. Lai *et al*. (2011) reported a similar phenomenon. The increase in swelling power was induced by the strong swelling property and water-holding capacity of DF in the added SE-AP while its amount was still low. However, as the amount of SE-AP continuously increased, the excessive dilution of wheat starch led to a gradual decrease in swelling power.

Effect of SE-AP addition on relative viscosity of wheat flour

Figure 2 illustrates that adding 12% SE-AP mixed powder reduced relative viscosity from 884.7 ± 20.51 to 761.3 ± 7.51 mPa s, compared to the control group. This resulted in a 14% decrease in relative viscosity. Nonetheless, increasing the amount of SE-AP to 16% decreased the relative viscosity by 0.21 times to 598 mPa s. Consequently, the addition amount of more than 12% of SE-AP exhibited decreasing trend in relative viscosity of the mixture, which could have been due to the addition of SE-AP that lowered the relative content and concentration of

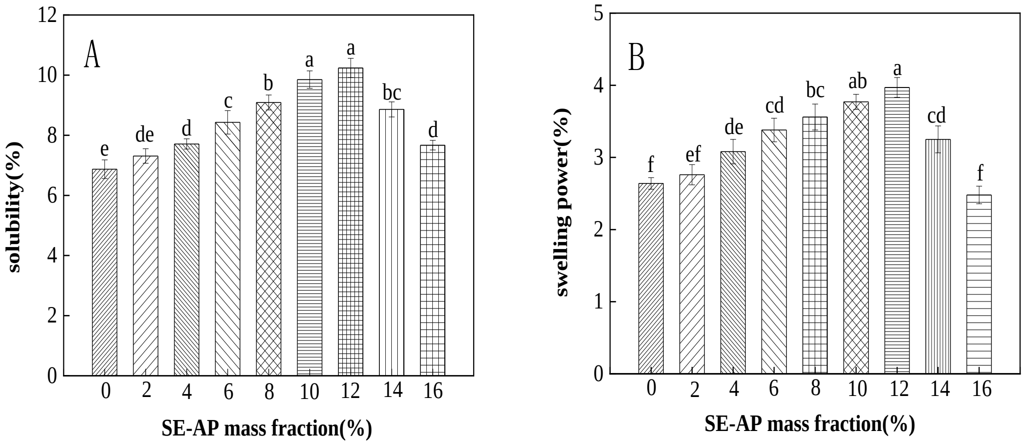

Figure 1. Effect of SE-AP on solubility **(a)** and swelling power **(b)** of wheat flour and SE-AP mixture.

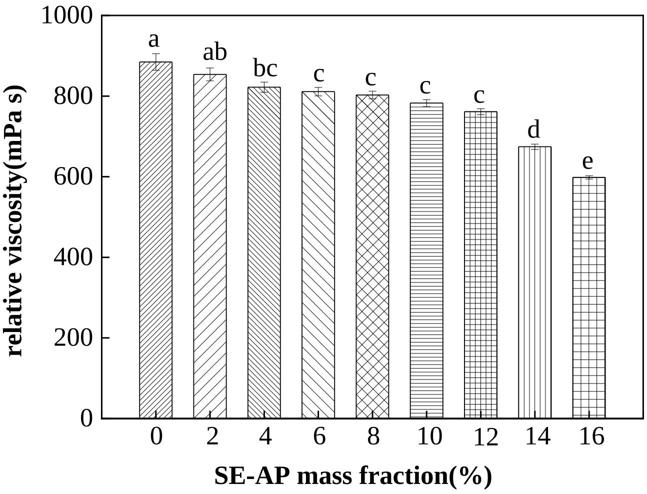

Figure 2. Effect of SE-AP on relative viscosity of wheat flour and SE-AP mixture.

starch. When the mixed powder was gelatinised, the hydrogen bond between amylopectin molecules was difficult to form, and the interaction force was weakened, resulting in a decrease in the relative viscosity (Alamri *et al*., 2012). The SDF in SE-AP showed strong water absorption, limiting the available moisture in the wheat flour, and resulting in a decrease in the final viscosity. In this instance, when SE-AP content increased, the relative viscosity of the wheat flour significantly decreased (Lee and Kim, 2020).

Effect of SE-AP addition on wheat powder retrogradation

Figure 3 demonstrates that an increase in the added amount of SE-AP led to a corresponding increase in the retrogradation value of wheat starch. Specifically, when the amount of SE-AP was increased from 0 to 12%, the retrogradation value of the wheat powder increased from 69.54 ± 0.50 to 82.05 ± 0.29%, representing a 12.51% increase. This increase in sedimentation volume could have been due to the presence of more swollen fibres in the precipitate, which increased the volume of the precipitate following water absorption and expansion (Biduski *et al*., 2018). With an increase in the addition of SE-AP, the retrogradation of wheat starch also increased, suggesting that the addition of SE-AP might have weakened the anti-aging ability of bread. However, Ziobro *et al*. (2013) revealed that the addition of inulin could effectively delay the aging of bread. The IDF contained in AP also settled after centrifugation, resulting in increased sedimentation value. This difference could have been due to the different compositions of DF in the additives.

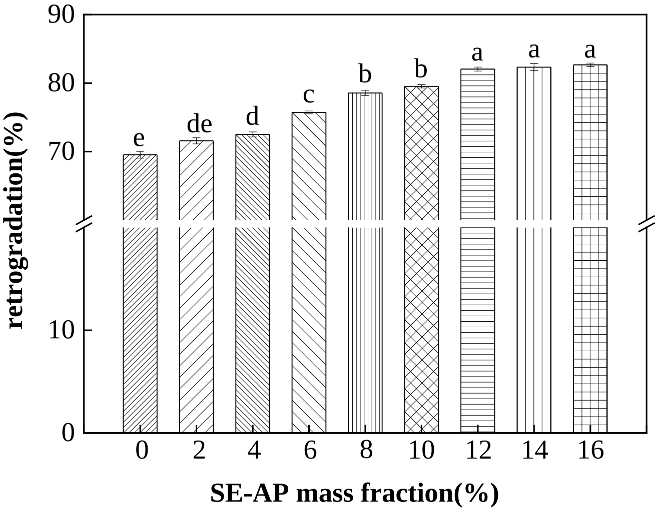

Figure 3. Effect of SE-AP on coagulability of wheat flour and SE-AP mixture.

Effect of SE-AP addition on texture characteristics of bread

To determine the influence of SE-AP on the textural properties of bread, it was added to high-gluten wheat flour in different proportions. The beneficial effects of SE-AP on bread-making are illustrated in Figure 4. When the addition amount of SE-AP was 0 - 10%, the springiness, resilience, and chewiness of bread remarkably increased, potentially enhancing the overall sensory properties of bread. However, as the addition amount of SE-AP increased and exceeded 10%, the springiness, chewiness, and resilience of bread gradually decreased. This could have been due to the dense network structure formed by DF and gluten proteins in SE-AP. The hardness of bread is an important index for evaluating bread quality. Figure 4D indicates that the hardness of bread gradually decreased with increasing amounts of SE-AP. This could have been due to the fact that DF in SE-AP formed more voids in the dough, which were conducive to the entry of air, and reduced bread hardness (Kou *et al*., 2019). DF exhibited strong water absorption and water retention. The addition of a certain proportion of DF can improve the combined water capacity of the dough, reduce water evaporation during the baking process, and soften the bread (Ho *et al*., 2013).

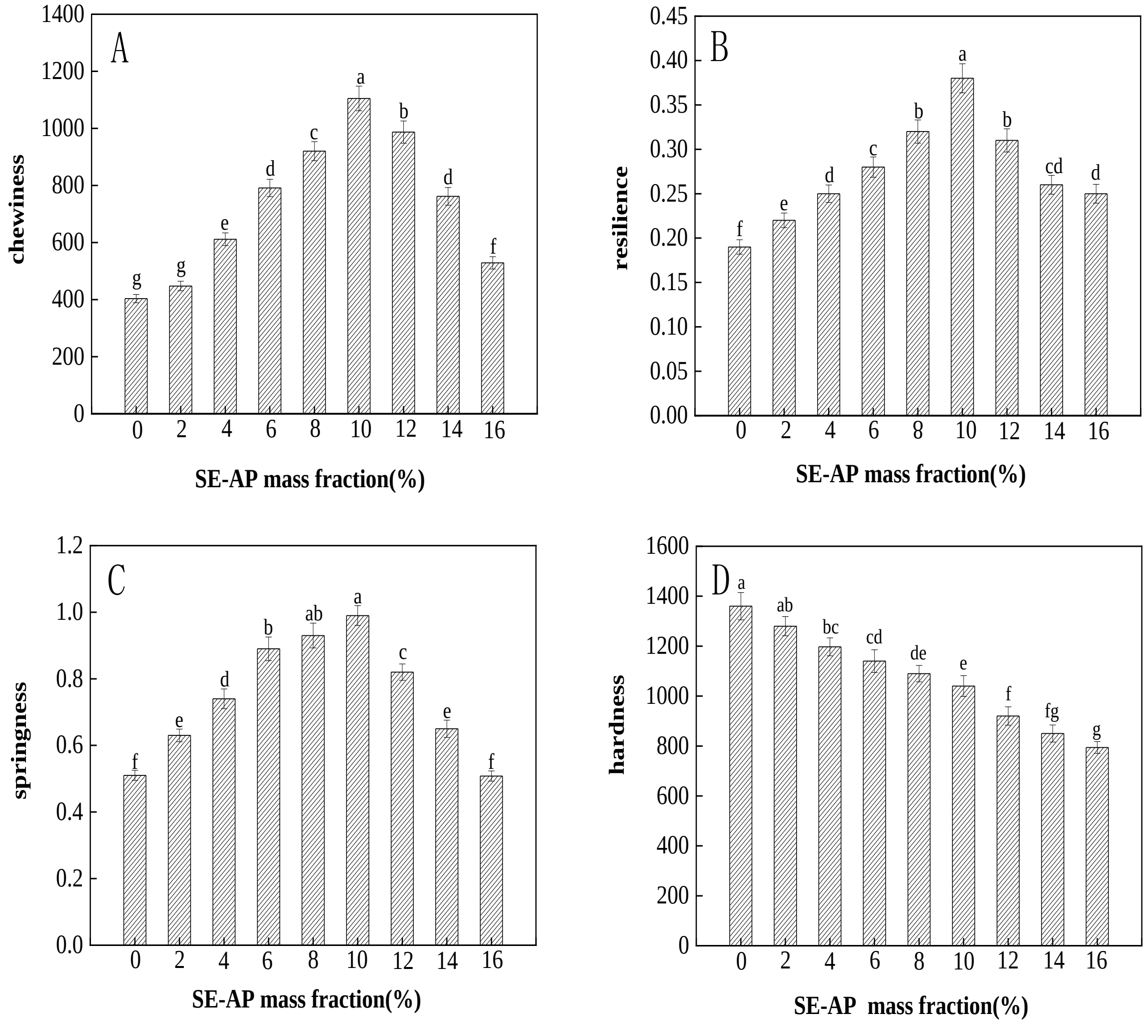

Figure 4. Effect of SE-AP on texture properties of bread.

Effect of SE-AP addition on bread specific volume and sensory analysis

The specific volume of bread reflects the degree of dough volume expansion and retention capabilities. In general, a specific volume is positively correlated with customer satisfaction (Guo *et al*., 2022). Table 2 shows that the specific volume of SE-AP breads varied with the addition amounts. The specific volume of bread was the highest when SE-AP was added at 8%. This could have been due to the fact that SE-AP contained more DF than wheat flour, which might have efficiently maintained gas in

Table 2. Specific volume and sensory characteristics of SE-AP bread with different additions.

SE-AP (%)	Specific volume	Structure	Crumb colour	Crust colour	Exterior appearance	Taste	Odour	Overall acceptability
0	2.15 ± 0.015^{d}	6.75 ± 0.17^{e}	5.54 ± 0.14^{f}	4.82 ± 0.12^{e}	5.52 ± 0.14^{f}	6.21 ± 0.20^{d}	5.28 ± 0.13^{f}	5.69 ± 0.28^{ef}
2	2.09 ± 0.006^{e}	7.25 ± 0.18^{d}	6.08 ± 0.15^{e}	5.09 ± 0.13^{e}	6.18 ± 0.15^{e}	6.39 ± 0.16^{cd}	5.82 ± 0.14^{e}	6.14 ± 0.29^{def}
4	2.22 ± 0.026^{c}	7.65 ± 0.25^{cd}	6.62 ± 0.22^{d}	5.76 ± 0.19^{d}	6.84 ± 0.22^{d}	6.57 ± 0.16^{cd}	6.42 ± 0.16^{d}	6.64 ± 0.25^{cde}
6	2.28 ± 0.029^{b}	8.10 ± 0.27^{bc}	7.34 ± 0.24^{c}	6.26 ± 0.20^{c}	7.50 ± 0.25^{c}	6.75 ± 0.22^{c}	7.02 ± 0.23^{c}	7.16 ± 0.26^{bc}
8	2.37 ± 0.023^{a}	8.51 ± 0.21^{ab}	7.97 ± 0.20^{b}	7.07 ± 0.23^{b}	8.16 ± 0.27^{b}	7.20 ± 0.24^{b}	7.74 ± 0.25^{b}	7.78 ± 0.23^{ab}
10	2.29 ± 0.012^{b}	8.91 ± 0.29^{a}	8.69 ± 0.28^{a}	8.15 ± 0.20^{a}	8.88 ± 0.22^{a}	8.55 ± 0.28^{a}	8.76 ± 0.29^{a}	8.66 ± 0.11^{a}
12	1.93 ± 0.053^{f}	8.42 ± 0.28^{b}	8.15 ± 0.20^{b}	7.20 ± 0.18^{b}	7.26 ± 0.18^{c}	7.29 ± 0.18^{b}	7.92 ± 0.19^{b}	7.71 ± 0.21^{ab}
14	1.86 ± 0.017^{g}	8.10 ± 0.20^{bc}	7.79 ± 0.19^{b}	6.03 ± 0.20^{cd}	6.00 ± 0.15^{e}	6.30 ± 0.15^{d}	6.84 ± 0.17^{c}	6.84 ± 0.37^{bcd}
16	1.82 ± 0.031^{g}	7.70 ± 0.19^{cd}	7.34 ± 0.18^{c}	4.28 ± 0.11^{f}	4.98 ± 0.12^{g}	4.77 ± 0.12^{e}	4.26 ± 0.10^{g}	5.56 ± 0.63^{f}

Means followed by different lowercase superscripts in similar column are significantly different ($p < 0.05$).

the dough and reduced gas cell coalescence during baking, thus enhancing the specific volume of the bread (Azari *et al*., 2020). However, high addition level of SE-AP (> 10%) resulted in a lower specific volume of bread compared to the control group. This was because high addition amount of SE-AP diluted the gluten in the flour, reduced the gluten content in the dough, disrupted the network structure of the gluten, reduced the gas-holding capacity of the dough, and made it difficult to maintain the original volume following fermentation, as reported by Ho *et al*. (2013). Guo *et al*. (2019) found that the addition of 10% sea buckthorn residue to bread increased its specific volume by 10.36% compared to the control group, which was consistent with our findings.

Table 2 displays the sensory analysis results for SE-AP bread with different addition amounts. Figure 5 shows a cross-sectional map of SE-AP bread with different addition amounts. The colour of the bread darkened due to the presence of a high content of reduced sugars in SE-AP. The Maillard reaction occurred during the baking process of bread, generating brown or brown-black melanin-like substances that darkened the colour of the bread. The unique aroma of SE-AP bread was also attributed to the Maillard reaction that occurred during the bread-baking process. Moreover, the colour of the SE-AP ingredients might have contributed to a darker crumb colour (Alongi *et al*., 2019). In combination with the results of sensory analysis, the aromatic odour of SE-AP bread was higher than that of the control bread, indicating that the addition of SE-AP could make bread flavour more appealing to consumers. Figure 5 demonstrates that the volume of SE-AP bread with 4 - 10% addition was higher than in the control group, which was consistent with the results of specific volume. However, compared to the SE-AP bread with 4 - 10% addition, the SE-AP bread with 12 - 16% addition amount had much darker colour and smaller volume. Consequently, the bread with 12 - 16% SE-AP addition gradually lost its appeal. Overall, SE-AP bread with addition amount of 10% had higher sensory score, and could be the most popular SE-AP bread among consumers.

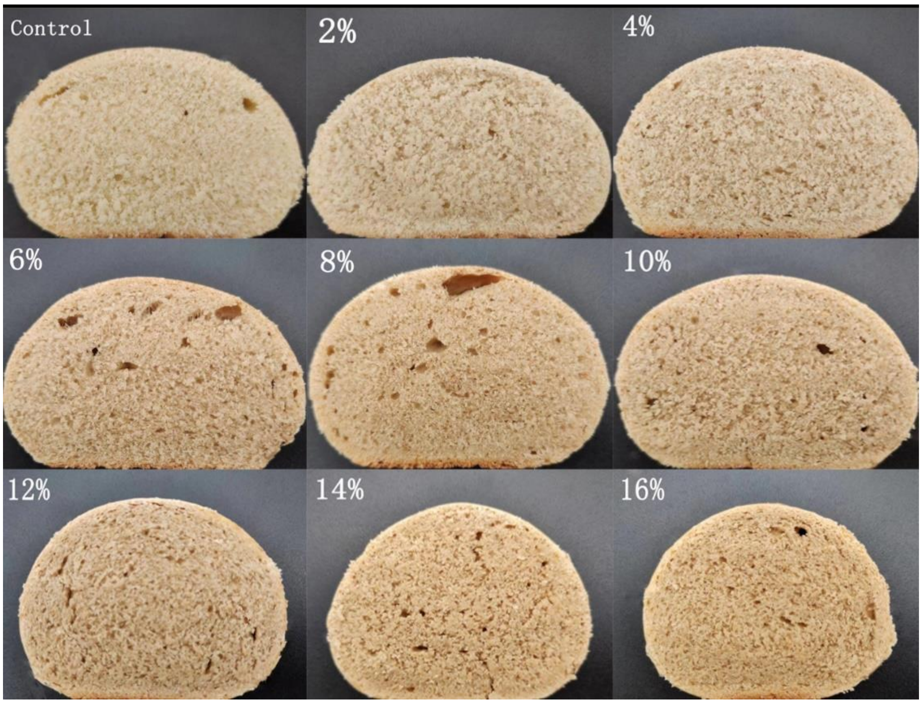

Figure 5. Cross-sectional view of breads with different additions of SE-AP.

Conclusion

The addition of SE-AP into wheat flour significantly altered its physicochemical properties. When the SE-AP level was less than 12%, the properties (swelling power and solubility) of the SE-AP/wheat flour mixture changed owing to the varying SDF, IDF, and wheat flour levels. The retrogradation of wheat flour increased with an increase in SE-AP content, implying that the anti-aging properties of mixed flour bread might have decreased. Simultaneously, combined with the analysis of the texture characteristics of bread, the addition of SE-AP decreased the hardness of mixed powder bread. Therefore, the increase in the coagulation value of the mixed powder could have been due to the sedimentation of DF in SE-AP. Therefore, the effect of adding SE-AP on the anti-aging performance warrants further investigation. The sensory evaluation findings revealed that when the additional amount of SE-AP was 10%, the quality of mixed flour bread was optimal. The addition of SE-AP in bread-making could increase the consumption of SDF while also improving the sensory quality of bread.

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