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Effects of modified starches on the dough rheological properties of wheat flour and frozen storage stability of frozen raw noodles

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ABSTRACT

Cryopreservation is typically used for the long-term storage of frozen noodles. However, the long-term cryopreservation of these high-moisture products may cause ice crystal growth on the substrate and crispy product surfaces. The aim of this study was to explore how hydroxypropyl starch (HPS), hydroxypropyl distarch phosphate, and oxidised starch improve the quality and storage stability of frozen raw noodles (FRN). Analyses of the pasting properties and swelling power indicated delays in the cracking of the substrate and rupture of granules during freezing. After 8 weeks of storage, the peak viscosity increased from 1110 to 1237, 1208, and 1197 cP, respectively. The addition of modified starch restricted the migration of water and reduced the weight loss rate by 3–5 %. The X-ray diffraction results showed that due to the interaction between modified starch and small molecular components, the V-type crystal structure increased, further stabilizing the structure.

1. Introduction

Noodles are among the three major staple foods in the world. They are rich in output, nutritious, tasty, easy to preserve, and highly favoured worldwide (Obadi et al., 2021). Noodles are consumed by hundreds of millions of people daily. More than 2000 kinds of noodle recipes have been developed to date. These recipes are diverse, have strong local characteristics, and reflect the different food cultures and traditions of various regions (Tan et al., 2009).

Fresh noodles typically have a relatively short shelf life ranging from a few days to a week. In modern food production, preservatives and alcohol are often added to inhibit microbial growth and reproduction, consequently delaying spoilage of fresh noodles and extending their shelf life. However, these products often have a strong preservatives or alcohol smell, which reduces their sensory quality. Therefore, frozen noodles have been prepared using cryopreservation technology to facilitate long-term storage and quality maintenance (Zhao, Hou, Liu, Liu, et al., 2023; Zhao, Jia, Hou, Xiao, et al., 2023; Zhao, Jia, Hou, Yang, et al., 2023

Frozen raw noodles (FRN) are a growing part of the global noodle market due to their convenience and high-quality preservation of sensory and nutritional attributes. However, maintaining the quality of FRN during long-term cryopreservation remains a significant challenge, particularly for high-moisture products prone to ice crystal formation, protein denaturation, and structural deterioration. These issues directly affect consumer satisfaction and lead to economic losses in production and distribution. Despite the increasing demand for frozen foods worldwide, research on effective and practical strategies to overcome these challenges is limited. Therefore, developing methods to improve the freezing quality and storage stability of FRN is essential for both the food industry and consumers. Modified starches (MS) provides a promising solution due to its unique physicochemical properties and effectiveness in improving the quality of frozen foods. Investigating the mechanisms by which these starches affect the quality of FRN during long-term storage not only addresses a critical gap in the literature, but also provides a scientific basis for advancing cryopreservation technology.

Food cryopreservation uses low temperatures to preserve food. The food is frozen and maintained in this state to slow down the rate of product decay. This enables long-distance transportation and short or long-term storage (Sun et al., 2023). Freezing technology is important for food preservation; its effectiveness has been demonstrated in the application of low-temperature storage and preservation of fresh noodles. Frozen noodles are based on cold-chain transportation technology

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and are subjected to rapid freezing to replace the traditional acid soaking process associated with conventional long-life noodles. This technology consequently extends their shelf life by inhibiting microbial activity (Wang et al., 2023). Furthermore, it maintains the original flavour, texture, and nutritional value of fresh wet noodles. In addition, the processing technology for FRN differs from that for FCN; FRN do not require pre-cooking before rapid freezing. Because FRN are not pre-cooked, they have a higher palatability than FCN and are closer to the taste of fresh noodles (Liu et al., 2022). Nevertheless, exclusive reliance on low-temperature technology for the long-term preservation of high-moisture products such as noodles may lead to undesirable outcomes. Noodles are prone to ice crystal growth on the substrate, protein degeneration, and crispy product surfaces. Therefore, the quality and stability of FRN during the freezing period must be evaluated to facilitate the development of methods that synergistically improve these properties.

Starch is often modified for better utilisation. Chemical modification, the most common method, involves the addition of functional groups to starch molecules. Common modification methods are oxidation, esterification, etherification, crosslinking, and grafting. Hydroxypropyl starch (HPS) is a starch ether product with excellent stability, as well as anti-freezing and anti-retrogradation characteristics. It is the most widely used MS in the food industry, as it is thick and adhesives (Jiang et al., 2024). This MS is particularly suitable for enhancing the quality of frozen food. The resistance stability of acidic, alkaline, thermal, and cold HPS is higher than that of primary starch. In addition, ether treatment significantly improves freezing stability and transparency. The improved gelatinisation properties of HPS have been attributed to an increase in the hydrophilicity of the starch molecule upon linkage to the hydroxyl group during etherification (Jia, Luo, et al., 2022; Jia, Yang, et al., 2022; Jia, Zhang, et al., 2022). Moreover, Wang et al. (Wang et al., 2024) showed that supplementation with HPS improved the strength and physical stability of a gel with a high internal phase. Hydroxypropyl distarch phosphate (HPDSP) is a chemically modified starch that undergoes hydroxypropylation and cross-linking through phosphate bonds. Hydroxypropylation enhances starch solubility and stability, while cross-linking improves thermal stability and shear resistance, maintaining the starch structure during freezing and thawing. As a result, HPDSP serves as an effective anti-freezing agent and stabilizer for frozen foods (Cui et al., 2014; Zhang et al., 2023; Zhao, et al., 2023).

Oxidised starch (OS) is another common MS. Oxidation, typically occurs on the surface of starch granules, consequently improving starch characteristics, such as solubility, viscosity, and stability. The presence of OS may enhance frost resistance in frozen foods, consequently maintaining stability at low temperatures (Ahsan et al., 2024). This prevents food issues problems caused by freezing, such as granule separation, water release, and textural changes. Moreover, OS has been used as a surface treatment agent to improve the appearance and texture of frozen foods.

In this study, we aimed to evaluate the mechanisms through which HPS, HPDSP, and OS improve the quality and storage stability of FRN. We hypothesised that these modified starches play positive roles in the long-term freezing quality of FRN.

2. Materials and methods

2.1. Materials

Wheat flour was purchased from Yihai Kerry Arawana Holdings Co., Ltd., (China); its water, crude protein, ash contents were 13.78, 11.74, and 0.48 wt%, respectively. Food-grade HPS, HPDSP, and OS were purchased from the Chinese companies Youbaojia Food Co., Ltd., Henan Wanbang Chemical Technology Co., Ltd., and Shanghai Xianwei Food Technology Co., Ltd., respectively, and used without further purification. Food-grade sodium chloride was purchased from Hubei Salt Industry Co., Ltd. (China).

2.2. Degree of swelling analysis

The degree of MS swelling was evaluated as previously described (Wang et al., 2014), with some modifications. A certain amount (M_0) of powder samples was dissolved to prepare 30 mL of a suspension with a mass fraction of 2 %. The suspension was heated at 60, 75, and 90 °C until complete gelatinised. The samples were cooled and centrifuged at 3000 ×*g* (TGL-20BR; Shanghai Anting Scientific Instrument Factory Co., Ltd., Shanghai, China); the mass of the starch precipitate was recorded as M_1. The supernatant was then dried at 105 °C and designated as water-soluble starch; its mass was recorded as M_2. The solubility and degree of swelling were calculated as follows:

$$\text{Solubility } (\%, S) = \frac{M_3 - M_2}{M_1} \times 10 \times 100\% \frac{M_2}{M_0} \times 100\% \tag{1}$$

$$\text{Degree of swelling } (\%) = \frac{M_3 - M_2}{M_1} \times 10 \times 100\% \frac{M_1}{M_0 \times (1 - S)} \times 100\% \tag{2}$$

2.3. Rapid viscosity analysis (RVA)

The pasting properties of MS, wheat flour, and freeze-dried FRN powder were determined as described previously (Jia, Luo, et al., 2022; Jia, Yang, et al., 2022; Jia, Zhang, et al., 2022).

A rapid viscosity analyser (RVA-Super 4; Perten Instruments, Stockholm, Sweden) was used to investigate the viscosities of the powder samples. The sample (approximately 3 g) was heated at 50 °C for 1 min, then increased to 95 °C at a constant rate of 12 °C/min, held at 95 °C for 2.5 min, and then cooled back to 50 °C at the same rate. The rotational speed was set to 960 rad/min for the first 10 s and maintained at 160 rad/min for the remainder of the test. The pasting curves and parameters of the samples were obtained using RVA software.

2.4. Farinograph analysis

Farinograph analysis was performed as previously described (Jia, Luo, et al., 2022; Jia, Yang, et al., 2022; Jia, Zhang, et al., 2022). In each experiment, 299.3 g of wheat flour was mixed with different concentrations of MS. Add water to achieve optimal dough consistency. The farinograph was operated until the dough reached a consistency of 480–520 FU. Parameters such as water absorption, dough development time, stability, degree of softening, and farinograph quality were measured (Brabender GmbH & Co., KG, Duisburg, Germany). All tests were performed in triplicate.

2.5. Extensograph analysis

Wheat flour dough was prepared as described in the farinograph analysis and determined according to Jia et al. (Jia, Luo, et al., 2022; Jia, Yang, et al., 2022; Jia, Zhang, et al., 2022). The dough, prepared in the farinograph, was transferred to an extensograph (Brabender GmbH & Co. KG, Duisburg, Germany), and weight two 150 g samples for rolling and resting. The energy, resistance at constant deformation (R_{50}), extensibility (E), maximum resistance (R_{max}), and ratio (R/E) of the samples were measured and recorded. All experiments were performed thrice and the results were averaged.

2.6. Preparation and storage of FRN

Wheat flour, sodium chloride (1.0 wt%), and water (32 wt%) were used to prepare the FRN. 6 wt% MS was added to the experimental group samples instead of wheat flour. FRN were produced as follows: all materials were mixed in a dough maker (Guangdong Lifeng Machinery Manufacturing Co., Ltd., Guangdong, China) and kneaded at 120 rpm for 1 min, followed by 230 rpm for 9 min. The intermediate product was

Table 1
The pasting and expansion properties of HPS, HPDSP, and OS.

MS	Pasting properties							Expansion properties	
	Peak /cP	Minimum /cP	Breakdown /cP	Final /cP	Setback /cP	Peak time /min	Temperature /°C	Solubility rate /%	degree of swelling
HPS	5008 ± 31^{a}	3429 ± 3^{a}	1579 ± 28^{a}	5668 ± 42^{a}	2239 ± 45^{a}	4.30 ± 0.04^{c}	72.65 ± 0.00^{b}	0.32 ± 0.09^{b}	1.59 ± 0.01^{b}
HPDSP	2722 ± 4^{b}	1920 ± 13^{b}	803 ± 18^{b}	3033 ± 23^{b}	1113 ± 10^{b}	5.24 ± 0.05^{b}	78.40 ± 0.00^{a}	0.78 ± 0.04^{a}	2.68 ± 0.17^{a}
OS	2784 ± 33^{c}	1991 ± 49^{b}	794 ± 16^{b}	2893 ± 71^{c}	903 ± 22^{c}	5.53 ± 0.00^{a}	78.35 ± 0.00^{a}	0.81 ± 0.05^{a}	2.60 ± 0.23^{a}

rested for 20 min at 25 °C; fed continuously through roll gaps of 5, 3.5, 2.5, and 2 mm; and cut using a noodle-cutting machine (Beijing Dongfu Jiuheng Instrument Technology Co., Ltd., Beijing, China). The FRN were pre-treated using an instant freezer (HY-150FL-8L3P, Guangzhou Huayu Refrigeration Equipment Co., Ltd., Guangdong, China) for 1 h at −40 °C and subsequently stored at −20 °C for 0, 2, 4, 6, or 8 weeks.

Vacuum freeze-drying was performed for 72 h immediately after sampling at different storage nodes. Samples were then ground and sieved (100 mesh) to obtain freeze-dried FRN powder.

2.7. Swelling power analysis

The prepared freeze-dried powder was weighted at different storage times as described by Zhang et al. (Zhang, Guo, et al., 2017). Approximately 0.25 g of each sample was stirred with 25 mL deionised water in a 50 mL centrifuge tube and heated at 70 °C and 95 °C for 15 min. The mixture was cooled in cold water for 5 min and centrifuged at 3000 ×*g* (TGL-20BR; Shanghai Anting Scientific Instrument Factory Co., Ltd.) for 10 min. Next the supernatant was discarded and weighed. The original mass of the powder was recorded as W_0, whereas the expanded samples before and after centrifugation were recorded as W_1 and W_2, respectively. The swelling power of FRN was calculated as follows:

$$\text{Swelling power } (g/g) = \frac{M_3 - M_2}{M_1} \times 10 \times 100\% \frac{W_2 - W_1}{W_0} \times 100\% \tag{3}$$

2.8. Freeze-thaw stability analysis

Freeze–thaw stability was evaluated as described previously (Qin et al., 2016). A 5 % (*w/v*) suspension of freeze-dried powder was stirred in water at 90 °C for 30 min, then cooled and weighed. The sample was frozen at −20 °C for 24 h and thawed at room temperature for 1 h. This cycle was repeated three times. The sample was subsequently centrifuged at 4000 ×*g* for 15 min, and the supernatant was removed and weighed. The mass of the starch paste in the centrifuge tube was recorded as M_{sp}, whereas that of the precipitate was recorded as M_p. The FRN dehydration rate was calculated as follows:

$$\text{Dehydration rate } (\%) = \frac{M_3 - M_2}{M_1} \times 10 \times 100\% \frac{M_{sp} - M_p}{M_{sp}} \times 100\% \tag{4}$$

2.9. Weight loss rate analysis

This analysis was conducted as described previously (Zhao, Hou, Liu, Liu, et al., 2023; Zhao, Jia, Hou, Xiao, et al., 2023; Zhao, Jia, Hou, Yang, et al., 2023). The FRN mass before freezing was recorded as M_{w0}, whereas that of the samples at different storage times (2-week intervals) was recorded as M_n. The weight loss rate of FRN was calculated using the following equation:

$$\text{Weight loss rate } (\%) = \frac{M_3 - M_2}{M_1} \times 10 \times 100\% \frac{M_{w0} - M_n}{M_{w0}} \times 100\% \tag{5}$$

2.10. X-ray diffraction

X-ray diffraction (XRD) was performed as previously described (Zhou et al., 2022), with some modifications. XRD patterns of freeze-dried FRN power were measured using an X-ray diffractometer (XRD; Rigaku SmartLab, Rigaku Corporation, Japan) at 45 KV and 40 mA using Cu-Kα irradiation. The samples were scanned at room temperature, at a scanning frequency of 2°/min ranging from 4° to 60°. The peaks of the images were analysed using MDI Jade 6 software.

2.11. Statistical analysis

All data were statistically analysed using one-way analysis of variance, and the mean values were compared using Duncan's multiple range test ($p < 0.05$). Curves were drawn using ORIGIN (version 9.0; Origin Lab Inc., USA). Statistical analyses were performed using SPSS software (version 19.0; IBM Corp., Armonk, NY, USA).

3. Results and discussion

3.1. Pasting and expansion properties of MS

The pasting and expansion of starch requires water and heat, which also depend on the concentration and temperature. The degree of gelatinization is influenced by amylose and amylopectin, with amylose more prone to gelatinization and retrogradation, while amylopectin tends to undergo long-term retrogradation (Jia, Luo, et al., 2022; Jia, Yang, et al., 2022; Jia, Zhang, et al., 2022). HPS, HPDSP, and OS also showed different pasting and swelling parameters owing to structural changes caused by the modification process.

Peak viscosity is an important indicator of pasting properties. The pasting and expansion parameters of the MS are listed in Table 1. In this study, HPS had higher viscosity than HPDSP and OS. In addition, its peak time and pasting temperature were the lowest. The lower temperature indicates that the granules required less heat for expansion and lysis. The pasting parameters of HPDSP and OS were similar; however, they obviously differed from those of HPS. Moreover, both provide analogous thermal sensitivities and stabilities (Cheng et al., 2022). The breakdown and setback viscosities showed granule stability and degree of retrogradation, respectively, in pasting parameters. These were significantly related to viscosity parameters, especially peak viscosity (Yang et al., 2021).

The degree of swelling measures the ability of starch granules to absorb water and swell. The expansion parameters of the MS are listed in Table 1. Different starch types may exhibit varying degrees of swelling. HPS exhibited the lowest degree of swelling in the present study, indicating that introduction of hydroxypropyl groups had a limited impact on the degree of swelling. HPDSP exhibited some swelling due to cross-linking, while oxidation in OS shortens the starch molecular chains, enhancing the water absorption and expansion. The degree of starch swelling is related to the amylose-to-amylopectin ratio and water-holding properties of granules (Vamadevan & Bertoft, 2020). The differences in pasting behavior among HPS, HPDSP, and OS were further contextualized with their molecular interactions. For instance, compared to OS, HPS has lower swelling ability, which is consistent with studies that hydroxypropylation introduces steric hindrance and limits water penetration into particles. On the contrary, oxidation breaks glycosidic bonds, increases hydrophilic groups, and enhances swelling. This mechanism strengthens the connection between structural changes and functional outcomes. This mechanism explains the relationship

Table 2
Effects of HPS, HPDSP, and OS on the pasting properties of wheat flour.

MS	Addition/%	Pasting properties						
		Peak /cP	Minimum /cP	Breakdown /cP	Final /cP	Setback /cP	Peak time /min	Temperature /°C
	0	1817 ± 7^{b}	1277 ± 21^{d}	539 ± 24^{a}	2312 ± 27^{c}	1035 ± 48^{c}	6.22 ± 0.04^{a}	90.47 ± 0.08^{a}
	3	1834 ± 7^{b}	1283 ± 35^{d}	551 ± 37^{a}	2360 ± 32^{bc}	1077 ± 67^{c}	6.16 ± 0.10^{ab}	89.38 ± 0.97^{ab}
HPS	6	1863 ± 78^{b}	1329 ± 22^{c}	533 ± 56^{a}	2438 ± 102^{b}	1108 ± 80^{bc}	6.18 ± 0.08^{ab}	89.03 ± 1.27^{ab}
	9	1982 ± 15^{a}	1402 ± 5^{b}	580 ± 10^{a}	2604 ± 7^{a}	1202 ± 8^{ab}	6.20 ± 0.00^{ab}	88.55 ± 0.48^{bc}
	12	2038 ± 28^{a}	1444 ± 20^{a}	594 ± 8^{a}	2688 ± 34^{a}	1244 ± 40^{a}	6.09 ± 0.03^{b}	87.47 ± 0.42^{c}
	0	1817 ± 7^{c}	1277 ± 21^{a}	539 ± 24^{c}	2312 ± 27^{d}	1035 ± 48^{a}	6.22 ± 0.04^{a}	90.47 ± 0.08^{a}
	3	1827 ± 7^{c}	1278 ± 17^{a}	549 ± 19^{bc}	2337 ± 4^{d}	1059 ± 19^{a}	6.18 ± 0.10^{ab}	89.30 ± 0.48^{b}
HPDSP	6	1862 ± 17^{b}	1285 ± 43^{a}	577 ± 27^{ab}	2386 ± 16^{c}	1100 ± 53^{ab}	6.11 ± 0.08^{abc}	88.78 ± 0.03^{b}
	9	1891 ± 9^{a}	1298 ± 7^{a}	600 ± 5^{a}	2428 ± 11^{b}	1128 ± 21^{b}	6.07 ± 0.00^{bc}	87.88 ± 0.12^{c}
	12	1911 ± 17^{a}	1306 ± 16^{a}	605 ± 9^{a}	2463 ± 14^{a}	1158 ± 17^{b}	6.05 ± 0.04^{c}	87.75 ± 0.48^{c}
	0	1817 ± 7^{a}	1277 ± 21^{a}	539 ± 24^{a}	2312 ± 27^{a}	1035 ± 48^{a}	6.22 ± 0.04^{a}	90.47 ± 0.08^{ab}
	3	1673 ± 24^{c}	1194 ± 44^{bc}	479 ± 24^{b}	2033 ± 15^{d}	839 ± 58^{b}	6.33 ± 0.12^{a}	91.7 ± 1.06^{a}
OS	6	1688 ± 17^{c}	1177 ± 13^{c}	512 ± 6^{ab}	2077 ± 11^{c}	900 ± 16^{b}	6.20 ± 0.07^{a}	90.45 ± 0.83^{ab}
	9	1717 ± 12^{b}	1222 ± 30^{bc}	495 ± 20^{b}	2114 ± 5^{b}	892 ± 35^{b}	6.26 ± 0.12^{a}	90.43 ± 0.83^{ab}
	12	1735 ± 1^{b}	1230 ± 9^{ab}	505 ± 8^{ab}	2141 ± 24^{b}	912 ± 33^{b}	6.24 ± 0.05^{a}	89.65 ± 0.00^{b}

between structural changes and functional outcomes.

3.2. Pasting properties of wheat flour

RVA was used to evaluate the effects of MS granule expansion on wheat flour after interaction with water during heating. The results are shown in Table 2.

The leaching rate of amylose, degree of complex formation by amylose combined with lipids or other small molecules, and competition for water between the leached amylose and incompletely gelatinised starch affect the change in peak viscosity (Zhang, Kim, & Lim, 2017). We hypothesised that the effect of MS on the pasting properties of wheat flour can be attributed to the competitive adsorption of water molecules between the MS and starch components of wheat flour during heating, as well as the interaction between starch chains.

The effects of HPS and HPDSP on wheat flour viscosity differed from those of OS in this study (Table 2). The viscosities of the samples increased with the concentrations of HPS and HPDSP. Within the range of 0 % to 12 %, the addition of HPS and HPDSP increased the peak viscosity from 1817 cP to 2038 cP and 1911 cP, respectively. Hydroxypropylation may increase starch solubility, thereby enhancing the interaction between starch and water molecules. This consequently increases the viscosity of the system. HPDSP maintained its viscosity at high temperatures owing to cross-linking. Thus, its viscosity was slightly lower than that of HPS (Witczak et al., 2012). A different trend was observed in the OS group. In the initial stages, the addition of non-gluten OS may dilute the gluten content of wheat flour, which is responsible for elasticity and viscosity. High water absorption was observed at high OS concentrations, resulting in an increase in the overall viscosity (Chan et al., 2009).

The temperature at which complete gelatinisation was achieved was within the acceptable range. All samples showed a decrease in temperature after the addition of MS (Table 2); the relatively low gelatinisation temperature of the MS affected those of the mixed system. However, the introduction of multiple hydrophilic groups improved the water retention of the system, causing rapid gelatinisation of starch molecules and reduced heat absorption. This suggests that the optimal cooking time of FRN increases with the addition of MS, thereby saving energy. Compared with the addition of OS, the addition of HPS and HPDSP resulted in a greater decrease in pasting temperature, dropping to 87.47 °C and 97.75 °C, respectively (with an addition amount of 12 %). Xanthan gum was used to improve the quality of frozen noodles and reduce energy consumption as described by Pan et al. (Pan et al., 2016).

3.3. Rheological properties of the doughs

3.3.1. Farinograph analysis

Dough quality affects the quality of FRN during storage. In this study, dough quality was evaluated based on classical rheological properties, including farinograph and extensograph analyses (Jia, Luo, et al., 2022; Jia, Yang, et al., 2022; Jia, Zhang, et al., 2022). The effects of MS on the farinograph properties of wheat flour are shown in Table 3.

The water absorption of the flour, dough development time, stability, and farinograph quality number of wheat flour dough decreasedwith the

Table 3
Effects of HPS, HPDSP, and OS on the farinograph properties of wheat flour.

MS	Addition /%	Farinograph properties				
		Water absorption /mL/100 g	Dough development /min	Stability /min	Degree of softening /FU	Farinograph quality number /mm
	0	62.2 ± 0.1^{a}	6.3 ± 0.3^{a}	7.3 ± 0.1^{a}	63 ± 1^{cd}	97 ± 2^{a}
	3	62.0 ± 0.1^{a}	6.0 ± 0.4^{a}	7.6 ± 0.1^{a}	58 ± 5^{d}	95 ± 3^{a}
HPS	6	61.3 ± 0.1^{b}	5.7 ± 0.4^{ab}	6.9 ± 0.2^{b}	68 ± 6^{bc}	83 ± 4^{b}
	9	60.7 ± 0.1^{c}	5.0 ± 0.4^{b}	6.6 ± 0.2^{b}	76 ± 1^{b}	79 ± 2^{c}
	12	59.9 ± 0.2^{d}	1.7 ± 0.0^{c}	5.6 ± 0.2^{c}	88 ± 4^{a}	64 ± 1^{d}
	0	62.2 ± 0.1^{a}	6.3 ± 0.3^{a}	7.3 ± 0.1^{a}	63 ± 1^{d}	97 ± 2^{a}
	3	60.5 ± 0.0^{b}	4.9 ± 0.2^{b}	6.6 ± 0.6^{b}	79 ± 1^{c}	76 ± 6^{b}
HPDSP	6	59.5 ± 0.0^{c}	2.1 ± 0.1^{c}	5.8 ± 0.0^{c}	84 ± 3^{c}	66 ± 0^{c}
	9	59.0 ± 0.0^{d}	2.7 ± 1.2^{c}	5.2 ± 0.0^{cd}	99 ± 9^{b}	61 ± 1^{c}
	12	58.6 ± 0.1^{e}	1.7 ± 0.0^{c}	4.7 ± 0.3^{d}	116 ± 4^{a}	53 ± 4^{d}
	0	62.2 ± 0.1^{a}	6.3 ± 0.3^{a}	7.3 ± 0.1^{a}	63 ± 1^{c}	97 ± 2^{a}
	3	61.0 ± 0.6^{b}	4.3 ± 0.1^{b}	5.6 ± 1.0^{b}	73 ± 11^{c}	73 ± 3^{b}
OS	6	61.1 ± 0.1^{b}	3.0 ± 0.4^{c}	4.4 ± 0.2^{c}	75 ± 1^{c}	60 ± 0^{c}
	9	60.7 ± 0.1^{b}	2.8 ± 0.4^{cd}	3.5 ± 0.2^{d}	90 ± 4^{b}	45 ± 4^{d}
	12	60.0 ± 0.1^{c}	2.1 ± 0.5^{d}	2.6 ± 0.1^{e}	104 ± 7^{a}	35 ± 1^{e}

Table 4
Effects of HPS, HPDSP, and OS on the extensograph properties of wheat flour.

MS	Addition /%	Extensograph properties				
		Enegry /cm^2	R_{50} /EU	Extensibility, E /mm	R_{max} /EU	R/E
HPS	0	56 ± 2^{b}	205 ± 6^{c}	156 ± 1^{a}	262 ± 10^{c}	1.4 ± 0.1^{c}
	3	60 ± 0^{a}	247 ± 11^{ab}	142 ± 3^{b}	305 ± 5^{a}	1.8 ± 0.1^{b}
	6	54 ± 1^{b}	260 ± 8^{a}	133 ± 6^{c}	309 ± 6^{a}	2.1 ± 0.1^{a}
	9	56 ± 1^{b}	244 ± 0^{ab}	136 ± 1^{bc}	294 ± 6^{ab}	1.8 ± 0.1^{b}
	12	49 ± 1^{c}	232 ± 13^{b}	131 ± 0^{c}	277 ± 8^{bc}	1.8 ± 0.1^{b}
HPDSP	0	56 ± 2^{a}	205 ± 6^{a}	156 ± 1^{a}	262 ± 10^{a}	1.4 ± 0.1^{b}
	3	53 ± 4^{ab}	213 ± 4^{a}	149 ± 2^{b}	265 ± 9^{a}	1.5 ± 0.1^{ab}
	6	49 ± 3^{ab}	205 ± 1^{a}	144 ± 0^{bc}	245 ± 11^{a}	1.4 ± 0.0^{ab}
	9	48 ± 6^{ab}	211 ± 3^{a}	139 ± 0^{c}	251 ± 18^{a}	1.6 ± 0.1^{a}
	12	44 ± 4^{b}	204 ± 7^{a}	130 ± 4^{d}	234 ± 11^{a}	1.6 ± 0.1^{a}
OS	0	56 ± 2^{a}	205 ± 6^{a}	156 ± 1^{a}	262 ± 10^{a}	1.4 ± 0.1^{a}
	3	46 ± 1^{b}	185 ± 1^{b}	144 ± 2^{b}	227 ± 3^{b}	1.3 ± 0.0^{a}
	6	33 ± 2^{c}	148 ± 6^{c}	134 ± 4^{c}	168 ± 8^{c}	1.1 ± 0.0^{b}
	9	32 ± 0^{c}	137 ± 1^{d}	140 ± 4^{bc}	154 ± 1^{c}	1.0 ± 0.0^{bc}
	12	27 ± 0^{d}	126 ± 3^{e}	135 ± 1^{c}	136 ± 0^{d}	1.0 ± 0.1^{c}

addition of HPS, HPDSP, and OS, whereas the degree of softening increased, indicating that the properties deteriorated. Some acidic groups in MS create a weakly acidic environment that may not be conducive to the formation of a stable gluten network (Chen et al., 2021). When the concentration of HPS was 3 %, the stability of the wheat flour dough was higher than that of the control in this study. This indicates that the farinograph properties of the dough were improved by HPS addition. Introducing an appropriate number of hydroxypropyl groups enabled water absorption by the system and stabilised the spatial network structure through hydrogen bonds; this effect was greater than the diluting effect of MS on gluten. As the MS concentrations increased, the dilution of gluten in the system led to insufficient conditions for the formation of a stable gluten network. This consequently prevented the interconnection and expansion of the gluten network, indicating that the farinograph quality number dropped significantly.

3.3.2. *Extensograph analysis*

Extensograph properties are also important indicators of the classic rheological properties of wheat flour dough. They reflect the resistance of the mechanical properties and extension of the dough (Jia, Luo, et al., 2022; Jia, Yang, et al., 2022; Jia, Zhang, et al., 2022). Table 4 shows the effects of MS on the extensographic properties of wheat flour dough.

The area of the curve, also called the energy, was used to characterise the work performed by stretching the sample. The energy of the sample containing 3 % HPS was higher than that of the control, indicating that the dough had a higher mechanical strength. The non-linear relationship between HPS concentration and dough stability was further explored. When adding 3 % HPS, the balance between hydroxypropyl-induced hydration and gluten dilution is beneficial for network stabilization. However, high concentrations can disrupt the network structure. This emphasizes the importance of optimizing the level of additives in industrial applications. In addition, the energy continued to decrease with an increase in HPDSP and OS concentrations. However, it decreased more in the OS group than in the HPDSP group.

Table 5
Effects of HPS, HPDSP, and OS on the pasting properties of FRN during 0–8-week frozen storage.

MS	Storage time/ weeks	Viscosity			
		Peak /cP	Minimum /cP	Final /cP	Setback /cP
Control	0	1158 ± 17^{ab}	894 ± 11^{bc}	1707 ± 31^{a}	813 ± 28^{a}
	2	1172 ± 9^{a}	920 ± 8^{a}	1698 ± 21^{a}	778 ± 29^{a}
	4	1148 ± 3^{b}	901 ± 10^{ab}	1666 ± 29^{a}	764 ± 38^{a}
	6	1145 ± 3^{b}	902 ± 5^{ab}	1708 ± 11^{a}	805 ± 8^{a}
	8	1110 ± 12^{c}	875 ± 14^{c}	1667 ± 9^{a}	792 ± 10^{a}
6 %HPS	0	1326 ± 18^{a}	1036 ± 17^{ab}	1917 ± 14^{a}	880 ± 13^{a}
	2	1292 ± 5^{a}	1031 ± 15^{ab}	1863 ± 6^{ab}	832 ± 21^{a}
	4	1225 ± 11^{b}	984 ± 18^{c}	1814 ± 53^{b}	830 ± 68^{a}
	6	1315 ± 21^{a}	1065 ± 30^{a}	1909 ± 30^{a}	844 ± 59^{a}
	8	1237 ± 30^{b}	1010 ± 23^{bc}	1836 ± 15^{b}	825 ± 22^{a}
6 % HPDSP	0	1279 ± 21^{a}	987 ± 17^{a}	1876 ± 14^{a}	889 ± 11^{a}
	2	1250 ± 9^{ab}	981 ± 21^{ab}	1813 ± 40^{b}	832 ± 57^{b}
	4	1174 ± 24^{d}	952 ± 15^{b}	1728 ± 33^{c}	777 ± 18^{c}
	6	1243 ± 20^{b}	973 ± 17^{ab}	1833 ± 20^{ab}	860 ± 7^{ab}
	8	1208 ± 9^{c}	966 ± 4^{ab}	1822 ± 25^{b}	856 ± 23^{ab}
6 %OS	0	1324 ± 14^{a}	1012 ± 23^{a}	1913 ± 17^{a}	901 ± 39^{a}
	2	1272 ± 11^{c}	991 ± 10^{ab}	1864 ± 31^{bc}	872 ± 39^{a}
	4	1228 ± 7^{d}	970 ± 9^{bc}	1844 ± 32^{c}	874 ± 39^{a}
	6	1295 ± 4^{b}	1013 ± 4^{a}	1890 ± 15^{ab}	878 ± 17^{a}
	8	1197 ± 19^{e}	951 ± 10^{c}	1845 ± 1^{c}	848 ± 17^{a}

The resistance at constant deformation (R_{50}) also characterises the extensograph properties of the dough. It reflects the gluten content and overall strength of the dough and is positively correlated with gluten strength. As shown in Table 4, the R_{50} of the wheat flour dough was significantly negatively correlated with the amount of OS added in the present study. R_{50} significantly decreased with an increase of added amounts in OS contents, indicating that the addition of OS reduced the strength of the dough. Different trends were observed for the HPS and HPDSP groups. The R_{50} increased significantly at lower concentrations of HPS, whereas it showed the opposite trend at higher concentrations, reaching a maximum value at 6 % HPS. This may be due to the structural characteristics and molecular weight of HPS, as well as the interaction between the introduced groups and the gluten network to consolidate the gluten structure (Zhao, Hou, Liu, Liu, et al., 2023; Zhao, Jia, Hou, Xiao, et al., 2023; Zhao, Jia, Hou, Yang, et al., 2023). Nevertheless, HPDSP had no significant effect on the dough. The maximum resistance (R_{max}) is the resistance under breaking, and its changing trend was consistent with that of R_{50} following the addition of MS.

3.4. *Pasting properties of FRN*

The viscosity of the system increases rapidly because starch absorbs a large amount of water and rapidly gelatinises upon heating. The viscosity of wheat flour was significantly and positively correlated with the sensory evaluation scores of frozen cooked noodles in a previous study

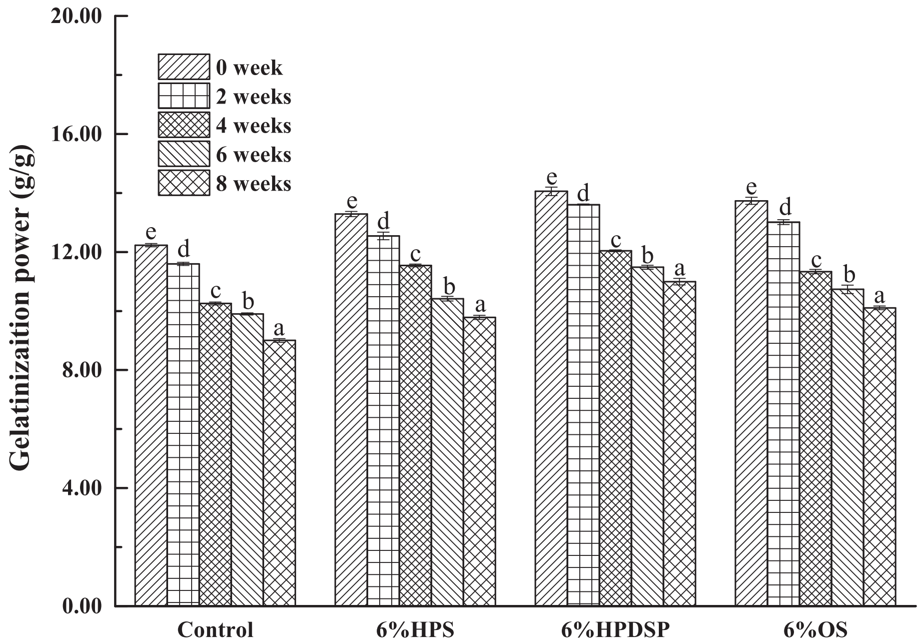

Fig. 1. Effects of HPS, HPDSP, and OS on the swelling power of FRN during 0–8-week frozen storage.

(Li et al., 2012). This indicates that modern food processing techniques tend to rely on raw materials with high viscosities to produce high-quality noodles. In addition, high energy consumption during FRN cooking remains a challenge. In this study a rapid viscosity analyser was used to measure and characterise changes in the viscosity of FRN containing MS. The results are shown in Table 5.

The observed viscosity attributed to starch adsorption and moisture retention under heating and stirring, which involved the gelatinisation of starch. The peak, minimum, and final viscosities of FRN decreased significantly during freezing storage (Table 5) in the absence of MS. The peak viscosity, minimum viscosity, and final viscosity of the untreated noodles decreased by approximately 4.15 %, 2.13 %, and 2.34 %, respectively, when stored until the 8th week. This indicates that freezing damaged the starch granules of FRN. Therefore, these granules failed to absorb more water molecules over time, indicating that the quality of FRN deteriorated. In contrast, the decrease in viscosity was significantly inhibited with the addition of MS.

After 8 weeks of freezing, the peak viscosity of FRN samples with MS added were 1237 cP (HPS), 1208 cP (HPDSP), and 1197 cP (OS), respectively, which were higher than the control group (1110 cP). A similar trend was observed for the minimum and final viscosities. This may be attributed to high molecular weight of MS, as well as the large number of molecular groups that promote the formation of hydrogen bonds. Starch paste is thicker because of the reduced loss of amylose and amylopectin by cross-linking. Consistent with these findings, the MS extended and adsorbed more water during starch gelatinisation in the

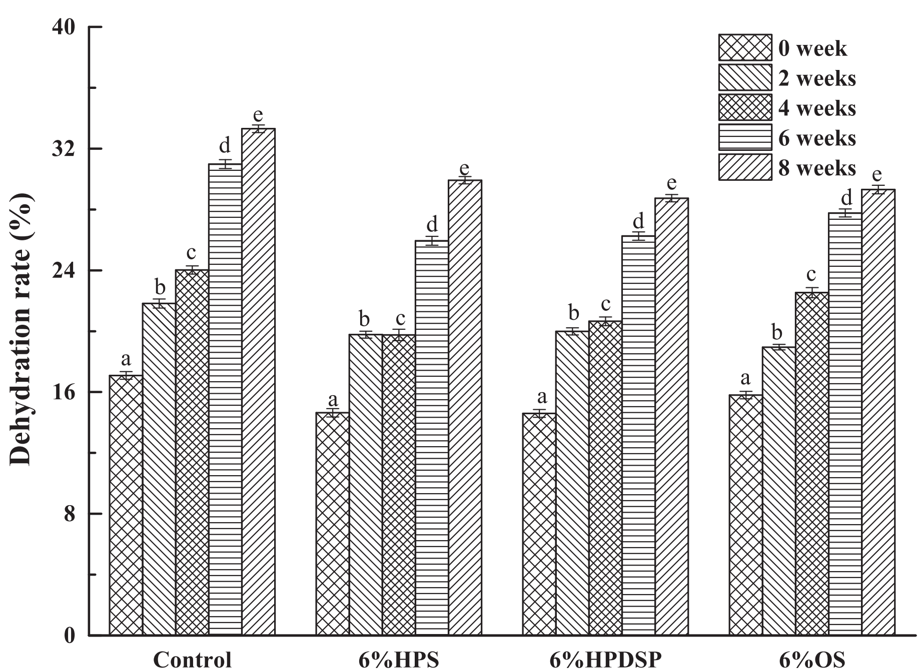

Fig. 2. Effects of HPS, HPDSP, and OS on the dehydration rate of FRN during 0–8-week frozen storage.

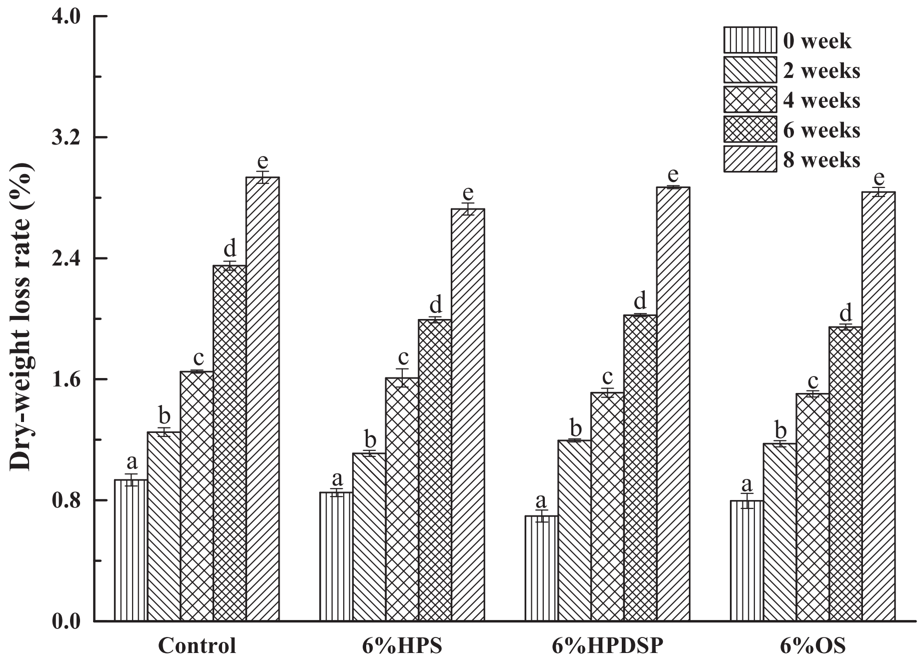

Fig. 3. Effects of HPS, HPDSP, and OS on the weight loss rate of FRN during 0–8-week frozen storage.

present study, thereby promoting the expansion of starch granules and increasing the FRN viscosity. In addition, MS interacted with the starch and protein of FRN, resulting in an increase in viscosity of the system. However, the effects on the viscosity of FRN differed among the MS. Under the same storage time, the peak and minimum viscosities of the HPS group were higher than those of the other two groups. This difference may be related to the modification category and chemical structure of each MS.

3.5. The swelling power of FRN

Swelling power refers to the ability of starch to form a gel during heating. Starch granules absorb water and gel within a certain temperature range to form gel-like structures. Measuring the swelling power usually involves observing the gel-forming properties and changing mass of the starch paste upon heating. A positive correlation has been observed between the swelling power and viscosity of starch (Li et al., 2017). The effects of MS on the swelling power of FRN during frozen storage are shown in Fig. 1.

Mechanical damage to FRN was accompanied by the disintegration and rupture of starch granules under long-term frozen storage conditions. In addition, the gluten network structure loosened and became unstable. The swelling power of FRN significantly decreased with an increase in freezing time in the present study (Fig. 1). The swelling power of the freeze-dried powder containing MS differed from that of the control. Overall, the swelling power of the experimental groups was higher than that of the control group. The introduction of starch components enabled the absorption of water molecules into the system and increased the contents of swollen granules. The introduction of functional groups to form MS breaks the hydrogen bond of the original starch molecule; this facilitates swelling. Our results demonstrated the maintenance of FRN quality during frozen storage.

3.6. Freeze-thaw stability analysis

Freeze thaw stability refers to the ability of food to maintain texture, structure, mouthfeel, and other characteristics during freezing and thawing (Fu et al., 2023). These properties are critical for the production and quality maintenance of frozen food quality. FRN also need to maintain good freeze thaw stability to ensure quality in taste and appearance after thawing. Moisture is frozen at low temperatures and melts as the temperature increases, thereby causing dehydration. This process may hold special significance for certain applications or fields, such as the food industry and freezing and preservation technology.

The dehydration rate reflects the freeze-thaw stability of starch during the freeze-thaw cycle. Changes in the dehydration rate of FRN after three freeze–thaw cycles at different storage times are shown in Fig. 2. The texture of starch was mechanically damaged after three freeze–thaw cycles. This leads to precipitation of moisture. Liu et al. demonstrated that the size of starch granules decreased after freeze–thaw treatment. They attributed this to the extrusion caused by the growth of ice crystals, resulting in the depression of starch (Liu et al., 2023). The freezing storage time had a significant impact on the freeze-thaw stability the of freeze-dried FRN powder in the present study.

All samples showed a significant ($p < 0.05$) increase in dehydration rate with increasing storage time, indicating that FRN quality deteriorated due to freezing. In addition, MS decreased the dehydration rate of the samples compared with the control under the same freeze–thaw cycles and freezing storage time. This indicates that MS may have an inhibitory effect on freeze-thaw dehydration. Furthermore, HPS, HPDSP, and OS exhibited different inhibitory effects on freeze-thaw dehydration at different time points. MS improved the freeze-thaw stability of FRN, which may be because the combination of the entire system was promoted.

In a previous study, corn and amaranth starch derived via hydroxypropylation demonstrated the poor freeze-thaw stability of unmodified starch. The resistance to syneresis improved with increasing MS concentrations. This was indicated by an increased number of freeze–thaw cycles showing a delay in syneresis (Pal et al., 2002).

3.7. Weight loss rate analysis

Weight loss refers to the difference in water vapour pressure caused by temperature changes during the freezing and storage of frozen food and the sublimation of ice crystals, which causes the surface to dry out and reduces food quality (Mulot et al., 2019). Food undergoes weight loss during the cooling, freezing, and refrigeration processes. This not only causes dehydration and weight loss, but also shrinks the surface and

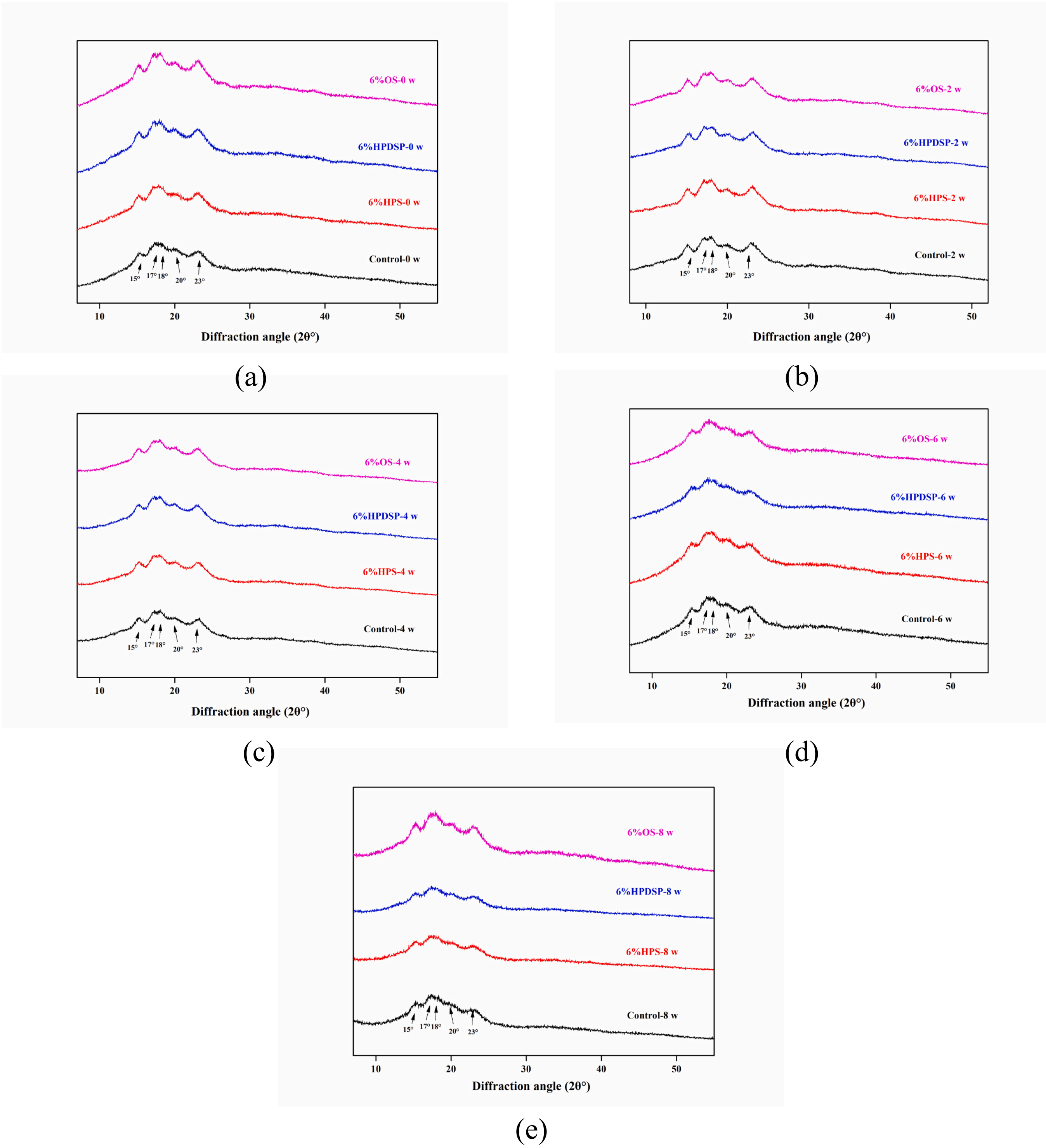

Fig. 4. Effects of HPS, HPDSP, and OS on the crystal structure of FRN during 0–8-week frozen storage. (a), (b), (c), (d) and (e) represent 0, 2, 4, 6, and 8 weeks of frozen storage, respectively.

reduces the quality of the food.

The intrinsic cause of weight loss is the evaporation of water or sublimation of ice crystals, which is essentially water loss (Mulot et al., 2019). This may result in product dehydration and weight loss, which affects the flavour and quality of the food. The effects of MS on the weight loss rate of FRN are shown in Fig. 3. The weight loss rate of FRN continued to increase over the frozen storage period, and the growth rate increased significantly ($p < 0.05$) with time. This may be because the partial pressure of water vapour on the surface of FRN is greater than that of air. The partial pressure of the water vapour medium often causes diffusion of the water molecules from the inside of the FRN to the outside. In addition, the formation of larger ice crystals damages the noodle substrate, further promoting water loss. Moreover, the sharp decline in the gluten network structure in the later stages of freezing causes more water molecules to escape the interior of the gluten and migrate to the noodle surface (Zhao, Hou, Liu, Liu, et al., 2023).

After the addition of the three MS, the weight loss rate decreased during the freezing period compared with that in the control. This indicates that the tendency of water molecules to flow to the surface was restricted. In addition, the decrease in the weight loss rate was not evident in the MS-FRN system during the first 4 weeks of frozen storage. However, the addition of MS in the 6th and 8th weeks of freezing significantly delayed the loss rate. This confirmed that the FRN moisture was retained, and that MS enhanced the frost resistance of the substrate.

3.8. XRD analysis

Starch granules are polycrystalline and typically have three spatial structures, strongly crystalline, sub-crystalline and amorphous (Su et al., 2020). In the present study, the crystal structure of starch was analysed using XRD to describe the changes in the starch crystallisation characteristics and long-range structure of FRN during frozen storage. The strongly crystalline structures showed sharp and strong peaks, whereas the weakly crystalline and non-crystalline structures showed dispersion peak characteristics. Fig. 4 shows the XRD pattern of FRN-MS powder during storage.

Sharp peaks appeared at diffraction angles (2θ) of 15°, 17°, 18°, and 23° in all samples. Strong diffraction peaks that are typical of wheat starch A-type crystal structures were observed. In addition, the three MS did not change the types of FRN crystal. The samples had smaller, stronger peaks at 2θ-20°, which were more easily observed in the MS groups. This is considered a typical V-type crystal structure (Zhao, Hou, Liu, Liu, et al., 2023; Zhao, Jia, Hou, Xiao, et al., 2023; Zhao, Jia, Hou, Yang, et al., 2023).

The hydrophobic molecules inside the amylose-helix combine with lipids or a series of other small molecules through phase transfer to produce V-type crystals, which belong to a single left-handed helix complex (Shi et al., 2017). The addition of MS increased the amount of amylose in the system, resulting in an increase in the number of amylose-lipid complexes and enhancement of the V-shaped crystal diffraction peak. The amylose-lipid complex is considered a V-type MS that is not easily metabolised by human pancreatic amylase in the small intestine. This may have increased the digestibility of FRN, which is also a potential fat additive. The increased V-type crystallinity in MS-containing FRN was tied to practical implications for slow digestibility and fat replacement. Polar and non-polar lipid molecules bind to glutenin and gliadin through hydrophobic and hydrogen bonds, respectively. This may promote the formation of the gluten network structure. Li and Dobraszczyk (Li et al., 2004) demonstrated that the effects of baking and rheological properties can be attributed to the interactions between gliadins and polar lipids. Therefore, we theorise that the increase of V-type crystalline complexes may maintain the structural stability of FRN during storage.

4. Conclusion

In the present study, the addition of HPS, HPDSP, and OS to wheat flour significantly improved the quality and frozen storage stability of FRN. In addition, it reduced energy consumption to a certain extent. The viscosity and extension properties of MS differed during heating, which was attributed to differences in the molecular mass, spatial structure, and functional groups. The pasting properties of wheat flour and FRN illustrated that their viscosities increased with MS concentrations. The decline in energy consumption was due to the faster endothermic rate caused by the decrease in pasting temperature. In addition, the farinographic and extensographic properties of the dough were enhanced by the addition of HPS at appropriate concentrations. Contrastingly, the dehydration rate of FRN under freeze–thaw conditions decreased after the addition of MS, indicating the inhibitory effect of MS on freeze-thaw dehydration. The moisture retention effect of MS on the FRN was also reflected in the weight loss rate. Finally, MS likely interacted with the components of FRN, further enhancing its quality and stability by increasing the number of V-shaped crystal structures. The study provides theoretical support for the application of MS in FRN.

CRediT authorship contribution statement

Yan Wu: Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis. **Shensheng Xiao:** Writing – original draft, Methodology, Investigation, Data curation. **Ziyang Jia:** Writing – original draft, Formal analysis, Data curation, Conceptualization. **Kaifeng Zhao:** Visualization, Software, Methodology, Formal analysis. **Lili Hou:** Methodology, Formal analysis. **Wenping Ding:** Resources. **Xuedong Wang:** Writing – review & editing, Validation, Supervision, Resources, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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