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# EFFECT OF DIFFERENT HEAT MOISTURE TREATMENT CONDITIONS ON POTATO STARCH PHYSICOCHEMICAL PROPERTIES

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## Abstract

**This work is devoted to the evaluation of the effects of different heating time, different heating temperature and different moisture content of heat moisture treatment (HMT)H on the swelling power, solubility, freeze-thaw stability, textural properties and other physicochemical properties. Different heating time samples(tHMT), different heating temperature samples (THMT) and different moisture content of starch system samples of heat-moisture treatment modified potato starch were prepared. The effects of heat moisture treatment on the swelling power, solubility, freeze-thaw stability, retrogradation, transparency and textural properties of native potato starch (NS) and heat moisture treatment (HMT) starch were investigated. The statistical analysis of the results was conducted by analysis of variance (ANOVA). The research results show that the transparency and retrogradation stability of potato starch after HMT were reduced, solubility and swelling power varied with the gelatinization temperature. HMT can significantly affect the textural properties of potato starch and the hardness, gumminess, chewiness and resilience of HMT starch gels first increased significantly and then decreased with the extension of treatment time. Short heating time (< 1.5 h), relatively low heating temperature (< 100 °C) and low moisture content (< 25 %) of HMT can significantly enhance the texture properties of HMT starch gels. Physical modification of starch involves increasing the functional activity and environmental safety of starches, and the study of their properties will expand their use in the production of structured foods.**

*Keywords:* potato starch; heat-moisture treatment; physicochemical properties; textural properties; starch gels.

# ВПЛИВ РІЗНИХ УМОВ ВОЛОГОТЕРМІЧНОГО ОБРОБЛЕННЯ НА ФІЗИКО-ХІМІЧНІ ВЛАСТИВОСТІ КАРТОПЛЯНОГО КРОХМАЛЮ

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## Анотація

**Дана робота присвячена оцінюванню впливу часу та температури нагрівання, різного вмісту вологи в процесі вологотермічного оброблення картопляного крохмалю (HMT) на процес набухання, розчинність, стабільність при заморожуванні-розморожуванні, текстуру та інші фізико-хімічні властивості. Були підготовлені зразки з різним часом нагрівання (tHMT), зразки з різною температурою нагрівання (THMT) та різним вмістом вологи у зразках модифікованого картопляного крохмалю. Досліджено вплив вологотермічного оброблення на набухання, розчинність, стабільність при заморожуванні-розморожуванні, ретроградацію, прозорість та текстуру нативного картопляного крохмалю (NS) і крохмалю, що зазнав вологотермічного оброблення (HMT). Статистичний аналіз результатів проводили за допомогою дисперсійного аналізу (ANOVA). Результати досліджень показали, що прозорість та стійкість до ретроградації картопляного крохмалю після HMT зменшилися, розчинність та набухання змінювались в залежності від температури гелеутворення. Вологотермічне оброблення може значно вплинути на структурно-механічні властивості крохмальних клейстерів, а твердість, липкість, жувальна здатність та пружність крохмальних гелей після HMT спочатку значно збільшувались, а потім зменшувались із часом оброблення. Невеликий час нагрівання (< 1.5 год), відносно низька температура нагрівання (< 100 °C) та низький вміст вологи (< 25 %) HMT можуть значно поліпшити текстурні властивості крохмальних гелей. Фізична модифікація крохмалю забезпечує підвищення функціональної активності та екологічної безпеки, а дослідження властивостей розробленого продукту дозволить використовувати модифікований крохмаль у виробництві структурованих продуктів харчування.**

*Ключові слова:* картопляний крохмаль; вологотермічне оброблення; фізико-хімічні властивості; текстурні властивості; крохмальні гелі.

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## Introduction

Starch is the main component of fruits, seeds, tubers and roots of green plants. Rice, corn, potatoes, taro, banana and other crops widely grown in the world contain a lot of starch. Starch is a carbohydrate or polysaccharide comprising a large number of glucose units linked together through glycosidic bonds with the molecular formula $(C_6H_{10}O_5)n$, n value is the degree of polymerization of starch molecule [1]. Potato is not only the fourth largest crop in world production after rice, wheat and corn, but also is among the most important crops for feeding the global population[2]. Potatoes are widely planted in China, and in 2015, China harvested nearly 95 million tons potatoes [3]. Majority of potatoes are processed into starch, flour, flakes and other products, while minority are consumed as fresh eating. Potato starch is mainly used as thickener, colloidal stabilizer, gelling agent, adhesive in food industry, and also used as bulking agent, water-retention agent [4].

With the advantages of being renewable, nontoxic, biodegradable and of relatively low cost, starch-based derivatives are nowadays used for many applications in food processing in order to achieve particular technological properties [5]. In this way, the native starch granules can be modified by applying physical, chemical or enzymatic modifications and enhance the physicochemical and physic-mechanical properties [6]. These modifications can promote molecular disorganization, polymer degradation, molecular rearrangement, polymer crosslinking, and addition of chemical groups [7]. Physical modification including heat moisture treatment is an appealing process in food industry applications over chemical and enzymatic modifications, as it does not involve the use of chemicals, which could contaminate the starch especially when the modified starch is to be utilized for food contact or in the biomedical industry [8]. Heat-moisture treatment (HMT) is a hydrothermal treatment technique, which requires the starch granules to be kept in a relatively high temperature (80–140 ℃) that above the glass transition temperature ($T_g$) and below the gelatinization temperature ($T_{gel}$) for a period of time with low levels of moisture (35 %) [9, 10]. The interactions of three factors including disruption of crystallites, interactions between starch chains and disruption of double helices in the amorphous region developed by HMT lead to starch granular swelling, crystallinity, amylose leaching parameters, gelatinisation, retrogradation, and thermal stability [11–13]. Previous researches had found that HMT could affect the swelling power, solubility, pasting properties, textural properties and other physicochemical properties of starch by promoting degradation of starch crystallites and/or interactions between the starch chains in amorphous and crystalline regions[14–16]. Due to diverse reaction conditions such as the starch source, moisture content, heating temperature, heating time and other process parameters, it is difficult to define the properties of HMT starches in definitive way. There is limited information on the effect of moisture content, heating temperature and heating length on the starch paste properties of starch during HMT. An understanding of the physicochemical, thermal, and textural properties of modified starches is important to predict their behaviors in food system, which is of great significance to the application of HMT modified starch in food industry. Therefore, the objective of this study was to investigate the effect of moisture content, heating temperature and heating time on the starch paste properties of potato starch during HMT.

## Materials and methods

*Materials.* Native potato starch (NS) was obtained from an unknown cultivar of potatoes purchased from a local market with the technology of wet milling extraction in Hezhou, China.

*Laboratory Methods*

*Sample preparation:* Potato starch was subjected to HMT in accordance with the method described by Chunli Deng [17]. (1) The moisture content of native starch powder (NS) was determined before heat- moisture treatment, and then heat-moisture treatment modified potato starch samples were prepared as following: (1) Different heating time groups (tHMT): 70 g native starch powder was weighed in 500 mL Duran laboratory bottle, and ultrapure water was added to adjust moisture content to 25 % and equilibrated for 24 hours at 25 ℃, samples were then heated at 110 ℃ for 1 h, 2 h, 3 h, 4 h,5 h and 6 h (tHMT1, tHMT2, tHMT3, tHMT4, tHMT5, tHMT6, respectively) in a hot-air oven. (2) Different heating temperature groups (THMT): Starches were weighed in different spiral blue-moth bottles, and ultrapure water was added to adjust moisture content to 25 % and equilibrated for 24 hours at 25 ℃, samples were then heated at 90 ℃, 100 ℃, 110 ℃, 120 ℃, 130 ℃ (THMT90, THMT100, THMT110, THMT120, THMT130, respectively) for 2 h in a hot- air oven. (3)

Different moisture content of starch system groups (CHMT): Starches were weighed in different spiral blue-moth bottle, and different volumes of ultrapure water were added to adjust moisture content to 15 %, 20 %, 25 %, 30 %, 35 %（CHMT15, CHMT20, CHMT25, CHMT30, CHMT35, respectively）and equilibrated for 24 h at 25 ℃, samples were then heated in an electric thermostatic drying oven for 2 h. All these three groups of treated samples were dried in a drying oven at 45 °C for 24 h to make sure the moisture content of the treated samples was less than 12 %. The dried potato starch was pulverized for 45 s using a universal pulverizer, passed through an 80-mesh sieve, vacuum-packed in polyethylene bags, and stored in an airtight container for conducting further studies.

*Determination of swelling power and solubility.* Swelling power (SP) and solubility (SOL) of potato starch samples were measured as Huan Li and Lihong Han with a slight modification [13, 18]. Briefly, starch sample (0.6 g, dry basis) was placed in a pre-weight centrifuge tube with ultrapure water (30 mL) and homogenized with vortex mixer. The slurry was heated for 30 min in a shaking water bath at 55 °C, 65 °C, 75 °C, 85 °C, 95 °C, respectively. Afterwards, the samples were centrifuged at 3000rpm for 20 min, the supernatants were dried to constant weight in a hot oven at 105 °C, and the precipitates formed at the bottom of the tube were weighed immediately. The swelling power and solubility of potato starch were calculated as follows:

Swelling power (g/g) = (weight of sediment×100) × [weight of sample × (1-solubility)]

Solubility (%) = weight of dried supernatant/weight of starch sample×100

*Determination of freeze-thaw stability.* The freeze-thaw stability of potato starch gels was investigated by putting samples through alternative freezing and thawing cycles (freezing for 24h at −18 ℃ and thawing for 2h at 30 ℃) according to the method of Yue Wu with a slight modification [19]. Potato starch suspension (5 %, w/w potato starch on a dry basis) were prepared by blending starch in ultrapure water and then the suspensions were gelatinized by placing in a water bath at 95 ℃ for 30 min with continuously stirring. The samples were held for 5 min before being poured in pre-weight centrifuge tubes (25mL), respectively. The weight of centrifuge tubes was recorded, and then the gel samples were frozen in refrigerator at −18 ℃ for 24h and then thawed in 30 ℃ for 2 h. This was one FT cycle and the FT cycle was repeated five times. After being centrifuged at 3000 rpm for 20 min, the resulting supernatant in the tubes was weighed and recorded. The syneresis rate was calculated as the percentage of supernatant weight to gelatinized gel weight.

*Determination of retrogradation.* Potato starch suspensions (1 %, w/w potato starch on a dry basis) were prepared by blending starch in ultrapure water and then the suspensions were gelatinized by placing in a boiling water bath for 40 min with continuous stirring. After the gelatinization was completed, the suspensions were taken out, cooled to room temperature, poured into 25 mL tube, and kept still in 25 ℃ incubator. The volumes of the starch paste supernatant were recorded every 2 h (total 16 h). The percentage of starch paste supernatant liquid volume in the total volume of starch paste changed over time characterizing its retrogradation property.

*Determination of transparency.* The transparency of potato starch was measured using the method described by Jizhong Wang with modifications [20]. Briefly, potato starch suspensions (1 %, w/w potato starch on a dry basis) were prepared by blending starch in ultrapure water and then the suspensions were gelatinized by placing in a water bath at 90 ℃ for 1 h. After the gelatinization was completed, the suspensions were taken out and cooled to room temperature. The transparency of the starch was measured at a wavelength of 640 nm and ultrapure water was used as a blank. The experiment was performed in parallel three times. After the first measurement, the starch-water suspension was stored at 4℃ for 120 h, and then measured every 24 h.

*Determination of texture profile analysis (TPA) of starch paste.* The potato starch gels were investigated according to the previous study with slight modification [21]. Potato starch suspensions (12 %, w/w potato starch on a dry basis) were prepared by blending starch in ultrapure water and then the suspensions were gelatinized by placing in a boiling water bath for 20 min with continuous stirring.

After the gelatinization was completed, potato starch gels were taken out and cooled to room temperature, the samples were then placed in the refrigerator (4 ℃) and frozen for 24 h. Then the selected starch gels were removed from the container, the size of the container was 55 mm diameter and 20 mm height. Before the measurement, the samples were equilibrated at room temperature for 1 h, and the tests were

performed by using texture analyzer (TA.XT PLUS, Stable Micro Systems, UK) with a plate probe with a diameter of 100 mm. The pre-test speed and post-test speed were set at 1.0 mm/s, the test speed was set at 2.00 mm/s, while the strain was fixed at 50 % with a trigger force of 5 g. All the textural parameters were measured and calculated by the instrument software from the resulting force-deformation curves, including hardness (g), adhesiveness, springiness, cohesiveness, gumminess, chewiness and resilience. The TPA measurement was carried out in parallel three times.

*Statistical analysis.* The statistical analysis of results was conducted by analysis of variance (ANOVA), the significant difference among samples were determined by Duncan's multiple range tests using DPSv7.05 statistical software, and Microsoft Office Excel was used to graph. The P value <0.05 was considered as significant.

## Results and discussion

*Effect of heat moisture treatment on swelling power and solubility of potato starch.* The swelling power of HMT starches and native potato starch (NS) at 55–95 °C were shown in Figs. 1–3. The swelling power of NS and HMT starches showed an increasing trend with the increase of test temperature. The swelling power of tHMT and THMT were significantly reduced ($p < 0.05$) in comparison with that of NS in the test temperature of 65–85 °C. The swelling power of HMT starches was increased in comparison with that of NS in the test temperature of 55 °C, which indicated that HMT increased the swelling power of potato starch in low temperature. At the same test temperature (65–95 °C), the swelling power of HMT starches decreased with the increasing heating time, heating temperature and moisture content, and these results were consistent with the result of a pervious study focusing on mung bean starch [22] and corn starch [23]. The reduction in swelling power of HMT starches could account for the rearrangement of starch molecule or / and re-associations of starch chains caused by HMT [24]. With high moisture content, HMT destroyed the crystal structure because of water molecules being able to enter the crystallization zone of starch granules and likely to interact with starch molecules in the destroyed crystals, resulting in a relatively high swelling power.

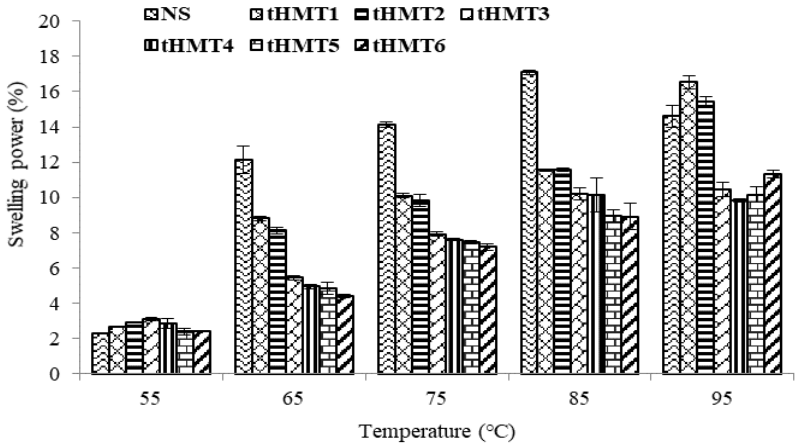


**Fig. 1. Effect of heat-moisture treatment on swelling power of potato starch under different heating time**

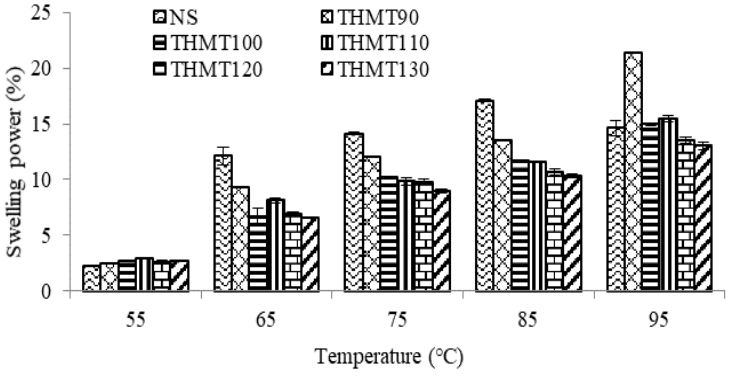


**Fig. 2. Effect of heat-moisture treatment on swelling power of potato starch under different heating temperature**

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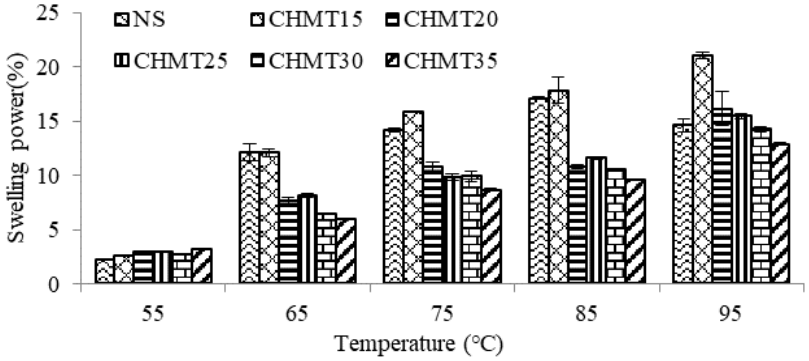


**Fig. 3. Effect of heat-moisture treatment on swelling power of potato starch under different mositure content**

The solubility HMT starches and native potato starch (NS) at 55–95 °C were shown in Figs. 4–6. The solubility of NS and HMT starches showed an increasing trend with the increase of test temperature (65–95 °C), but lower than that of low temperature (55 °C). HMT starches showed higher solubility in comparison of NS in low test temperature (55–75 °C), which indicated that HMT destroyed the structure of starch granules, preventing amylose and lipids to form complex at low temperature, thereby increased the solubility. Amylose in starch granules was hard to leach out after HMT, and formed a stable structure with amylopectin in starch molecules [25], thereby the solubility of HMT starch was lower than that of NS, which was consistent with the results of previous researches on the modification of corn starch [23]. In general, HMT decreased starch swelling power and solubility, which were suitable in noodles processing.

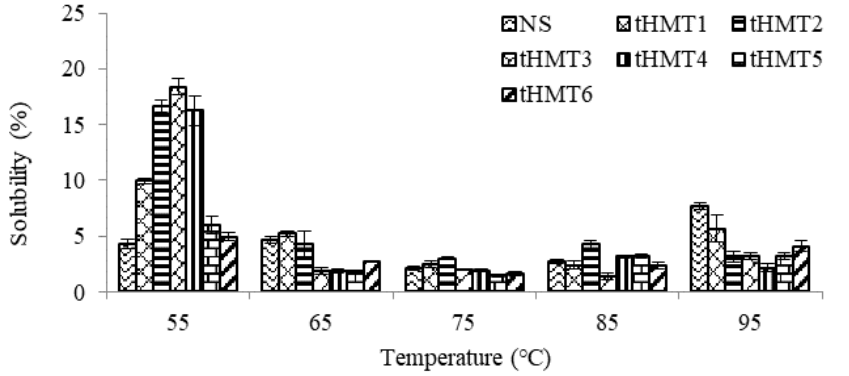


**Fig. 4. Effect of heat-moisture treatment on solubility of potato starch under different heating time**

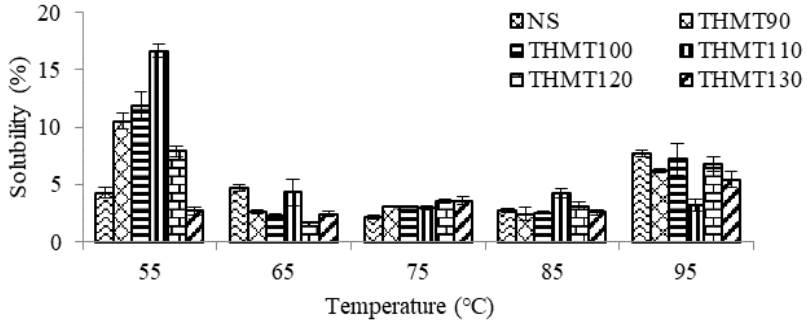


**Fig.5. Effect of heat-moisture treatment on solubility of potato starch under different heating temperature**

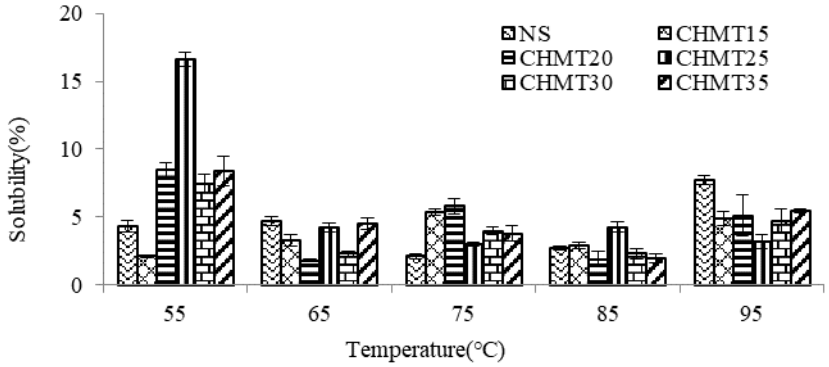


**Fig. 6. Effect of heat-moisture treatment on solubility of potato starch under different mositure content**

*Effect of heat moisture treatment on freeze-thaw stability of potato starch.* Freeze-thaw stability represents the ability of starch withstand the undesirable physical changes that may occur during freezing and thawing. Thermal energy fluctuation and phase change of water during freeze-thaw are the possible cause of disruption of the gel matrix of starch. When a starch gel is frozen, starch- rich regions are created in the matrix, where water remains partially unfrozen. High solid concentration in the regions facilitates the starch chains to associate forming thick filaments, whereas water molecules coagulate into ice crystals forming a separate phase. Upon thawing, ice transforms to bulk phase water, which can be readily released from the polymeric network (syneresis). The water release consequently leaves the starch gel sponge-like [26].

The freeze-thaw stabilities during FT cycles (1FTC, 2FTC, 3FTC, 4FTC, 5FTC) were shown in Figs. 7–9 with the percentage of syneresis as an index. The syneresis of all the starch gels including NS increased with the increasing of freezing-thawing cycles. Compared with NS, tHMT, THMT 90 and CHMT15 starch gels had lower syneresis, which indicated that HMT could improve the freeze-thaw stability of starch gels under such conditions. With further increase of treatment heating time, treatment heating temperature and moisture content, destruction of starch granules increased significantly, starch molecules were rearranged, which limited the ability of starch molecules and water molecules to bind to each other through hydrogen bonds, thereby the water in starch granules was more easily precipitated, resulting in poor freeze-thaw stability of starch gels.

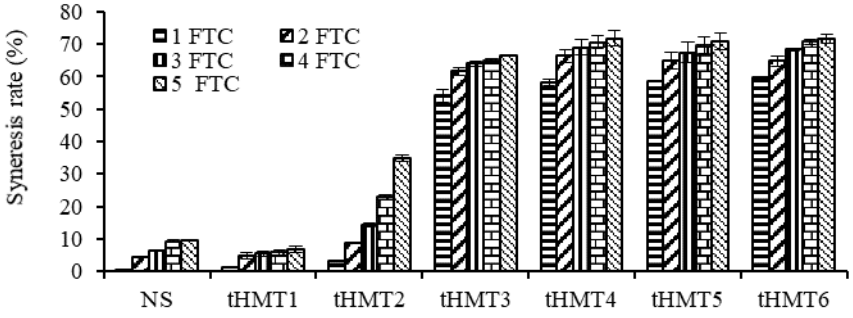


**Fig. 7. Effect of heat-moisture treatment on freeze-thaw stability of potato starch under different heating time**

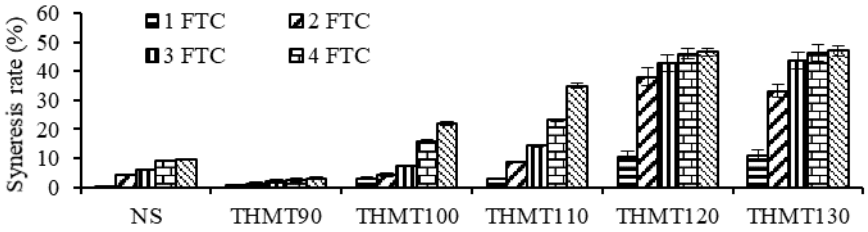


**Fig. 8. Effect of heat-moisture treatment on freeze-thaw stability of potato starch under different heating temperature**

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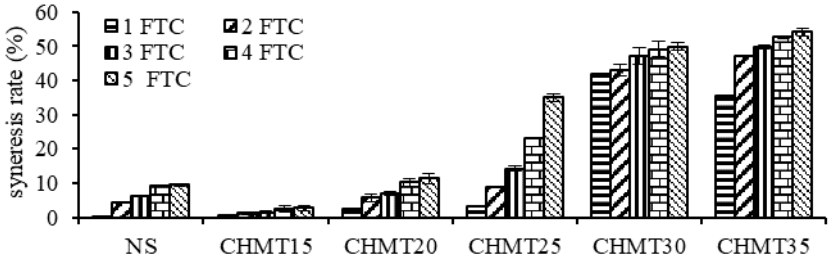


**Fig.9. Effect of heat-moisture treatment on freeze-thaw stability of potato starch under different starch moisture content**

*Effect of heat moisture treatment on retrogradation of potato starch.* The retrogradation of starch is the process of gelatinizing starch molecules from disordered state to orderly rearrangement, final coagulation and sedimentation. In the gelatinization process of starch by heating, the ordered starch molecules become disordered under the action of water and heat. During cooling and storage, due to the influence of molecular potential energy, the disorder of high-energy states gradually changes into the order of low-energy states. NS and HMT starches were gelatinized and stored at 25 ℃ for 16 h and the starch paste supernatant liquid volumes were recorded every 2 h. The retrogradation of HMT starches and native potato starch (NS) is shown in Figs. 10–12. As can be seen from Figs. 10–12, the retrogradation of NS and HMT starches increased and tended to balance with the extension of storage time. HMT destroyed the starch granules structure and reduced the hydrogen bonds between starch molecules and water molecules, which was prone to retrogradation, resulting in great retrogradation of potato starch. Starch retrogradation was generally considered to have an adverse effect on starch-containing foods because it shortens the shelf life of food and reduces their consumer and sensory value. However, HMT starch can be used in the production of vermicelli and other food products due to its ability to retrograde easily. To some extent, starch retrogradation is also important from a nutritional point of view because retrograded starch is slowly digested by human digestive enzymes in the upper gut, which can facilitate the release of glucose into the bloodstream, resulting in a reduced postprandial glycemic and insulin response [27].

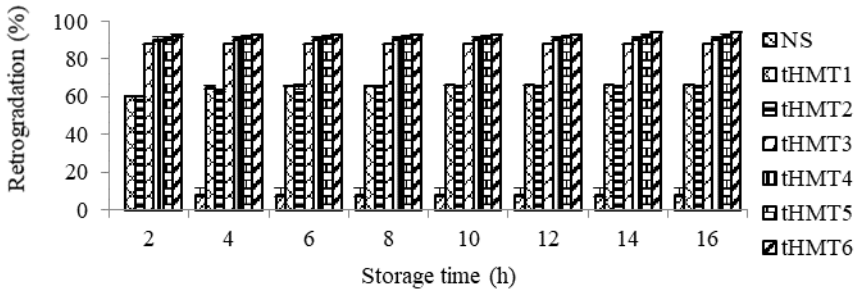


**Fig. 10. Effect of heat-moisture treatment on retrogradation of potato starch under different heating time**

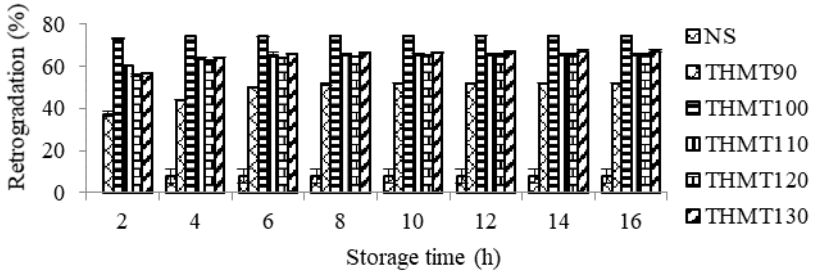


**Fig. 11. Effect of heat-moisture treatment on retrogradation of potato starch under different heating temperature**

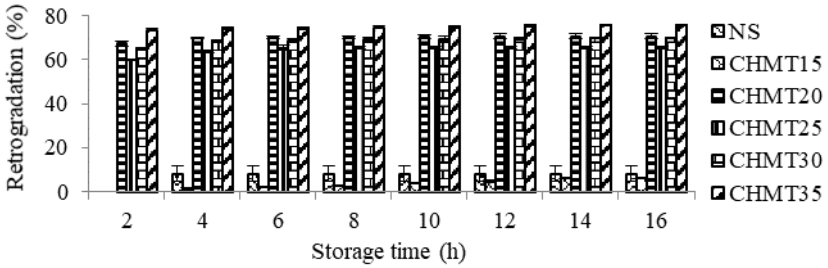


**Fig. 12. Effect of heat-moisture treatment on retrogradation of potato starch under different moisture content**

*Effect of heat moisture treatment on transparency of potato starch.* The transparency of starch paste is an important indicator for product characteristics, which is closely related to the appearance and acceptability of starch and its processed products, also reflects the ability of starch molecules to bond with water molecules [28]. As shown in Figs. 13–15, the starch pastes retrograded during storage which affected the transparency, thereby, the transparency of NS and HMT starches decreased with the extension of storage time. As the exposure time, exposure temperature and moisture content increased, the transparency of starch pastes decreased significantly. HMT destructed starch granules, which led to the rearrangement of starch molecules and destruction of crystal structure. The number of unexpanded starch granules and incompletely broken remaining starch granules increased during the heating gelatinization process, which caused the light scattering as it passed through the starch paste, reducing the transparency of the starch pastes [29].

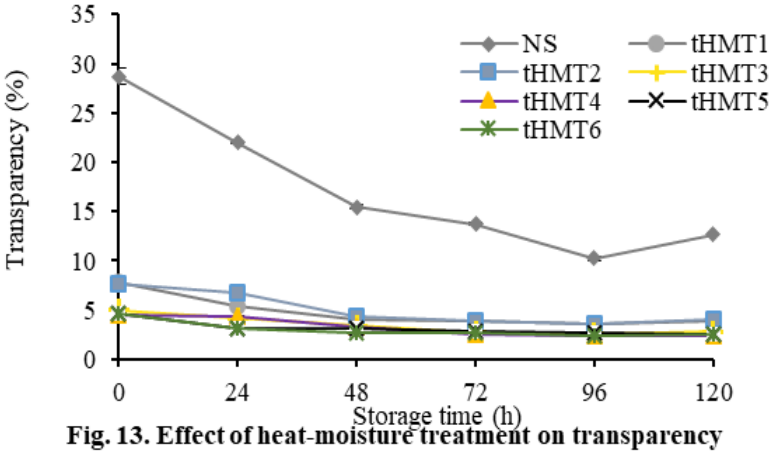


**Fig. 13. Effect of heat-moisture treatment on transparency of potato starch under different heating time**

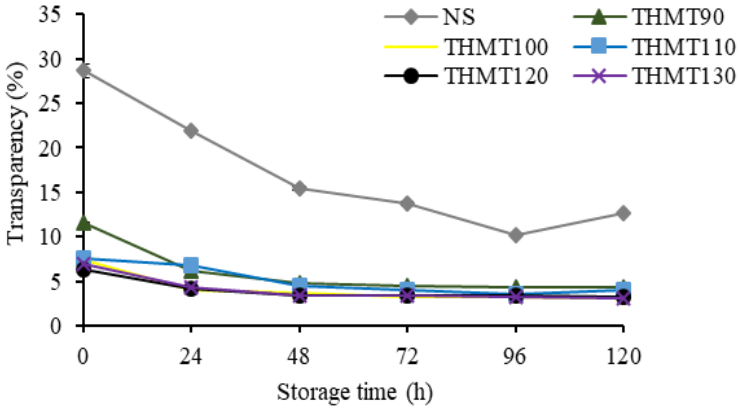


**Fig. 14. Effect of heat-moisture treatment on transparency of potato starch under different heating temperature**

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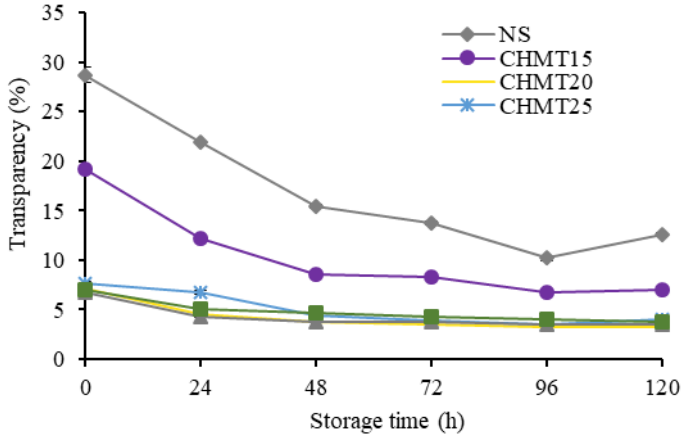


**Fig. 15. Effect of heat-moisture treatment on transparency of potato starch under different mositure content**

*Effect of heat moisture treatment on Texture profile analysis (TPA) of potato starch paste.* Starch gelatinization refers to the process in which the crystalline structure of the starch-water suspension melts at a certain temperature, and the starch granules are highly swollen or even broken and gelatinized. This is an irreversible process from an ordered structure to a disordered structure. This process is accompanied by water swelling of starch granules, precipitation of amylose, water association and crystal loss, and finally a network structure gel is formed, which is closely related to the quality characteristics of food.

Textural properties of the native potato starch (NS) gel and HMT starch (THMT, tHMT, CHMT) gels, including hardness, springiness, cohesiveness, gumminess, chewiness and resilience, were investigated as the determination of texture profile analysis (TPA) of starch paste. The results were presented in Tables 1–3.

*Table 1*

**Textural parameters of native potato starch (NS) and tHMT starch gel (10 %, w/w) determined by TPA test**

| Starch gel | Hardness g | Springiness (mm) | Cohesiveness (-) | Gumminess (g) | Chewiness (g·mm) | Resilience (-) |
|---|---|---|---|---|---|---|
| NS | 2705.55±3.11$^{c}$ | 0.83±0.01$^{a}$ | 0.63±0.01$^{a}$ | 1700.43±11.44$^{c}$ | 1403.77±29.88$^{c}$ | 0.40±0.03$^{a}$ |
| tHMT1 | 5528.36±3.03$^{b}$ | 0.65±0.02$^{b}$ | 0.59±0.04$^{a}$ | 3286.67±224.62$^{b}$ | 2137.88±95.10$^{b}$ | 0.41±0.03$^{a}$ |
| tHMT2 | 7037.943±1.69$^{a}$ | 0.69±0.00$^{b}$ | 0.54±0.01$^{b}$ | 3765.31±70.58$^{a}$ | 2577.18±29.67$^{a}$ | 0.34±0.03$^{b}$ |
| tHMT3 | 2448.32±6.65$^{e}$ | 0.57±0.04$^{c}$ | 0.30±0.00$^{c}$ | 738.17±7.20$^{d}$ | 420.26±22.52$^{d}$ | 0.084±0.01$^{c}$ |
| tHMT4 | 2639.09±38.55$^{d}$ | 0.54±0.03$^{c}$ | 0.28±0.00$^{c}$ | 750.92±24.03$^{d}$ | 403.55±32.02$^{d}$ | 0.08±0.01$^{c}$ |
| tHMT5 | 2239.92±44.15$^{f}$ | 0.49±0.01$^{d}$ | 0.24±0.02$^{d}$ | 537.14±33.75$^{d}$ | 263.57±11.25$^{e}$ | 0.08±0.01$^{c}$ |
| tHMT6 | 1534.46±12.27$^{g}$ | 0.41±0.04$^{e}$ | 0.20±0.00$^{d}$ | 309.20±3.56$^{e}$ | 126.16±2.76$^{f}$ | 0.07±0.01$^{c}$ |

*Table 2*

**Textural parameters of native potato starch (NS) and THMT starch gel (10 %, w/w) determined by TPA test**

| Starch gel | Hardness g | Springiness (mm) | Cohesiveness (-) | Gumminess (g) | Chewiness (g·mm) | Resilience (-) |
|---|---|---|---|---|---|---|
| NS | 2705.55±3.11$^{e}$ | 0.83±0.00$^{c}$ | 0.63±0.01$^{b}$ | 1700.43±11.44$^{d}$ | 1403.77±29.88$^{d}$ | 0.40±0.03$^{b}$ |
| THMT90 | 10203.52±3.09$^{a}$ | 0.93±0.00$^{a}$ | 0.82±0.01$^{a}$ | 8382.18±105.69$^{a}$ | 7782.81±92.20$^{a}$ | 0.59±0.04$^{a}$ |
| THMT100 | 8308.08±102.65$^{b}$ | 0.84±0.01$^{b}$ | 0.55±0.01$^{c}$ | 4585.48±37.33$^{b}$ | 3856.21±14.00$^{b}$ | 0.38±0.01$^{b}$ |
| THMT110 | 7037.943±1.69$^{c}$ | 0.68±0.00$^{e}$ | 0.54±0.01$^{c}$ | 3765.31±70.58$^{c}$ | 2577.18±29.67$^{c}$ | 0.34±0.03$^{b}$ |
| THMT120 | 2955.38±13.97$^{d}$ | 0.72±0.00$^{d}$ | 0.40±0.00$^{d}$ | 1189.55±11.89$^{e}$ | 858.24±4.37$^{e}$ | 0.23±0.03c |
| THMT130 | 1230.64±2.45$^{f}$ | 0.54±0.00$^{f}$ | 0.27±0.01$^{e}$ | 327.36±9.35$^{f}$ | 178.43±6.48$^{f}$ | 0.11±0.00$^{d}$ |

*Table 3*

**Textural parameters of native potato starch (NS) and CHMT starch gel (10 %, w/w) determined by TPA test**

| Starch gel | Hardness g | Springiness (mm) | Cohesiveness (-) | Gumminess (g) | Chewiness (g·mm) | Resilience (-) |
|---|---|---|---|---|---|---|
| NS | 2705.55±3.11$^{f}$ | 0.83±0.01$^{a}$ | 0.63±0.00$^{b}$ | 1700.43±11.44$^{d}$ | 1403.77±29.88$^{c}$ | 0.40±0.03$^{b}$ |
| CHMT15 | 7349.3460.48$^{b}$ | 0.83±0.00$^{a}$ | 0.87±0.01$^{a}$ | 6383.39±172.05$^{a}$ | 5266.54±160.00$^{a}$ | 0.61±0.04$^{a}$ |
| CHMT20 | 7560.91±14.97$^{a}$ | 0.74±0.00$^{b}$ | 0.44±0.03$^{d}$ | 3307.93±33.28$^{c}$ | 2449.48±17.63$^{b}$ | 0.28±0.02$^{cd}$ |
| CHMT25 | 7037.94±1.69$^{c}$ | 0.68±0.00$^{c}$ | 0.54±0.01$^{c}$ | 3765.31±70.58$^{b}$ | 2577.178±29.67$^{b}$ | 0.34±0.03$^{bc}$ |
| CHMT30 | 3380.40±147.33$^{e}$ | 0.58±0.01$^{d}$ | 0.33±0.03$^{f}$ | 1071.25±46.45$^{e}$ | 620.51±14.04$^{e}$ | 0.13±0.01$^{e}$ |
| CHMT35 | 3774.98±16.10$^{d}$ | 0.66±0.02$^{c}$ | 0.40±0.01$^{e}$ | 1506.15±25.61$^{d}$ | 995.78±42.49$^{d}$ | 0.22±0.01$^{d}$ |

**Note: all values are the mean of triplicate determinations ± SD. The means within the same column with different letters are significantly different (P<0.05).**

As can be seen from Tables 1–3, the hardness, gumminess, chewiness and resilience of HMT starch gels increased significantly and then decreased with the extension of treatment time. Short heating time (< 1.5 h), relatively low heating temperature (< 100 ℃) and low moisture content (< 25 %) of HMT can significantly enhance the texture properties of HMT starch gels. With the increase of treatment time, temperature and moisture content, the textural property parameters of HMT starch gels decreased gradually. The texture properties of starch gels were related to the type of starch, the structure and the ratio of amylose and amylopectin [30]. HTM caused damage to the granular structure of potato starch to varying degrees, and amylose dissolution was suppressed by HMT. Meanwhile, HMT caused the molecular structure of starch to change and starch gelatinization to occur. Proper heat moisture treatment of starch is beneficial to improve the texture properties of starch gel, which favors the use of HMT-modified starch in noodles. Previous studies have shown improved texture (stickiness, chewiness, and tensile strength) of noodles prepared with HMT-modified rice starch or sweet potato starch [31; 32].

## Conclusions

In this study, the effect of HMT on the swelling power, solubility, freeze-thawing stability, retrogradation, transparency and textural properties of NS and HMT starch were investigated. The research results show that the transparency and retrogradation stability of potato starch after HMT were reduced, solubility and swelling power varied with the gelatinization temperature. HMT can significantly affect the textural properties of potato starch and the hardness, gumminess, chewiness and resilience of HMT starch gels, which first increased significantly, and then decreased with the extension of treatment time. Short heating time (< 1.5 h), relatively low heating temperature (< 100 ℃), and low moisture content (< 25 %) of HMT can significantly enhance the texture properties of HMT starch gels. The changes of physicochemical and textural properties of HMT starches could account for destruction of starch granules, the rearrangement of starch molecule or / and re-associations of starch chains caused by HMT, which limited the ability of starch molecules and water molecules to bind to each other through hydrogen bonds.

The physicochemical properties of starch directly affect the quality of starchy food. The modification of starches by HMT makes it possible to obtain appropriate characteristics, such as gelatinisation, heat stability, solubility and textures, for the most diverse industrial applications, mainly in the food sector. Extensive researches are also required to broaden the applications of HMT starch in food product development.

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