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Impact of cooking conditions on the properties of rice: Combined temperature and cooking time

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ABSTRACT

Changes in the properties of cooked rice under various cooking conditions were investigated. Waxy, low-, and high-amylose rice were subjected to treatment with different cooking temperatures (50, 70, 90 °C) for different cooking times (15, 30, 45 min). The results showed that cooking greatly increased the swelling behavior of waxy rice but decreased the swelling behavior and amylose leaching of low- and high-amylose rice. As the cooking temperature increased, rapidly digestible starch increased significantly for all rice products, whereas slowly digestible starch and resistant starch had a certain degree of reduction. Variation in the cooking time produced little effects on starch digestibility. Gelatinization temperature was positively correlated with temperature and time, whereas gelatinization enthalpy was negatively correlated with temperature and time. Pasting properties of all rice products decreased significantly as cooking temperature and time increased. The study showed that both cooking temperature and cooking time had significant impacts on the physicochemical properties and starch digestibility of waxy, low-, and high-amylose rice to various extents. Temperature had a more pronounced impact on the extent of change to the *in vitro* digestibility than did cooking time.

1. Introduction

Rice, as a staple food on which billions of people live, is widely cultivated globally. Rice is a good source of nutrition and energy. However, it should be cooked before consumption to improve its hardness and eating quality [1]. Cooking is the process of rice starch gelatinization at higher cooking temperatures and times. Before cooking, soaking is commonly carried out to achieve a uniform water distribution and total starch gelatinization [2]. Generally, the standard ratio of water-to-rice for rice cooking ranges from 10:1 to 20:1. The excess water method is most commonly used in industrial rice cooking to maintain uniform heating in the flow. Changes occur in the properties of rice during cooking, i.e., water absorption and volume expansion. Altheide, et al. [3] found that water absorption in cooked rice was influenced by the cooking time, whereas the volume expansion of cooked rice had a relationship with the cooking temperature.

During cooking, rice starch undergoes water absorption, swelling, amylose leaching and gelatinization. Attaining a certain temperature within the rice is essential to start the process of starch gelatinization. Many studies have examined the impact of cooking temperature on rice starch gelatinization [4–6]. Cooking for a certain length of time is also a necessity for rice starch to absorb water and achieve complete gelatinization. Some studies have shown that the milling degree, amylose content, particle appearance, starch final gelatinization temperature and other factors can affect the required cooking time and can change the structure, texture and quality of rice [1,7,8]. Additionally, the influence of different heating temperatures and times on the physical properties of rice starch paste and the digestibility of heat-moisture treated maize starch have been studied, showing that heating temperature is the more vital factor in determining starch properties [9].

Physicochemical characteristics and starch digestibility are responsible for eating quality, processing characteristics and the end-use of cooked rice in industry. The different physicochemical characteristics of various types of rice may be correlated with differences in amylose content, grain size, and crystallinity [10–12]. Researchers have also attempted to correlate the physicochemical properties of cooked rice with cooking characteristics such as cooking duration and cooking methods [13,14]. During cooking, the dynamics of the solvation of starch and protein contribute to the alteration of physicochemical characteristics. Cooking time can also affect the digestibility of cooked rice to some extent.

The impacts of cooking temperature, cooking time and physicochemical properties on rice have been studied separately [8,13,15]. However, there is limited information on the impact of the combined treatments of cooking temperature and cooking time on the physicochemical properties and digestibility of rice. Additionally, there are

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few studies summarizing the mechanisms by which cooking temperature and cooking time affect rice physicochemical properties. Such studies would provide more information on the effects of cooking conditions on rice. The objective of this study was to investigate the impacts of cooking temperature and cooking time together on the physicochemical properties and starch digestibility of waxy, low-, and high-amylose rice.

2. Material and methods

2.1. Materials

Three rice cultivars were chosen for use: waxy rice (WR, YF4), low-amylose rice (LAR, QG), and high-amylose rice (HAR, LH6684). WR, LAR and HAR were purchased from Jiahao Gardening Company (Suqian, China). Amyloglucosidase (EC 3.2.1.3, 300 AGU mg^{-1}), pancreatin from porcine pancreas (EC 232.468.9, 228 USP mg^{-1}) and guar gum were supplied by Sigma Chemical Co. (St. Louis, MO, USA). Glucose assay reagent was purchased from Megazyme International Ireland Ltd. (Wicklow, Ireland). All chemicals and solvents were of analytical grade.

2.2. Chemical components analysis

The moisture content of the grains was calculated using the standard AOAC method [16]. The starch content was analyzed from ground rice flour using a GOPOD assay kit. The crude lipid content was determined by Soxhlet extraction following AOAC method 920.39C [17]. The protein content was determined using an auto Kjeldahl analytical instrument (FOSS Kjeltec 8400, Denmark). An amylose quantification kit (Megazyme, Ireland) was used to determine the amylose contents of the three cultivars.

2.3. Cooking treatment

The rice was dehusked and polished by an experimental rice milling machine (TM05C-C, Satake Manufacturing (Suzhou) Co., Ltd., China) to a milling yield of 90–91%. Broken kernels were removed from the grains.

The excess water method was used to cook the rice according to a previously described procedure with minor modifications [2]. First, 80 mL of distilled water was poured into a 250-mL beaker, then a lid was added and the beaker was incubated in a water bath for at least 1 h. A thermometer was used to monitor whether the water temperature in the beaker reached the set temperature. Milled rice samples (4 g) were weighed and immersed in 80 mL of distilled water in another beaker at room temperature for 30 min. Then, the water was decanted and the rice was poured onto filter paper. When the water bath temperature in the 250-mL beaker reached 50, 70 or 90 °C, the rice was added and timing was immediately started. A spoon was used to thoroughly stir the mixture every 5 min. The samples were removed from the water bath after a cooking time of 15, 30 or 45 min and immediately cooled with tap water for 30 s. The rice was drained of water and spread as a thin layer on an aluminum tray, frozen in a freezer at −20 °C and then freeze-dried. After two days, the dried samples were ground into powder and passed through a 40-mesh sieve. Then, the cooked rice flour was labelled and placed in a desiccator for storage.

2.4. Swelling power and solubility index

The swelling power (SP) and solubility index (SOL) of each sample were determined using a previously described procedure with minor modifications [14]. Cooked rice flour slurries (1.0 g db in 40 mL of distilled water) in 50-mL centrifuge tubes were thoroughly mixed by vortex, then kept in a water bath at 85 °C for 30 min. After cooling to ambient temperature, the tubes were centrifuged at 1000 ×*g* for 20 min. The SP was estimated as the ratio of the weight of the wet sedimented gel to its dry weight. The SOL was expressed by drying the supernatant to a constant weight at 110 °C in a hot-air oven. Values were presented as the percentage of dried solid weight relative to the weight of dry cooked rice flour.

2.5. Amylose leaching

Cooked rice flour (20 mg, db) in distilled water (10 mL) was heated in a screw-capped tube at 85 °C for 30 min. After cooling to room temperature, tubes were centrifuged at 2300 rpm for 10 min. The aqueous solution (0.1 mL) was removed, and the amylose content was estimated as previously described by Varatharajan, et al. [18].

2.6. In vitro starch digestibility

The nutritional fractions of rapidly digestible starch (RDS), slowly digestible starch (SDS), and resistant starch (RS) in the cooked rice flour were determined according to the method of Englyst, et al. [19] with modifications. Cooked rice flour samples (550 mg, db) and distilled water (10 mL) were added to polypropylene screw-capped centrifuge tubes. Then, pepsin (0.1 g) and HCl (12 mol L^{-1}, 0.08 mL) were mixed into each tube and incubated at 37 °C for 30 min. Procine pancreatic a-amylase (4.5 g) was dispersed in 30 mL of distilled water and centrifuged at 3000 rpm for 10 min The supernatant was removed to a tube and mixed with 3.9 mL of amyloglucosidase. Following this, guar gum (50 mg), 15 glass beads (0.5 mm diameter), and 10 mL of sodium acetate buffer (0.25 mol L^{-1}, pH 5.2) were added to each tube. The tubes with cooked rice flour samples were incubated with the mixed enzymes at 37 °C in a shaking water bath. After 20 and 120 min of incubation, the hydrolyzate (0.5 mL) was removed and 20 mL of 80% ethanol was added to stop the reaction. The amount of released glucose was determined using a glucose oxidase assay kit. The contents of RDS, SDS, and RS in the cooked rice flour samples were analyzed according to the method by Englyst, Kingman and Cummings [19].

2.7. Determination of thermal properties

The thermal properties of the samples were determined using a differential scanning calorimeter (DSC) (TA 2910, TA Instruments, Wilmington, DE, USA). Samples (2 mg, db) were mixed with 6 μL of distilled water in an aluminum pan. The pan was hermetically sealed and equilibrated at room temperature for at least 2 h before the test, then heated at a rate of 5 °C min^{-1} from 30 °C to 110 °C, along with an empty sealed pan as a reference.

2.8. Determination of pasting properties

A Rapid Visco-Analyzer (RVA) (Newport Scientific, Warriewood, Australia) was used for the determination of pasting properties of the samples. Cooked rice flour samples (3 g, 140 g kg^{-1}moisture basis) were mixed with Milli-Q water in the RVA sample canister to obtain a total weight of 28 g. The mixture was stirred using a plastic paddle for at least 1 min. A programmed heating and cooling cycle was used, in which the samples were held at 50 °C for 1 min, heated to 95 °C over 7.5 min, and held at 95 °C for 5 min before cooling to 50 °C over 7.5 min and then being held at 50 °C for 2 min.

2.9. Statistical analysis

All analyses were determined at least in triplicate. Differences between the physicochemical properties and starch digestibility of the samples produced as a function of cooking temperature and cooking time were established using analysis of variance (ANOVA). Duncan's multiple range tests ($p < 0.05$) were carried out to analyze the differences. Statistical analysis was performed using Statistical Analysis System for windows (SAS Institute Inc., Cary, USA).

3. Results and discussion

3.1. Chemical components analysis

The contents of amylose and related chemical components in the three rice varieties are shown in Table 1. As seen from Table 1, the moisture, protein and lipid contents of the three rice varieties were significantly different ($p < 0.05$), all following the order of WR > LAR > HAR. There was no difference in the total starch content between LAR and HAR, but the content in these two varieties was significantly higher ($p < 0.05$) than that of WR.

3.2. Amylose leaching

The amylose leaching (AL) measurements of native and cooked WR, LAR, HAR are shown in Fig. 2. It is well known that WR has less amylose content, so the impact of cooking temperature and cooking time on WR was limited. For LAR, cooking resulted in a constant decrease in AL. For HAR, the AL of HAR cooked for 15–45 min increased at 50 °C but decreased rapidly from 70 °C to 90 °C. The amylose leaching of cooked rice products occurred at different degrees due to a gradual dissociation when the rice was subjected to various cooking conditions [6]. Higher cooking temperatures may result in more extensive networks of amylose chains between fragmented granules through the dissolution of starch molecules, which can restrict amylose leaching of non-waxy rice [20].

3.3. Swelling power and solubility index

The effects of cooking temperature and cooking time on the swelling power (SP) and solubility index (SOL) of WR, LAR, HAR are shown in Fig. 1. Results showed that cooking produced various effects on the SP of all three varieties of cooked rice. Cooking generally resulted in an increase in the SP for WR products but a decrease in SP for LAR and HAR products. When WR was cooked for a constant time, the values of SP increased at temperatures between 50 and 70 °C and decreased at 90 °C. The effect of cooking time on the SP of cooked WR was producing a decrease in SP as cooking temperature increased. For LAR and HAR, the SP changes were in the following order: 50 °C–70 °C > 90 °C for constant cooking times. When the cooking temperature was constant, the SP value remained constant or only slightly changed with different cooking times between 15 and 45 min.

Changes in the SOL of WR, LAR, and HAR are presented in Fig. 1b. With the increase in temperature, the SOL of WR and LAR cooked for a constant time increased significantly ($p < 0.05$), with the exception of the SOL of LAR cooked for 45 min. For example, the SOL of WR cooked for 15 min was 3.8% at 50 °C and increased to 15.3% at 90 °C. At constant cooking temperature, the changes in the SOL of cooked WR were in the following order: 15 min < 30 min < 45 min. The SOL values for HAR were unchanged at 50 to 70 °C and decreased significantly at 90 °C.

When a starch granule is cooked in excess water, heat and moisture transfer will occur when the granule is heated to the gelatinization temperature. The swelling behavior is primarily a property of amylopectin, whereas amylose acts as both a diluent and an inhibitor of swelling. The maximal swelling is related to the molecular weight and fine structures of amylopectin [21]. Changes in the cooking temperature may improve the swelling of the amorphous domains of starch. Swelling of the amorphous domains generates instability in the crystallites. Upon the disruption of the crystallites, the particles lose their organization and interact with water molecules through hydrogen bonding, resulting in the starch granule swelling to several times its initial size [22].

The reduction of swelling power in cooked LAR and HAR could attribute to the fact that the interplay of the additional chain interaction (amylose-amylose, amylose-amylopectin, amylopectin-amylopectin) and the formation of amylose-lipid complex. Such chain interactions and formation of amylose-lipid complex cannot be occurred in cooked waxy rice. This type of mechanism may also be partly responsible for the observed differences in amylose leaching between LAR and HAR. Hoover, et al. [23] suggested that the starch swelling behavior is related to the packing arrangement of the starch chains. Higher cooking temperature may destroy the organization of the double helix arrangement in crystalline lamellae [24]. Longer cooking time may improve the mobility of amylose and the formation of chain interaction, resulting in a decrease in SP and SOL in non-waxy rice [25]. Vermeylen, et al. [26] also found that longer cooking time caused the disruption of more hydrogen bonding stabilization in the double helical model of starch molecules.

3.4. In vitro digestibility

Amounts of rapidly digestible starch (RDS), slowly digestible starch (SDS) and resistant starch (RS) in WR, LAR and HAR are shown in Fig. 3. Compared to the starch in the native rice, cooking resulted in an increase in the RDS values and a decrease in the SDS and RS values for all varieties, with the exceptions of the SDS of HAR increasing at 70 °C and the RS of WR remaining unchanged. We noticed that as cooking temperature was increased from 50 °C to 90 °C, the RDS increased significantly for all varieties, whereas SDS and RS showed a degree of reduction. For example, the RDS of WR, LAR and HAR cooked for 15 min was 49.4%, 26.3% and 1.4%, respectively, at 50 °C and significantly increased to 57.2%, 62.2% and 51.4% at 90 °C. In contrast, cooking time generated little effect on digestibility. When rice was cooked at 90 °C, the RDS values of WR, LAR and HAR cooked for 15–45 min were 57.2%–59.4%, 62.2%–63.4% and 51.4%–58.1%, respectively. Cooking temperature had a more pronounced effect on the *in vitro* digestibility than did cooking time.

Compared to low-amylose rice and waxy rice starches, the high-amylose rice starch had a higher proportion of amylose and less swelling ability, which have the capacity to form more stable double helices and stronger crystallites to reduce enzyme susceptibility. Cooking increased the spaces around the crystallites through the swelling of starch grains and decreased the continuity in the construction of proteins by changing the structure of starch molecules, which increased the accessibility of the starch matrix to α-amylase [27,28]. In this study, the sudden increase of the RDS of HAR cooked at a higher temperature may be attributed to the greater extent of starch structure disruption, including disintegration of the double helices of amylopectin, loss of the crystalline order and disruption of amylose-amylose and/or amylose-amylopectin interactions [24]. This claim is further supported by the results of gelatinization enthalpy of HAR which was reduced to a larger

Table 1
Chemical components of WR, LAR and HAR.

Rice variety	Water content (g kg^{-1})	Protein content (g kg^{-1})	Lipid content (g kg^{-1})	Total starch content (g kg^{-1})	Amylose content (g kg^{-1})
WR	140.5 ± 0.02^a	90.4 ± 0.10^a	26.5 ± 0.05^a	863.4 ± 0.90^b	15.0 ± 0.00^c
LAR	123.1 ± 0.01^b	82.0 ± 0.01^b	22.4 ± 0.05^b	885.7 ± 0.65^a	156.2 ± 0.25^b
HAR	114.6 ± 0.08^c	76.2 ± 0.03^c	18.2 ± 0.04^c	894.9 ± 0.83^a	220.7 ± 0.39^a

All data represent the mean of triplicates.
Values in each column with different superscripts are significantly different ($p < 0.05$).

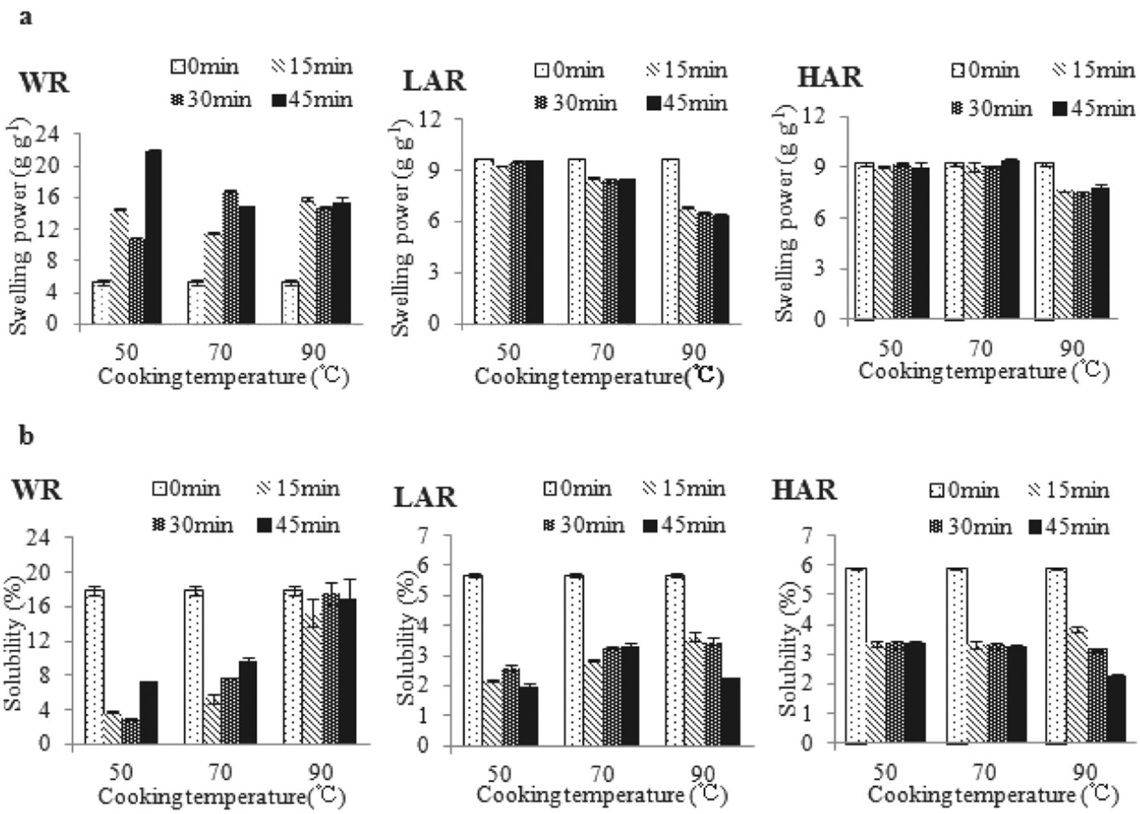

Fig. 1. Impacts of cooking temperature and cooking time on (a) the swelling power (g g^{-1}) and (b) the solubility (%) of waxy, low amylose and high amylose rice.

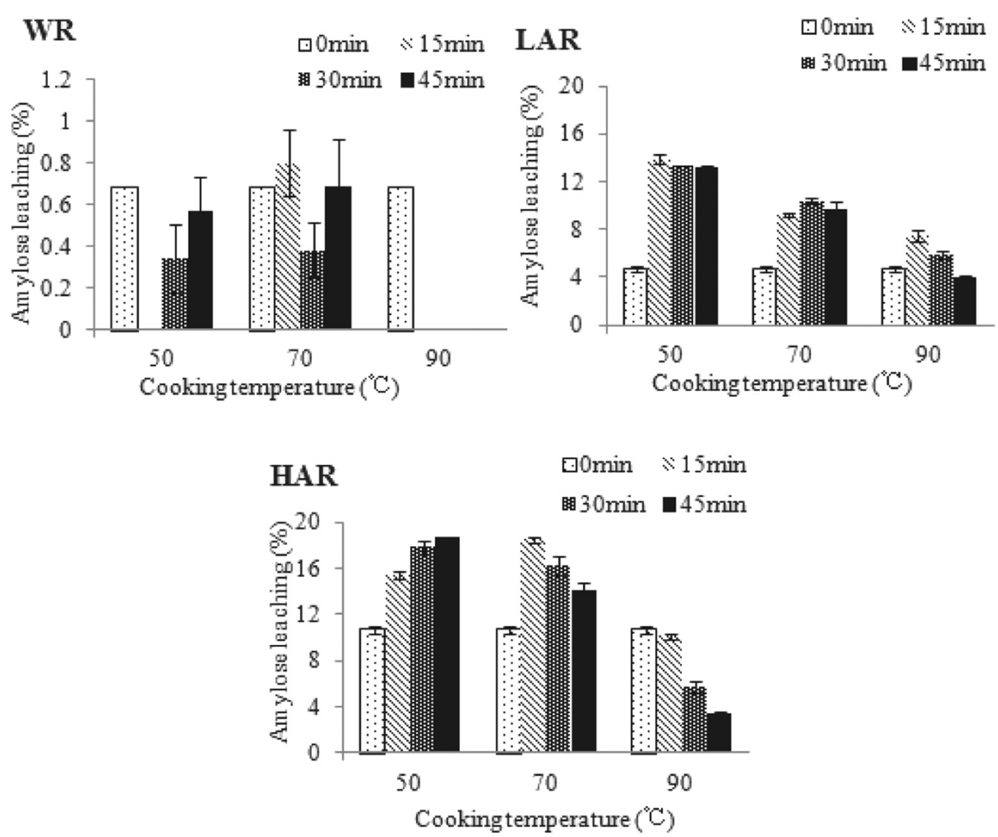

Fig. 2. Impact of cooking temperature and cooking time on the amylose leaching (%) of waxy, low amylose and high amylose rice.

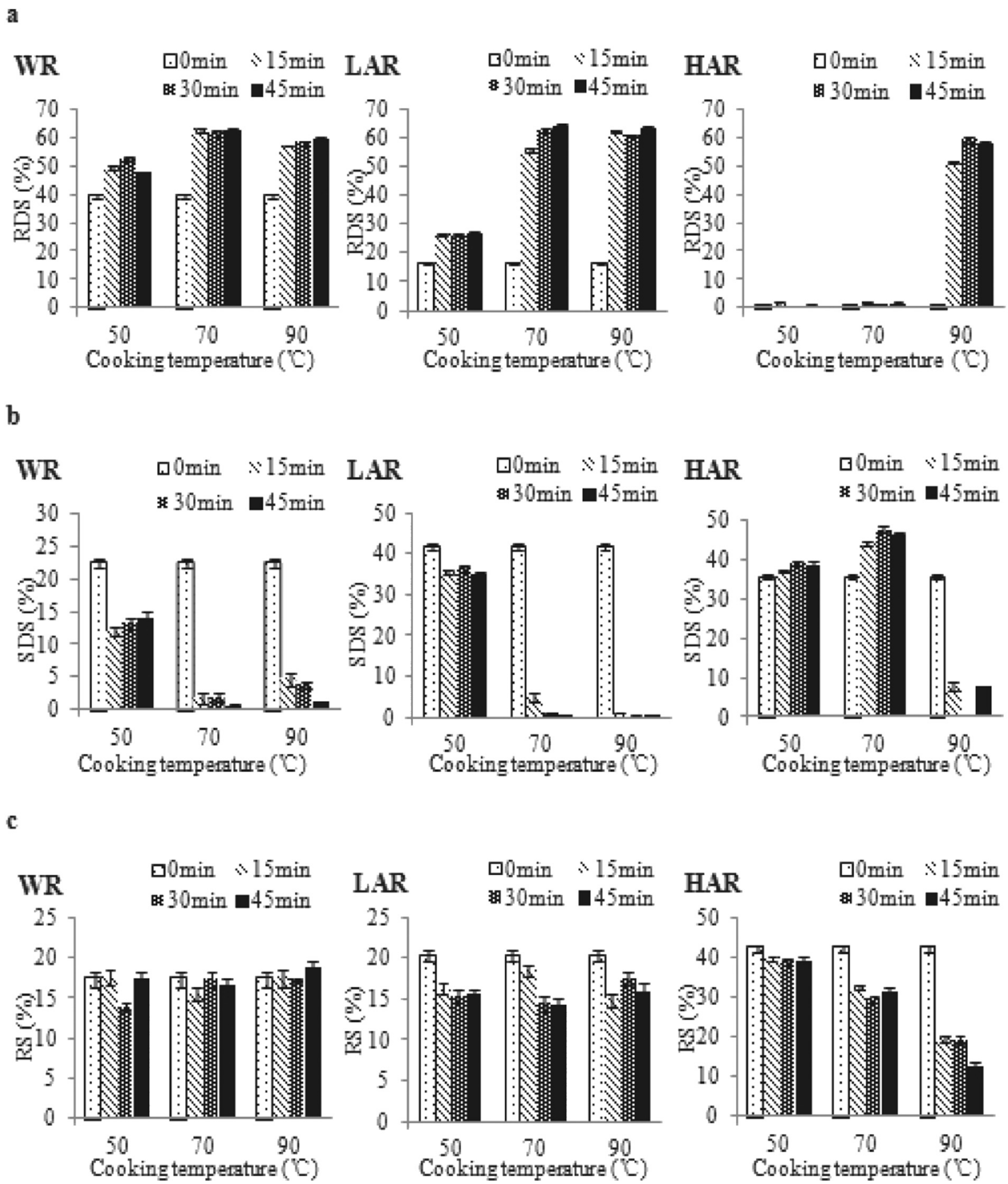

Fig. 3. Impact of cooking temperature and cooking time on the *in vitro* digestibility of waxy, low amylose and high amylose rice (a) RDS (%), (b) SDS (%), (c) RS (%).

extent after cooking at 90 °C. Cooking temperature is a vital factor in gelatinization and produced a greater effect on starch digestibility. When cooking time was prolonged, more water absorption may have destroyed the original molecular structure of starch and improved gelatinization, leading to the leaching of amylose and an increase in the RDS content. In addition, a few interactions between proteins and starch may have been interrupted to different degrees, and some protein molecules may have begun to unfold, forming a relatively disordered structure and increasing the RDS content. More interactions in the amorphous regions and a more organized structure in the crystalline regions were responsible for the reduction of the RDS content [29].

3.5. Thermal properties

The thermal properties of WR, LAR and HAR determined by DSC are summarized in Table 2. Results showed that T_o, T_p and T_c had a positive correlation with the cooking parameters of temperature and time, while T_c-T_o and ΔH was negatively correlated with the parameters. The T_o, T_p and T_c values of the three varieties followed the order of HAR > LAR > WR. The ranges of the T_o, T_p and T_c were 58.19–80.10, 64.83–84.26 and 72.50–91.71 °C, respectively. Variations in the cooking conditions produced a reasonably wide gap among the values of enthalpy. For example, the value of ΔH for HAR cooked for 15 min was 13.94 J g^{-1} at 50

Table 2
Impact of cooking temperature and cooking time on the thermal properties of WR, LAR and HAR.

Rice variety	Cooking temp. (°C)	Cooking time (min)	T_o (°C)	T_p (°C)	T_c (°C)	T_c-T_o (°C)	ΔH (J g^{-1})
WR	0	0	59.43 ± 0.28^{o}	67.78 ± 0.06^{k}	78.30 ± 0.18^{g}	18.87 ± 0.46^{a}	10.83 ± 1.05^{ef}
	50	15	58.19 ± 0.25^{q}	65.14 ± 0.54^{no}	73.39 ± 0.78^{l}	15.20 ± 0.52^{b}	11.04 ± 0.36^{e}
		30	58.44 ± 0.06^{q}	64.83 ± 0.57^{o}	72.50 ± 0.48^{n}	14.06 ± 0.54^{de}	11.74 ± 0.05^{d}
		45	59.37 ± 0.52^{o}	65.46 ± 0.85^{mn}	72.78 ± 0.41^{mn}	13.42 ± 0.11^{ef}	10.98 ± 0.07^{e}
	70	15	61.45 ± 0.25^{n}	67.85 ± 0.01^{jk}	75.62 ± 0.45^{j}	14.17 ± 0.19^{cd}	9.45 ± 0.43^{h}
		30	61.94 ± 0.18^{m}	68.68 ± 0.14^{i}	75.96 ± 0.23^{ij}	14.02 ± 0.04^{de}	8.06 ± 0.17^{j}
		45	62.82 ± 0.13^{l}	69.85 ± 0.20^{g}	77.57 ± 0.00^{h}	14.75 ± 0.13^{bc}	6.49 ± 0.42^{l}
	90	15	n.d.	n.d.	n.d.	n.d.	n.d.
		30	n.d.	n.d.	n.d.	n.d.	n.d.
		45	n.d.	n.d.	n.d.	n.d.	n.d.
LAR	0	0	65.08 ± 1.06^{i}	72.57 ± 0.52^{f}	80.12 ± 1.27^{f}	15.04 ± 2.33^{b}	9.00 ± 0.29^{i}
	50	15	59.19 ± 0.45^{op}	66.29 ± 0.00^{l}	74.19 ± 0.49^{k}	15.00 ± 0.04^{b}	10.08 ± 0.31^{g}
		30	59.31 ± 0.08^{o}	65.65 ± 0.03^{m}	73.16 ± 0.13^{lm}	13.85 ± 0.04^{de}	10.31 ± 0.06^{g}
		45	58.94 ± 0.06^{p}	64.78 ± 0.25^{o}	72.82 ± 0.28^{lmn}	13.89 ± 0.35^{de}	10.51 ± 0.58^{fg}
	70	15	63.07 ± 0.18^{l}	68.24 ± 0.51^{j}	75.92 ± 0.74^{ij}	12.85 ± 0.57^{fg}	7.98 ± 0.06^{j}
		30	63.73 ± 0.13^{k}	69.25 ± 0.37^{h}	76.26 ± 0.13^{i}	12.53 ± 0.27^{g}	7.25 ± 0.05^{k}
		45	64.53 ± 0.08^{j}	69.58 ± 0.38^{gh}	76.10 ± 0.03^{ij}	11.58 ± 0.05^{h}	5.72 ± 0.08^{m}
	90	15	67.71 ± 0.01^{h}	72.48 ± 0.16^{f}	77.68 ± 0.59^{h}	9.97 ± 0.60^{i}	0.49 ± 0.05^{o}
		30	n.d.	n.d.	n.d.	n.d.	n.d.
		45	n.d.	n.d.	n.d.	n.d.	n.d.
HAR	0	0	77.64 ± 0.16^{c}	81.73 ± 0.02^{b}	88.07 ± 0.13^{b}	10.43 ± 0.03^{i}	10.35 ± 0.38^{g}
	50	15	73.69 ± 0.16^{g}	77.65 ± 0.08^{e}	84.01 ± 0.09^{d}	10.32 ± 0.06^{i}	13.94 ± 0.23^{a}
		30	73.69 ± 0.20^{g}	77.68 ± 0.16^{e}	83.46 ± 0.41^{de}	9.77 ± 0.21^{i}	12.30 ± 0.41^{c}
		45	73.89 ± 0.03^{g}	77.91 ± 0.16^{de}	83.73 ± 0.10^{de}	9.84 ± 0.13^{i}	11.77 ± 0.02^{d}
	70	15	75.00 ± 0.19^{f}	78.23 ± 0.16^{d}	83.29 ± 0.34^{e}	8.30 ± 0.15^{j}	13.42 ± 0.61^{b}
		30	75.59 ± 0.22^{e}	78.72 ± 0.18^{c}	83.58 ± 0.37^{de}	7.99 ± 0.16^{j}	13.45 ± 0.08^{b}
		45	76.09 ± 0.07^{d}	79.07 ± 0.13^{c}	83.96 ± 0.16^{d}	7.86 ± 0.09^{j}	13.25 ± 0.62^{b}
	90	15	78.40 ± 0.45^{b}	81.38 ± 0.46^{b}	86.25 ± 0.99^{c}	7.85 ± 0.54^{j}	5.49 ± 0.23^{m}
		30	80.10 ± 0.02^{a}	84.26 ± 0.04^{a}	91.71 ± 0.83^{a}	11.62 ± 0.81^{h}	1.33 ± 0.14^{n}
		45	n.d.	n.d.	n.d.	n.d.	n.d.

All data represent the mean of triplicates.
Values in each column with different superscripts are significantly different ($p < 0.05$).
T_o, onset gelatinization temperature; T_p, peak gelatinization temperature; T_c, conclusion gelatinization temperature; T_c–T_o, gelatinization temperature range; ΔH, gelatinization enthalpy.
n.d. represents not determined.

°C and decreased to 5.49 J g^{-1} at 90 °C. However, ΔH increased at low cooking temperature for all tested rice cultivars when compared to that of native flour, which is more pronounced in HAR.

It was reported that the amorphous domain of starch showed thermal instability and absorbed more water at low temperatures near T_o. Starch showed a disordered behavior and reacted with more water molecules, resulting in a decrease in the gelatinization temperature [30,31]. Rice cooking in excess water at low temperature may cause annealing process, resulting in an increase in gelatinization enthalpy. Tester and Debon [32] proposed that annealing represents the physical reorganization of starch granule when heated in water at a temperature above its glass transition temperature, but below the temperature at which onset of gelatinization occurs. The increase in ΔH of annealing waxy and normal starches was attributed to: (i) improved the helical associations and structure; (ii) increased rigidity of amorphous zones. Annealing does not appear to introduce any new double helices, except in high-amylose starches. Annealing of high amylose starches could facilitate compartmentalization of amylose and amylopectin double helices, leading to a significant increase in gelatinization enthalpy of HAR [32].

When the cooking temperature increased, the swelling of the amorphous domain stimulated greater dissolution of the crystalline region, until both the crystalline and amorphous domains were finally gelatinized and decreased the value of ΔH [20]. Gunaratne and Corke [33] found that extensive formation of amylose chains increased the gelatinization temperature and decreased ΔH through the formation of amylose-lipid complexes. The process of plasticization by water was shown to bring changes to the starch structure, lowering the phase transformation temperature of cooked rice. When the cooking time was prolonged, amylose mobility was increased, generating more chain networks and delaying the process of gelatinization. ΔH decreased significantly as cooking carried on. Cooke and Gidley [34] and Tester and Morrison [35] found that gelatinization enthalpy reflects the melting of double helices and overall crystallinity. Some of the double helices present in crystalline and in non-crystalline regions of granules may be disrupted under the conditions of cooking treatment. Thus, fewer double helices would unravel and melt during the gelatinization process of cooked rice starch [36].

In the results, we found some missing values at 90 °C, including the absence of ΔH (Table 2), which may have been because the samples were gelatinized at this temperature. There are two possible mechanisms to explain the changes in enthalpy—the melting of starch crystallites and the crystallization of amylose-lipid complexes [37]. At 90 °C, the water absorption and expansion of amorphous regions could forcefully tear starch chains from the crystallites. When all crystals were stripped at high levels of moisture content, no crystals would be found due to melting of the remaining crystallites. In addition, amylose and lipid may have complexed together through an endothermic process.

3.6. Pasting properties

The pasting properties of WR, LAR and HAR before and after cooking are given in Table 3. Cooking significantly increased the peak viscosity, trough viscosity, final viscosity, breakdown and setback of WR compared to native starch. For example, the peak viscosity (PV) of native WR was 22.08 RVU and increased to 283.59 RVU after 15 min cooking at 50 °C. Our results showed that the peak viscosity, trough viscosity, final viscosity and setback of LAR cooked for 15–45 min decreased significantly ($p < 0.05$) at 70–90 °C, while that of HAR cooked for 15–45 min significantly decreased ($p < 0.05$) at 90 °C. At 90 °C, the breakdown values of rice cooked for 15–45 min (WR, LAR and HAR) increased gradually. After 45 min of cooking at 90 °C, the peak viscosity, trough viscosity, final viscosity and setback of cooked WR, LAR and HAR reached the lowest points.

At first, as cooking temperature increased, starch swelling capacity increased, which meant the deformation was increased and the rigidity was lowered, leading to a decrease in the peak viscosity value [38].

Table 3
Impact of cooking temperature and cooking time on the pasting properties of WR, LAR and HAR.

Rice variety	Cooking temp. (°C)	Cooking time (min)	Peak viscosity (RVU)	Trough viscosity (RVU)	Breakdown (RVU)	Final viscosity (RVU)	Setback (RVU)
WR	0	0	22.08 ± 4.60^{u}	10.63 ± 2.18^{s}	11.46 ± 2.42^{p}	16.04 ± 2.89^{r}	5.42 ± 0.71^{p}
	50	15	283.59 ± 0.59^{a}	97.83 ± 0.35^{ij}	185.75 ± 0.24^{a}	124.21 ± 1.47^{j}	26.38 ± 1.12^{ij}
		30	284.54 ± 0.06^{a}	95.54 ± 0.41^{jk}	189.00 ± 0.47^{a}	121.83 ± 1.41^{j}	26.29 ± 1.00^{ij}
		45	222.88 ± 0.06^{c}	79.58 ± 0.71^{m}	143.29 ± 0.65^{b}	92.46 ± 0.53^{m}	12.88 ± 0.18^{mno}
	70	15	247.21 ± 1.00^{b}	100.83 ± 0.71^{hi}	146.38 ± 0.29^{b}	126.34 ± 2.24^{j}	25.51 ± 1.53^{ij}
		30	210.21 ± 1.94^{d}	90.25 ± 0.82^{l}	119.96 ± 1.12^{c}	109.04 ± 0.41^{k}	18.79 ± 0.41^{klm}
		45	189.21 ± 1.94^{h}	82.92 ± 0.94^{m}	106.29 ± 1.00^{d}	100.79 ± 0.06^{l}	17.88 ± 0.88^{lmn}
	90	15	89.25 ± 3.54^{o}	72.42 ± 4.83^{n}	16.84 ± 1.29^{o}	109.34 ± 3.06^{k}	36.92 ± 1.77^{h}
		30	74.63 ± 9.84^{p}	63.13 ± 11.60^{o}	11.50 ± 1.77^{p}	85.17 ± 15.44^{n}	22.04 ± 3.83^{jkl}
		45	70.88 ± 2.41^{q}	46.42 ± 4.48^{p}	24.46 ± 6.89^{n}	66.25 ± 1.65^{p}	22.79 ± 1.95^{jkl}
LAR	0	0	145.54 ± 6.31^{k}	72.58 ± 4.01^{n}	72.96 ± 2.30^{f}	176.33 ± 3.18^{i}	103.75 ± 0.82^{de}
	50	15	190.38 ± 4.31^{gh}	122.59 ± 3.77^{f}	67.80 ± 0.53^{g}	228.54 ± 4.19^{f}	105.96 ± 0.42^{de}
		30	195.05 ± 1.24^{f}	137.21 ± 3.13^{cd}	57.84 ± 1.89^{h}	238.42 ± 1.77^{e}	101.21 ± 1.36^{e}
		45	207.42 ± 4.48^{d}	125.54 ± 5.01^{ef}	81.88 ± 0.53^{e}	235.38 ± 4.42^{e}	109.84 ± 0.59^{cd}
	70	15	151.83 ± 4.45^{j}	108.06 ± 5.42^{g}	43.78 ± 2.87^{j}	209.31 ± 3.05^{g}	101.25 ± 3.25^{e}
		30	138.25 ± 1.77^{l}	106.00 ± 0.82^{gh}	32.25 ± 0.95^{m}	196.71 ± 1.24^{h}	90.71 ± 0.42^{f}
		45	122.33 ± 1.41^{n}	97.29 ± 1.12^{ij}	25.04 ± 0.30^{n}	177.34 ± 1.18^{i}	80.05 ± 0.06^{g}
	90	15	70.19 ± 1.63^{q}	63.59 ± 3.02^{o}	6.61 ± 2.96^{r}	97.00 ± 3.89^{lm}	33.42 ± 1.15^{h}
		30	52.21 ± 1.24^{r}	44.30 ± 1.24^{p}	7.92 ± 0.00^{pqr}	75.54 ± 1.82^{o}	31.25 ± 0.59^{hi}
		45	48.56 ± 0.67^{r}	37.92 ± 2.11^{q}	10.64 ± 2.67^{pq}	62.25 ± 1.81^{p}	24.33 ± 1.01^{jk}
HAR	0	0	127.17 ± 0.47^{m}	91.33 ± 9.90^{kl}	35.83 ± 9.43^{lm}	197.08 ± 15.56^{h}	105.75 ± 25.46^{de}
	50	15	177.50 ± 1.17^{i}	137.13 ± 1.59^{d}	40.38 ± 2.76^{jk}	249.79 ± 3.83^{d}	112.67 ± 2.24^{bc}
		30	181.17 ± 0.47^{i}	129.67 ± 2.00^{e}	51.50 ± 2.47^{i}	258.17 ± 2.95^{c}	128.50 ± 4.95^{a}
		45	199.71 ± 3.13^{e}	147.09 ± 7.54^{ab}	52.63 ± 4.42^{i}	272.17 ± 6.84^{a}	125.08 ± 0.71^{a}
	70	15	189.25 ± 3.65^{h}	148.88 ± 0.18^{a}	40.38 ± 3.47^{jk}	262.96 ± 3.13^{bc}	114.09 ± 3.30^{bc}
		30	179.79 ± 0.65^{i}	142.38 ± 3.12^{bc}	37.42 ± 2.47^{kl}	258.71 ± 3.36^{c}	116.33 ± 6.48^{b}
		45	193.50 ± 0.11^{fg}	151.92 ± 8.37^{a}	41.59 ± 8.25^{j}	267.33 ± 2.12^{ab}	115.42 ± 10.49^{bc}
	90	15	68.25 ± 0.95^{q}	61.67 ± 2.35^{o}	6.58 ± 1.41^{r}	84.33 ± 2.12^{n}	22.67 ± 0.23^{jkl}
		30	36.08 ± 0.00^{s}	29.09 ± 0.94^{r}	7.00 ± 0.95^{qr}	40.96 ± 0.30^{q}	11.88 ± 0.64^{no}
		45	31.75 ± 1.06^{t}	24.46 ± 0.88^{r}	7.30 ± 0.18^{qr}	35.25 ± 1.17^{q}	10.80 ± 0.29^{op}

All data represent the mean of triplicates.
Values in each column with different superscripts are significantly different ($p < 0.05$).

Bagley and Christianson [39] found that there were two factors depending on cooking time, including the degree of swelling and the resultant plasticization of starch granules. With the increase of cooking time, the extent of swelling also increased, resulting in an increase in the peak viscosity. However, when dilatancy disappeared, increasing the temperature and time resulted in a greater extent of starch disruption and formation of amylose chains and amylose-lipid networks between broken pieces, which was responsible for lowering the peak viscosity values [20,40,41].

4. Conclusion

Cooking changed the physicochemical properties and starch digestibility of waxy, low- and high-amylose rice as a function of cooking temperature and cooking time. The thermal properties of gelatinization temperature showed a positive correlation with cooking temperature and cooking time, while the gelatinization enthalpy and peak viscosity, trough viscosity, and final viscosity of pasting properties showed negative correlation. With the increase in cooking temperature from 50 °C to 90 °C, the RDS increased significantly for all varieties, while the SDS and RS showed a degree of reduction. However, the cooking time had few effects on starch digestibility. Our results showed that cooking temperature had more pronounced effects on the extent of change than did cooking time regarding physicochemical properties and starch digestibility.

Although a large body of evidence has shown the impact of different cooking conditions on rice quality, the combined effect of cooking temperature and cooking time on the physicochemical properties of rice was still unclear. In the current study, we provided results indicating that cooking temperature and cooking time had significant impacts on the physicochemical properties and starch digestibility of rice to various extents. This can not only summarize or supplement the basic knowledge of rice cooking but can also give some guidance to the food industry for production on a large scale.

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