The Improved Chemical, Mechanical, Rheological, and Pasting Characteristics of Protein-Rich Brown Rice by Parboiling Process Integrated with Nitrogen Fertilization

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Abstract

The effects of nitrogen fertilization (NF, 60-100 kg ha^{-1}) and parboiling operation (soaking temperature (SoT, 50-80°C) and steaming time (StT, 10-15 min)) on the protein content (PC), amylose content (AC), gelatinization temperature (GT), hardness value (HV), peak viscosity (PV), trough viscosity (TV), final viscosity (FV), breakdown (BD), setback (SB) point, peak time (PTi), and pasting temperature (PTe) of brown rice were evaluated. Results showed that the GT, HV, FV, and TV were significantly increased by increasing the NF, SoT, and StT levels. An increase in the SoT and StT levels led to a significant reduction in PC, AC, BD, and TV values. The AC (17.13-16.83%) and PV (1605-1588 cP) values were decreased by increasing the NF level, while the PC (8.78-9.46%) and BD (226.9-247.7 cP) values were increased. Rheological parameters of BD (336.4 cP), FV (3608.5 cP), and SB (1843.5 cP) were notably increased using the combined treatment of 100 kg ha^{-1} NF and of 80°C SoT. The best triple treatments for the improved GT (5.0 °C), HV (19.37 N), as well as FV (3923 cP), and SB (1949 cP) were 60 kg ha^{-1} NF+80°C SoT+15 min StT, 100 kg ha^{-1} NF+80°C SoT+15 min StT, and 100 kg ha^{-1} NF+80°C SoT+10 min StT, respectively.

Key words: fertilization, nitrogen, parboiling, rice (*Oryza sativa* L.), rheology, texture

Abbreviations

AC: amylose content, BD: breakdown, BR: brown rice, FV: final viscosity GABA: γ-aminobutyric acid, GT: gelatinization temperature, HV: hardness value, NF: nitrogen fertilizer, PC: protein content, PTe: pasting temperature, PTi: peak time, PV: peak viscosity, RVA: rapid visco analyzer, SB: setback, SGs: starch granules, SoT: soaking temperature, StT: steaming time, TV: trough viscosity.

Introduction

Rice is the second commonly produced cereal in the world with ~800 million metric tons in 2018. The main producers of paddy rice are China, India, Indonesia, Bangladesh, and Viet Nam, respectively (FAOSAT, 2018). This major cereal crop has high nutritional value due to a high number of bioactive constituents such as polyphenols, ferulic acid, and γ-aminobutyric acid (Gharibzahedi, 2018). The presence of health-promoting phytochemicals, vitamins, and minerals has been also proved in the flour obtained from brown (unpolished) rice (BR) (Zhang *et al.*, 2019). Compared with wheat flour, there are higher fiber (1.2 vs. 0.85% w/w) and lower protein (8.5-9.5 vs. 12.6% w/w) levels in BR flour (Nalinanon, and Karnjanapratum, 2020). The presence of a tough highly fibrous layer in the outer coat of RB grains has been caused a significant reduction in its consumption compared to well-milled white rice (Indriani *et al.*, 2020). Hence, there is a necessity to find some solutions to increase the protein content and digestibility of BR in gluten-free bakery products (Păucean *et al.*, 2017).

The use of chemical fertilizers such as nitrogen fertilizers (NF) is one of the preliminary approaches in improving the growth, development, and nutritional quality of rice. However, the unbalanced consumption of these fertilizers due to environmental pollution and achieving the peak production yield has recently led to a significant reduction in the quality of cereal crops, especially in rice (Salantă *et al.*, 2016; Păucean *et al.*, 2017; Naher *et al.*, 2020). Thus, one of the most important challenges facing societies is the further production of high-quality foods under the reduced fertility of soils (Naher *et al.*, 2020). The deficit and excess nitrogen amounts have an adverse effect on the growth and development of cereals (Panasiewicz *et al.*, 2017).

More than 20% of the world's NFs are used in Asian paddy lands. In most Asian rice-producing countries, farmers utilize 80-150 kg NF per hectare to achieve a yield of ~5-7 tons of rice per hectare. But, the efficiency of using nitrogen in most paddy fields is only limited to ~25-40% of the nitrogen consumed by farmers (Păucean *et al.*, 2016; Xiao *et al.*, 2019). On the other hand, the production yield of rice can be even reduced by the excess nitrogen or fertilizer imbalance, owing to the increased number of infertile claws, the decreased grain filling efficiency, the development of long stems or, vegetative growth, as well as the spread of bacterial diseases (Xiao *et al.*, 2019). This fact shows that there is a necessity in determining the utilized amount of NF to maximize plant growth and grain nutritional quality.

Parboiling is another solution for maintaining the nutritional value and improving the textural, rheological, sensorial, cooking, and digestibility properties, as well as shelf life of rice. This integral part of post-harvest rice processing is a hydrothermal process in which the crystalline form of starch present in paddy rice is changed into an amorphous one due to the irreversible swelling and fusion of starch (Fos' hat *et al.*, 2011; Saha and Roy, 2020). This technology is involved in two-unit operations of soaking at high temperatures and steaming at low pressures. After the soaking and moisture absorption of paddy rice in hot/warm water for 4-24 h, a conducive environment after cooling down is provided for enzymes, nutrients, and pigment transformation. The soaked paddy is then steam-heated to be gelatinized so that cooked parboiled rice is firmer and less sticky compared to raw rice (Yamuangmorn and Dell, 2018). During the pressurized steaming process, a set of physicochemical processes such as starch retrograding, pigment transformation, enzymatic deactivation reactions are facilitated which can be resulted in the improved flavor, color-change, and cooking characteristics of rice (Xia *et al.*, 2019). Moreover, the temperature in the pressurized steaming step is able to kill pathogen microorganisms and to move inward of vitamins, especially thiamine, from the embryo on to the inner section of grains, increasing the content of endosperm protein. Subsequently, the drying facilitates the de-husking of steam-parboiled paddy due to the compression of gelatinous amylose starch compresses in a compact mass (Rocha-Villarreal *et al.*, 2018).

To the best of our knowledge, there is no specific investigation on the combined effect of NF rate and parboiling conditions (e.g., soaking temperature (SoT) and steaming time (StT) on the BR quality in terms of textural, pasting, and nutritional characteristics. Thus, this study aimed to assess the best levels of NF and parboiling conditions with the improved quality properties of BR.

Materials and methods

Field experiment site and fertilizer treatments

A commonly cultivated rice variety in Iran, namely Hashemi, was grown at the National Institute of Rice Research (Rasht, Iran) farm (37°20′N, 49°40′E, altitude 5 m), and harvested in August 2019. Based on the yield increase of rice grains, NF levels of N1 (60 kg ha^{-1}), N2 (80 kg ha^{-1}), and N3

(100 kg ha^{-1}) were used to fertilize the soil of rice fields. Out-of-range levels significantly reduced the production yield of rice in field studies.

Parboiling processing and brown rice preparation

A set of modified soaking and steaming regimes were used to parboil the paddy rice. The soaking setup consisted of a stainless-steel cylindrical container, an electrical heater, a basket for water-soaking, and a temperature control system. Two hundred grams of rice in each treatment were soaked in one liter of deionized water in a water-bath system (C1, 50°C and C2, 80°C for 6 h). To have a possibility to penetrate water molecules into the core part of grains, samples after soaking were taken out of the water and put in a plastic sack for 4 h at ambient temperature (25±2°C) (Taghinezhad *et al.*, 2016). Then, 150 g of soaked paddy rice grains were put into a parboiling vessel on top of a boiler containing about 8 L of boiling water (95±3°C) and steamed under the low pressure (0.8 kg cm^{-2}) at 119°C for 10 min (T1) and 15 min (T2).

The selected SoT and StT levels were assessed based on the results of quality parameters in preliminary studies. Thus, the selected range of SoT and StT led to the best quality mechanical and visco-pasting properties of parboiled rice grains. The steamed samples were then spread on trays and dried in a hot-air oven at 50±1°C for 8 h to decrease the moisture content by 12-14% w.b. The tray position at the end of every hour was switched to dry the rice completely (Chavan *et al.*, 2018). Then, BR was produced from the parboiled rice grains after de-hulling and milling by a rice huller (ST50 model, Yanmar Co., Osaka, Japan).

Chemical analyses

The moisture content was assessed by drying ground samples in a hot-air oven at 130°C for 1 h (ASAE, 1994). The nitrogen content was determined by the Kjeldahl method. The total protein content (PC) was then calculated by multiplying total nitrogen by 5.95 as the protein conversion factor (Guo *et al.*, 2020). The amylose content (AC) was determined by simplifying the method developed by Juliano (1971), based on the color rating. The movement rate of gel produced from flour samples according to the changes occurred in rice endosperm was considered to determine the gelatinization temperature (GT) (Little, 1985). All the chemical tests were carried out triplicate.

Hardness measurement

The hardness property of parboiled rice grains was measured using a texture analyzer machine (TA.XT Plus, Stable Micro Systems, Ltd, Surrey, England), equipped with a 500 N load cell and integrator. The measurement accuracy of force and deformation was 0.001 N and 0.001 mm, respectively. Each individual grain was loaded between two 12-mm flat probes and compressed until rupture occurred in the force-deformation curve. The hardness value (HV) was assessed by a break in the force-deformation curve. The loading was stopped when this point was detected. The hardness tests were performed at the loading rate of 1 mm min^{-1} (Taghinezhad *et al.*, 2016).

Viscosity and pasting profile evaluation

The viscosity and rheological attributes of parboiled BR grains were determined using a rapid visco analyzer (RVA-3D model, Newport Scientific Pty, Warriewood, Australia), according to the AACC International Method 61-02 (AACC, 1999). In brief, the moisture content of all the samples using a vacuum oven was initially measured to estimate the sample size for RVA. An RVA paddle was placed in each canister and the content was firmly mixed (at 960 rpm for 10 s) to make a homogeneous solution. The mixing rate after 10 s was reduced to 160 rpm and maintained until the run end (Habibi and Foroughi, 2014). The RVA was equipped with Thermocline software version 2.2 for Windows. A standard program of the heating-cooling cycle for the obtained sample was set up: holding at 50°C for 1 min, heating to 95°C in 3.45 min, holding at 95°C for 2.7 min, cooling to 50°C in 3.91 min, and finally holding at 50°C for 1.24 min (AACC, 1999). A typical curve with pasting parameters measured by RVA is illustrated in Fig. 1. The viscosity characteristics of the pasting curve were provided in terms of peak viscosity (PV (cP), the maximum viscosity of paste obtained in the heating stage of the profile, Stage 2), trough viscosity (TV (cP), the minimum viscosity of paste achieved after holding at the maximum temperature, Stage 3), final viscosity (FV (cP), the viscosity at the end of the run), breakdown (BD (cP), the difference between PV and TV), setback (SB (cP), the difference between FV and PV), peak time (PTi (s), the record time of the PV point), and pasting temperature (PTe (°C), the swelling and

Table 1. Mean comparison of the chemical and textural properties for different levels of nitrogen fertilizer, soaking time, and steaming temperature

Independent variable	Response variables (chemical and textural properties)[a]			
	PC (%)	AC (%)	GT (°C)	HV (N)
Nitrogen fertilizer (NF)				
N1 (60 kg ha^{-1})	8.78±0.48[b]	17.13±1.72[a]	4.13±0.09[a]	8.81±0.76[c]
N2 (80 kg ha^{-1})	9.27±0.27[a]	16.99±1.28[b]	4.09±0.11[a]	9.27±1.02[a]
N3 (100 kg ha^{-1})	9.46±0.31[a]	16.83±1.32[b]	3.47±0.06[b]	9.45±0.98[a]
Soaking temperature (SoT)				
C1 (50°C)	9.42±0.25[a]	17.81±0.35[a]	3.32±0.09[b]	16.38±0.47[b]
C2 (80°C)	8.92±0.11[b]	16.83±0.18[b]	4.47±0.14[a]	17.34±0.51[a]
Steaming time (StT)				
T1 (10 min)	9.31±0.21[a]	17.68±0.46[a]	3.63±0.05[b]	16.59±0.99[b]
T2 (15 min)	9.03±0.12[b]	16.96±0.65[b]	4.16±0.03[a]	17.19±0.78[a]

[a] The data (mean ± SD) with dissimilar letters in each column are significantly different ($p < 0.05$)

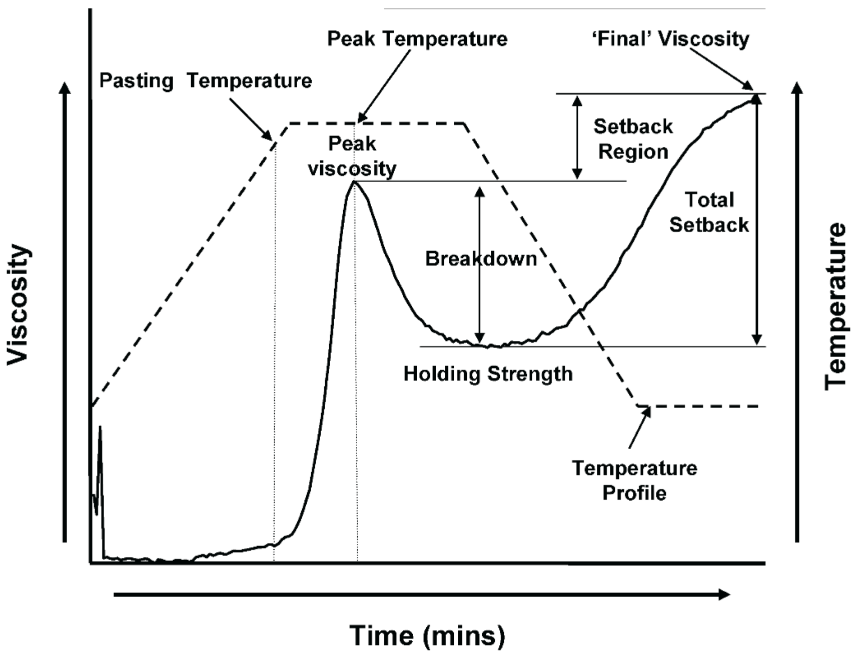

Figure 1. The viscosity characteristics of rice pasting curve developed by RVA

gelatinization temperature of starch granules (SGs) with an increase of 25 cP over a 20 s period) (Juhász and Salgó, 2008). The measurements for each sample were performed at least in triplicate.

Statistical analysis

All of the data were analyzed with the SPSS software, version 22.0 (SPSS Inc., Chicago, IL, USA). The fertilizing and parboiling treatments were subjected to analysis of variance (ANOVA). Duncan's multiple ranges test was used to separate means at a 5% level of significance.

Results and discussion

Chemical characteristics

The ANOVA of the data concerning the chemical properties of parboiled BR revealed that the linear effects of NF, SoT, and StT on the AC, PC, and GT were significant ($p < 0.01$; $p < 0.05$). Moreover, the mutual interaction effects of NF × SoT, NF × StT, and SoT × StT were not significant on the AC and PC of parboiled BR ($p > 0.05$), while the GT was significantly affected ($p < 0.01$). There was a similar result for the triple interaction effect

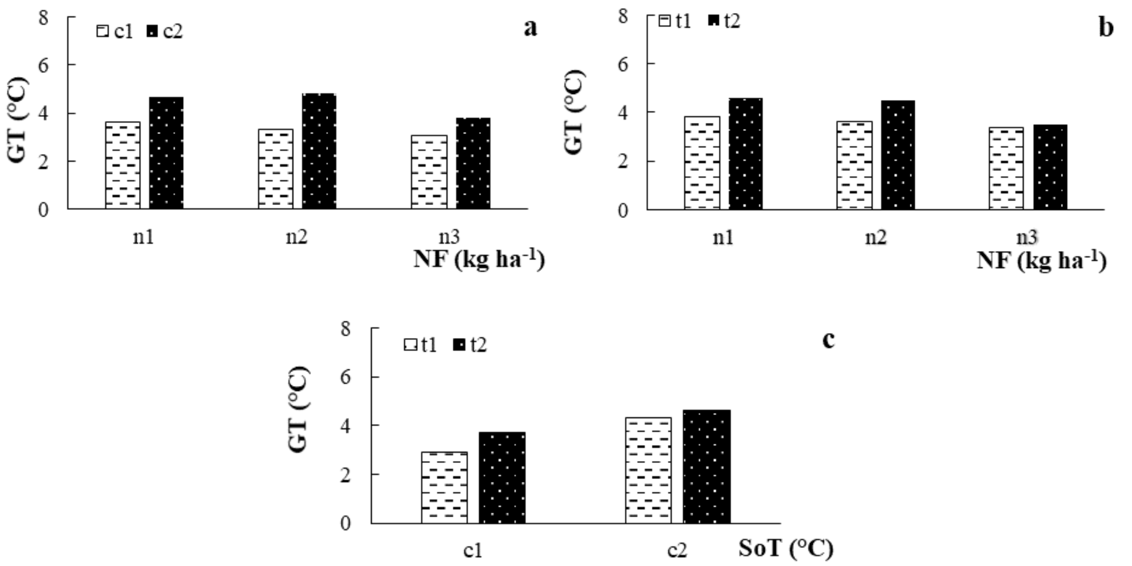

Figure 2. The mutual interactive effects of all the independent variables (a, NF×SoT; b, NF×StT; c, SoT×StT) on the GT

(NF × SoT × StT) on the AC ($p > 0.05$), PC ($p > 0.05$), and GT ($p < 0.01$) (Table 1).

The AC and GT were significantly reduced by increasing the NF level from 60 to 100 kg ha^{-1}. However, the PC was increased with an increase in the level of NF (Table 1). An increase in SoT (from 50 to 80°C) and StT (from 10 to 15 min) led to a significant reduction in the AC and PC, while the GT was increased (Table 1). Among the chemical parameters, only the GT was significantly influenced by the mutual and triple interaction terms of independent variables (Fig. 2 and 3a). Figs. 2 and 3a show that a single and simultaneous increase in SoT (80°C) and StT (15 min) levels and initial NF (60 and 80 kg ha^{-1}) were associated with high GT values.

Increasing the PC of rice is of vital significance for the health status of people in low-income developing countries because this staple food is usually considered as a source rich of proteins with enough content of essential amino acids like lysine. An increase in the PC of rice grains by increasing the soil nitrogen was earlier reported by Sher *et al.* (2016) who demonstrated that the nitrogen rate is linearly related to the value of protein. A higher dose of N resulted in the maximum PC, while the minimum was found from zero N application. The increased uptake of nitrogen by rice grains may be attributed to the improved activity of key enzymes involved in the nitrogen metabolism such as nitrate reductase, glutamine synthetase, and glutamine transversase (Nasrollah Zadeh, 2014; Tayefe *et al.*, 2014). The decreased PC under the severe parboiling conditions is due to the increased leaching of protein substances as a result of the spontaneous ruptures of protein native structure. The high SoT/StT amounts probably sink the protein bodies into the compact mass of gelatinized starch grains, making them less extractable to determine the PC (Chukwu and Oseh 2009). Ibukun (2008) also showed that the magnitude of losses of nutrients, especially proteins, is higher under the prolonged parboiling. Overall, the slight reduction in quality chemical traits of parboiled BR such as PC can be compensated with improved physical qualities such as easy hulling, less breakage, good head rice yield, color, proper gelatinization, etc (Niba *et al.*, 2002).

Reducing the AC with increasing the NF level may be associated with the increased activity of starch-digesting enzymes (Nasrollah Zadeh, 2014). Other researchers also reported that the apparent AC could be significantly decreased by adding NFs to the soil (Gu *et al.*, 2015). Similar to our results, a negative correlation between AC and PC with increasing NF levels was also detected (Lee, 2006). Gu *et al.* (2015) assumed that the grain endosperm contains two types of SGs, including A-type granules forming the greatest section of endosperm (size >10 μm), and B-type with a greater number of smaller granules (size <

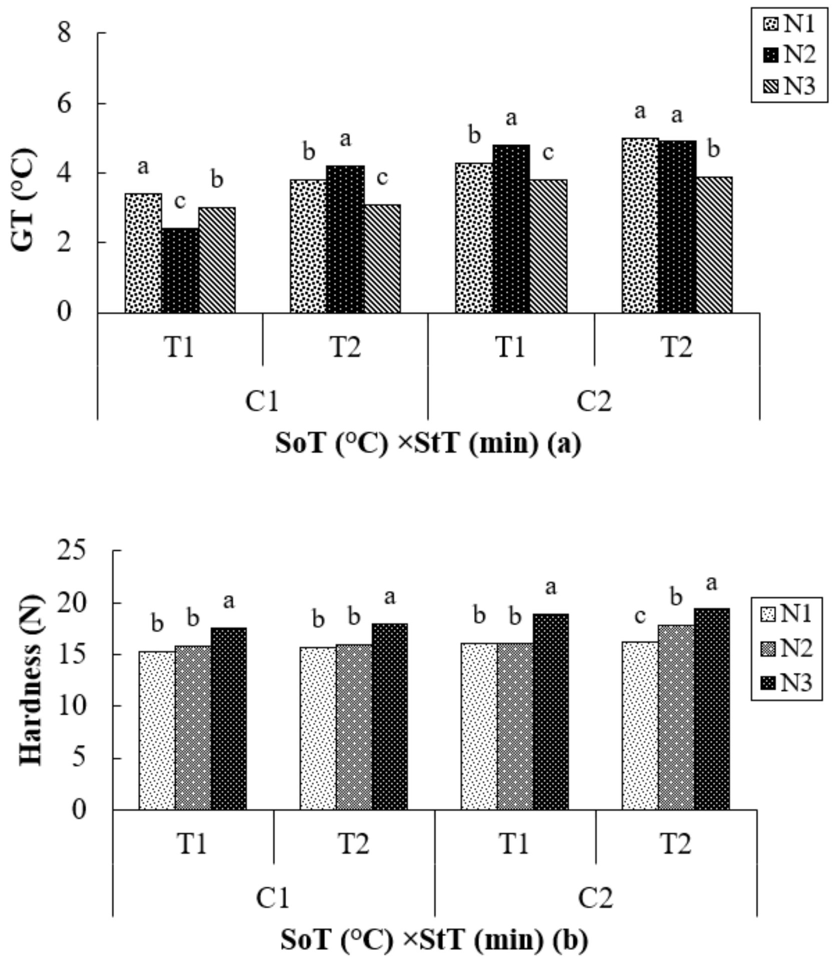

Figure 3. The triple interaction effect of nitrogen fertilizer (NF), soaking time (SoT), and steaming temperature (StT) on the GT (a) and HV (b) of parboiled BR grains

10 μm). In general, A-type granules contain higher AC and show lower GT. Therefore, it seems that the increased levels of NF decrease the section of A-type granules which could explain lower AC in BR grains in our research. Zohoun *et al.* (2018) showed that the steaming of low-amylose variety rice for 45 min reduced the AC from 29.4 to 20.4%. This fact indicates that the AC of parboiled rice samples depended on the variety and StT. Hence, the decreased AC by rising StT can be attributed to amylose leaching during soaking and steaming processes.

More concentrations of NF in the soil cause the formation of large-size SGs with a higher proportion of amylopectin. Since the presence of amylose in the granule structure limits the swelling of amorphous regions, increasing the amylopectin improves the gelatinization of crystallinity and the GT (Zhu *et al.*, 2017). The direct association between GT and SoT/StT has been recently reported (Taghinezhad *et al.*, 2016). It was shown that the long-time steaming accompanied by the soaking process at high temperatures increased the water absorption capacity of SGs as a result of the breaking of molecular bonds in the endosperm and the release of many hydroxyl groups capable of forming hydrogen bonds. The increased GT under this condition may be ascribed to the irreversible breakdown of the highly-compacted structure of SGs and molecular interactions of amylose-amylose and amylose-amylopectin during annealing (Sittipod and Shi, 2016).

Textural hardness

According to statistical analyses, the effects of NF, SoT, and StT on the HV were significant ($p < 0.01$). But, none of the mutual interaction terms significantly affected the HV. Interestingly, the HV was significantly influenced by the triple

Table 2. Mean comparison of the viscosity and pasting properties as a function of nitrogen fertilizer and parboiling conditions

Independent variable	Response variables (viscosity and pasting properties)[a]						
	PV (cP)	TV (cP)	FV (cP)	BD (cP)	SB (cP)	PTi (s)	PTe (°C)
NF							
N1 (60 kg ha^{-1})	1605.0±35[b]	1379.3±25[b]	2999.3±65[b]	226.9±8[b]	1402.2±32[c]	5.89±0.2[a]	91.87±5.9[a]
N2 (80 kg ha^{-1})	1635.4±44[a]	1405.6±27[a]	3043.0±55[a]	234.1±10[b]	1431.7±39[b]	5.88±0.2[a]	88.68±7.1[a]
N3 (100 kg ha^{-1})	1588.1±42[b]	1345.5±24[c]	3044.6±60[a]	247.7±16[a]	1452.1±45[a]	5.91±0.1[a]	88.53±6.4[a]
SoT							
C1 (50°C)	1667.5±21[a]	1397.5±45[a]	2893.6±71[b]	273.0±17[a]	1348.1±40[b]	5.82±0.2[a]	91.86±6.1[a]
C2 (80°C)	1551.5±10[b]	1356.1±34[b]	3164.6±92[a]	199.5±10[b]	1609.3±56[a]	6.01±0.2[a]	90.88±7.0[a]
StT							
T1 (10 min)	1826.1±18[a]	1472.4±71[a]	3326.0±102[a]	357.6±18[a]	1503.7±55[a]	5.75±0.4[a]	90.41±4.6[a]
T2 (15 min)	1392.8±29[b]	1282.1±85[b]	2732.2±95[b]	114.8±20[b]	1353.7±37[b]	6.33±0.5[b]	91.79±4.1[a]

The data (mean±SD) with dissimilar letters in each column are significantly different ($p<0.05$).

interaction effect of independent variables ($p < 0.05$). Table 1 shows that the HV was increased from 8.81 to 9.45 N by increasing the NF level in the studied range. A similar increasing behavior in the HV was recorded with an increase in the SOT and StT levels (Table 1, Fig. 3b). A significant positive correlation was observed between the HV and GT of parboiled BR.

As mentioned earlier, an increase in the NF level leads to a reduction in the number of amylose units in SGs. It was demonstrated that the HV could be decreased by 0.12 units with a one-unit increase in AC (Zohoun *et al.*, 2018). Moreover, the surface hardening of rice grains at high NF levels can be related to the increased accumulation of protein in the surface layer. The presence of proteins in the outer layers inhibits the water absorption and expansion in the thickness of rice grains, increasing the HV Altogether, the low AC, and high PC at high NF levels could lead to an increase in the HV. Similar results were also reported by Gunaratne *et al.* (2011), who found the gel hardness of rice flour reduced by adding the NF. The hardness increase of parboiled BR under higher SoT and longer StT levels is owing to the more gelatinization of grains causing the increased fracture resistance (Taghinezhad and Brenner, 2017). On the other hand, utilizing the parboiling processing under the severe SoT and StT conditions accelerates the penetration rate of moisture into the inner layers of rice grains. The increased gelatinization will continuously strengthen the structural integration of the grain against the rupture force, increasing the HV (Xia *et al.*, 2019).

Viscosity and pasting properties

The ANOVA results of viscosity and pasting properties showed that the PV, TV, BD, SB, and PTe values were significantly influenced by the linear and interaction (mutual and triple) terms of all the independent variables ($p < 0.01$). The NF and SoT had a significant linear effect on the FV ($p < 0.01$), while they did not have any significant effect on the PTi. Furthermore, the linear effect of StT was significant on both FV and PTi ($p < 0.01$). All the interaction terms of independent variables for the FV were significant ($p < 0.01$), whereas the PTi was only affected by the interaction of NF × SoT ($p < 0.01$). Table 2 shows that the values of PV, FV, BD, and SB were increased with an increase in the NF level from 60 to 100 kg ha^{-1}. Moreover, the highest TV (1405.58 mPa.s) was obtained at the NF level of 80 kg ha^{-1}. Also, a significant reduction in the PV, TV, and BD amounts was found by increasing the SoT from 50 to 80°C, while the FV and SB quantities were significantly increased. All the rice pasting characteristics except PV were increased by increasing the StT level from 10 to 15 min (Table 2).

The evaluation of the interactive mutual effects of three independent variables showed that the maximum PV and TV values were in treatments of C1T1, N2C1, and N2T1 (1818.0-1914.8 cP; $p < 0.05$). Overall, the highest FV (3466.2-3608.5 cP) and SB (1603.5-1843.5 cP) values were observed

Table 3. Interactive mutual effects of nitrogen fertilizer and parboiling conditions on the viscosity and pasting properties of rice grains

Treatment	Viscosity and pasting properties						
	PV (cP)	TV (cP)	BD (cP)	FV (cP)	SB (cP)	PTi (s)	PTe (°C)
NF×SoT							
N1C1	1763.1[b]	1445.0[b]	320.1[b]	3164.2[b]	1415.8[c]	5.90[b]	88.95[a]
N1C2	1446.8[c]	1313.6[c]	132.3[c]	2835.1[c]	1389.4[c]	6.21[a]	89.46[a]
N2C1	1818.0[a]	1482.8[a]	340.4[a]	3035.3[c]	1268.3[d]	5.94[b]	89.74[a]
N2C2	1452.8[c]	1328.3[c]	128.0[c]	3050.2[b]	1559.4[b]	6.18[a]	88.15[a]
N3C1	1421.3[c]	1264.6[d]	158.8[c]	2481.9[d]	1061.7[e]	6.11[a]	89.26[a]
N3C2	1754.8[b]	1426.3[b]	336.4[a]	3608.5[a]	1843.5[a]	5.94[b]	89.41[a]
NF×StT							
N1T1	1788.0[b]	1462.0[b]	337.4[b]	3122.6[b]	1346.3[d]	5.82[a]	91.87[a]
N1T2	1422.0[c]	1296.6[d]	126.1[c]	2877.2[c]	1458.1[c]	5.98[a]	90.62[a]
N2T1	1868.3[a]	1529.6[a]	342.0[b]	3466.2[a]	1603.5[a]	5.68[a]	88.68[a]
N2T2	1402.5[c]	1281.5[d]	125.8[c]	2619.2[d]	1260.1[e]	6.20[a]	90.46[a]
N3T1	1822.1[a]	1426.6[c]	404.0[a]	3389.2[a]	1562.4[b]	6.12[a]	91.01[a]
N3T2	1354.0[d]	1268.3[e]	92.8[d]	2966.1[d]	1342.0[d]	6.22[a]	91.84[a]
SoT×StT							
C1T1	1914.8[a]	1507.3[a]	412.4[a]	3162.3[b]	1258.0[c]	6.09[a]	88.90[a]
C1T2	1420.1[c]	1287.6[c]	133.6[c]	2624.2[d]	1238.9[c]	6.04[a]	90.41[a]
C2T1	1737.4[b]	1435.5[b]	303.2[b]	3489.3[a]	1749.8[a]	6.14[a]	89.14[a]
C2T2	1365.5[c]	1276.6[c]	95.5[d]	2839.7[c]	1469.3[b]	6.07[a]	91.07[a]

C1 and C2 are soaking temperatures at 50 and 80°C, respectively; T1 and T2 are steaming times at 10 and 15 min, respectively; N1, N2, and N3 are levels of nitrogen fertilizer at 60, 80, and 100 kg ha^{-1}, respectively.

Table 4. Significant interaction effects of nitrogen fertilizer and parboiling conditions on the viscosity and pasting properties of rice grains

Treatment [a]	Viscosity and pasting properties				
(NF×SoT×StT)	PV (cP)	TV (cP)	BD (cP)	FV (cP)	SB (cP)
N1C1T1	1918[b]	1478[b]	445[b]	2991[d]	1097[f]
N1C1T2	1608[c]	1412[b]	195[d]	3336[c]	1732[b]
N1C2T1	1658[c]	1446[b]	209[d]	3253[c]	1594[c]
N1C2T2	1235[f]	1181[e]	58[h]	2418[e]	1184[e]
N2C1T1	2145[a]	1636[a]	512[a]	3640[b]	1502[c]
N2C1T2	1490[d]	1329[c]	168[e]	2431[e]	1034[f]
N2C2T1	1591[d]	1423[b]	172[e]	3292[c]	1704[b]
N2C2T2	1314[e]	1233[d]	84[g]	2808[d]	1485[d]
N3C1T1	1681[c]	1408[b]	279[c]	2855[d]	1174[e]
N3C1T2	1161[g]	1121[e]	38[i]	2106[f]	947[g]
N3C2T1	1963[b]	1437[b]	527[a]	3923[a]	1949[a]
N3C2T2	1546[d]	1415[b]	145[f]	3292[c]	1737[b]

[a] C1 and C2 are soaking temperatures at 50 and 80°C, respectively; T1 and T2 are steaming times at 10 and 15 min, respectively; N1, N2, and N3 are levels of nitrogen fertilizer at 60, 80, and 100 kg ha^{-1}, respectively.

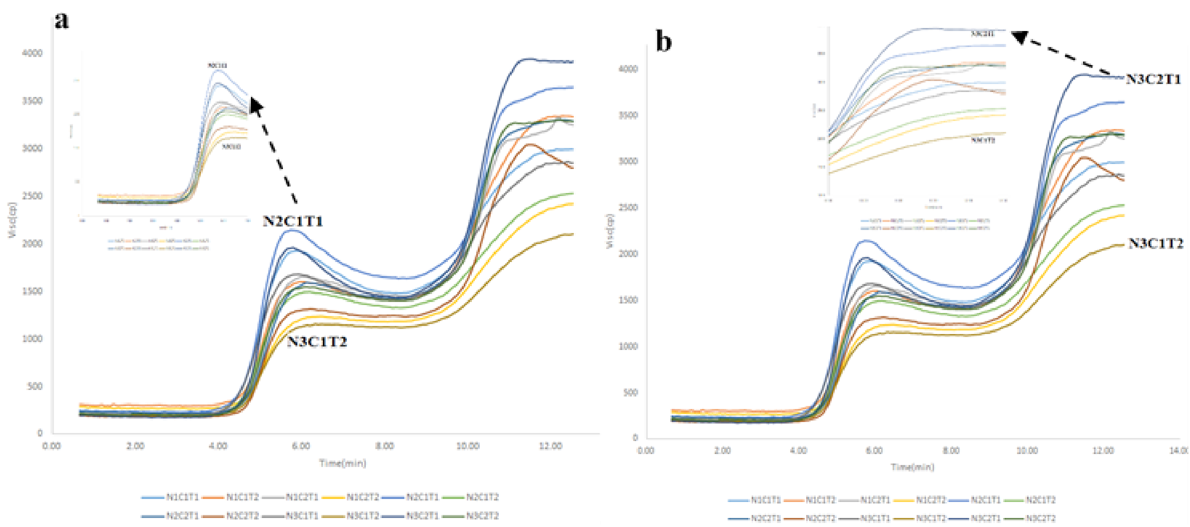

Figure 4. The viscogram curve of interaction effects of nitrogen fertilizer and parboiling processing on the PV (a) and FV (b)

in samples treated with N3C2, N2T1, and C2T1 (Table 3).

The lowest BD values were found in samples of N3T2 (92.8 cP) and C2T2 (95.5 cP) ($p < 0.05$).

There were no significant differences among PTe values (88.15-91.87°C) of the mutual treatments. The discrepancy in PTi values (5.90-6.21 s) was significant only among the mutual treatment of NF×SoT.

Table 4 also reveals that the maximum values of PV (2145 cP), TV (1636 cP), and BD (512 cP) can be simultaneously obtained with the combination of 80 kg ha^{-1} NF, 50°C SoT, and 10 min StT ($p < 0.05$). The RVA curve in Fig. 4a also shows that the highest PV value was for the treatment of N2C1T1. In addition, the highest FV (3923 cP) and SB (1949 cP) values were for the parboiled BR sample treated with 100 kg ha^{-1} NF, 80°C SoT, and 10 min StT ($p < 0.05$). Conversely, the combined triple treatment of 100 kg ha^{-1} NF, 80°C SoT, and 15 min StT led to the lowest FV (2106 cP) and SB (947 cP) values (Table 4). Fig. 4b also depicts that the treatments of N3C2T1 and N3C1T2 respectively had the maximum and minimum FV among the other samples.

The RVA parameters can be used to evaluate the quality of rice because they reflect starch gelatinization, disintegration, swelling, and gelling properties. Since the PV shows the water-binding capacity of the starch, this rheological index is influenced by starch properties including the AC, the ratio of amylose to amylopectin, and the total amount of starch (Zhang *et al.*, 2008). The FV shows the conversion ability of starch to gel after cooking (Niba *et al.*, 2002). Also, the rupture potential of swollen SGs at high temperatures under continuous shearing can be defined as BD viscosity.

The higher the BD viscosity, the lower the starch ability to withstand heating and shear stress during cooking (Patindol *et al.*, 2008). Moreover, the SB is a key index to show the firmness of cooked rice grains so that higher SB value indicates a firmer texture (Niba *et al.*, 2002; Zhang *et al.*, 2008). The high PV, FV, BD, and SB values at high NF levels can be attributed to the decreased apparent AC and the ratio of amylose to amylopectin (Zhou *et al.*, 2020). Increasing the NF inputs possibly increased the size of SGs due to the higher proportion of short branch-chain amylopectin in the starch structure and surface proteins (Zhou *et al.*, 2020).

The molecular interactions between amylopectin and rice proteins such as glutelin and prolamin fractions may form a three-dimensional gel-network with high ability in water-holding and shear strength (Xia *et al.*, 2019). A close finding was found by Liangjun *et al.* (2006), who reported that the NF input of 225 kg ha^{-1} could gradually increase the PV and BD values, while the effect of NF on FV varied with different cultivars. Our results also showed that the TV, PV, FV, SB, and BD values were reduced at 80°C SoT and 15 min StT. In general, the paste viscosity in the RVA process is a function of the number of native SGs accessible for hydration. These pasting parameters can be improved in the presence of a high number of SGs available to be hydrated. Increasing the parboiling severity at high levels of SoT and StT might lead to the extensive gelatinization and structural disruption of SGs. Partial starch retrogradation after the gelatinization integrates the granular structure and inhibits the increase of swelling rate (Himmelsbach *et al.*, 2008; Graham *et al.*, 2015). On the other hand, amylose residues at lower temperatures tend to create an internal order and stay closer to the amylose chains, forming more hydrogen bonds between amylose units, making them more prone to retrograde. Thus, the SB and FV will be increased by increasing the SoT (Niba *et al.*, 2002).

Conclusion

This the chemical, mechanical, and rheological properties of parboiled BR produced as a function of NF and parboiling parameters (i.e., SoT and StT). The quality parameters of processed rice grains were more affected by parboiling factors than NF levels. An increase in the NF level from 60 to 100 kg ha^{-1} led to a significant increase in the PC, GT, HV, FV, BD, and SB amounts. An increase in the SoT level substantially increased the AC, PC, TV, and BD amounts, whereas the GT, HV, FV, and SB were increased. Also, an increase in the StT could significantly increase the GT, HV, PV, and PTi values, whereas other chemical and rheological parameters were reduced. The most significant mutual interaction effect on the increase of rheological parameters of BD, FV, and SB was the treatment of N3C2 (100 kg ha-1 NF + 80°C SoT). Accordingly, the combined mutual treatments of N2C2, N2T1, and C1T1 resulted in the highest GT, TV, and PV amounts, respectively. Overall, the best treatments for the improved PV, HV, FV, and SB, as well as GT, were N2C1T1, N3C2T2, N3C2T1, and N1C2 T2, respectively. Specific combined treatments of NF, SoT, and StT depending on the final quality characteristics can be utilized to produce parboiled rice grains suitable for developing high-quality food products.

Further studies should be directed to evaluate the effect of the NF and parboiling process on the improvement of color attributes and the reduction of the phytic acid content of RB. The optimization of the parboiling process and NF addition level using model-based methodologies such as RSM would be very helpful in identifying the best-combined treatment to achieve nutritional and technological quality.

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