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Physicochemical and rheological properties of cooked extruded reformed rice with added protein or fiber

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ABSTRACT

The effect of soy protein isolate (SPI) and dietary fibers [maize bran (MB), resistant maltodextrin (RMD)] on cooked extruded rice quality-related parameters and relating rheology to the human gastric emptying measurement of Lag phase were investigated. DSC onset temperature (T_o) and peak temperature (T_p) of extruded rice substituted with 20 % SPI (20SPI-ER) were higher than of extruded rice substituted with 20 % MB (20MB-ER) and substituted with 20 % RMD (20RMD-ER). Peak viscosity of 20SPI-ER was lower than that of 20MB-ER and 20RMD-ER, indicating that SPI delayed starch gelatinization. Hardness and stickiness values of cooked 20SPI-ER were significantly higher than those of the control, 20MB-ER, and 20RMD-ER. Storage modulus (G') value of cooked 20SPI-ER was also higher than the control. It is possible that the swelling of starch granules was decreased when 20%SPI was supplemented. For human gastric emptying, cooked 20SPI-ER resulted in the highest lag phase, indicating that the time of grinding and mixing in the stomach took longer for this reformed rice. Overall the soy-containing cooked extruded rices were somewhat harder than the fiber-containing rices, which may not be as appealing to consumers, though they had a slightly longer Lag phase in the stomach which could relate feeling of fullness.

1. Introduction

In recent years, consumer preferences have shifted towards better-quality rice, particularly towards varieties with good eating quality. Nutritional value of cooked rice is also becoming important to consumers, particularly regarding starch digestion and glycemic response, though eating quality must be good, which is dependent on its physicochemical properties and rheological properties. Apart from genetic improvement, a way of improving nutritional quality of rice is by making extruded reformed rice with added macro- and micronutrients. We recently reported that addition of protein or dietary fibers can be used to favorably change starch digestion kinetic profiles (Na-Nakorn et al., 2019). Reformed rice is made from rice flour using extrusion processing and has the same size and shape as regular rice grain. The extrusion process easily allows for the incorporation of a wide variety of ingredients such as protein, dietary fibers, vitamin A, minerals, emulsifiers and other cereals in order to improve nutritional quality of extruded rice (Bett-Garber et al., 2004; Murphy et al., 1992; Na-Nakorn et al., 2019; Noguchi et al., 1982; Pinkaew et al., 2013; Wang et al., 2013; Yoo et al., 2013; Zhuang et al., 2010). For protein supplementation, the SPI incorporation can form a fine-stringed structure in a starch matrix of extruded rice (Noguchi et al., 1982). Protein denaturation and starch fragmentation during extrusion may bring about further inter- and intramolecular interactions between both polymers (Kumar et al., 2017). For fibers, since fibers may be insoluble, non-viscous soluble or viscous soluble, they affect physicochemical or rheological properties of cereal products in different ways. For instance, maize bran (MB) addition decreased water-holding capacity of rice flour and viscosity properties of gelatinized pastes, which resulted in a lower expansion ratio and softer textural properties of extruded rice noodles (Baek et al., 2014). Insoluble fiber can improve satiety consumption (Clark & Slavin, 2013; Schroeder et al., 2009). For non-viscous soluble fibers, resistant maltodextrin (RMD) is good ingredient because of its transparency in solution, low viscosity, and high stability. RMD showed good potential for maize snacks by extrusion (Han et al., 2018). Moreover, the addition of Fibersol-2™ to peach-flavored Nestea enhanced satiety by stimulating

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the production of satiety hormones (Ye et al., 2015). Protein and fibers also modify the rheological properties of cooked extruded rice that may be undesirable for eating quality (i.e. alter cooked product hardness or stickiness), but in the stomach could be desirable by potentially delaying gastric emptying for a satiating effect. Rheological properties (deformation and flow) are important factors affecting transportation, hydrolysis, and absorption of hydrolyzed nutrients within the gastrointestinal tract, which influence gastric emptying rate (Wu et al., 2016). Therefore, extruded reformed rice with high protein or high fiber is a potential path towards healthy food products. However, the relationship between the rheological properties of added-macronutrient reformed rice and gastric digestive properties has never been reported. Moreover, a systematic comparison between insoluble fiber and non-viscous soluble fiber supplementation of foods on gastric digestion has rarely been studied.

A food's form can influence satiety, digestive processes, and post-absorptive metabolism (Dhillon et al., 2016). We recently reported changes in starch digestion kinetics in extruded reformed rice with added macronutrients (Na-Nakorn et al., 2019), and in the current study physicochemical and rheological properties were investigated. In addition, the potential relationship of kernel rheological properties of cooked extruded reformed rice with added protein or fiber to human gastric Lag phase, a measure of time to grind food in the stomach before emptying, was monitored.

2. Materials and methods

2.1. Materials

Rice flour (25.78 % amylose) was a gift from General Food Products Co., Ltd. (Nakhon Ratchasima, Thailand). Soy protein isolate (Profam 974) (minimum protein content of 90%) was purchased from the ADM Company (Chicago, IL, USA). Resistant maltodextrin (Fibersol-2™), soluble dietary fiber from starch, was also purchased from the ADM Company (Chicago, IL, USA). Maize bran (NF10085) which is insoluble fine bran was supplied by Bunge Milling Company (St. Louis, MO, USA).

2.2. Extruded reformed rice

The reformed rice samples were extruded rice flour (control), and extruded rice flour supplemented with 20 % soy protein isolate (20SPI-ER), 20 % maize bran (20MB-ER), and 20 % resistant maltodextrin (20RMD-ER). The raw materials were adjusted to 28 % moisture content. The raw materials were extruded using a twin-screw extruder (APV MPF19:25, APV Baker, Inc., Grand Rapid, MI, USA) with a rice-shaped die. The feed rate was 0.5 kg/h. The barrel temperatures of 4 zones were set at 70, 90, 90, and 70 °C. The screw speed was 30 rpm. Extruded rice samples were cooled at room temperature for 12 h and stored in polyethylene bags for further analysis.

2.3. Cooking of extruded reformed rice

The ratio of extruded reformed rice and water was 1:1.8. The rice was cooked in a pressure cooker, followed by a 10 min holding period at the warm setting of the cooker.

2.4. Water absorption index (WAI)

Water absorption index (WAI) was measured according to Anderson et al. with slight modification (Anderson et al., 1970). A sample (about 1 g) was dispersed in 10 mL distilled water, and then incubated in a shaking water bath (SW22, JULABO GmbH, Germany) at 174 rpm for 30 min. The incubation temperature was 90 °C. Samples were centrifuged at 2000 g for 15 min. The sediment was weighed and the supernatant was dried in an oven at 105 °C to determine solid content. The measurement was conducted in three replications. WAI was calculated as follows:

$$\text{WAI (g/g)} = \text{weight of water absorbed/weight of dry sample} \quad (1)$$

2.5. Gelatinization properties

Gelatinization thermal properties of extruded reformed rice were determined using a differential scanning calorimeter (DSC) (DSC1, Mettler Toledo, Switzerland) following the method of Lebail et al. (2000) with slight modification. Ground samples (7 mg) were weighed and distilled water was added in 60 μL stainless steel pans to obtain a sample/water ratio of 1:3 (w/w). DSC runs were performed from 25 to 140 °C at a heating rate of 3 °C/min. The onset temperature (T_o), peak temperature (T_p), conclusion temperature (T_c) and enthalpy (ΔH) were calculated by STAR^e software version 10.0 (Mettler Toledo, Switzerland).

2.6. Pasting properties

Pasting profiles of extruded reformed rice were monitored using a Rapid Visco Analyser (RVA-4, Perten Instruments, Warriewood, Australia). Extruded reformed rice samples were ground. Sample suspensions (10 %, w/w, db) were equilibrated at 50 °C for 1 min, heated at a rate of 6 °C/min to 95 °C, maintained at 95 °C for 5 min, and then cooled to 50 °C at a rate of 6 °C/min. The paddle rotating speed was at 960 rpm for the first 10 s, followed by 160 rpm for the remainder of the analysis (Reed et al., 2013).

2.7. Rheology of cooked extruded rice samples

Dynamic viscoelasticity of the cooked extruded rice samples was studied using a modified method of Li et al. (2016). Dynamic viscoelasticity measurements were carried out using a stress-controlled rheometer AR G2 (TA instruments, New Castle, DE, USA) with a controlled temperature of 37 °C. A four-bladed vane geometry with a diameter of 28 mm and a length of 42 mm, and a cup with a diameter of 40 mm was used. After cooking, 25 g of cooked rice were immediately loaded into the cup and gently packed to remove air. The vane was then lowered to a distance of 4 mm from the bottom of the cup and was completely immersed in the rice bulk. At the vane temperature of 37 °C, the rice samples were allowed to rest for 5 min before the test was performed. First, an oscillatory stress sweep test from 0.1 to 1000 Pa at a constant frequency of 10 rad/s and 37 °C was conducted to set the upper limit of the linear viscoelastic region (LVR). Second, a frequency sweep over a range of 0.1–100 rad/s at 37 °C was performed at the oscillatory stress of 2 Pa, which was within LVR for all rice samples. Viscoelastic parameters, storage or elastic modulus (G'), loss or viscous modulus (G''), and loss tangent ($\tan \delta = G''/G'$) as a function of angular frequency (ω) were measured.

2.8. Gastric Lag phase analysis

Rheological properties of cooked reformed rice may have an impact on digestibility and gastric Lag phase. The Human Research Protection Program IRB of Purdue University approved aspects of this research (protocol#1608018056) as a part of our previous study with the protocol used as described (Na-Nakorn et al., 2019).

Briefly, sixteen healthy adult participants were recruited for a crossover design study involving acute feeding and testing of cooked extruded rice (50 g available carbohydrate). The meal included cooked extruded rice (control), and cooked extruded rice supplemented with 20SPI-ER, 20MB-ER, and 20RMD-ER. Subjects having fasted for at least 10 h arrived to the testing room before 8 a.m. and were asked to refrain from any heavy physical activity outside their normal routine in that period. They were instructed to consume all of the meal and breath samples were collected every 15 min for 4 h. The meal treatments were given to subjects at least a one week in between treatment arms as a washout period. Lag phase was measured using a ^{13}C-labeled octanoic acid breath test (POCone, Otsuka Electronics Co, Ltd, Osaka, Japan).

The percent dose ^{13}C recovery per hour (PDR), and cumulative percentage dose recovery over time (CPDR) were calculated using equations (2) and (3), respectively. CO_2 production was assumed to be 300 mmol/(m^2 body surface area x hour), with body surface area calculated using the formula developed by Haycock et al. (1978).

$$PDR = at^{b}e^{-ct} \tag{2}$$

where.

PDR = percentage dose recovery per hour, t = time in hours, a, b, and c = constants.

$$CPDR = m\left(1 - e^{-kt}\right)^{\beta} \tag{3}$$

where.

CPDR = cumulative percentage dose recovery over time, t = time in hours,

k, and β = constants, and m = total cumulative dose recovery when time is infinite.

After calculating PDR and CPDR values from the obtained data set, these functions were modeled using the following Lag phase (time required for the $^{13}CO_2$ excretion rate to attend its maximal level) calculation by equation (4) (Sanaka & Nakada, 2010)

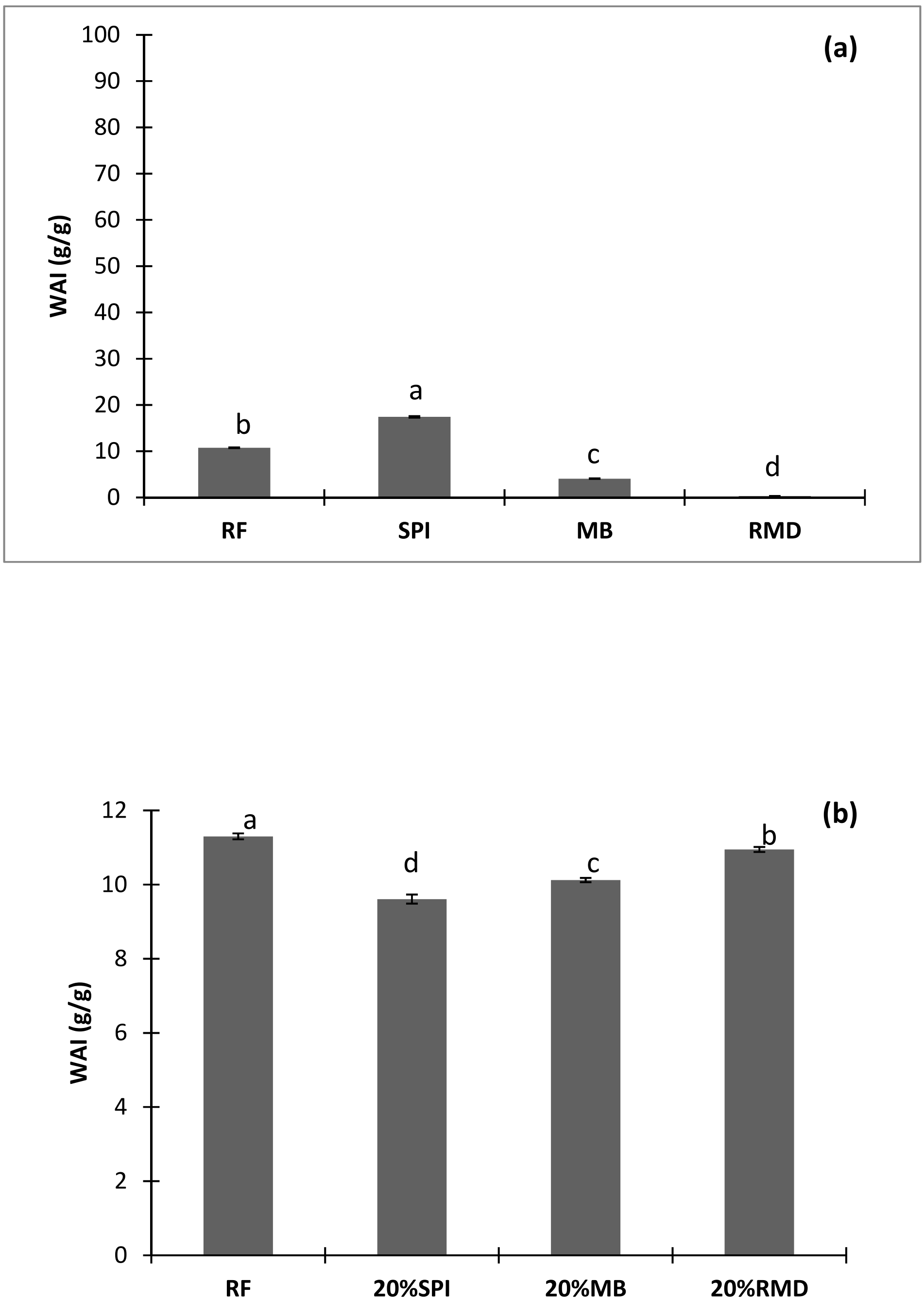

Fig. 1. Water absorption index (WAI) at 90 °C of rice flour (RF), soy protein isolate (SPI), maize bran (MB) and resistant maltodextrin (RMD) (a) and WAI at 90 °C of rice flour at 20 % substituted soy protein isolate (20%SPI), maize bran (20%MB) and resistant maltodextrin (20%RMD) (b).

$$T_{lag} = (\ln \beta) / k \tag{4}$$

2.9. Statistical analysis

Differences among results were analyzed by analysis of variance (ANOVA). Duncan's multiple-range test was used to compare treatment means at $P < 0.05$. The statistical analysis was performed with the SPSS software for Windows version 13.0 (SPSS Inc., Cary, NC, USA).

3. Results and discussion

Rheological properties differed for the extruded reformed rices with the different protein and fiber supplements. Higher hardness, stickiness and G' were found for cooked extruded rice with 20 % supplementation level of SPI (20SPI-ER), compared to the control or those with added dietary fibers. SPI also induced a high gelatinization temperature and high elastic property of cooked extruded rice. Although the addition of SPI made a firmer cooked reformed rice with a potential sensory downside for consumers, it positively had longer gastric Lag phase, indicating longer time in the stomach for reducing particle size that is related to satiety.

3.1. Water absorption index (WAI)

Water absorption of raw materials at 90 °C (i.e. similar to the extrusion temperature) refers to the water binding ability of ingredients used in the study (SPI, MB, RMD) compared to rice flour alone. WAI of SPI was highest and its WSI was significantly higher than that of rice flour (Fig. 1a). On the other hand, WAI of RMD was lowest (Fig. 1a), likely related to its being a non-viscous soluble fiber (Ohkuma & Wakabayashi, 2008). For MB, as the insoluble fiber, the WAI was significantly lower than that of SPI and of rice flour, but significantly higher than that of RMD (Fig. 1a). Previous researchers have shown high water imbibing capacities at pH 7 for soy 11S and 7S proteins when denatured at temperatures higher than 80 °C, which modifies the quaternary structure and unfolds the polypeptide chains of soy proteins, and were shown to produce high water imbibing capacities at pH 7 (Chove et al., 2001; Remondetto et al., 2001). For mixtures of rice flour and the supplements, the 20%SPI had the lowest WAI at 90 °C (Fig. 1b). This could be due to its better absorption of water in the mixture making less available water for starch and restricting starch granule swelling during cooking. (Lu et al., 2016). WAI's of the mixtures of rice flour supplemented with 20%MB and 20%RMD were also significantly lower than that of rice flour alone (Fig. 1b). The decreased WAI of both MB and RMD mixtures after heating could be attributed to lower rice flour content which is more efficient to access water than MB and RMD.

3.2. Physical characteristics of cooked extruded reformed rices

3.2.1. Gelatinization properties

The gelatinization properties of native rice flour, extruded rice control, 20SPI-ER, 20MB-ER, and 20RMD-ER are shown in Table 1. A biphasic endotherm was found in native rice flour which could be due to the commercial rice flour containing various rice varieties. The gelatinization enthalpies of all extruded rice flours were significantly lower than that of native rice flour, due to a significant portion of starch being gelatinized in the extrusion process. The onset transition temperature (T_o), peak temperature (T_p) and conclusion temperature (T_c) of 20SPI-ER was shifted to higher temperature. This was likely due to the water absorption property of the protein, making less available water for the gelatinization process (Ribotta et al., 2007). These results are similar to those found in other studies (Li et al., 2007; Ribotta et al., 2007; Yu et al., 2015). The T_o, T_p and, T_c of 20MB-ER were the lowest of the samples tested. This may be due to more available water for starch gelatinization (Acquistucci et al., 1997), or that the MB particles increased the surface area of the mass for water accessibility into rice starch granule. The T_o and T_p of 20RMD-ER were not significantly different from those of the control. Thus, RMD did not compete for the water with rice flour, as was observed in its lowest WAI (Fig. 1a).

Table 1
Gelatinization properties of rice flour (RF), extruded rice (control) and extruded rice supplemented with 20 % soy protein isolate (20SPI-ER), 20 % maize bran (20MB-ER), 20 % resistant maltodextrin (20RMD-ER).

Sample	T onset (°C)		T peak (°C)	T endset (°C)	Enthalpy (J/g)
RF	T_{o1} 60.5 ± 0.05	T_{o2} 70.4 ± 0.04 c	75.9 ± 0.10 d	80.7 ± 0.23 b	5.9 ± 0.23 c
Control	nd	73.2 ± 0.04 b	77.9 ± 0.11 b	80.4 ± 0.40 b	2.0 ± 0.05 b
20SPI-ER	nd	74.7 ± 0.20 a	79.1 ± 0.03 a	81.9 ± 0.02 a	1.3 ± 0.11 a
20MB-ER	nd	70.2 ± 0.01 c	76.1 ± 0.05 c	79.3 ± 0.09 c	1.5 ± 0.16 a
20RMD-ER	nd	73.0 ± 0.08 b	78.0 ± 0.03 b	82.3 ± 0.10 a	1.1 ± 0.07 a

Mean values with different letters within each column are significantly different ($P < 0.05$).
nd = not detected.

3.2.2. Pasting properties

The pasting profiles of extruded rice with 20 % substitution of SPI, MB and RMD are showed in Fig. 2. The extrusion process that promotes starch gelatinization would be expected to decrease peak viscosities because of the lower amount of native starch granules. Peak and final viscosities of 20SPI-ER were lower than other samples. A similar result was reported by Mayachiew et al. (2015) in that the addition of soybean flour decreased the peak, trough, and final viscosity of a soybean-rice powder extruded porridge. This result was related to the lower WAI of the SPI rice flour mixture at 90 °C (Fig. 1b), meaning that the swelling power and gelatinization of 10SPI-ER was decreased. Peak viscosities of 20MB-ER and 20RMD-ER were higher than for 20SPI-ER.

3.3. Rheological properties of cooked extruded rice

The rheological properties of cooked extruded rice are displayed in Table 2. The consistency coefficient (K*) and loss tangent (tan δ) were used to express hardness and stickiness of the samples (Fig. 3) It relates to degree of swelling of starch granules and of cooked rice (Li et al., 2016). The hardness and stickiness of cooked 20SPI-ER were significantly higher than those of the control, 20MB-ER, and 20RMD-ER. The storage modulus (G') value of cooked 20SPI-ER was also higher than that of the control, suggesting that G' was attributed to the formation of networks of swollen starch granules associated with protein giving a stiffer reformed rice (Ramírez Ortiz et al., 2008). The SPI also markedly changed the viscoelastic properties of the extruded rice to become more elastic than viscous with higher K* represents higher elasticity, i.e. a harder texture. Tan δ was significantly higher for the cooked 20SPI-ER, reflecting viscous characteristic corresponding to the stickiness of the cooked rices (Li et al., 2016). A similar result was reported by Qiu et al. (2015) in that the addition of SPI slightly increased the apparent viscosity of maize starch and waxy maize starch. The hardness and stickiness values (Table 2), and G' (Fig. 3) of the cooked 20MB-ER were higher compared with values of the control. This may be because the added maize bran provided hard particles in the starch gel. Such an insoluble fiber-starch mixed system was shown previously to form a stronger structure than the single starch system (Sun et al., 2015). RMD had a low impact on the G' (Fig. 3) of cooked 20RMD-ER, although the hardness and stickiness of cooked 20RMD-ER were significantly higher than that of the control (Table 2). It is probable that the RMD did not form network with the starch gel due to its small size [low degree of polymerization (DP) 1–9] (Hashizume & Okuma, 2009).

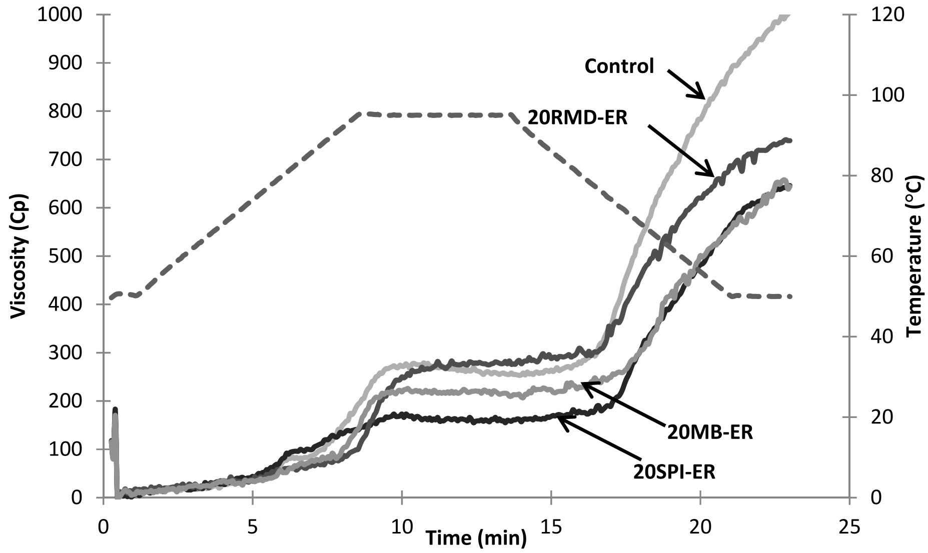

Fig. 2. Pasting profiles of extruded rice (control) and extruded rice at 20 % substituted of soy protein isolate (20SPI-ER), maize bran (20MB-ER) and resistant maltodextrin (20RMD-ER).

Table 2
Rheology properties of cooked extruded rice (control), cooked extruded rice supplemented with 20 % soy protein isolate (20SPI-ER), 20 % maize bran (20MB-ER), and 20 % resistant maltodextrin (20RMD-ER).

Sample	K*	tan δ at 10 rad/s
Control	313.42 ± 1.27 c	0.066 ± 0.002 c
20SPI-ER	838.21 ± 17.71 a	0.085 ± 0.001 a
20MB-ER	816.79 ± 27.89 a	0.072 ± 0.003 b
20RMD-ER	376.88 ± 8.44 b	0.069 ± 0.003 b

Mean values with different letters within each column (a-d) are significantly different ($P < 0.05$).

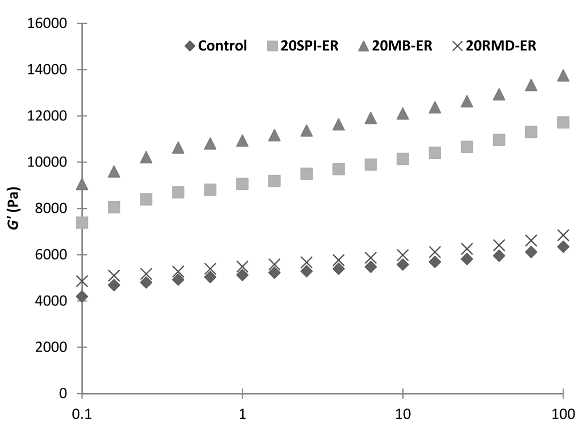

Fig. 3. Storage modulus of cooked extruded rice (control), cooked extruded rice supplemented with 20 % soy protein isolate (20SPI-ER), 20 % maize bran (20MB-ER), and 20 % resistant maltodextrin (20RMD-ER).

3.4. Gastric Lag phase of cooked extruded rice

Gastric Lag phase of cooked extruded rice was measured to examine if the high viscoelastic properties of cooked extruded rice delay holding time due to grinding of samples to a small particle size for gastric emptying. This was part of a data set with gastric emptying previously reported (Na-Nakorn et al., 2019) with Lag phase data related here to rheological properties of the cooked extruded reformed rice samples. Sixteen healthy subjects completed all 5 visits. 20SPI-ER showed the highest lag phase median and interquartile range box (50 % of data) (Fig. 4). It suggests that the presence of the SPI in the reformed rice, with higher hardness and stickiness, might induce a longer period for grinding and mixing of ingested food before gastric emptying (Lag phase). Cooked 20RMD-ER had the lowest lag phase median implying that cooked 20RMD-ER had faster gastric breakdown and holding in the stomach.

4. Conclusion

SPI fortification (20 %) of extruded reformed rice increased cooked kernel hardness, stickiness, and G' of cooked 20SPI-ER, which was related to a longer Lag phase period of grinding and mixing in the stomach that occurs before gastric emptying. MB addition brought about the faster starch gelatinization of extruded rice and increased hardness, stickiness and G' of the cooked 20MB-ER compared to the control. However, MB particle may leach out from the cooked reformed rice

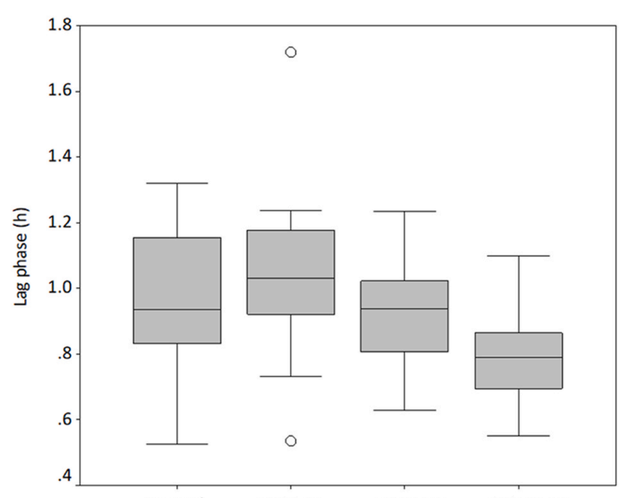

Fig. 4. Lag phase boxplot of cooked extruded rice (control), cooked extruded rice supplemented with 20 % soy protein isolate (20SPI-ER), 20 % maize bran (20MB-ER), and 20 % resistant maltodextrin (20RMD-ER).

during the digestion (Na-Nakorn et al., 2019); and MB was not found to significantly impact the Lag phase. RMD addition to the extruded reformed rice did not appreciably alter physicochemical or rheological properties of the cooked rice, but it decreased Lag phase of the cooked rice. Overall, macronutrient supplementation to extruded reformed rice impacts water availability to the starch granule, and physicochemical properties (pasting and gelatinization properties) of extruded rice, which influenced rheological properties and gastric Lag phase.

Declaration of competing interests

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

CRediT authorship contribution statement

Kuenchan Na-Nakorn: Substantial contribution to design the experiments, Data collection, Formal analysis, Writing – original draft. **Bruce R. Hamaker:** Supervision, Substantial contribution to design the experiments, Data interpretation, Manuscript correction. **Sunanta Tongta:** Supervision, Substantial contribution to conception, Design the experiments, Data interpretation, Writing – review & editing.

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