

Correlation Among Physical Properties of Parboiled Milled Rice During Hydrothermal Pretreatment Processing

Jhauharotul Muchlisyyah^{1,2}, Rosnah Shamsudin^{1,3*}, Roseliza Kadir Basha¹, Radhiah Shukri⁴ and Syahmeer How¹

¹Department of Process and Food Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia

²Department of Food Science and Biotechnology, Faculty of Agricultural Technology, Universitas Brawijaya, Jalan Veteran Malang, 65145, Indonesia

³Laboratory of Halal Science Research, Halal Products Research Institute, Universiti Putra Malaysia, Putra Infoport, 43400 Serdang, Selangor, Malaysia

⁴Department of Food Technology, Faculty of Food Science and Technology, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia

ABSTRACT

The rice cultivar MR297 has a high harvesting yield but a low milling and head rice yield. Parboiling is one of the methods to increase the head yield of rice varieties. The colour of parboiled rice is intense due to husk colour absorption during soaking. This study researched the influence of hydrothermal pretreatment (soaking time and temperature) on the physical properties such as dimension, thousand kernel weight (TKW), density, volume expansion (V_e), colour, and hardness of parboiled milled rice. MR297 raw rice cultivars were soaked at 1:1 (w/w). Paddy was soaked at 50, 60, and 70°C for 1, 2, 3, 4, and 5 hr and steamed at 100°C for 20 min prior to drying for 24 hr at 38°C. It was discovered that the effects of soaking time and temperature varied with the physical properties of rice. Soaking time and temperatures were found to be significant ($p < 0.05$) in terms of dimensional properties

(length [L], width [W], and thickness [T]), TKW, density, V_e , colour (L^* , a^* , b^*) and hardness of parboiled rice. The L, W, T, V_e , TKW, a^* , and b^* increase proportionally as time and temperature increased, while the density and L^* were negatively correlated. The hardness was negatively correlated with the L and colour b^* (yellowness) rice measurements. The principal component analysis (PCA) results revealed that the

ARTICLE INFO

Article history:

Received: 18 August 2023

Accepted: 03 October 2023

Published: 26 April 2024

DOI: <https://doi.org/10.47836/pjtas.47.2.07>

E-mail addresses:

lisyah@ub.ac.id (Jhauharotul Muchlisyyah)

rosnahs@upm.edu.my (Rosnah Shamsudin)

roseliza@upm.edu.my (Roseliza Kadir Basha)

radhiah@upm.edu.my (Radhiah Shukri)

syahmeerhow@upm.edu.my (Syahmeer How)

* Corresponding author

soaking time was associated with L, W, T, density, V_c , and colour properties based on the loading analysis in the PC1. In contrast, the temperature, TKW and hardness were associated with PC2.

Keywords: Correlation, hydrothermal, paddy MR297, parboiling, physical properties, soaking condition

INTRODUCTION

A new rice cultivar created by the Malaysian Agricultural Research and Development Institute (MARDI) is called MR297. The parents of MRQ76 and P446 were used to begin breeding MR297 in 2006/2007. The cultivars were then made public in the off-season of 2014. MARDI SIRAJ 297 is another name for MR297 (Ramli & Kamaruzaman, 2020). The cultivars MR253, MR263, and MR269 are well known for yielding crops of greater quality. Esa et al. (2020) found that MR297 types had higher disease resistance than MR263, which was advantageous for farmers. However, MR263 has a 65.5% milling yield and an 88% head rice yield, while the milling yield of this crop is only 61.4% and the head rice yield is only 67.8%. Because of this, the variety may have a lesser economic value to the milling factories. By using the parboiling technique, broken rice varieties might be fixed instead. Parboiling gelatinises the whole grain's starch to maximise head rice's recovery and reduce breakage, which has been a considerable loss during processing (Buggenhout et al., 2014).

Rice starch undergoes structural and physical modifications during parboiling

(Dutta & Mahanta, 2012; Iqbal et al., 2021; Muchlisiyah et al., 2023; Roy et al., 2019). Before milling, the parboiling method calls for soaking, steaming, and drying the rice. This process aims to enhance rice's physical, functional, and nutritional properties. Hydrothermal treatment is a crucial phase in the parboiling process that significantly impacts the overall quality of the parboiled rice. Hydrothermal treatments can enhance the physical properties of rice grain during parboiling, such as its size, hardness, and colour (Azuka et al., 2021; Saleh & Meullenet, 2015; Sivakamasundari et al., 2020). The treatment also gives the rice a yellowish tone, changing its colour (Saleh et al., 2018). Rice's dimensional characteristics, such as length and the length-to-breadth ratio, are positively correlated. On the other hand, the colour of rice grains has a detrimental effect on the price of rice at the point of marketing price (Rachmat et al., 2016). The primary reason for consumers' preference for local rice is mostly attributed to its physical attributes and aroma, which are comparable to those of locally produced fragrant rice (Rahim et al., 2023).

Previous studies have been researched on the influence of single soaking treatment on the physical properties of rice and paddy (Bello et al., 2004, 2007; Ji-u & Inprasit, 2019; Rattanamechaikul et al., 2023). Some of the previous scientific papers reported on the physical and chemical changes to the rice kernel during soaking (Behera & Sutar, 2018; Hu et al., 2021; Liu et al., 2021; Saleh et al., 2018; Zhu et al., 2019). Mir and Bosco

(2013) examined how soaking affected the physical and practical characteristics of rice farmed in temperate parts of India. The parameters were tested on the soaked paddy, which will undergo further changes in the other steps of parboiling. Other studies also examined the effect of soaking, along with the other parboiling step parboiling to the physicochemical properties of parboiled rice (Ebuehi & Oyewole, 2008; Jayaraman et al., 2019; Panda et al., 2021; Roy et al., 2019; Y. Tian et al., 2014; Z. Wu et al., 2021). To the best of our knowledge, there are still limited studies regarding the effect of soaking treatment on the physical characteristics of dried parboiled rice. Because there is no information on the soaking behaviour of parboiled milled Malaysian rice varieties, the current study sought to evaluate the influence of time (1, 2, 3, 4, and 5 hr) and temperature (50, 60, and 70°C) as the effect of hydrothermal pretreatment processing of MR297 parboiled rice on the physical characteristics changes, and to determine the best correlations can display the soaking behaviour of rice under the analysed condition.

METHODOLOGY

Sample Preparation

Fresh paddy (MR297) was sown in June 2022 and harvested in November 2022 by a regional farmer in Tanjung Karang, Selangor, Malaysia. Fresh paddy grain was delivered to the laboratory and kept at 10°C in an airtight container until further analysis. A moisture analyser was used to examine the initial moisture content of the

paddy (MX50, A&D, USA). The initial moisture content was $19.5\pm 0.6\%$. During the cleaning process, sticks, stones, leaves, and other plant fragments were physically removed from the foreign materials (Reddy & Chakraverty, 2004).

Parboiling Procedure

The parboiling procedure consisted of soaking, steaming, and dehydrating. Fresh paddy from MR297 was parboiled in the laboratory using a heat immersion procedure. In the beginning, a water bath (WNB22, Memmert, Germany) was utilised to heat 100 ml of water in a beaker glass size 250 ml to the desired temperature (50, 60, and 70°C). The beaker was sealed with aluminium foil. When the water in the beaker glass attained the desired temperature (50, 60, or 70°C), 100 g of paddy was added (1:1 paddy to water ratio) to prevent excessive evaporation (Jannasch & Wang, 2020). Gentle mixing was performed. The paddy was soaked for one, two, three, four, and five hours in a separate beaker glass for each temperature to ensure that the paddy was thoroughly saturated. The paddy was steamed for 20 min at 100°C using a domestic steamer (VC1401, Tefal, France). The steamed paddy was then cooled at ambient temperature for one hour (Bootkote et al., 2016). Then, the paddy was dehydrated in an oven at 38°C for 24 hr (DO6836, Memmert, Germany) (J. Tian et al., 2018; Roy et al., 2019; Villanova et al., 2017).

Using a dehusker (THU-35, Satake Corporation, Japan), dried parboiled rice

was dehulled and milled for 150 s (TM05-C, Satake, Japan) (Liang et al., 2008). The head rice grains were sorted from broken rice using a laboratory-grade instrument (TWL05C-T, Satake Corporation, Japan). The term “head rice yield” (HRY) refers to the ratio of dried parboiled rough rice mass to head parboiled rice mass. The physical characteristics of the milled rice were examined next, including dimension, TKW, density, volume expansion, colour, and hardness.

Determination of Physical Properties

Dimensions. Using a vernier calliper (Mitutoyo Corporation, Japan), the average length (L), width (W), and thickness (T) of 100 paddy grains were calculated (± 0.01 mm) (Zainal & Shamsudin, 2021). Figure 1 depicts the axis’s major (L), medium (W), and minor (T) dimensions.

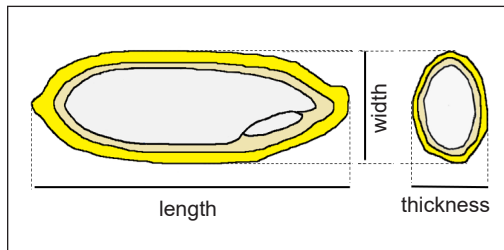


Figure 1. Dimensional characteristics of MR297 paddy grain

Thousand Kernel Weight (TKW). TKW measures paddy yield and milling quality (W. Wu et al., 2018). TKW is the weight of one thousand seeds in g. TKW was determined by manually counting and weighing one hundred grains of milled head rice on an electronic scale (ER-120A, AND,

Japan) (± 0.0001 g). The results were then multiplied by ten to calculate the mass of one thousand grains.

Volume Expansion. Rice grain volume represents the quantity of space occupied by the entire grain. The volume of the paddy was assumed to be constant and calculated using the relationship that follows between its dimensions (Bhat & Riar, 2016; Mir & Bosco, 2013; Nádvořníková et al., 2018):

$$V_c = \frac{\pi}{6} L (WT)^2 \quad [Equation 1]$$

where, V_c = Volume calculated (mm^3); L = Major axis (length) (mm); W = Medium axis (width) (mm); and T = Minor axis (thickness) (mm)

The volume expansion was a dimensionless number calculated by the ratio of parboiled paddy volume divided by the raw paddy volume:

$$\text{Volume expansion} = \frac{\text{Parboiled paddy volume}}{\text{Raw paddy volume}} \quad [Equation 2]$$

Density. Paddy’s density was determined by calculating the mass divided by its volume.

$$\rho_T = \frac{\text{Mass of grain}}{\text{True volume}} \quad [Equation 3]$$

Colour. Using a colourimeter (FRU WR10, China), 50 g of each variety of milled rice was randomly selected and placed in a Petri dish. The colour reader was calibrated using a whiteboard with black-and-white writing. L (lightness), a* (redness), and b* (yellowness) scales were measured by placing the colourimeter next to the Petri dish containing the rice samples and photographing it with a 40 mm lens against a plain white paper background (Shamsudin et al., 2021; Shen et al., 2009).

Hardness. The greatest force applied during the initial compression was used to determine the hardness. The hardness of samples was analysed by using a texture analyser (TA-XT2, Stable Micro Systems, United Kingdom). Individual rice grains were compressed using a single compression force-versus-time program at a test speed of 2 mm/s and a post speed of 10 mm/s using a stainless-steel probe with a 5 mm diameter (P5) (Kumar & Prasad, 2018).

Statistical Analysis

Each experiment was carried out three times. The effects of soaking time and temperature on dimensions, physical, colour and hardness were assessed using analysis of variance (two-way-ANOVA). Tukey's honestly significant difference (HSD) tests ($p < 0.05$) were performed to investigate the significant impact across polishing time levels. Pearson correlation analysis was used to analyse the connections between the physical characteristics of the parboiled rice MR297. To illustrate the change in

parboiled paddy and rice properties at various soaking times and temperatures, the PCA was carried out using the Minitab Software (version 19).

RESULTS AND DISCUSSION

Effect of Soaking Time and Temperature on the Dimensional Properties of Parboiled Paddy

The results showed a significant effect of the soaking time on the L, W, and T of MR297 long-grain paddy ($p < 0.05$). The soaking temperature significantly affected the W and T of the parboiled paddy. The interaction effect between soaking time and soaking temperature is not statistically significant, indicating that the influence of soaking time remained constant across all levels of soaking temperature and vice versa. Table 1 displays the various dimensional properties of parboiled MR297 long-grain paddy with varying soaking times and temperatures. It was found that there is an increase of the W (2.30–2.36 mm) and T (2.03–2.06 mm) of parboiled paddy with increasing soaking time and temperature ($p < 0.05$). However, the L of the parboiled paddy slightly increases with the increase of soaking time ($p < 0.05$), and there is no significant increase of the L of the paddy by the increasing soaking temperature ($p > 0.05$).

Due to the physical and chemical interactions that occur during hydrothermal treatment, the paddy endures distinct transformations. The L, W, and T of the rice grew by 12 to 15% from its unprocessed state. According to previous research, parboiling decreases unpolished and brown

Table 1

Effect of soaking time and temperature of parboiled rice on dimensional properties

	L (mm)	W (mm)	T (mm)
Soaking time (hr)			
1	10.16±0.07 ^b	2.30±0.02 ^c	2.03±0.02 ^c
2	10.30±0.02 ^a	2.31±0.01 ^c	2.04±0.02 ^c
3	10.32±0.01 ^a	2.32±0.01 ^b	2.05±0.01 ^{bc}
4	10.37±0.04 ^a	2.34±0.01 ^b	2.06±0.02 ^b
5	10.37±0.01 ^a	2.36±0.02 ^a	2.09±0.02 ^a
Soaking temperature (°C)			
50	10.29±0.11 ^a	2.31±0.02 ^b	2.03±0.02 ^c
60	10.31±0.08 ^a	2.33±0.02 ^a	2.06±0.02 ^b
70	10.32±0.08 ^a	2.34±0.02 ^a	2.07±0.02 ^a

Note. Data are expressed mean±SD; Different letters indicate statistically significant differences exist $p<0.05$ for each column. Means do not share a letter is significantly different. Tukey's test was applied with 95% simultaneous confidence intervals. L = Length; W = Width; T = Thickness

rice's length and dorsiventral diameter (Rocha-Villarreal et al., 2018). Due to the irreversible swell of starch granules caused by water diffusion and heat treatment, parboiled rice kernels are bulkier and shorter than non-parboiled rice kernels (Patindol et al., 2008). This change was observed during parboiling under the surplus water system but not under water restrictions like dry heat and pressure (Sittipod & Shi, 2016). During the soaking process, the volume of milled rice changed as water molecules moved from the external medium to the interior kernel (Hu et al., 2021). Table 1 shows that as time and temperature increase, the growth in dimension will mostly affect the medium and minor axes rather than the major axis (L). It indicates that the husk is swollen. Due to water penetrating amorphous starch granules and forming hydrate through hydrogen bonding, paddy's dimensions increased (Ji-u & Inprasit, 2019). After the first hour of soaking, the growth of the

paddy's size slows down (Hanucharoenkul et al., 2021; Ji-u & Inprasit, 2019; Yadav & Jindal, 2007).

Effect of Soaking Time and Temperature on the TKW of Parboiled Paddy

The soaking time and temperature affected the TKW of parboiled paddy (Table 2). The TKW increased substantially from 27.70 to 28.04 g as the soaking time increased from 1 to 4 hr ($p<0.05$). However, 5 hr of immersion demonstrated that the TKW decreased with time. At a given level of parboiling, the TKW mass will increase. Our research revealed that the TKW of parboiled paddy increased to a certain point in time and temperature, which decreased as the soaking time increased. The soluble amylose will significantly decrease at a high parboiling temperature, so the parboiled rice weight will appear quite lower (Dutta & Mahanta, 2012; Tao et al., 2019). The levels

Table 2

Effect of soaking time and temperature of parboiled rice on thousand kernel weight (TKW), density, and volume expansion

	TKW (g)	Density (g/mL)	Volume expansion
Soaking time (hr)			
1	27.70±0.54 ^b	0.95±0.02 ^a	1.69±0.07 ^d
2	27.93±0.64 ^{ab}	0.94±0.01 ^{ab}	1.72±0.05 ^d
3	28.12±0.62 ^{ab}	0.92±0.02 ^{bc}	1.77±0.04 ^c
4	28.36±0.27 ^a	0.90±0.01 ^c	1.82±0.03 ^b
5	28.04±0.20 ^{ab}	0.85±0.03 ^d	1.91±0.07 ^a
Soaking temperature (°C)			
50	27.68±0.47 ^b	0.93±0.03 ^a	1.72±0.08 ^c
60	27.95±0.43 ^b	0.90±0.04 ^b	1.80±0.08 ^b
70	28.46±0.25 ^a	0.90±0.04 ^b	1.83±0.08 ^a

Note. Data are expressed mean±SD; Different letters indicate statistically significant differences exist $p<0.05$ for each column. Means do not share a letter is significantly different. Tukey's test was applied with 95% simultaneous confidence intervals

of soluble amylose influence the weight of parboiled rice per thousand kernels.

Effect of Soaking Time and Temperature on the Volume Expansion

Table 2 demonstrates the effect of various soaking times and temperatures on the volume expansion of parboiled rice. In this study, the volume expansion increased from 1.69 to 1.91 with increasing duration and temperature of the soaking process ($p<0.05$). The increase of dimensions (L, W, and T) in the “Effect of Soaking Time and Temperature on the Dimensional Properties of Parboiled Paddy” affected the volume expansion of the parboiled paddy. The volume of the paddy was determined using a mathematical method that incorporates the measurements of the paddy's dimensions (Bhat & Riar, 2016; Mir & Bosco, 2013; Nádvořníková et al., 2018). Consequently, the dimension

enhancement resulting from hydrothermal treatment would result in a corresponding rise in volume expansion. The greater the severity of the parboiling procedure, the greater the increase in volume expansion (Wahengbam & Hazarika, 2019).

Effect of Soaking Time and Temperature on the Density

Table 2 also shows the effect of different soaking times and temperatures in the parboiled conditions on the density. In this study, the density was decreased with increasing time and temperature of the soaking process ($p<0.05$). Parboiled paddy has a density that ranges from 0.85 to 0.95 g/ml. In this study, the density decreased (0.95 to 0.85 g/ml) as the soaking process' time and temperature increased ($p<0.05$). The decrease in density might be due to the increase in volume expansion in the “Effect of Soaking Time and Temperature on the

Volume Expansion.” The ratio between mass and volume of paddy calculated the density of paddy. The increase in mass was found to be smaller than the increase in the dimensions. The mass was more influenced by the change of mass of the rice inside the paddy, whereas the husk was more influenced by the dimensional change. The density of paddy is lower than that of dehusked paddy due to eliminating the bran component during the milling procedure. The bran has a relatively low density, and its removal leads to an increased dehusked paddy density. Rice is traded by weight on international markets; grains with a higher density fetch a higher price. According to Mir et al. (2013), some rice varieties grown in temperate India were 1.22–1.40 g/ml. Nigerian native rice has a density ranging from 1.03–2.07 g/ml (Azuka et al., 2021). The density of the parboiled rice will differ due to the range in size and TKW, as discussed previously.

Effect of Soaking Time and Temperature on the Colour

The lightness of milled rice reduced when it was parboiled. According to the results of the two-way ANOVA, there is no interaction impact between soaking time and soaking temperature. The average value of lightness, yellowness, and redness of milled parboiled rice as impacted by the soaking process conditions is shown in Table 3. The lightness dropped significantly (67.89–63.95) when the soaking time and temperature increased ($p < 0.05$). The degree of consumer acceptance regarding rice exports is contingent upon the observable yellowness exhibited by parboiled milled rice. Table 3 illustrates the effect of parboiled rice soaking time and temperature on yellowness (b^*) attributes. The yellowness increased significantly (30.12–33.49) with increasing temperature time and temperature (Table 3). Also, the redness of parboiled milled rice has an impact on consumer acceptability of rice

Table 3
Effect of soaking time and temperature of parboiled rice on colour properties

	L*	a*	b*
Soaking time (hr)			
1	67.89±1.48 ^a	7.34±0.30 ^c	30.12±1.03 ^c
2	67.12±1.28 ^a	7.48±0.20 ^c	31.45±1.47 ^{bc}
3	65.43±0.96 ^b	8.20±0.19 ^b	31.87±1.60 ^b
4	65.19±0.90 ^b	8.24±0.28 ^b	32.14±1.32 ^{ab}
5	63.95±0.58 ^c	8.92±0.29 ^a	33.49±2.53 ^a
Soaking temperature (°C)			
50	67.05±1.87 ^a	7.83±0.60 ^b	30.13±0.49 ^c
60	65.60±1.66 ^b	8.07±0.61 ^a	32.07±1.59 ^b
70	65.11±1.18 ^b	8.20±0.68 ^a	33.24±1.86 ^a

Note. Data are expressed mean±SD; Different letters indicate statistically significant differences exist $p < 0.05$ for each column. Means do not share a letter is significantly different. Tukey’s test was applied with 95% simultaneous confidence intervals. L* = Lightness; a* = Redness; b* = Yellowness

markets. Table 3 illustrates the effect of parboiled rice soaking time and temperature on redness (a^*) attributes. The redness (a^*) grew significantly ($p<0.05$) as the soaking time and temperature increased (Table 3).

The soaking temperature intensified the colour (Mir & Bosco, 2013). The endosperm absorbs the husk colour during the process, causing the rice to turn amber when parboiled. The elevated levels of reducing sugar, free α -amino nitrogen, and glucose-to-fructose isomerisation in parboiled rice indicate a non-enzymatic Maillard colour change (Balbinoti et al., 2018). Increasing the soak water temperature, steaming time, and steaming pressure for poorly hydrated grains improves the colour of parboiled rice (Hu et al., 2019). Higher soaking temperatures cause the husk to absorb more colour, and coloured materials like folic acid absorb into the soaking water, colouring the rice kernel. Lamberts et al. (2008) found that the transformation from white to amber rice after parboiling was caused by the diffusion of bark and bran pigments, as well as non-enzymatic Maillard and enzymatic browning, to a lesser extent. Maillard reactions (increased furosine levels) following gelatinisation led to the darkening of rice. Pigment taken from husks altered the colour (Sareepuang et al., 2008).

Effect of Soaking Time and Temperature on the Hardness

It was found that the hardness was significantly affected by the different soaking times and temperatures of the parboiling process. The hardness increased

(3,077.26–3,268.67 g) with the increasing temperature of the soaking process. However, the hardness was significantly ($p<0.05$) decreased (3,545.83–3,087.82 g) with the increase of time of the soaking process. The hardness of the kernel is influenced by soaking time and temperature. According to Graham-Acquaah et al. (2015), the stiffness of rice increases with steaming time and decreases with soaking water temperature. After parboiling, the rice kernel's ultimate tensile strength and elastic modulus are raised four to five times. The steaming duration and starch gelatinisation directly influence Hardness levels.

Table 4 illustrates how soaking time and temperature treatment affected the parboiled rice's hardness. An increase in soaking time would result in a reduction in hardness ($p<0.05$). However, a slight

Table 4
Effect of soaking time and temperature of parboiled rice on hardness

Time	Hardness (g)
Soaking time (hr)	
1	3545.43±125.50 ^a
2	3244.05±203.21 ^b
3	3025.02±54.97 ^{bc}
4	3008.21±171.96 ^{bc}
5	3087.82±78.26 ^c
Temperature (°C)	
50	3077.26±217.29 ^a
60	3200.40±206.82 ^{ab}
70	3268.67±274.59 ^b

Note. Data are expressed mean±SD; Different letters indicate statistically significant differences exist $p<0.05$ for each column. Means do not share a letter is significantly different. Tukey's test was applied with 95% simultaneous confidence intervals

increase in hardness was observed after 5 hr of soaking time. At the beginning of the soaking period, the hardness was decreased upon amylose leaching; the increase in soaking time would severe the gelatinisation of rice starch. Upon heating, the process of leaching caused the migration of short-chain amylose, which subsequently penetrated the indentations on the surface of the cooked rice. During this period, the amylose with elongated chains underwent cross-linking, resulting in the eventual formation of three-dimensional network architectures by hydrogen bonding (Yang et al., 2016). Rising the soaking temperature would result in an elevation in rice hardness ($p < 0.05$). The observed phenomenon can be attributed to the heightened gelatinisation of starch, which is directly influenced by the duration of soaking (Miah et al., 2002).

Parboiled rice has a distinct texture when cooked and less breaking when milled because of its increased strength. Gelatinisation, thermal starch degradation, and recrystallisation of starch with lipid-amylose inclusion complexes are the three processes that contribute to the altered hardness of rice that has been parboiled (Dutta & Mahanta, 2012). The types of starch polymorphs generated in rice during the parboiling process determine the texture of the rice after it has been cooked.

The Correlation between Dimensional, Physical, Colour, and Texture Properties

Pearson's correlation coefficients among the physical characteristics of parboiled rice with

the different soaking times and temperatures are shown in Table 5. There is a significant correlation across the different properties of parboiled rice MR297, including hardness, L, W, T, V_v , TKW, density, and colour L, a, and b ($p < 0.05$). The hardness was highly negatively correlated with the major axis ($r = -0.770$, $p < 0.01$) and a^* ($r = -0.0557$, $p < 0.005$). The correlation coefficients between L and the W, T, V_v , TKW, a^* , and b^* were highly positive with values of 0.758, 0.634, 0.766, 0.556, 0.761, and 0.612, respectively. Meanwhile, correlation coefficients between the major axis and the L* and density were highly negative -0.734 and -0.0798, respectively ($p < 0.05$).

The medium axis was highly positively correlated with the minor axis ($r = 0.931$, $p < 0.01$), volume expansion ($r = 0.985$, $p < 0.01$), TKW ($r = 0.565$, $p < 0.05$), a^* ($r = 0.938$, $p < 0.01$), and b^* ($r = 0.825$, $p < 0.01$). The correlation coefficients between the minor axis with volume expansion, TKW, a^* , and b^* were highly positive with values of 0.973, 0.645, 0.831, and 0.867, respectively ($p < 0.01$). On the other hand, correlation coefficients between the medium axis and the minor axis with density and L* were highly negative -0.968, -0.927, -0.924, and -0.895, respectively ($p < 0.01$). These results indicate that the increase of dimensions decreased proportionally with the increase in density and L*. The same results were found by Megat-Ahmad-Azman et al. (2020), in which the dimensions were negatively correlated with the density.

As indicated in Table 5, volume expansion increases proportionally with

Table 5

Pearson correlation coefficients for physical properties of parboiled paddy and milled rice MR297

	Hardness	L	W	T	V	TKW	density	L*	a*	b*
Hardness	1									
L	-.770**	1								
W	-0.426	.758**	1							
T	-0.158	.634*	.931**	1						
V	-0.362	.766**	.985**	.973**	1					
TKW	-0.158	.556*	.565*	.645**	.624*	1				
Density	0.392	-.734**	-.968**	-.924**	-.966**	-0.407	1			
L*	0.456	-.798**	-.927**	-.895**	-.937**	-.670**	.889**	1		
a*	-.557*	.761**	.938**	.831**	.911**	0.432	-.928**	-.927**	1	
b*	-0.214	.612*	.825**	.867**	.863**	.652**	-.781**	-.808**	.745**	1

Note. * = Correlation is significant at the 0.05 level (2-tailed); ** = Correlation is significant at the 0.01 level (2-tailed); TKW = Thousand kernel weight

TKW ($r=0.624$, $p<0.05$), a^* ($r=0.911$, $p<0.01$), and b^* ($r=0.863$, $p<0.01$). The volume expansion was negatively correlated with the density (-0.966) and L^* (-0.934). TKW was highly positively correlated with b^* ($r=0.652$, $p<0.01$). TKW was conversely highly negative with L^* ($r=-0.670$, $p<0.01$). These results indicate volume expansions and TKW decreased proportionally with the decrease in b^* . However, it also decreased proportionally with the increase in L^* . The correlation coefficient between density and L^* was highly positive, with a value of 0.889. Volume had a highly negative correlation with a^* (-0.928) and b (-0.781) ($p<0.01$). L^* was highly negatively correlated with the a^* ($r=-0.927$, $p<0.01$) and b^* ($r=-0.808$, $p<0.01$). Meanwhile, a^* was highly positively correlated with the b^* (0.745). The results showed that the increase in volume expansion, TKW, a^* and b^* decreased proportionally with density and L^* .

Figure 2 displays the score plot of the physical and dimensional characteristics

of MR297 parboiled paddy grain and the hardness and colour of milled parboiled rice as the effect of temperature and time of soaking. This plot is based on the principal component analysis. The PCA score plot shows the variations in the characteristics of MR297 across a range of different treatments. The variance was divided into two halves. The first (PC1) and second (PC2) principal components (PC) accounted for 71.5% and 17.4%, which together accounted for 88.9% of the variation (Table 6). The PC1 was by far the most important component for providing data that was plotted in the PCA. According to Table 7, PC1 considers all physical properties except hardness, TKW, and temperature of soaking to be equally important. However, the important qualities in PC2 were temperature, hardness, and TKW, which were less important in PC1. Additionally, Figure 2 noted that the sample load positively towards the PC1, the higher the soaking temperature. Also, the increase in soaking time was loading

Table 6
Explained variance (Eigenanalysis) of the correlation matrix

Eigenvalue	8.585	2.089	0.789	0.227	0.143	0.082	0.034	0.030	0.013	0.008	0.000	0.000
Proportion	0.715	0.174	0.066	0.019	0.012	0.007	0.003	0.002	0.001	0.001	0.000	0.000
Cumulative	0.715	0.889	0.955	0.974	0.986	0.993	0.996	0.998	0.999	1.000	1.000	1.000

Table 7
Correlation loadings for paddy in different temperatures and times of soaking and 12 physical characteristics

Variable	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10	PC11	PC12
Temperature	0.158	0.592	0.174	-0.232	0.068	-0.275	-0.487	0.025	0.042	-0.469	-0.023	0.011
Time	0.298	-0.318	-0.044	0.110	0.037	0.173	-0.088	0.703	-0.352	-0.370	0.026	0.030
Hardness	-0.165	0.531	-0.422	0.298	-0.182	-0.183	0.034	0.459	-0.067	0.374	0.025	-0.003
L	0.286	-0.235	0.375	-0.048	-0.598	-0.459	-0.079	0.156	0.176	0.256	-0.034	0.152
W	0.333	-0.008	-0.171	0.093	0.016	0.313	-0.567	-0.253	-0.234	0.377	-0.039	0.411
T	0.318	0.186	-0.215	0.199	-0.204	0.114	0.453	-0.150	0.246	-0.373	-0.057	0.542
V expansion	0.336	0.055	-0.138	0.108	-0.185	0.155	-0.005	-0.096	0.068	-0.013	-0.695	-0.547
TKW	0.224	0.313	0.629	0.420	0.107	0.360	0.126	0.064	0.075	0.164	0.245	-0.160
Density	-0.321	0.053	0.348	-0.043	0.261	0.048	0.060	0.237	0.002	0.112	-0.663	0.434
Lightness	-0.330	-0.015	-0.039	-0.178	-0.389	0.555	-0.285	0.211	0.508	-0.090	0.072	-0.002
a*	0.320	-0.140	-0.188	-0.019	0.544	-0.151	-0.078	0.219	0.658	0.188	0.038	-0.010
b*	0.296	0.230	-0.004	-0.757	-0.006	0.227	0.338	0.148	-0.151	0.269	0.060	-0.008

Note. PC 1-12 = Principal components 1-12, respectively; L = Length; W = Width; T = Thickness; V expansion = Volume expansion; TKW = Thousand kernel weight; a* = Redness ; b* = Yellowness

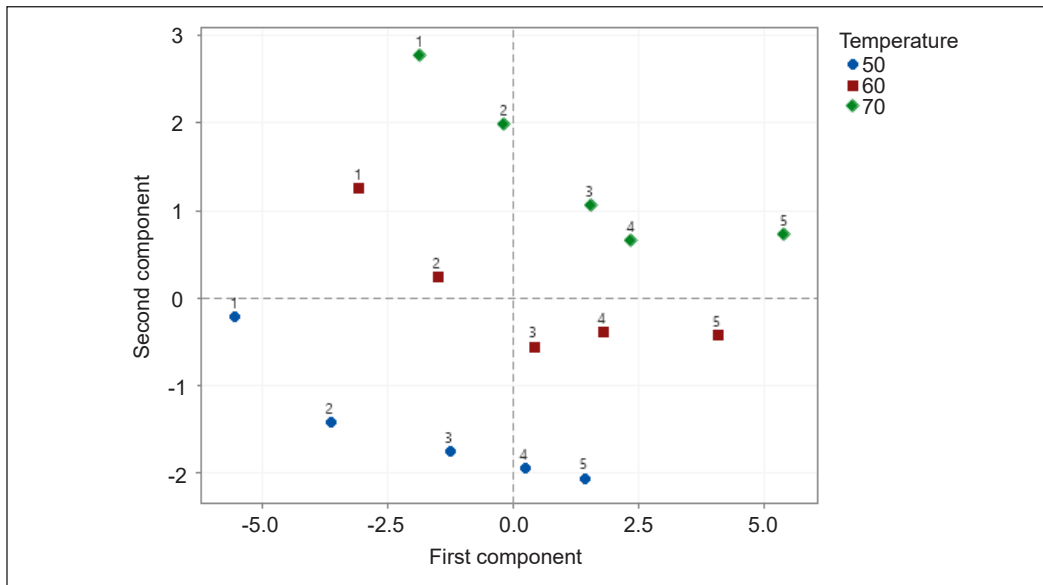


Figure 2. Score plot for principal components 1 and 2

positively towards the increase of the soaking temperature. It was further agreed by the study's earlier portion, where the time and temperature of the soaking treatment during parboiling affects proportionally with no interaction for the dimensional, physical, hardness, and colour properties of parboiled paddy and milled rice.

CONCLUSION

Soaking time and temperature were all important in parboiled paddy and rice properties. However, there was no interaction between time and temperature due to all the changes in physical properties. The hydrothermal treatment has expanded the dimensions of parboiled rice compared to raw rice; therefore, it has increased the volume expansion. Hydrothermal also modified the TKW, density, and colour properties of parboiled rice. The colour turns into a yellowish colour due to the Maillard

reaction and the imbibition of the colour of the husk. Increasing the soaking duration decreases the hardness, while raising the soaking temperature increases the hardness. Several significant correlations between the properties of parboiled rice were discovered. The dimensions, volume expansion, TKW, a^* and b^* were negatively correlated with the density and L^* . After parboiling, the hardness was negatively correlated with L and b^* . The study will be very important for parboiled rice producers regarding the effect of soaking time and temperature on the physical characteristics of parboiled paddy and rice.

ACKNOWLEDGEMENTS

A special thanks to Universiti Putra Malaysia for the technical and facilities support given when conducting this research work and to Bernas Malaysia for technical support. The present work is part of a PhD program

funded by the joint scholarship between the Centre for Education Funding Service, the Indonesian Ministry of Education, Culture, Research and Technology and the Indonesian Endowment Fund for Education, Ministry of Finance Republic Indonesia.

REFERENCES

- Azuka, C. E., Nkama, I., & Asoiro, F. U. (2021). Physical properties of parboiled milled local rice varieties marketed in South-East Nigeria. *Journal of Food Science and Technology*, *58*, 1788–1796. <https://doi.org/10.1007/s13197-020-04690-1>
- Balbinoti, T. C. V., Nicolin, D. J., de Matos Jorge, L. M., & Jorge, R. M. M. (2018). Parboiled rice and parboiling process. *Food Engineering Reviews*, *10*, 165–185. <https://doi.org/10.1007/s12393-018-9177-y>
- Behera, G., & Sutar, P. P. (2018). A comprehensive review of mathematical modeling of paddy parboiling and drying: Effects of modern techniques on process kinetics and rice quality. *Trends in Food Science and Technology*, *75*, 206–230. <https://doi.org/10.1016/j.tifs.2018.03.015>
- Bello, M. O., Tolaba, M. P., & Suarez, C. (2007). Water absorption and starch gelatinization in whole rice grain during soaking. *LWT - Food Science and Technology*, *40*(2), 313–318. <https://doi.org/10.1016/j.lwt.2005.09.017>
- Bello, M., Tolaba, M. P., & Suarez, C. (2004). Factors affecting water uptake of rice grain during soaking. *LWT - Food Science and Technology*, *37*(8), 811–816. <https://doi.org/10.1016/j.lwt.2004.02.014>
- Bhat, F. M., & Riar, C. S. (2016). Cultivars effect on the physical characteristics of rice (rough and milled) (*Oryza sativa* L.) of temperate region of Kashmir (India). *Journal of Food Science and Technology*, *53*, 4258–4269. <https://doi.org/10.1007/s13197-016-2420-8>
- Bootkote, P., Soponronnarit, S., & Prachayawarakorn, S. (2016). Process of producing parboiled rice with different colors by fluidized bed drying technique including tempering. *Food and Bioprocess Technology*, *9*, 1574–1586. <https://doi.org/10.1007/s11947-016-1737-7>
- Buggenhout, J., Brijs, K., Van Oevelen, J., & Delcour, J. A. (2014). Milling breakage susceptibility and mechanical properties of parboiled brown rice kernels. *LWT - Food Science and Technology*, *59*(1), 369–375. <https://doi.org/10.1016/j.lwt.2014.05.001>
- Dutta, H., & Mahanta, C. L. (2012). Effect of hydrothermal treatment varying in time and pressure on the properties of parboiled rices with different amylose content. *Food Research International*, *49*(2), 655–663. <https://doi.org/10.1016/j.foodres.2012.09.014>
- Ebuehi, O. A. T., & Oyewole, A. C. (2008). Effect of cooking and soaking on physical, nutrient composition and sensory evaluation of indigenous and foreign rice varieties in Nigeria. *Nutrition and Food Science*, *38*(1), 15–21. <https://doi.org/10.1108/00346650810847972>
- Esa, N., Puteh, A., Mat, M., Ismail, R., & Yusop, M. R. (2020). Increasing yield of susceptible and resistant rice blast cultivars using silicon fertilization. *Indonesian Journal of Agricultural Science*, *21*(2), 49. <https://doi.org/10.21082/ijas.v21n2.2020.p49-58>
- Graham-Acquaah, S., Manful, J. T., Ndindeng, S. A., & Tchatcha, D. A. (2015). Effects of soaking and steaming regimes on the quality of artisanal parboiled rice. *Journal of Food Processing and Preservation*, *39*(6), 2286–2296. <https://doi.org/10.1111/jfpp.12474>
- Hanucharoenkul, P., Theerathanan, C., & Pongsawatmanit, R. (2021). Influence of soaking temperature and time on the kinetics of water

- absorption and pasting properties of glutinous rice. *Agriculture and Natural Resources*, 55, 193–200. <https://doi.org/10.34044/j.anres.2021.55.2.05>
- Hu, Z., Shao, Y., Lu, L., Fang, C., Hu, X., & Zhu, Z. (2019). Effect of germination and parboiling treatment on distribution of water molecular, physicochemical profiles and microstructure of rice. *Journal of Food Measurement and Characterization*, 13, 1898–1906. <https://doi.org/10.1007/s11694-019-00108-5>
- Hu, Z., Yang, Y., Lu, L., Chen, Y., Zhu, Z., & Huang, J. (2021). Kinetics of water absorption expansion of rice during soaking at different temperatures and correlation analysis upon the influential factors. *Food Chemistry*, 346, 128912. <https://doi.org/10.1016/j.foodchem.2020.128912>
- Iqbal, S., Zhang, P., Wu, P., Ge, A., Ge, F., Deng, R., & Chen, X. D. (2021). Evolutions of rheology, microstructure and digestibility of parboiled rice during simulated semi-dynamic gastrointestinal digestion. *LWT*, 148, 111700. <https://doi.org/10.1016/j.lwt.2021.111700>
- Jannasch, A., & Wang, Y.-J. (2020). Development of a limited-water soaking method on the fortification of rice with calcium and iron by parboiling. *Journal of Cereal Science*, 94, 103014. <https://doi.org/10.1016/j.jcs.2020.103014>
- Jayaraman, R., Uluvar, H., Khanum, F., & Singh, V. (2019). Influence of parboiling of red paddy varieties by simple hot soaking on physical, nutrient, phytochemical, antioxidant properties of their dehusked rice and their mineral, starch, and antioxidant's bioaccessibility studies. *Journal of Food Biochemistry*, 43(7), e12839. <https://doi.org/10.1111/jfbc.12839>
- Ji-u, P., & Inprasit, C. (2019). Effect of soaking conditions on properties of Khao Dawk Mali 105. *Agriculture and Natural Resources*, 53, 378–385. <https://doi.org/10.34044/j.anres.2019.53.4.08>
- Kumar, S., & Prasad, K. (2018). Effect of parboiling and puffing processes on the physicochemical, functional, optical, pasting, thermal, textural and structural properties of selected Indica rice. *Journal of Food Measurement and Characterization*, 12, 1707–1722. <https://doi.org/10.1007/s11694-018-9786-4>
- Lamberts, L., Rombouts, I., Brijs, K., Gebruers, K., & Delcour, J. A. (2008). Impact of parboiling conditions on Maillard precursors and indicators in long-grain rice cultivars. *Food Chemistry*, 110(4), 916–922. <https://doi.org/10.1016/j.foodchem.2008.02.080>
- Liang, J., Li, Z., Tsuji, K., Nakano, K., Robert Nout, M. J., & Hamer, R. J. (2008). Milling characteristics and distribution of phytic acid and zinc in long-, medium- and short-grain rice. *Journal of Cereal Science*, 48(1), 83–91. <https://doi.org/10.1016/j.jcs.2007.08.003>
- Liu, J., Liu, Y., Wang, A., Dai, Z., Wang, R., Sun, H., Strappe, P., & Zhou, Z. (2021). Characteristics of moisture migration and volatile compounds of rice stored under various storage conditions. *Journal of Cereal Science*, 102, 103323. <https://doi.org/10.1016/J.JCS.2021.103323>
- Megat-Ahmad-Azman, P. N., Shamsudin, R., Che-Man, H., & Ya'acob, M. E. (2020). Kinetics of quality changes in soaking water during the retting process of pepper berries (*Piper nigrum* L.). *Processes*, 8(10), 1255. <https://doi.org/10.3390/pr8101255>
- Miah, M. A. K., Haque, A., Douglass, M. P., & Clarke, B. (2002). Parboiling of rice. Part II: Effect of hot soaking time on the degree of starch gelatinization. *International Journal of Food Science and Technology*, 37(5), 539–545. <https://doi.org/10.1046/j.1365-2621.2002.00611.x>
- Mir, S. A., & Bosco, S. J. D. (2013). Effect of soaking temperature on physical and functional properties of parboiled rice cultivars grown in temperate region of India. *Food and Nutrition*

- Sciences*, 4(3), 282–288. <https://doi.org/10.4236/fns.2013.43038>
- Mir, S. A., Bosco, S. J. D., & Sunooj, K. V. (2013). Evaluation of physical properties of rice cultivars grown in the temperate region of India. *International Food Research Journal*, 20(4), 1521-1527.
- Muchlisiyah, J., Shamsudin, R., Basha, R. K., Shukri, R., How, S., Niranjan, K., & Onwude, D. (2023). Parboiled rice processing method, rice quality, health benefits, environment, and future perspectives: A review. *Agriculture*, 13(7), 1390. <https://doi.org/10.3390/agriculture13071390>
- Nádvořníková, M., Banout, J., Herák, D., & Verner, V. (2018). Evaluation of physical properties of rice used in traditional Kyrgyz Cuisine. *Food Science and Nutrition*, 6(6), 1778–1787. <https://doi.org/10.1002/fsn3.746>
- Panda, B. K., Panigrahi, S. S., Mishra, G., & Shrivastava, S. L. (2021). Microwave-assisted hydration of freshly harvested paddy (*Oryza sativa* L.): Process development based on soaking characterization and energy utilization. *Food and Bioprocess Technology*, 14, 1844–1856. <https://doi.org/10.1007/s11947-021-02682-3>
- Patindol, J., Newton, J., & Wang, Y.-J. (2008). Functional properties as affected by laboratory-scale parboiling of rough rice and brown rice. *Journal of Food Science*, 73(8), E370–E377. <https://doi.org/10.1111/j.1750-3841.2008.00926.x>
- Rachmat, R., Thahir, R., & Gummert, M. (2016). The empirical relationship between price and quality of rice at market level in West Java. *Indonesian Journal of Agricultural Science*, 7(1), 27-33. <https://doi.org/10.21082/ijas.v7n1.2006.p27-33>
- Rahim, H., Ariff, E. E. E., & Hosni, H. (2023). Bridging the gap between consumer preferences and the development of fragrant rice varieties in Malaysia. *Agricultural Research*, 12, 462-472. <https://doi.org/10.1007/s40003-023-00666-7>
- Ramli, A., & Kamaruzaman, R. (2020). Breeding strategies for rice in Malaysia. In P. Lestari, K. Mulya, D. W. U. D. Satyawan, Supriadi., & Mastur. (Eds.), *Strategies and technologies for the utilization and improvement* (pp. 25-36). IAARD Press.
- Rattanamechaiskul, C., Junka, N., & Prakotmak, P. (2023). Modeling and optimization of moisture diffusion of paddy and brown rice during thermal soaking. *Journal of Food Process Engineering*, 46(4), e14902. <https://doi.org/10.1111/jfpe.14302>
- Reddy, B. S., & Chakraverty, A. (2004). Physical properties of raw and parboiled paddy. *Biosystems Engineering*, 88(4), 461–466. <https://doi.org/10.1016/j.biosystemseng.2004.05.002>
- Rocha-Villarreal, V., Serna-Saldivar, S. O., & García-Lara, S. (2018). Effects of parboiling and other hydrothermal treatments on the physical, functional, and nutritional properties of rice and other cereals. *Cereal Chemistry*, 95(1), 79–91. <https://doi.org/10.1002/cche.10010>
- Roy, M., Dutta, H., Jaganmohan, R., Choudhury, M., Kumar, N., & Kumar, A. (2019). Effect of steam parboiling and hot soaking treatments on milling yield, physical, physicochemical, bioactive and digestibility properties of buckwheat (*Fagopyrum esculentum* L.). *Journal of Food Science and Technology*, 56, 3524–3533. <https://doi.org/10.1007/s13197-019-03849-9>
- Saleh, M., & Meullenet, J.-F. (2015). Cooked rice texture and rice flour pasting properties; Impacted by rice temperature during milling. *Journal of Food Science and Technology*, 52, 1602–1609. <https://doi.org/10.1007/s13197-013-1180-y>
- Saleh, M., Akash, M., & Ondier, G. (2018). Effects of temperature and soaking durations on the hydration kinetics of hybrid and pureline parboiled brown rice cultivars. *Journal of Food Measurement and Characterization*, 12, 1369–1377. <https://doi.org/10.1007/s11694-018-9751-2>

- Sareepuang, K., Siriamornpun, S., Wiset, L., & Meeso, N. (2008). Effect of soaking temperature on physical, chemical and cooking properties of parboiled fragrant rice research unit of drying technology for agricultural products. *World Journal of Agricultural Sciences*, 4(4), 409–415.
- Shamsudin, R., Ariffin, S. H., Zainol@Abdullah, W. N. Z., Azmi, N. S., & Abdul-Halim, A. A. (2021). Modelling the kinetics of color and texture changes of Dabai (*Canarium odontophyllum* Miq.) during blanching. *Agronomy*, 11(11), 2185. <https://doi.org/10.3390/agronomy11112185>
- Shen, Y., Jin, L., Xiao, P., Lu, Y., & Bao, J. (2009). Total phenolics, flavonoids, antioxidant capacity in rice grain and their relations to grain color, size and weight. *Journal of Cereal Science*, 49(1), 106–111. <https://doi.org/10.1016/j.jcs.2008.07.010>
- Sittipod, S., & Shi, Y.-C. (2016). Changes of starch during parboiling of rice kernels. *Journal of Cereal Science*, 69, 238–244. <https://doi.org/10.1016/j.jcs.2016.03.015>
- Sivakamasundari, S. K., Moses, J. A., & Anandharamakrishnan, C. (2020). Effect of parboiling methods on the physicochemical characteristics and glycemic index of rice varieties. *Journal of Food Measurement and Characterization*, 14, 3122–3137. <https://doi.org/10.1007/s11694-020-00551-9>
- Tao, K., Li, C., Yu, W., Gilbert, R. G., & Li, E. (2019). How amylose molecular fine structure of rice starch affects functional properties. *Carbohydrate Polymers*, 204, 24–31. <https://doi.org/10.1016/j.carbpol.2018.09.078>
- Tian, J., Cai, Y., Qin, W., Matsushita, Y., Ye, X., & Ogawa, Y. (2018). Parboiling reduced the crystallinity and *in vitro* digestibility of non-waxy short grain rice. *Food Chemistry*, 257, 23–28. <https://doi.org/10.1016/j.foodchem.2018.03.005>
- Tian, Y., Zhao, J., Xie, Z., Wang, J., Xu, X., & Jin, Z. (2014). Effect of different pressure-soaking treatments on color, texture, morphology and retrogradation properties of cooked rice. *LWT - Food Science and Technology*, 55(1), 368–373. <https://doi.org/10.1016/J.LWT.2013.09.020>
- Villanova, F. A., Vanier, N. L., de Avila Madruga, N., Pesek, J., Matyska-Pesek, M., Elias, M. C., & de Oliveira, M. (2017). Improvement of the quality of parboiled rice by using anti-browning agents during parboiling process. *Food Chemistry*, 235, 51–57. <https://doi.org/10.1016/j.foodchem.2017.05.053>
- Wahengbam, E. D., & Hazarika, M. K. (2019). Quality of ready-to-eat komal chawal produced by brown rice parboiling method. *Journal of Food Science and Technology*, 56, 187–199. <https://doi.org/10.1007/s13197-018-3472-8>
- Wu, W., Zhou, L., Chen, J., Qiu, Z., & He, Y. (2018). GainTKW: A measurement system of thousand kernel weight based on the android platform. *Agronomy*, 8(9), 178. <https://doi.org/10.3390/agronomy8090178>
- Wu, Z., He, Y., Yan, W., Zhang, W., Liu, X., Hui, A., Wang, H., & Li, H. (2021). Effect of high-pressure pre-soaking on texture and retrogradation properties of parboiled rice. *Journal of the Science of Food and Agriculture*, 101(10), 4201–4206. <https://doi.org/10.1002/jsfa.11058>
- Yadav, B. K., & Jindal, V. K. (2007). Modeling changes in milled rice (*Oryza sativa* L.) kernel dimensions during soaking by image analysis. *Journal of Food Engineering*, 80(1), 359–369. <https://doi.org/10.1016/J.JFOODENG.2006.06.005>
- Yang, L., Sun, Y.-H., Liu, Y., Mao, Q., You, L.-X., Hou, J.-M., & Ashraf, M. A. (2016). Effects of leached amylose and amylopectin in rice cooking liquid on texture and structure of cooked rice. *Brazilian Archives of Biology and Technology*, 59, e16160504. <https://doi.org/10.1590/1678-4324-2016160504>

- Zainal, N., & Shamsudin, R. (2021). Physical properties of different cultivar local glutinous rice (susu and siding) and commercial Thai cultivar. *Advances in Agricultural and Food Research Journal*, 2(1), a0000178. <https://doi.org/10.36877/aafjr.a0000178>
- Zhu, L., Cheng, L., Zhang, H., Wang, L., Qian, H., Qi, X., & Wu, G. (2019). Research on migration path and structuring role of water in rice grain during soaking. *Food Hydrocolloids*, 92, 41–50. <https://doi.org/10.1016/j.foodhyd.2019.01.051>