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Hydration Effect and Kinetic Studies for Physical and Hardness Properties of Parboiled Rice MR297

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ABSTRACT

Soaking is a crucial step in the parboiling process that directly impacts the overall quality of parboiled rice. The aim of this study was to investigate the impact of soaking time and temperature on the kinetics of colour, dimensions, and hardness of parboiled rice MR297. In this study, MR297 paddy was soaked at different temperatures (50 °C, 60 °C, and 70 °C) for 1, 2, 3, 4, and 5 hours. Kinetic models assessed for quality changes in parboiled rice included the zero-order, first-order, and second-order models. The data showed that the total colour change (6.95–15.09), chroma (30.46–36.94), browning index (61.59–90.05), length (9.61–10.38 mm), width (2.06–2.37 mm), and thickness (1.80–2.11 mm) increased. Whereas the Hue angle (77.21–74.14) and hardness (3576.61–3167.4) decreased as the temperature (50 °C–70 °C) and time (1–5 hours) of soaking increased. The alterations in colour, dimensions, and hardness were satisfactorily explained by the kinetic models (zero, first, and second-order). Most of the reaction rate constant (k) of the change greatly depended on the soaking temperature. The kinetic models for colour (total colour change, chroma, hue, and browning index), dimensional (length, width, and thickness), and hardness alterations followed the Arrhenius equation. Hence, the fitted kinetic models of the quality alteration can be employed

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to forecast the immersion procedure of parboiled rice MR297. The significance of this study lies in providing predictive models that can optimise the parboiling process for the MR297 rice variety, enabling producers to better control product quality while potentially reducing processing time and energy consumption. These findings contribute to the scientific understanding of rice parboiling and can be valuable for industrial applications in the rice processing industry.

Keywords: Kinetic models, parboiled rice, soaking, quality changes

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INTRODUCTION

Rice is a densely nutritious staple food, rich in carbohydrates and containing a small amount of protein, vitamins, fats, and minerals. Parboiled rice has gained widespread popularity around the globe (Balbinoti, Nicolin et al., 2018). Owing to the unique parboiling process, this rice has a distinct texture and flavour from the regular white rice. The parboiling process involves soaking and steaming the rice while it is still enclosed in its husk. This method protects the essential nutrients present in the rice grain (Muchlisyiyah et al., 2023). During the procedure, nutrients are transferred from the rice husk to the rice grains, resulting in greater health benefits than white rice alone (Jayaraman et al., 2019). In addition, the parboiling procedure makes the rice grains harder and less sticky (Onmankhong et al., 2021). The benefits of the parboiled rice include a greater number of nutraceuticals, improved palatability, and increased shelf life (Alexandre, 2020).

The texture is one of the characteristics that distinguishes the parboiled rice from the ordinary white rice, which is known for its special qualities. During the parboiling procedure, the starch in rice grains undergoes structural changes that account for this difference. Parboiling alters the starch structure of rice grains, making them denser and more cohesive (Sittipod & Shi, 2016). Initially, unstructured and loosely bound starch becomes more structured and tightly bound (Li et al., 2021). This results in rice that is softer and chewier after heating. The parboiled rice grains retain their integrity when cooked without becoming excessively sticky or falling apart (Srichamnong & Lasukhang, 2022). Moreover, alterations in the starch structure influence the absorption of water during heating. Rice grains that have been parboiled are better at incorporating water, resulting in rice that is chewier and less sticky (Wiruch et al., 2019). Its delicate, chewy texture, and non-sticky consistency make the parboiled rice the choice for fried rice, congee, and other rice dishes.

The soaking phase before parboiling significantly affects the colour and texture of the parboiled rice produced. During soaking, water permeates the rice grains, altering the starch structure and resulting in firmer and fluffier rice grains after parboiling (Jagtap et al., 2008). Higher temperatures can accelerate the transformation of the starch structure in rice grains during soaking. Rice grains can undergo the desired structural change after the parboiling procedure to gain more resistance to stress during milling and obtain a higher head rice yield (HRY) (Jaiboon et al., 2016). On the other hand, the soaking process will result in a colour change due to the penetration of colour from the husk into the grain (Tian et al., 2014). The soaking process also resulted in some chemical changes, especially in the starch, protein, and lipid substances, which alter both the texture and colour of rice (Fonseca et al., 2011).

Significant research has been conducted on the kinetics and models of the rice parboiling process, especially focussed on the soaking process. The objective of the studies is to understand the physical and chemical changes that occur in rice during the soaking process and to develop a more accurate mathematical model to describe this phenomenon. Previous studies have investigated the hydration kinetics of paddy and rice during soaking (Balbinoti, Jorge et al., 2018; Ji-u & Inprasit, 2019; Nacimento et al., 2022; Sridhar & Manohar, 2003). Martins et al. (2021) conducted a study to investigate the impact of soaking on the moisture content and textural qualities of rice by employing kinetic models (zero, first, and second-order) as well as response surface methods. Rattanamechaiskul et al. (2023) simulated moisture diffusion during soaking paddy and rice and calculated the energy activation of the Khao Dawk Mali 105 paddy Thailand variety. Fonseca et al. (2011) found that temperature and time can optimise the rice soaking process to achieve the highest quality parboiled rice. Other studies have described the multiple steps of parboiling, including soaking, steaming, and drying, using various models (Mahfeli et al., 2022; Oludolapo & Akinoso, 2020; Shaju et al., 2022; Yousaf et al., 2017).

Therefore, modelling the changes in rice as a result of soaking after undergoing the entire parboiling procedure is crucial for predicting and monitoring the quality of parboiled rice, especially in terms of colour, dimensional, and textural changes. In addition to understanding physical changes, this research seeks to develop a mathematical model that can more precisely characterise the soaking process. By employing a valid mathematical model, researchers could better anticipate the degree of parboiling and final characteristics of parboiled rice. However, the alterations in colour and texture caused by soaking are not explained by any established empirical data or formal model. The best-fit model that might be used in research on other agricultural commodities is important as an insight. Kinetic data will make it easier to determine the ideal processing parameters and estimate the quality losses caused by soaking (Devi & Das, 2017; Shamsudin et al., 2021, 2022). The rate equations quantitatively demonstrate the effect for the zero, first, and second orders (Chikpah et al., 2022). Then, the rate equation includes the reaction orders (Azman et al., 2020). The Arrhenius equation was used to explain the parameters under study because they were temperature-dependent. Furthermore, the k revealed that temperature and duration were the two most crucial variables in blanching, which is typically defined by Arrhenius' behaviour. The incorporation of the Arrhenius equation into the kinetic models resulted in the substitution of temperature as a predictor for the quality factors.

This study examines how soaking affects the rate at which the colour, dimensional hardness, and textural hardness of parboiled rice change. The model can also be used to forecast time-dependent variations in the colour, dimensions, and textural firmness of parboiled rice grains resulting from different soaking temperatures and times. Studying the kinetics and models of rice soaking yields useful information for developing efficient parboiling methods. Thus, a comprehensive understanding of parboiled rice soaking conditions and related factors is essential for achieving optimal parboiled rice quality.

METHODOLOGY

Sample Preparation

A local farmer in Tanjung Karang (Selangor, Malaysia) provided fresh MR297 paddy planted in June 2022 and harvested in November 2022. Random samples of fresh paddy grain were collected and afterwards transported to a laboratory setting in sacs for secure conveyance. Upon arrival at the laboratory, the paddy was carefully transferred into polypropylene bags, which were then vacuum-packed. This step was undertaken to further ensure the preservation of the paddy's quality and integrity for subsequent analysis. The paddy was then preserved within a refrigeration unit at 10 °C (Reddy & Chakraverty, 2004). Manual cleaning was performed to remove foreign objects such as sticks, stones, leaves, and other plant components. A moisture content of 19.5% was recorded at the beginning of the experiment.

Parboiling Process

The parboiling method involved three sequential steps: soaking, steaming, and drying. Fresh MR297 paddy was parboiled in a laboratory using a heated soaking procedure. Water (100 mL) in a 250 mL beaker was heated in a water bath (Memmert, WNB22, Germany) to the desired temperatures (50 °C, 60 °C, and 70 °C) (Muchlisyiyah et al., 2024a). Aluminium foil was used to seal the receptacle to prevent excessive evaporation. When the specified temperature (50 °C, 60 °C, and 70 °C) was attained, 100 g of paddy was poured into the water contained in the glass beaker. The rice-to-water ratio was 1:1 (Jannasch & Wang, 2020). A moderate mixing was performed to ensure that all the paddy was soaked. The paddy was immersed for 1, 2, 3, 4, and 5 hours. The rice was then steamed for 20 minutes at 100 °C using a domestic steamer (TEFAL VC1401, France). The rice was cooled at ambient temperature for one hour (Bootkote et al., 2016). This paddy was then dried in an oven at 38 °C for 24 hours (Memmert DO6836, Germany) (Roy et al., 2019; Tian et al., 2018; Villanova et al., 2017). Steaming and drying were not taken into account in this study due to the specific condition of the operation. The paddy was subsequently examined to ascertain its dimensions. The dehulling procedure of desiccated parboiled rice was carried out employing a Satake THU-35 dehusker (THU-35, Satake Corp., Japan), followed by a milling duration of 2.5 minutes using a TM05-C mill (Satake, Japan) (Liang et al., 2008). The milled rice was then analysed for its hardness and colour properties.

Dimensional Measurement

In order to determine the mean size of the paddy grains, a sample of 100 grains was randomly chosen, and the length (L), width (W), and thickness (T) were measured using a Mitutoyo digital vernier calliper with a minimum measurement resolution of 0.01 mm. Figure 1 displays the major (L), medium (W), and minor (T) axis measurements.

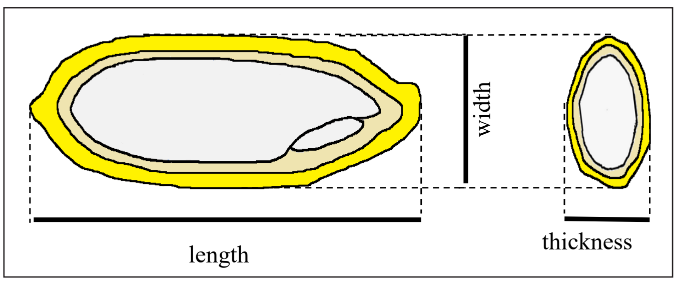

Figure 1. Dimensional characteristic of MR297 paddy (Muchlisyiyah et al., 2024b)

Colour Measurement

Using a colourimeter, 50 g of each milled rice grain variety was selected at random and deposited in a petri dish. The colour properties (CIE L*, a*, and b* scale) of the parboiled rice were identified by placing the colourimeter next to the petri dish containing the samples. The samples were captured using a 40 mm lens (FRU WR10, China) against a white blank paper background. The L*, a*, and b* values can be used to calculate ΔE, browning index (BI), chroma (C*), and hue angle (H) using Equations 1 to 4 (Devi & Das, 2017):

$$\Delta E = [(L_0^* - L^*)^2 + (a_0^* - a^*)^2 + (b_0^* - b^*)^2]^{1/2} \quad [1]$$

$$H = tan^{-1}\frac{b^*}{a^*} \quad [2]$$

$$C^* = [(a^*)^2 + (b^*)^2]^{1/2} \quad [3]$$

$$BI = 100\ (x - 0.31)/0.17 \quad [4]$$

Where $x = \frac{a^* + 1.75\ (L^*)}{5.645\ (L^*) + a^* - 3.012\ (b^*)}$

Where L_o, a_o, and b_o are the initial L, a, and b values of the sample, L*, a*, and b* denote the values of L,* a*, and b* under the observed conditions.

Hardness Measurement

Hardness was defined as the maximal force encountered during initial compression. The determination of rice grain hardness was performed using a texture analyser (TA-XT2, Stable Micro Systems, Godalming, UK) by subjecting the grains to pressure. In this study, a stainless-steel probe with a diameter of 5 mm (referred to as P5) was employed to compress individual rice kernels in the direction of their T (minor axis). The compression was conducted at a testing velocity of 2 mm/s, followed by a post-speed of 10 mm/s (Kumar & Prasad, 2018).

Kinetic for Colour, Dimensional, and Hardness Changes

Several published models have described the reaction kinetics-based changes in the dimensions, colour, and hardness of food ingredients as a result of soaking time (Amini et al., 2022; Devi & Das, 2017; Sahoo et al., 2022). Typically, the rate of change can be expressed as Equation 5:

$$\frac{dC}{dt} = -\,kC^n \quad [5]$$

The equation represents the relationship between the reaction rate constant (k), the concentration of the target parameter (C) at a specific time (t), and the order of the reaction (n). The rate of process change can be assessed using zero-order, first-order, and second-order kinetic models, as outlined in Equations 6 to 8 (Azman et al., 2020).

$$Zero\ order = C = C_0 - kt \quad [6]$$

$$Fist\ order = Ln\ C = -kt + LnC_0 \quad [7]$$

$$second\ order = \frac{1}{C} = kt + \frac{1}{C_0} \quad [8]$$

Where C is the experimental value for each parameter for parboiled rice. C_o is the initial value (in quantitative form).

The temperature dependence of the reaction rate can be described using the Arrhenius equation, which provides insights into the activation energy (*Ea*) involved in the process. Equation 9 represents the Arrhenius equation.

$$K = A\,e^{\frac{Ea}{RT}} \quad [9]$$

Where A represents the reaction constant at infinite temperature, *Ea* represents the activation energy, R represents the gas constant at 8.3145 J/mol K, and T represents the absolute temperature in Kelvin. The Arrhenius equation is subsequently transformed into Equation 10, where the y-axis represents the Ln k, the x-axis represents the reciprocal of the blanching temperature in Kelvin (1/T), and the slope is determined as the negative ratio of the activation energy to the gas constant (-*Ea*/R).

$$Ln\,K = \frac{Ea}{R}\,\frac{1}{T} + Ln\,A \qquad [10]$$

Statistical Analysis

The experiment was conducted three times for every test. The statistical analyses were conducted using Minitab 12.0 (PA, USA). The chosen level of significance for assessing differences in analysis of variance (ANOVA) was established at a threshold of $p < 0.05$.

RESULTS AND DISCUSSION

Kinetics of Colour Changes

The changes in the appearance of MR297 rice cultivar samples, soaked at controlled temperatures and after 1, 2, 3, 4, and 5 hours of soaking at 50 °C, 60 °C, and 70 °C soaking temperatures, are presented in Figure 2. After soaking, there is an increasing effect on grain colour as soaking time extends, highlighting the significant impact of soaking duration on

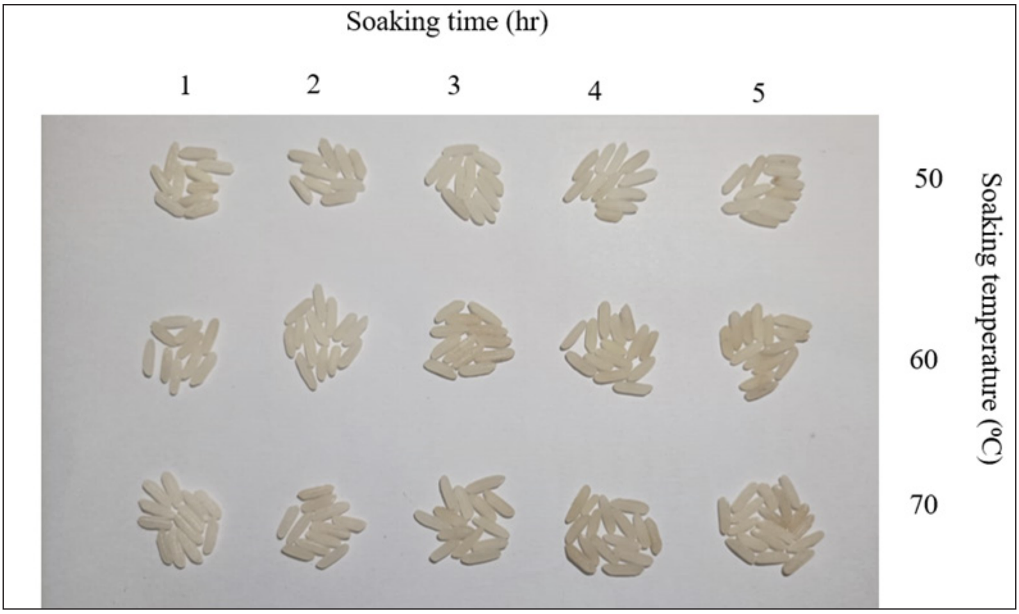

Figure 2. MR297 parboiled rice with different soaking conditions

the physical properties of parboiled rice. The colour properties were obtained using CIE scale variables, specifically a* (representing the presence of redness or greenness), b* (representing the presence of yellowness or blueness), and L* (representing the presence of whiteness or brightness). Afterwards, the L, a*, and b* parameters were used to calculate other colour properties, specifically total ΔE, C*, H, and BI.

Figure 3 depicts the influence of the time and temperature of soaking on many parameters of parboiled rice MR 297, including ΔE*, C*, H, BI, L, W, T, and hardness. The

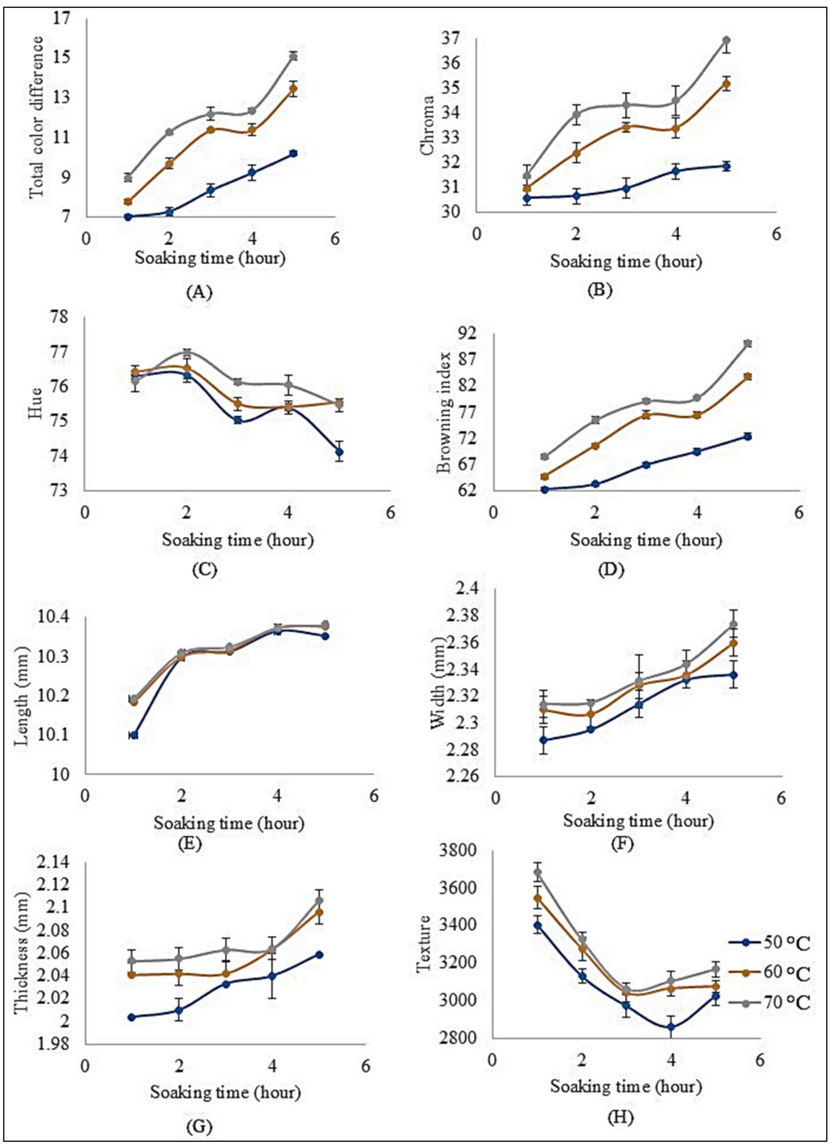

Figure 3. Effect of soaking time and temperature on the (a) total colour change, (b) chroma, (c) hue, (d) browning index, (e) length, (f) width, (g) thickness, and (h) hardness of parboiled rice MR297

immersion method employed in parboiling has the potential to modify the visual appearance of processed rice by affecting its colouration. The application of increased intensity in the parboiling process, characterised by longer soaking duration and higher temperature, resulted in a discernible alteration in the colour of the parboiled rice, manifesting as a yellow-brownish hue. Consequently, this intensified parboiling process led to an overall augmentation in the ΔE, C*, and BI while simultaneously causing a reduction in the H. On the other hand, the longer the time and temperature of soaking, the larger the dimension of the parboiled paddy was observed, thus increasing the L, W, and T. Meanwhile, there was a decrease in the hardness of parboiled rice until 3 hours of soaking, then the hardness increased as the soaking duration increased. Generally, increasing the soaking temperature also increases the hardness. The change in the quality parameters was then plotted in the kinetic models. This study investigates the reaction rate (k) and coefficient of determination (R^2) associated with the zero-order, first-order, and second-order kinetic models in relation to colour parameter changes. Colour changes (ΔE*, C*, H, and BI) as the impact of soaking temperatures (50 °C, 60 °C, and 70 °C) on parboiled rice MR297 are shown in Table 1.

Total Colour Change (ΔE*) is crucial for assessing rice quality, optimising the parboiling process, and predicting outcomes, significantly influencing consumer acceptance and production efficiency. The ΔE notion in parboiled rice, as described by Lamberts, Bie, et al. (2006), denotes the noticeable colour transition from raw rice to the golden or amber tones evident post-parboiling. The transformation is affected by processing parameters like soaking and steaming durations and moisture content (Bootkote et al., 2016; Lv et al., 2009). The transformation is affected by processing parameters like soaking and steaming durations and moisture content. The process of parboiling results in noticeable darkening and yellowing of milled rice, with the extent of colour change contingent upon the intensity of the parboiling application (Lamberts, Brijs, et al., 2006).

ΔE* exhibits a significant decrease during soaking, as evidenced by the high initial values (C = 6.970) and k across all temperature conditions. The magnitude of k increases with increasing temperature, ranging from -0.683 at 50 °C to -1.477 at 70 °C, indicating a faster rate of colour change at higher temperatures. The first and second-order models provide slightly better fits, as indicated by higher R^2 values, but the zero-order model adequately describes the data in most cases. The temperature-dependent colour shift aligns with observations in other food items, like pumpkins and popped rice, where elevated temperatures result in more significant colour changes (Chikpah et al., 2022; Devi & Das, 2017). The research conducted by Oli et al. (2016) corroborates this, indicating that ΔE values increase when soaking temperatures surpass 90 °C, highlighting the essential influence of temperature in the parboiling procedure.

Chroma (C*) is an essential aspect of colour perception, denotes the intensity or saturation of colour and is one of three primary properties with hue (H) and lightness (L*). In the specific domain of parboiled rice, the term "chroma change" applies to the

Table 1
The reaction rate (k) and coefficient of determination of the zero, first, and second-order kinetic models of changes of dimensions of the parboiled paddy and colour parameter (ΔE, chroma, hue, and browning index) and hardness of parboiled rice MR297 Long grain rice due to the soaking step in parboiling

Colour change parameter	**Temperature (°C)**	**Zero-order**				**First Order**				**Second Order**			
		C_0	**k**	**R^2**	**SEE**	**C_0**	**k**	**R^2**	**SEE**	**C_0**	**k**	**R^2**	**SEE**
ΔE* (total colour change)	50	6.970	-0.683	0.919	0.425	1.942	-0.082	0.930	0.047	0.144	-0.010	0.939	0.005
	60	6.970	-1.283	0.964	0.516	1.942	-0.131	0.957	0.058	0.144	-0.014	0.936	0.008
	70	6.970	-1.477	0.948	0.725	1.942	-0.140	0.922	0.086	0.144	-0.014	0.871	0.012
Chroma	50	30.455	-0.302	0.906	0.204	3.416	-0.010	0.908	0.007	0.033	-0.000	0.910	0.000
	60	30.455	-0.915	0.954	0.421	3.416	-0.028	0.956	0.013	0.033	-0.001	0.956	0.000
	70	30.455	-1.196	0.928	0.699	3.416	-0.036	0.927	0.021	0.033	-0.001	0.925	0.001
Hue	50	77.214	0.556	0.893	0.402	4.347	0.007	0.893	0.005	0.013	9.72E-05	0.892	7.08E-05
	60	77.214	0.353	0.822	0.343	4.347	0.005	0.822	0.005	0.013	6.07E-05	0.822	5.90E-05
	70	77.214	0.284	0.669	0.417	4.347	0.004	0.670	0.006	0.013	4.87E-05	0.671	7.14E-05
Browning Index	50	61.699	-2.257	0.945	1.136	4.122	-0.034	0.950	0.016	0.016	-5.12E-04	0.954	2.34E-04
	60	61.699	-4.318	0.967	1.666	4.122	-0.060	0.967	0.023	0.016	-8.43E-04	0.963	3.46E-04
	70	61.699	-5.118	0.951	2.422	4.122	-0.068	0.948	0.034	0.016	-9.23E-04	0.935	5.06E-04
L (length)	50	10.096	-0.060	0.822	0.058	2.312	-0.006	0.821	0.006	0.099	-0.001	0.820	0.001
	60	10.096	-0.057	0.903	0.039	2.312	-0.006	0.901	0.004	0.099	-0.001	0.899	0.004
	70	10.096	-0.057	0.886	0.043	2.312	-0.006	0.884	0.004	0.099	-0.001	0.882	0.000
W (Width)	50	2.284	-0.012	0.949	0.006	0.826	-0.005	0.950	0.003	0.438	-0.002	0.950	0.001
	60	2.284	-0.014	0.942	0.007	0.826	-0.006	0.942	0.001	0.438	-0.003	0.942	0.001
	70	2.284	-0.016	0.944	0.008	0.826	-0.007	0.944	0.004	0.438	-0.003	0.945	0.002
T (Thickness)	50	2.000	-0.012	0.946	0.006	0.693	-0.006	0.947	0.003	0.500	-0.003	0.948	0.002
	60	2.000	-0.016	0.861	0.013	0.693	-0.008	0.862	0.006	0.500	-0.004	0.861	0.003
	70	2.000	-0.016	0.810	0.017	0.693	-0.008	0.808	0.008	0.500	-0.004	0.806	0.004
	50	3581.630	131.329	0.785	143.618	8.184	0.041	0.782	0.045	2.792E-04	1.27E-05	0.777	1.42E-05
Hardness	60	3581.630	120.762	0.829	114.787	8.184	0.037	0.829	0.035	2.792E-04	1.11E-05	0.828	1.06E-05
	70	3581.630	116.446	0.704	157.803	8.184	0.035	0.704	0.047	2.792E-04	1.03E-05	0.702	1.40E-05

alteration in the intensity or saturation of colour exhibited by the rice because of the parboiling procedure (Bhattacharya, 1996). In parboiled rice, chromatic alterations signify the movement of pigment from the outer to inner layers during the parboiling process, influencing the colour intensity and saturation (Lamberts, Brijs et al., 2006; Lamberts, Bie et al., 2006). The chroma values (C*) follow a similar trend to ΔE*, with high initial values (C_0 = 30.455) that decrease during soaking. The temperature dependence of k is more pronounced for chroma, with k at 70 °C being nearly four times higher than at 50 °C. The first- and second-order models yield lower C_0 and k values but comparable R^2 values to the zero-order model. This pattern parallels observations in other culinary processes, such as popped rice and pumpkins, where the application of heightened heat leads to more pronounced colour changes (Chikpah et al., 2022; Devi & Das, 2017).

The hue angle (H) indicates visual colour perception and is an essential measure for evaluating the quality of parboiled rice (Bett-Garber et al., 2012). In contrast to the other colour parameters, hue exhibits a slight increase during soaking, as indicated by the positive k values. However, the magnitude of change in hue is relatively small compared to the other parameters, and the k decreases with increasing temperature. The reaction order has a minimal impact on the kinetic description of hue, with all three models providing similar C_0, k, and R^2 values. These findings correspond with the extensive food science literature, where analogous thermal processes influence colour characteristics, highlighting the significance of temperature and processing conditions in colour dynamics (Dixon et al., 2020).

The browning index (BI) quantitatively assesses the degree of browning or colour change in rice after parboiling, principally resulting from browning processes and pigment degradation (Lamberts, Brijs et al., 2006). The parboiling process involves Maillard reactions, as seen by furosine levels, which are prominent in the outer bran layers and the endosperm, signifying the progression of browning (Taghinezhad et al., 2015). The BI successfully reflects these changes, utilising kinetic models for comprehensive quantitative analysis. The browning index undergoes a substantial decrease during soaking, with high initial values (C_0 = 61.699) and large negative k values. The effect of temperature on the browning index is significant, with the k at 70 °C being more than double that at 50 °C. The first and second-order models offer marginal improvements in R^2 compared to the zero-order model. The temperature dependency is essential for comprehending the BI dynamics since elevated temperatures expedite pigment degradation and Maillard reactions, resulting in more significant colour alterations. This conclusion aligns with research on other food products, indicating that elevated temperatures augment browning indices (Devi & Das, 2017). Moreover, initial hydration can alleviate certain browning effects during milling; however, extended hydration causes pigments to penetrate further into the endosperm, rendering them more difficult to eliminate (Oli et al., 2016).

The length of rice grains is a key quality attribute affecting consumer preference and market value. The initial length of the paddy (C_0) is 10.096 mm, which decreases slightly during soaking as indicated by the negative reaction k. The magnitude of k is consistent across all temperature conditions, ranging from -0.057 to -0.060, suggesting that the change in length is not significantly influenced by temperature. The first- and second-order models provide similar fits to the data as the zero-order model, with comparable R^2 values.

The width of rice grains affects the texture and mouthfeel of the cooked rice. The width of the paddy follows a similar trend to length, with an initial value (C_0) of 2.284 mm that decreases during soaking. The k are negative and increase in magnitude with increasing temperature, indicating a faster rate of change at higher temperatures. The first and second-order models yield similar k and R^2 values to the zero-order model, suggesting that the reaction order has minimal impact on the kinetic description of width change.

The thickness of rice grains is critical for ensuring uniform cooking and texture. The initial thickness of the paddy (C_0) is 2.000 mm, which decreases during soaking as evidenced by the negative k values. The k values are consistent across the temperature range of 50 °C to 70 °C, indicating that temperature has a limited influence on the rate of thickness change. The R^2 values for the zero, first, and second-order models are comparable, with a slight decrease at higher temperatures. The textural characteristics of parboiled rice MR297, namely hardness, were meticulously measured utilising zero, first, and second-order kinetic models to analyse the influence of soaking temperature on textural alterations in rice (Table 1). The hardness of the rice exhibits a significant decrease during soaking, with high initial values (C_0 = 3581.630) and large positive k. The magnitude of k decreases with increasing temperature, suggesting that higher temperatures lead to a faster rate of softening. The R^2 values for the zero, first, and second-order models are similar, indicating that the reaction order has minimal impact on the kinetic description of hardness change. The decreasing effectiveness of hardness reduction at elevated temperatures may result from the denaturation of proteins or other thermally stable constituents inside the rice grains.

The identified trends among the models and temperatures highlight the intricate relationship between temperature, soaking duration, and the textural characteristics of rice. The decline in k across all models with rising temperature indicates a gradual stabilisation or restriction in textural alteration, emphasising the thermal sensitivity of rice hardness during the parboiling process. The outcomes of this study enhance the comprehension of optimal processing parameters necessary for attaining specific textural qualities in parboiled rice, with ramifications for industrial practices and product quality assurance.

Energy (Ea) Analysis

Table 2 presents the activation energy (Ea) and R^2 values for zero-, first-, and second-order kinetic models, assessing the influence of soaking on the physical and textural attributes of parboiled rice MR297 (Mohapatra & Bal, 2015). These models help understand the energy required for changes in attributes like colour (ΔE*, Chroma, Hue), texture (Hardness), and dimensions (Length, Width, Thickness), which are crucial for optimising the soaking process to maintain rice quality essential for consumer satisfaction and market competitiveness.

Table 2
The activation energy (Ea) and coefficient of determination (R^2) of the kinetic models (zero, first, and third order) according to the changes of parameters of MR297 parboiled paddy and milled rice due to soaking

Parameters	**Zero Order**		**First Order**		**Second Order**	
	***Ea* (kJ/mol)**	**R^2**	***Ea* (kJ/mol)**	**R^2**	***Ea* (kJ/mol)**	**R^2**
ΔE*	35.781	0.892	24.784	0.852	15.376	0.768
C*	63.762	0.900	60.413	0.894	57.200	0.889
Hue	-31.138	0.966	-31.555	0.966	-31.922	0.965
Browning Index	37.942	0.908	32.507	0.893	27.321	0.874
Length	-2.669	0.787	-2.764	0.789	-2.886	0.791
Width	13.676	1.000	13.297	1.000	12.925	1.000
Thickness	13.311	0.857	12.718	0.856	12.158	0.854
Hardness	-5.565	0.958	-7.562	0.970	-9.613	0.976

For ΔE*, Ea decreases from 35.781 kJ/mol in the zero-order model to 15.376 kJ/mol in the second-order model, indicating that less energy is needed for colour changes as model complexity increases (R^2 of 0.892). Chroma, sensitive to soaking conditions, shows Ea ranging from 63.762 to 57.200 kJ/mol, necessitating precise control to preserve colour quality. Hue demonstrates negative Ea across all models, suggesting that colour changes during soaking may lead to energy release, potentially due to pigment breakdown, with first-order kinetics providing a reliable prediction of these changes. The browning index varies from 37.942 to 27.321 kJ/mol, with first-order kinetics offering a more precise description of browning reactions.

Dimensional changes show varied responses; length displays a slight negative Ea, indicating low resistance to alterations during soaking, while width shows a notable Ea of 13.676 kJ/mol, reflecting its high sensitivity to soaking conditions with exceptional R^2 values of 1.000. Thickness Ea, ranging from 13.311 to 12.158 kJ/mol, suggests that these models intensively represent the fluctuations in thickness during soaking. The textural properties indicate that the hardness of rice grains decreases upon soaking, with the second-order model showing the lowest Ea value at -10.192 kJ/mol, illustrating the grains' natural propensity to soften —a key factor for achieving optimal culinary quality. This analysis underscores the need for meticulous regulation of soaking parameters to maintain optimal colour characteristics in parboiled rice, as significant energy is required for colour alterations.

CONCLUSION

The current study examined the impact of soaking temperature and time on the kinetics of colour, size, and hardness alteration. The quality change of parboiled rice MR297 was comprehensively characterised by the kinetic models (zero, first, and second-order). ΔE*, C*, BI, L, W, and T increased, whereas H and hardness decreased throughout the soaking process. The best fit for the colour parameter was the browning index following the first-order reaction kinetic model ($R^2 = 0.967$). For the dimensions, the best-plotted parameter for the kinetic model was the W in the second-order reaction kinetic model ($R^2 = 0.950$). The rate of change of colour (ΔE*, C*, H, and BI), dimensional (L and T), and hardness are significantly affected by the soaking temperature and follow the Arrhenius equation. Hence, the colour, dimensional, and hardness change kinetics parameters can be valuable in forecasting alterations in the soaking quality of parboiled rice MR297 during the hot water soaking process.

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