processes

MDPI

Article

Pulsed Electric Field for Quick-Cooking Rice: Impacts on Cooking Quality, Physicochemical Properties, and In Vitro Digestion Kinetics

Saban Thongkong [1], Supaluck Kraithong [2], Jaspreet Singh [3], Pipat Tangjaidee [1,4], Artit Yawootti [5], Wannaporn Klangpetch [1], Pornchai Rachtanapun [1,4], Saroat Rawdkuen [6] and Suphat Phongthai [1,4,7,*]

[1] Division of Food Science and Technology, Faculty of Agro-Industry, Chiang Mai University, Chiang Mai 50100, Thailand; sabanpth@gmail.com (S.T.); pipat.t@cmu.ac.th (P.T.); wannaporn.u@cmu.ac.th (W.K.); pornchai.r@cmu.ac.th (P.R.)
[2] Guangdong Provincial Key Laboratory of Food Quality and Safety, College of Food Science, South China Agricultural University, Guangzhou 510642, China; supak0504@gmail.com
[3] School of Food and Advanced Technology, Massey University, Palmerston North 4410, New Zealand; j.x.singh@massey.ac.nz
[4] Center of Excellence in Agro Bio-Circular-Green Industry (Agro BCG), Faculty of Agro-Industry, Chiang Mai University, Chiang Mai 50100, Thailand
[5] Department of Electrical Engineering, Faculty of Engineering, Rajamangala University of Technology Lanna, Chiang Mai 50300, Thailand; yartit@rmutl.ac.th
[6] Unit of Innovative Food Packaging and Biomaterials, School of Agro-Industry, Mae Fah Luang University, Chiang Rai 57100, Thailand; saroat@mfu.ac.th
[7] Lanna Rice Research Center, Chiang Mai University, Chiang Mai 50100, Thailand
* Correspondence: suphat.phongthai@cmu.ac.th

Abstract: Pulsed electric field (PEF) is one of the emerging technologies that has been applied in many aspects of the food industry. This study examined the impacts of a PEF on the cooking quality, physicochemical properties, nutritional factors, and in vitro protein and starch digestion of two varieties of rice, including Jasmine 105 (white non-glutinous rice) and San Pa Tong 1 (white glutinous rice). Response surface methodology (RSM) and a three-level, three-factor Box–Behnken design were employed to assess the effects of the pulse number, electric field strength, and frequency on cooking time. The findings demonstrated that the number of pulses was a crucial factor influencing cooking time. Under optimal conditions (3347–4345 pulses, electric field strengths of 6–8 kV/cm, and frequencies ranging from 6 to 15 Hz), the rice cooking time was significantly reduced by 40–50% ($p < 0.05$) when compared to a conventional method. Moreover, PEF-treated rice showed a significant enhancement in in vitro protein and starch digestibility ($p < 0.05$), as well as retained a higher content of rapidly digestible starch. These results suggested that PEF treatment is a promising green technology for producing a novel quick-cooking rice with an improved eating quality.

Keywords: rice; pulsed electric field (PEF); cooking quality; starch; in vitro digestion

check for updates

Citation: Thongkong, S.; Kraithong, S.; Singh, J.; Tangjaidee, P.; Yawootti, A.; Klangpetch, W.; Rachtanapun, P.; Rawdkuen, S.; Phongthai, S. Pulsed Electric Field for Quick-Cooking Rice: Impacts on Cooking Quality, Physicochemical Properties, and In Vitro Digestion Kinetics. *Processes* **2024**, *12*, 2577. https://doi.org/10.3390/pr12112577

Academic Editor: Mustafa Mortas

Received: 1 September 2024
Revised: 23 October 2024
Accepted: 15 November 2024
Published: 17 November 2024

1. Introduction

Rice is a crucial staple meal for over half of the global population, particularly Asians and Africans. The primary constituent of rice, carbohydrates, supplies the majority of the major energy that humans need for daily life [1,2]. Thailand was the second-largest rice exporter, with about 8.2 million metric tons of rice worldwide in 2023–2024 [3]. Two of the most popular Thai rice varieties are Jasmine 105, a non-glutinous rice with a pandan-like aroma that contains 20–30% amylose, making it has a soft texture once cooked [4–6]; and, San Pa Tong 1, a glutinous rice that offers a superior energy source compared to regular white rice [7]. It contains a lower amylose content (0–2% on a dry basis) and a high amount of amylopectin, which is responsible for the sticky texture of cooked rice [8,9]. Traditionally, polished rice, depending on the variety and grain size (long, medium, or short), requires even 20–35 min to cook to satisfactory acceptability. As a result, this may not be suitable for consumers who live an urban lifestyle and have less time to prepare food at home.

Researchers have extensively researched and produced quick-cooking rice, which cooks significantly faster than conventional rice, using a variety of processes, including the freeze–thawing process [10], high hydrostatic pressure process [4], and infrared radiation heating [11]. Those mentioned processing methods differently affect grain structures, resulting in varying cooking times for rice. Traditionally, thermal treatment creates substantial cracks in the grains, which facilitates the rapid absorption of water that can reduce the cooking time; however, it can also cause a loss of nutrients. Consequently, manufacturers and researchers have devoted significant attention to non-thermal processes in order to produce faster-cooking rice that maintains the same nutritive value and grain integrity. Freeze–thawing is a non-thermal procedure that has been generally utilized for creating numerous pores on the surface of the rice grains [10]. Nevertheless, this procedure is impractical due to the extended processing time, which can result in an increase in production costs.

Pulsed electric field (PEF), an emerging non-thermal process, involves delivering a short pulse with a high electric field strength to materials placed between two electrodes at room temperature. The intensity of the electric field generated between the electrodes influences the transmembrane potential differential, resulting in "electroporation" that can cause pore formation on the cell membrane. PEF has the potential to be a nonthermal food preservation technology that preserves the integrity of food and inactivates microorganisms. Mass transfer enhancement, enzyme deactivation, meat processing, and extraction are among the numerous applications of a PEF in the preparation of foods [12,13]. Several studies have demonstrated the significant benefits of this phenomenon in enhancing the extraction efficiency of bioactive compounds from plant materials, such as rice bran [14], onion [15], and blueberry pomace [16]. This is achieved by breaking down the cell walls, which subsequently increases the diffusion rate of solvents used in the internal structure of these materials. In this regard, a PEF might also be helpful to create pores on the rice grains and accelerate water absorption during cooking, which might reduce the cooking time of rice [17].

Aside from the cooking time, digestibility should be regarded as a second key aspect for developing a successful quick-cooking rice product. Previous studies utilizing various rice varieties suggest that the amylose concentration and structure of rice starch, due to its physicochemical properties, contribute to its starch digestibility [18–20]. Moreover, the processing procedures employed for rice can affect the rate of starch breakdown. This is because differing processing methods result in double helices or starch–lipid complexes, which make starch less digestible [20]. To the best of our knowledge, there has been little investigation into the possible applications of PEF technology in producing quick-cooking polished rice, as well as the impacts of these treatments on in vitro protein and starch digestibility. This study aims to create PEF-based processes as a unique approach for generating quick-cooking rice from two rice varieties, San Pa Tong 1 (glutinous rice) and Jasmine 105 (non-glutinous rice). The processing parameters, such as the number of pulses, electric field intensity, and frequency, were optimized to achieve the quickest cooking time. Furthermore, the physicochemical properties, microstructure, and in vitro protein and starch digestion of quick-cooking rice were investigated.

2. Materials and Methods

2.1. Materials

The rice used in the experiment was supplied by the Lanna Rice Research Center, Chiang Mai University, Thailand. The composition and amylose content of rice used in this study were determined by the Association of Official Analytical Chemists' method [21] and the method of Jiamyangyuen et al. [22], respectively. Jasmine 105, a white non-glutinous rice, contained 12.10 ± 0.02% moisture, 78.82 ± 0.08% carbohydrates, 6.82 ± 0.04% protein, 0.74 ± 0.07% fat, 0.08 ± 0.01% crude fiber, 1.55 ± 0.00% ash, and 20.07 ± 0.05% amylose.

San Pa Tong 1, a white glutinous rice, is comprised of 11.87 ± 0.00% moisture, 80.03 ± 0.06% carbohydrates, 5.88 ± 0.05% protein, 0.66 ± 0.01% fat, 0.07± 0.01% crude fiber, 1.60 ± 0.02% ash, and 6.25 ± 0.02% amylose. Both varieties were 120-day-crop rice. The enzymes used in the experiment, including trypsin (EC.3.4.21.4, 10,000 BAEE units/mg protein) from bovine pancreas, pepsin (EC.3.4.23.1, 250 units per milligram solid) from porcine gastric mucosa, and α-amylase from porcine pancreas (500KU, A3176), were purchased from Merck KGaA, Darmstadt, Germany.

2.2. Methods

2.2.1. Pre-Gelatinization of Rice

Rice was pre-gelatinized using a method similar to the one described by Boluda-Aguilar et al. [4]. The non-glutinous rice was soaked in water for 3 h in a 1:1 ratio; instead, the glutinous rice was soaked in water for 6 h in a 1:3. The rice was then drained for 2–3 min. The pre-gelatinized rice was cooked in an electric steamer for 60 and 45 min, respectively.

2.2.2. Optimization of Quick-Cooking Rice Production Using a PEF

The experimental design was generated with Stat-Ease software (Design-Expert version 6.0.2, Minneapolis, MN, USA). Response surface methodology (RSM) and a three-level, three-factor Box–Behnken design were used to evaluate the effects of the number of pulses (X_1, 2000–6000 pulses), electrical field strength (X_2, 6–10 kV/cm), and frequency (X_3, 3–15 Hz) on the cooking time. The experimental design included 17 treatments with five replications of the central point, as shown in Tables 1 and 2 for Jasmine 105 and San Pa Tong 1, respectively.

Table 1. Cooking times of 17 different PEF treatment combinations of Jasmine 105 rice.

No.	Experimental Design			Cooking Time (min)
	Number of Pulses (Pulse)	**Field Strength (kV/cm)**	**Frequency (Hz)**	
1	2000	6	5	6
2	4000	6	5	4
3	2000	10	5	5
4	4000	10	5	5
5	2000	8	3	6
6	4000	8	3	3
7	2000	8	7	6
8	4000	8	7	4
9	3000	6	3	5
10	3000	10	3	4
11	3000	6	7	4
12	3000	10	7	5
13	3000	8	5	4
14	3000	8	5	4
15	3000	8	5	3
16	3000	8	5	4
17	3000	8	5	3

The PEF treatments were conducted on an exponentially declining pulse in a batch system. A total of 200 ± 10 g of pre-gelatinized rice was mixed with water in a 1:1 ratio (*w*/*v*), and then placed in a cylindrical chamber with a diameter of 6 cm and a height of 24 cm. The container contained a probe electrode with a width of 3 cm. The samples were treated using the conditions shown in Tables 1 and 2. The treated samples were subsequently dried by following the method in Section 2.2.4. Afterward, the cooking time, as mentioned in Section 2.2.5 was evaluated and used as a response value.

Table 2. Cooking times of 17 different PEF treatment combinations of San Pa Tong 1 rice.

No.	Experimental Design			Cooking Time (min)
	Number of Pulses (Pulse)	Field Strength (kV/cm)	Frequency (Hz)	
1	4000	6	10	5
2	6000	6	10	5
3	4000	10	10	4
4	6000	10	10	4
5	4000	8	5	5
6	6000	8	5	6
7	4000	8	15	5
8	6000	8	15	3
9	5000	6	5	6
10	5000	10	5	3
11	5000	6	15	3
12	5000	10	15	4
13	5000	8	10	3
14	5000	8	10	4
15	5000	8	10	4
16	5000	8	10	4
17	5000	8	10	3

The experimental data were fitted to a second-order polynomial model, and regression coefficients were obtained. The generalized second-order polynomial model used in the response surface analysis was as follows:

$$Y = \beta_0 + \sum_{i=1}^{3} \beta_i X_j + \sum_{i=1}^{3} \beta_{ii} X_i^2 + \sum_{i-1}^{2} \sum_{j=2}^{3} \beta_{ij} X_i X_j \quad (1)$$

where β_0 is defined as a constant, β_i is the linear coefficient, β_{ii} is the quadratic coefficient, and β_{ij} is the interaction coefficient. X_i and X_j are the levels of independent variables.

A table displaying the results of an analysis of variance (ANOVA) was created. An analysis was conducted on the factor and regression coefficients of individual linear, quadratic, and interaction terms. The significance of each term in the equation for the model was determined by calculating the F-value at a probability (p-value) of 0.05. The regression coefficients were utilized to perform statistical mathematics, which created three-dimensional response surface contour plots based on the regression models.

Optimization of the conditions to produce quick-cooking rice under the variables examined was achieved through the application of RSM. The experiment was designed to achieve the optimum value of the shortest cooking time. Furthermore, the response was also examined after the optimized conditions were verified through follow-up experiments. The model's validity was verified by comparing the experimental and predicted values. Additionally, the cooking time of the sample from the optimal PEF conditions was compared to that of the conventional freeze–thawing method.

2.2.3. Quick-Cooking Rice Production Using Freeze–Thawing

The freeze–thawing procedure, which is based on the method described by Dollete et al. [10], was employed with certain modifications. Pre-gelatinized Jasmine 105 (200 ± 10 g) and pre-gelatinized San Pa Tong 1 (200 ± 10 g) were furfure subjected to freezing at −18 ± 1 °C for 16 h in a freezer, followed by thawing at 4 ± 1 °C for 8 h in a chiller. The treated samples were subsequently dried by following the method in Section 2.2.4. Afterwards, the cooking time was evaluated as mentioned in Section 2.2.5.

2.2.4. Dehydration of Pre-Treated Rice

All samples that were pre-gelatinized (control), frozen–thawed, and treated with PEF were dried in a hot air oven at 65 °C for 12–14 h until the moisture content was less than

12% [23]. The dried samples were then placed in a ziplock plastic bag and frozen until further use.

2.2.5. Determination of the Cooking Quality

Cooking Time

The cooking time was established utilizing the methodology proposed by Dollete et al. [4] and Jiao et al. [24], with some minor adjustments. A total of 10 g of each dried sample was mixed with 150 mL of water in a 250 mL beaker. The mixture was then covered with a watch glass and subjected to microwave radiation at a power of 900 W. Subsequently, a single rice grain was placed between two glass plates every minute, and the cooking process was monitored until a minimum of 90% of the grains exhibited neither an opaque core nor a well-cooked center.

Water Uptake Ratio

The water absorption ratio was determined using the method outlined by Chin et al. [25]. Ten grams of dried rice was added to 150 mL of distilled water and subjected to microwave cooking at a power of 900 W for the minimum duration, as established in Section of cooking time determination. Once the rice was cooked, it was drained, and any excess water on the surface was eliminated by pressing it between pieces of filter paper. Afterward, the rice obtained was measured in terms of weight, and the water uptake ratio was determined using the following equation:

$$\text{water uptake ratio (g/g)} = (\text{weight of cooked grain} - \text{weight of uncooked grain})/\text{weight of uncooked grain}. \quad (2)$$

Cooking Loss

The cooking loss was determined using the methods described by Chin et al. [25] and Jaroenkit et al. [26]. Ten grams of rice was mixed with 150 mL of distilled water and microwaved at 900 W for the minimum cooking time (as specified in Section 2.2.5). After cooking, the water was drained, and the samples were pressed between filter paper to remove any excess surface water on the surface of cooked rice. The cooked rice was dried in a hot air oven at 65 °C for 12–14 h until the moisture content reached 8–12%. Finally, dried samples were weighed, and the percentage of cooking loss was calculated using the following equation:

$$\text{cooking loss (\%)} = [(\text{weight of uncooked rice} - \text{weight of dried cooked rice})/\text{weight of uncooked rice}] \times 100. \quad (3)$$

2.2.6. Rice Grain Morphological Analysis

Scanning electron micrographs of the uncooked rice samples were taken using a scanning electron microscope (JSM-5910LV, JEOL Ltd., Tokyo, Japan) with magnifications of 500× and 1000×.

2.2.7. Analysis of the Vitamin B1 and B3 Contents

The modified method of Van et al. [27] was employed to determine the vitamin B1 and B3 contents. In a centrifuge tube, 1 g of ground rice samples was mixed with 1 g of trichloroacetic acid (TCA). The mixture was incubated at −20 °C for 5 min after the addition of 5 mL of distilled water. Subsequently, it was centrifuged at 3000× g for 30 min at 4 °C. The supernatant was collected and diluted with distilled water to a volume of 5 mL. The Poroshell 120 EC-C18 column (4.6 × 150 mm, 4 µm internal diameter) was injected with 20 µL of each sample at a rate of 0.8 mL/min. HPLC-LC/MS (Agilent 1260 Infinity II Series, LC/MSD XT, Agilent Ltd., CA, USA) was used for the analysis. Solution A (90% of the mobile phase) consisted of 2.4% acetic acid, 15% methanol, and 0.1 M potassium dihydrogen phosphate, while solution B (10%) was composed of acetonitrile. The average peak areas at 240 nm were employed to estimate the vitamin contents from the standard curve.

2.2.8. Evaluation of In Vitro Digestibility

Digestible and Resistant Starch Contents

They were measured according to the method of the digestible starch and resistant starch assay kit (K-DSTRS, Megazyme, Wicklow, Ireland).

In Vitro Starch Digestion Kinetics

The kinetics of in vitro starch digestion were investigated using the method of Kraithong et al. [28], with a few modifications. The sample powder (0.1 g) was boiled in 15 mL of a phosphate-buffered saline solution (0.2 M, 10 mL, pH 6.0) for 30 min. Subsequently, the solution was incubated with 1 mL of the enzyme solution (α-amylase 20 units/mL in phosphate-buffered saline, pH 6) at 37 °C without agitation. The containers were meticulously turned upside down before aliquots (100 µL) were removed at varying intervals (0, 5, 20, 40, 60, 90, and 120 min). Subsequently, 300 µL of a 0.5 M sodium carbonate solution was immediately added to terminate the reaction. Subsequently, the solutions were centrifuged at 2200× *g* for 5 min, and the supernatant (100 µL) was employed to estimate the concentration of D-glucose equivalents using the para-hydroxybenzoic acid hydrazide assay (pHBH assay) [29]. Ten microliters of the sample were combined with 1 mL of a freshly prepared mixing solution, which included 0.5 M sodium hydroxide and 5% (*w*/*v*) para-hydroxybenzoic acid hydrazide in 0.5 M hydrochloric acid. The mixture was heated to 100 °C for 5 min and then allowed to settle. Lastly, the absorbance of the set aside solution was tested at 410 nm. The logarithm of slope (LOS) model, which was proposed by Butterworth et al. [30], was used to fit the data from the digestion curves, as shown in the following equation:

$$\ln\left(\frac{dC}{dt}\right) = \ln(C_{\infty}k) - kt \tag{4}$$

where t represents the digestion time (min), C represents the amount of digested starch (%) at digestion time t, and k is the apparent digestion rate coefficient (min^{-1}). C_{∞} is the digestion at an infinite time. Lastly, the k value was determined by plotting the slope of a linear least-squares fit of a plot of $\ln(dC/dt)$ against t.

In Vitro Protein Digestion

Protein digestion was conducted using the methodology described by Phongthai et al. [31]. A solution with a protein concentration of 1% was prepared and its pH adjusted to 1.5 by adding 3.0 M HCl. A weight-to-weight ratio of 1:100 was employed to mix pepsin into the protein solution. The mixture was thereafter placed in an incubator and maintained at a temperature of 37 °C for a period of 120 min. Subsequently, the blend was neutralized by adding a 3.0 M NaOH solution. Subsequently, trypsin was introduced to the protein mixture at a similar enzyme-to-protein ratio as before and maintained at a temperature of 37 °C for a period of 120 min. To suppress the trypsin activity, the mixture was subjected to a temperature of 95 °C for a period of 10 min. Following the process of digestion, the protein underwent dehydration using a freeze drier. The protein content was determined using the Kjeldahl method, with a conversion factor of $N \times 5.95$. The protein digestibility % was calculated using the following equation:

$$\text{protein digestibility (\%)} = [(\text{protein in the sample} - \text{protein in the undigested fraction})/\text{protein in the sample}] \times 100 \tag{5}$$

2.2.9. X-Ray Diffraction Analysis

The X-ray diffraction (XRD) patterns of rice samples, including pre-gelatinized (control), frozen–thawed, and optimal PEF-treated samples, were obtained using an Empyrean X-ray diffractometer (PANalytical, Almelo, The Netherlands) at an accelerating voltage of 40 kV and a current of 40 mA using CuKα radiation with a wavelength of 0.154 nm. The scanning zone was configured to span from 10 to 40 degrees of the diffraction angle 2θ, with a step size of 0.026° and a scan rate of 70.125 s/step. The crystalline peak area and amorphous area were identified using PeakFit software (Version 4.0, Systat Software Inc., San Jose, CA, USA). The relative crystallinity was calculated by dividing the crystalline peak area by the overall diffraction area.

2.2.10. Statistical Analysis

One-way analysis of variance (ANOVA) followed by Duncan's multiple range test were used to compare the means between the groups and determine significant differences ($p < 0.05$). The analysis was conducted using SPSS Statistics version 17.0 (SPSS Inc., Chicago, IL, USA).

3. Results and Discussion

3.1. The Optimization of PEF Treatment for Quick-Cooking Rice Production

3.1.1. Model Fitting

The impacts of three parameters, including the number of pulses (X_1, 2000–6000 pulses), the electric field strength (X_2, 6–10 kV/cm), and frequency (X_3, 3–15 Hz), were assessed on the duration required for rice cooking. The cooking time for Jasmine 105 and San Pa Tong 1 treated with a PEF ranged from 3 to 6 min, as shown in Tables 1 and 2, respectively.

The ANOVA and *p*-values illustrated the impacts of the three factors on the cooking time of each variety of rice (Table 3). The generalized second-order polynomial model of cooking time was based on regression Equations (6) and (7), which demonstrated an empirical relationship between the cooking time and the studied variables.

$$\text{Cooking time of Jasmine 105} = 3.60 - 0.87X_1 + 0.13X_3 + 0.50X_1X_2 + 0.25X_1X_3 + 0.50X_2X_3 \; 0.83X_1^2 + 0.57X_2^2 + 0.33X_3^2 \quad (6)$$

$$\text{Cooking time of San Pa Tong 1} = 3.60 - 0.13X_1 - 0.50X_2 - 0.63X_3 - 0.75X_1X_3 + 1.00X_2X_3 + 0.83X_1^2 + 0.075X_2^2 + 0.32X_3^2 \quad (7)$$

Table 3. ANOVAs of Jasmine 105 and San Pa Tong 1 rice.

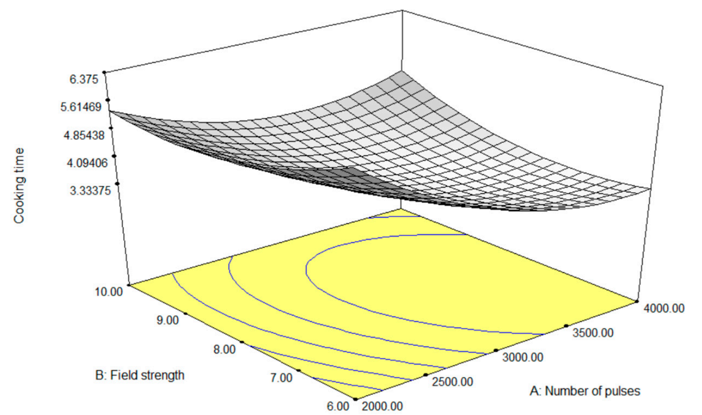
Rice	Source	Sum of Squares	DF	Mean Square	*F*-Value	*p*-Value
Jasmine 105	Model	13.67	9	1.52	4.34	0.0330 [Sig]
	X_1	6.13	1	6.13	17.50	0.0041 [Sig]
	X_2	0.000	1	0.000	0.000	1.0000 [NS]
	X_3	0.12	1	0.12	0.36	0.5689 [NS]
	X_1^2	2.87	1	2.87	8.19	0.0243 [Sig]
	X_2^2	1.39	1	1.39	3.98	0.0863 [NS]
	X_3^2	0.44	1	0.44	1.27	0.2968 [NS]
	$X_1 X_2$	1.00	1	1.00	2.86	0.1348 [NS]
	$X_1 X_3$	0.25	1	0.25	0.71	0.4260 [NS]
	$X_2 X_3$	1.00	1	1.00	2.86	0.1348 [NS]
	Residual	2.45	7	0.35		
	Lack of Fit	1.25	3	0.42	1.39	0.3678 [NS]
	Pure Error	1.20	4	0.30		
	Cor Total	16.12	16			
San Pa Tong 1	Model	15.02	9	1.67	8.06	0.0059 [Sig]
	X_1	0.13	1	0.13	0.60	0.4627 [NS]
	X_2	2.00	1	2.00	9.66	0.0171 [Sig]
	X_3	3.13	1	3.13	15.09	0.0060 [Sig]
	X_1^2	2.87	1	2.87	13.83	0.0075 [Sig]
	X_2^2	0.024	1	0.024	0.11	0.7452 [NS]
	X_3^2	0.44	1	0.44	2.15	0.1863 [NS]
	$X_1 X_2$	0.000	1	0.000	0.000	1.0000 [NS]
	$X_1 X_3$	2.25	1	2.25	10.86	0.0132 [Sig]
	$X_2 X_3$	4.00	1	4.00	19.31	0.0032 [Sig]
	Residual	1.45	7	0.21		
	Lack of Fit	0.25	3	0.083	0.28	0.8395 [NS]
	Pure Error	1.20	4	0.30		
	Cor Total	16.47	16			

"DF" represents degree of freedom, "NS" represents no statistical significance, while "Sig" represents statistical significance at $p < 0.05$.

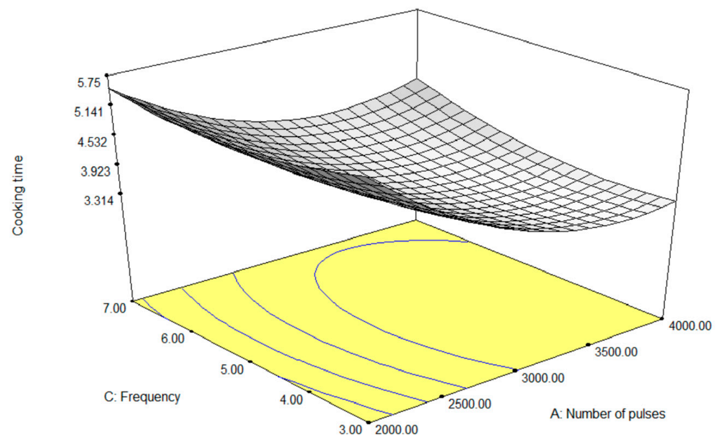
The model may clarify the correlation between the dependent and independent variables using the *F*-test to determine the significance of each coefficient in the regression equation. The model equations for Jasmine 105 and San Pa Tong 1 were statistically significant ($p < 0.05$) in accurately representing the experimental data (Table 3). The cooking time model coefficient of determination (R^2) for Jasmine 105 and San Pa Tong 1 was 0.8480 and 0.9120, respectively, which indicated that the model was suitable to explain 84.80% and 91.20% of the variability in cooking time for each variety. Meanwhile, the adjusted *R*-squared values of the models for Jasmine 105 and San Pa Tong 1 were 0.6526 and 0.7988, respectively. These values suggested that the model fits well with the experimental data. Furthermore, the lack of fit value ($p > 0.05$) confirms that the constructed model accurately represents the relationship between the study variables.

3.1.2. Response Surface Methodology Analysis

Figure 1 shows three-dimensional response surface plots that illustrate the relationship between the studied parameters and cooking time of Jasmine 105 rice. The pulse number mainly had a linear negative effect on the cooking time (X_1, coefficient = −0.87, and X_1^2, coefficient = 0.83). Meanwhile, the cooking time was not significantly affected by electric field strength and frequency ($p > 0.05$). The shortest time was achieved using 3000 pulses (Figure 1). A high number of pulses can cause fissures or pore formation on the surface of plant cells, allowing water to more easily reach the rice endosperm during cooking and resulting in a reduced cooking time. Similarly, Ignat et al. [32] discovered that treating potato cubes with 810–9000 pulses at electric field strength of 0.75–2.50 kV/cm resulted in greater water penetration than leaving the sample untreated, providing a softer texture while preserving their natural appearance.

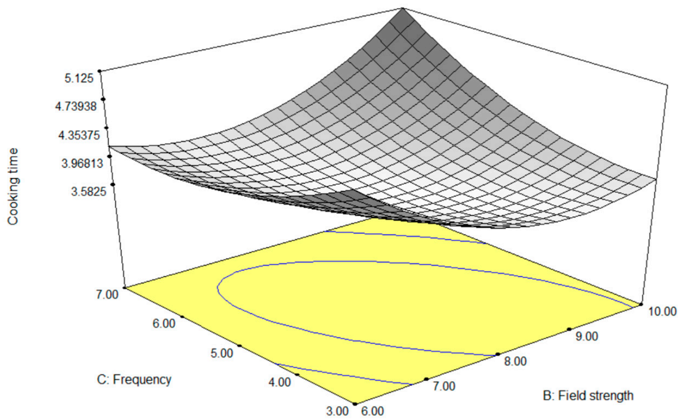


(**a**)



(**b**)

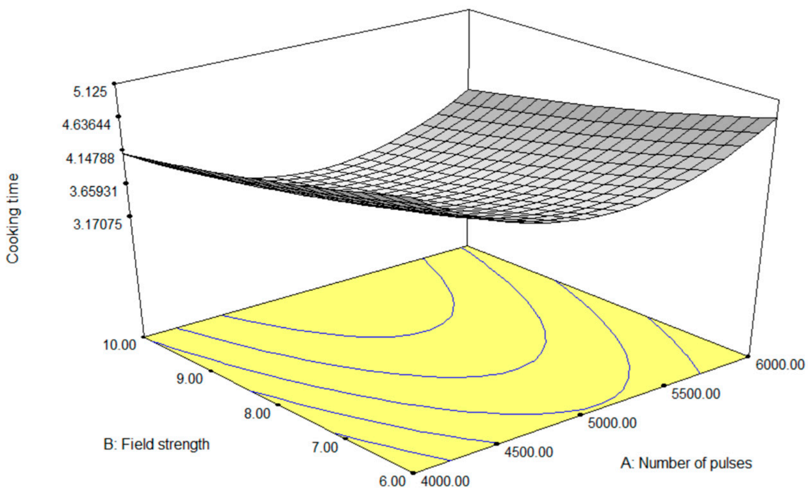
Figure 1. *Cont.*



(**c**)

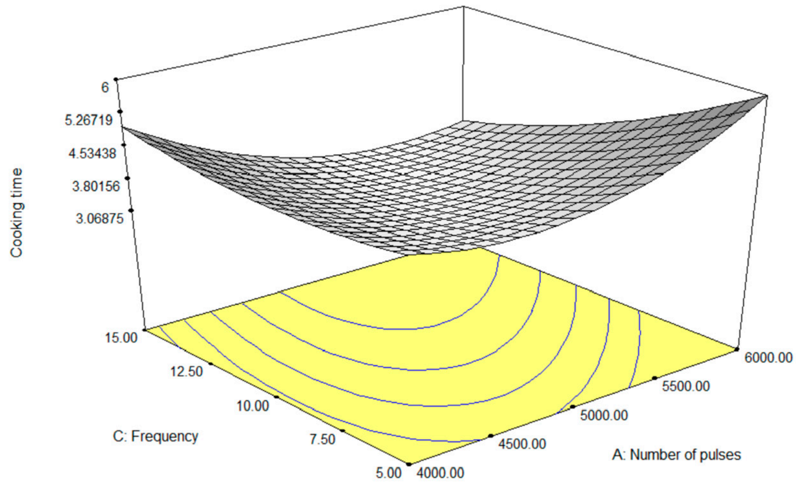
Figure 1. Three-dimensional response surface contour plots demonstrating the impacts of the field strength and number of pulses (**a**), the frequency and the number of pulses (**b**), the frequency and the field strength (**c**), on the cooking time of Jasmine 105 rice.

In addition, the interaction term of the electric field strength and the frequency had the most significant positive impact on the cooking time of San Pa Tong 1 rice (coefficient = 1.00, $p < 0.05$), as illustrated in Figure 2. As result, when the strength of the electric field increased, the duration of cooking likewise increased. This is because an excessive frequency and field strength interrupted build-up of transmembrane potential at the cell membrane that directly prevented pore formation, as well as delayed water penetration into the rice grain structure. This result was consistent with the study by Thongkong et al. [5], who revealed that increasing the frequency from 5 to 7 Hz during PEF treatment largely extended cooking time of Kum Chao Mor Chor 107 rice from 4.5 to 7.6 min. In addition, Toepfl et al. [33] found that the application of too high of an electrical current can also cause a reduction in the water removal rate, resulting in crust formation on the dried cured beef surface. However, some intrinsic factors regarding complexity of the cell wall matrix, compactness of the grain/raw materials, and chemical composition might also affect electroporation efficiency.

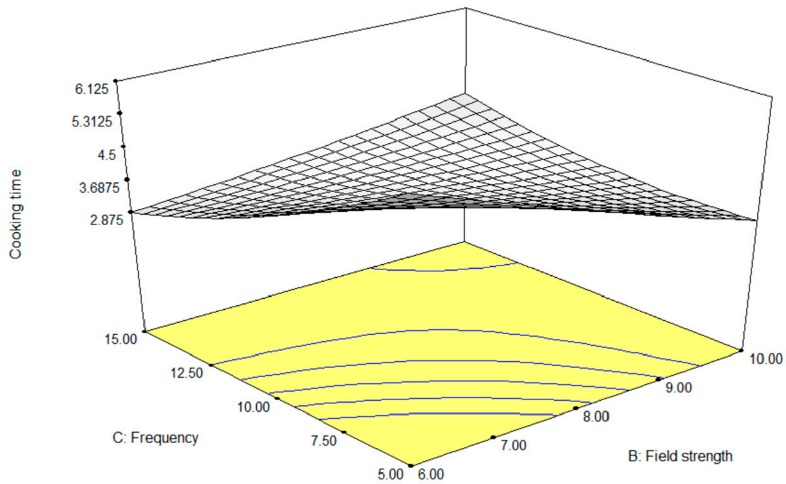


(**a**)

Figure 2. *Cont*.



(**b**)



(**c**)

Figure 2. Three-dimensional response surface contour plots demonstrating the impacts of the field strength and number of pulses (**a**), the frequency and the number of pulses (**b**), the frequency and the field strength (**c**), on the cooking time of San Pa Tong 1 rice.

3.1.3. Verification and Optimization

Table 4 presents the predicted and experimental values for the optimal conditions for quick-cooking rice production using a PEF. The treatment conditions for Jasmine 105 included 3347 pulses, an electric field strength of 6 kV/cm, and a frequency of 6 Hz. Meanwhile, the optimal PEF treatment conditions for San Pa Tong 1 consisted of 4345 pulses, an electric field strength of 8 kV/cm, and a frequency of 15 Hz. The optimal cooking time for Jasmine 105 and San Pa Tong 1 was 4 min. Hence, we found reasonable agreement between the predicted and experimental values, and even a one-minute error can be found for the cooking time of Jasmine 105. According to the study by Rizk et al. [34], polished rice grains normally require 20–35 min of cooking time. Thus, it can be concluded that the optimized PEF treatment in this study could reduce the cooking time by approximately 5.0–8.7 fold. However, PEF treatment only reduced the cooking time of two unpolished rice varieties, including Kum Chao Mor Chor 107 and Kum Doi Saket, by about 2.22–3.96 fold, as reported in our previous study [5]. When compared to the freeze–thawing method, the optimized PEF treatment successfully shortened the cooking time of Jasmine 105 and San Pa Tong 1 rice by about 40–55%.

Table 4. Verification and optimization of the cooking time.

Rice Variety	Process Parameter Setting			Cooking Time (min)		
	Number of Pulses (Pulse)	Electric Field Strength (kV/cm)	Frequency (Hz)	PEF-Predicted Value	PEF-Experiment Value	Freeze–Thawing
Jasmine 105	3347	6	6	4	3	5
San Pa Tong 1	4345	8	15	4	4	9

3.2. The Effect of the PEF Treatment on Rice Quality

3.2.1. Rice Grain Morphology

The morphological characteristics of frozen and thawed rice, optimal PEF-treated rice, and the control sample were observed under a scanning electron microscope, as shown in Figure 3. Clearly, the control rice samples displayed a lack of porosity characteristics. Conversely, the rice samples that underwent freeze–thawing and optimized PEF treatments exhibited distinct alterations in their structural porosity. However, each treatment resulted in unique pore formation due to the different mechanisms employed by the core approach. Based on a prior investigation, the process of freezing and thawing has been widely used to create pores in the structure of rice grains. This phenomenon occurs when water undergoes a freezing process, resulting in the formation of ice crystals. Porosity develops after the water has undergone a phase change from a solid to a liquid state, resulting in the formation of a honeycomb-like porous structure [10,35,36].

The rice samples treated with PEF exhibited distinct surface characteristics, including an extensive pore size and numerous fissures. The results were consistent with the research conducted by Angersbach et al. [37] and Asavasanti et al. [38], who proposed that the pulsed electric field method induces electroporation, causing an electric potential to accumulate on plant cell membranes and resulting in increased porosity in unpolished Thai rice grains [5]. Once the electric potential reaches a certain threshold, it will cause plant cells to permeabilize, fracture, and break. Therefore, these alterations can serve as solid proof of the decreased duration of cooking. According to the study by Qiu et al. [39], a degree of porosity on the rice surface enables water and other elements to enter the rice grain while cooking, resulting in a shorter cooking time.

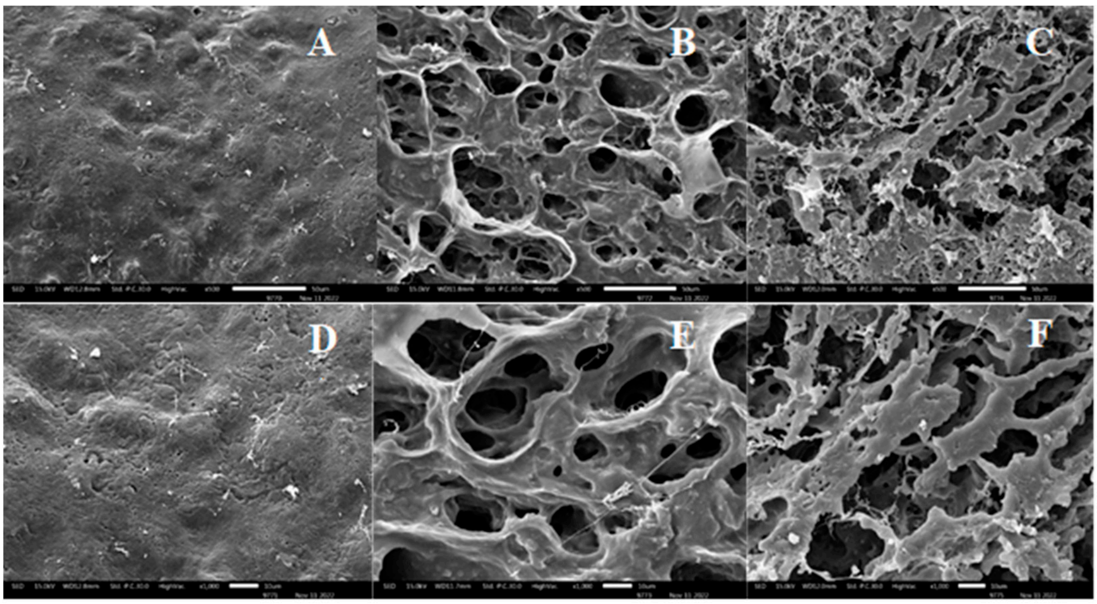


Figure 3. *Cont.*

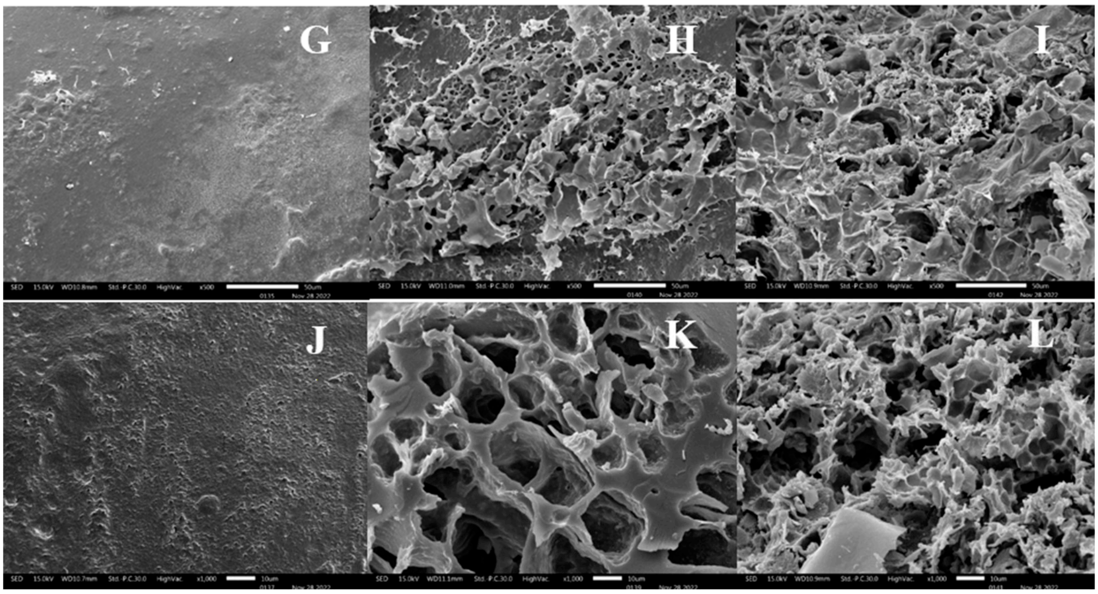


Figure 3. SEM images of Jasmine 105 rice samples: control (**A**, 500× and **D**, 1000×), freeze–thawing (**B**, 500× and **E**, 1000×), and optimized PEF treatments (**C**, 500× and **F**, 1000×). SEM images of San Pa Tong 1 rice samples: control (**G**, 500× and **J**, 1000×), freeze–thawing (**H**, 500× and **K**, 1000×), and optimized PEF treatments (**I**, 500× and **L**, 1000×).

3.2.2. Cooking Quality

The qualities of rice samples treated with PEF and freeze–thawing were compared. The cooking times between the two processes were obviously different. PEF treatment significantly reduced the cooking time when compared to control and frozen and thawed samples ($p < 0.05$). The shortest cooking times for optimal PEF-treated Jasmine 105 and San Pa Tong 1 rice were 3 and 4 min, respectively. The results were related to the porosity of the rice grain surface, as shown in Figure 3. Similarly, the PEF treatment successfully decreased the cooking time of unpolished pigmented rice by about 40–50% [5]. In addition, Lang et al. [11] revealed that the application of infrared radiation can cause a fissure in the grain endoscope and reduce the cooking time from 13.50 to 5.17 min. Thus, a reduction in cooking time is associated with an increase in the intensity of fissures, which can enhance water absorption into rice grains.

Subsequently, the water absorption ratios of both untreated and treated samples were evaluated. The water uptake ratio of Jasmine 105 rice treated with the optimized PEF was the greatest, measuring 2.12 ± 0.16 g/g ($p < 0.05$, Table 5). The induced holes, cracks, and fissures on the rice grain facilitate the penetration of water into the rice endosperm more effectively compared to the rice subjected to the freeze–thaw treatment. Consequently, the PEF process enables the rice grains to increase their water absorption and size. Additionally, it decreases the duration of cooking and enhances the physicochemical properties of rice. Polachini et al. [40] discovered that the application of a PEF treatment had a positive effect on the germination of wheat malt. The wheat malt seeds subjected to 200 pulses at an electric field strength of 3 kV/cm and an energy input of 19.8 kJ/kg exhibited a 25% increase in water absorption in comparison to untreated seeds. Nevertheless, both freeze–thaw-treated San Pa Tong 1 rice (1.48 ± 0.03 g/g) and optimal PEF-treated San Pa Tong 1 rice (1.45 ± 0.02 g/g) exhibited identical water absorption ratios, which were even lower than those of non-glutinous rice, as indicated in Table 5. The decreased water absorption ratio may be attributed to a reduction in the amount of water-soluble amylopectin, which is a branched molecular structure that exhibits stronger affinity for water during the cooking process. Initially, water molecules penetrate the crystalline areas of starch granules as a result of the densely packed branches of amylopectin chains, causing the starch to expand

and fracture [41]. As a result, this can lead to the release of starch granules and subsequently decrease the water absorption capacity of rice grains.

Table 5. Characteristics of rice treated with freeze–thawing and PEF.

Characteristics	Jasmine 105			San Pa Tong 1		
	Control	Freeze–Thawing	PEF	Control	Freeze–Thawing	PEF
The cooking quality						
Cooking time (min)	7.0 ± 0.58 [a]	5.0 ± 0.00 [b]	3.0 ± 0.00 [c]	15.0 ± 0.58 [a]	9.0 ± 0.58 [b]	4.0 ± 0.00 [c]
Water uptake ratio (g/g)	1.53 ± 0.05 [c]	1.87 ± 0.03 [b]	2.12 ± 0.16 [a]	2.03 ± 0.07 [a]	1.48 ± 0.03 [b]	1.45 ± 0.02 [b]
Cooking loss (%)	3.63 ± 0.23 [c]	10.15 ± 0.46 [a]	7.77 ± 0.15 [b]	9.17 ± 0.30 [b]	13.55 ± 1.62 [a]	12.08 ± 0.98 [a]
Nutrition factors						
Vitamin B1 (μg/100 g)	176.70 ± 0.01 [a]	32.31 ± 0.56 [c]	80.05 ± 0.18 [b]	33.77 ± 0.12 [a]	32.69 ± 0.14 [b]	23.59 ± 0.08 [c]
Vitamin B3 (μg/100 g)	12.04 ± 0.00 [a]	11.18 ± 0.06 [b]	12.02 ± 0.00 [b]	3.04 ± 0.00 [a]	3.00 ± 0.08 [a]	2.98 ± 0.07 [a]
In vitro digestibility						
Protein digestibility (%)	52.28 ± 1.51 [a]	52.19 ± 0.96 [a]	54.38 ± 2.36 [a]	15.18 ± 2.15 [c]	28.43 ± 3.74 [b]	36.92 ± 3.44 [a]
Digestible and resistant starch (g/100 g in dry basis)						
RDS	10.57 ± 0.04 [b]	13.30 ± 0.10 [a]	9.95 ± 0.00 [c]	12.75 ± 0.01 [b]	13.62 ± 0.25 [a]	13.69 ± 0.05 [a]
SDS	4.15 ± 0.02 [b]	3.01 ± 0.12 [c]	6.21 ± 0.24 [a]	1.01 ± 0.02 [c]	2.47 ± 0.31 [b]	3.60 ± 0.04 [a]
TDS	14.78 ± 0.01 [c]	21.03 ± 0.05 [a]	17.29 ± 0.02 [b]	15.08 ± 0.04 [b]	15.03 ± 0.03 [b]	19.91 ± 0.07 [a]
RS	0.03 ± 0.00 [b]	0.04 ± 0.00 [b]	0.48 ± 0.01 [a]	0.03 ± 0.00 [b]	0.03 ± 0.00 [b]	0.04 ± 0.01 [a]
Total starch	14.81 ± 0.01 [c]	21.07 ± 0.05 [a]	17.77 ± 0.04 [b]	15.11 ± 0.04 [b]	15.06 ± 0.03 [b]	19.96 ± 0.08 [a]
In vitro starch digestion kinetics						
k (min^{-1})	0.0429	0.0386	0.0388	0.0317	0.0503	0.0465
C_{120} (%)	72.36 ± 0.78 [a]	69.96 ± 2.82 [a]	72.44 ± 0.91 [a]	68.42 ± 0.63 [b]	91.35 ± 0.10 [a]	92.12 ± 0.46 [a]
C_∞ (%)	75.11	72.76	76.66	73.78	87.24	92.68

Different letters in each row for each rice variety represent significantly different mean values ($p < 0.05$). RDS = rapidly digestible starch, SDS = slowly digestible starch, TDS = total digestible starch, RS = resistant starch.

Meanwhile, the optimized PEF treatment clearly resulted in a reduction in rice grain weight following the cooking process. Nevertheless, the cooking loss was approximately 1.47–2.38% lower than that of the frozen and thawed sample. San Pa Tong 1 rice treated with the optimized PEF exhibited a higher cooking loss than Jasmine 105 rice (7.77 ± 0.15% and 12.08 ± 0.98%, respectively), which was consistent with the water uptake ratio. The size of the pores generated by each process may be the reason for the difference in cooking loss between the PEF treatment and freeze–thawing. The PEF treatment generates tiny pores, whereas the freeze–thawing process generates larger pores. Thus, the size of the generated pores directly correlates with the cooking loss.

3.2.3. Retention of Vitamins B1 and B3

The quantities of vitamins B1 and B3 in the cooked rice samples are listed in Table 5. The control sample of Jasmine 105 rice had the highest levels of vitamins B1 and B3, measuring 176.70 ± 0.01 μg/100 g and 12.04 ± 0.00 μg/100 g, respectively. In contrast, San Pa Tong 1 rice contained significantly lower amounts of these vitamins, with levels of 33.77 ± 0.12 μg/100 g and 3.04 ± 0.00 μg/100 g, respectively. The use of the optimized PEF treatment and freeze–thawing techniques had a significant impact on vitamin B1 retention in Jasmine 105 rice. One main reason why vitamin loss occurs could be the release of water-soluble vitamins, especially vitamin B1, which is abundant in Jasmine 105 rice, through the pores created through PEF treatment and freeze–thawing. Furthermore, a variety of factors, such as pH, light, and heat, can degrade vitamin B1. On the other hand, the investigated techniques slightly reduced the vitamin B1 content of San Pa Tong 1 rice, which was significantly lower than that of Jasmine 105 rice. Moreover, the freeze–thawing and optimized PEF treatments slightly changed the vitamin B3 level of the rice samples. This is most likely the result of a very low initial level of vitamin B3; nevertheless, it is the most stable water-soluble vitamin and is usually highly resistant to air, oxygen, acids, heat, and light [42].

As a result, the traditional cooking method (control) showed superior benefits in terms of rice's nutritional value, as it properly preserved vitamins B1 and B3 compared to the other techniques assessed. Nevertheless, the application of PEF is more effective than the commonly used freeze–thaw approach in creating quick-cooking rice.

3.3. The Effect of the PEF Treatment on In Vitro Digestibility

3.3.1. Starch Digestibility

The rapidly digestible starch (RDS), slowly digestible starch (SDS), total digestible starch (TDS), resistant starch (RS), total starch content, and in vitro starch digestibility of Jasmine 105 and San Pa Tong 1 rice are summarized in Table 5. The total starch content of Jasmine 105 rice (control) was 14.81–21.07 g/100 g dry sample, including 14.78–21.03 g TDS/100 g dry sample. PEF-treated Jasmine 105 rice had the lowest RDS content at 9.95 ± 0.00 g/100 g dry weight and the highest SDS content at 6.21 ± 0.24 g/100 g dry weight ($p < 0.05$). Furthermore, the PEF-treated sample had the highest RS content (0.48 ± 0.01 g/100 g dry sample). The total starch content in San Pa Tong 1 rice (control) was 15.06–19.96 g/100 g dry sample, with a TDS content of 15.03–19.91 g/100 g dry sample. Frozen and thawed and PEF-treated samples had no significant difference in the RDS content ($p > 0.05$). The RDS content of the samples treated using both techniques exceeded that of the control sample. The open or significant holes created by PEF and freeze-thawing could potentially expose the interior surface area of the rice microstructures to enzymatic attack. Furthermore, improving mass transfer between cells results in higher porosity on the cell surface. Enzymes can thus enter the cell and attach to their substrate, thereby promoting hydrolytic digestion [43,44]. PEF treatment resulted in increases in SDS and RS levels in San Pa Tong 1, with 3.60 ± 0.04 g/100 g dry sample and 0.04 ± 0.01 g/100 g dry sample, respectively. As a result, the PEF treatment appeared to have a positive effect on the amounts of RS and SDS in Jasmine 105 rice and San Pa Tong 1. Jasmine 105 rice's rich amylose content, which undergoes starch retrogradation after heating–cooling treatment, may also contribute to the increased RS content. This may result in a lower glycemic index (GI), because foods raise blood sugar levels slowly. Therefore, the beneficial effects of PEF treatment on blood glucose and insulin levels make quick-cooking Jasmine 105 rice suitable for diabetic patients' diets. However, the starch digestibility of each starch is also dependent on the ratio of amylose to amylopectin, the crystal structure of starch granules, the grain size of rice grains, and the texture of rice grains [45–47].

3.3.2. Starch Digestibility Kinetics

With a longer digestion time—0, 5, 20, 40, 60, 90, and 120 min—the amount of digested starch increased in Jasmine 105 and San Pa Tong 1 rice, as shown in Figure 4. During small intestinal digestion, the starch digestion curve of both varieties of rice was defined by an initial fast rate followed by a slower rate that reached a plateau approximately 40 min later. Each treatment of the Jasmine 105 quick-cooking rice produced basically no variations (Figure 4). Jasmine 105 rice primarily contains a slightly branched and tightly helical form of amylose, which is often more difficult to digest than amylopectin in San Pa Tong 1 rice [48,49]. In contrast, in San Pa Tong 1, the freeze–thawing and optimized PEF techniques greatly accelerated the degree and rate of starch digestion (Figure 4). This is because the open or large pores of the rice microstructure provide a significant internal surface area accessible for enzyme activity. Enzymes can thus enter the cell to attach to their substrate, enhancing hydrolytic digestion [43,44]. The first-order equation model was used to find the kinetic constant (k) and equilibrium starch hydrolysis percentage (C_∞) for each cooked rice sample. These are presented in Table 5. Figure 4 shows the LOS model's fit to the digestion curves of San Pa Tong 1 and Jasmine 105. The starch digestibility of PEF-treated Jasmine 105 and San Pa Tong 1 rice was 72.44% ± 0.91% and 92.12% ± 0.46%, respectively, which was 0.11–25.73% greater than that of the control sample, at 120 min (C_{120}). In PEF-treated cooked rice, C_∞ and starch digestibility values were higher than those of untreated samples. Particularly in glutinous San Pa Tong 1 rice, the PEF treatment clearly increased starch digestibility more effectively than the freeze–thawing method.

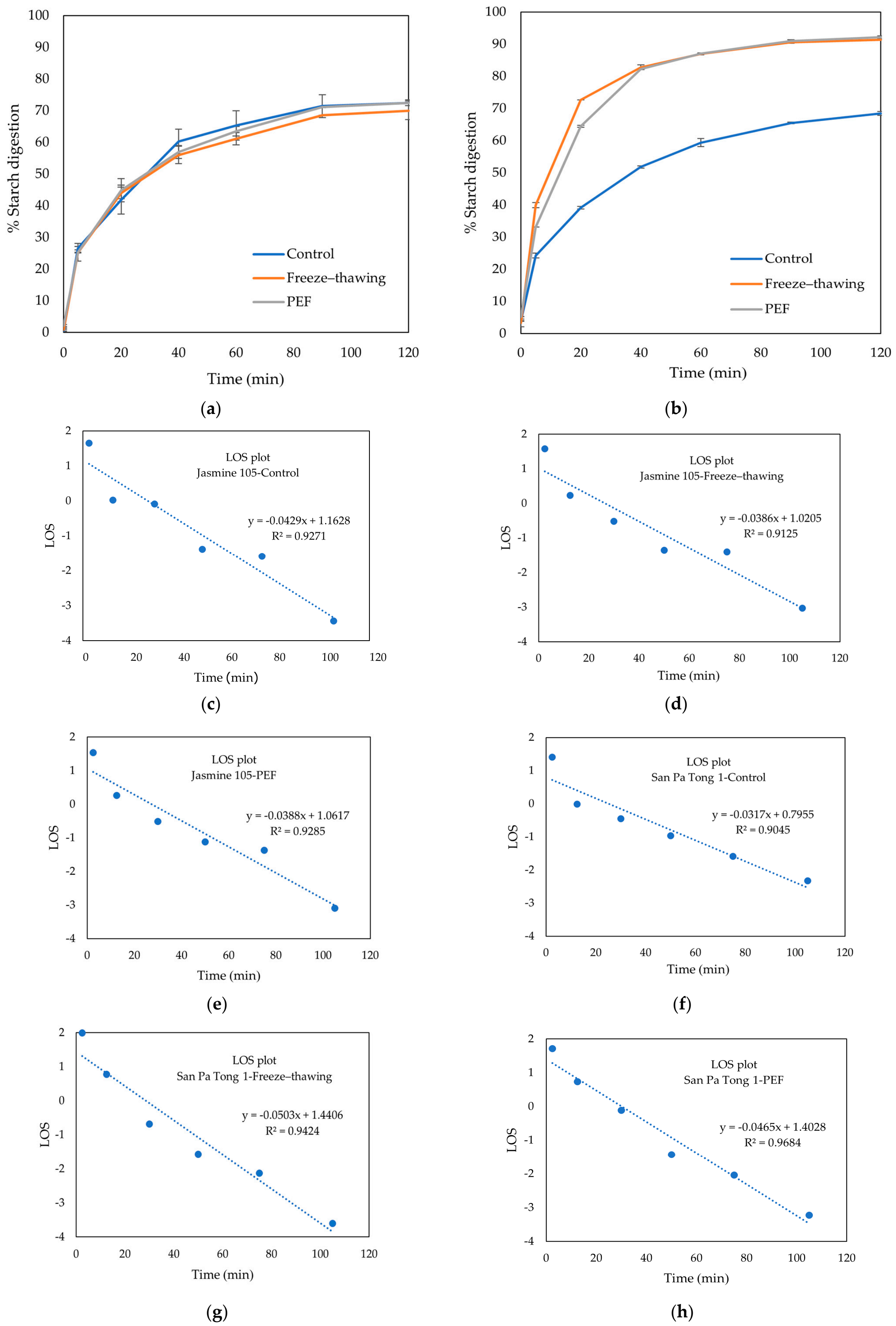


Figure 4. Starch digestion curves for Jasmine 105 (**a**) and San Pa Tong 1 (**b**). The single-phase logarithm of slope (LOS) plots of the starch digestibility data for Jasmine 105 (**c**–**e**) and San Pa Tong 1 (**f**–**h**) rice under control, freeze–thawing, and optimized PEF treatments.

3.3.3. Protein Digestibility

The in vitro protein digestibility of rice samples is reported in Table 5. The protein digestibility of Jasmine 105 and San Pa Tong 1 rice samples was reported at 52.28 ± 1.51% and 15.18 ± 2.15%, respectively. Obviously, the samples treated with PEF reached their maxima at 54.38 ± 2.36% and 36.92 ± 3.44%, respectively, which were higher than those of freeze–thawing-treated samples. These results were in agreement with our previous study by Thongkong et al. [14]. The PEF treatment makes the rice bran protein in Kum Chao Mor Chor 107 and Kum Doi Saket rice more digestible by changing the polypeptide chain's folded structure into an unfolded structure. Consequently, the substrate's susceptibility to the digestive enzymes during simulated in vitro gastrointestinal digestion appeared to increase [50]. This results in an increase in the digestibility of protein. However, proteases are specific to the type of amino acid and the structure of proteins found in raw materials, making the rice species an additional factor to consider [51,52].

3.4. XRD Pattern and Relative Crystallinity

In general, Thai rice exhibits an A-type X-ray diffraction (XRD) pattern, characterized by main diffraction peaks at 15°, 17°, 18°, and 23° (2Θ), as described by Kraithong et al. [53]. After undergoing various pre-gelatinization processes, both Jasmine 105 and San Pa Tong 1 lost this characteristic XRD pattern (Figure 5). For Jasmine 105, PEF-treated Jasmine 105 displayed the lowest crystallinity. This is likely because the PEF treatment can damage the crystalline structures of starch more extensively than freeze–thaw treatment [54]. Conversely, the control process seemed to cause greater destruction of the crystalline structure in San Pa Tong 1, while the PEF and freeze–thawing treatments might help preserve or even promote the crystalline regions of the rice. The differences in how pre-gelatinization processes affect rice crystallinity may be influenced by the inherent structure and amylose–amylopectin content of the rice samples, which warrant further investigation. Among all pre-gelatinization processes, the freeze–thawing treatment appeared to maintain crystallinity in both rice varieties. This preservation of crystallinity may be due to the freeze–thaw treatment promoting the reorganization of the amorphous regions within the starch granules, as observed by Wang et al. [55] in their study of the effects of freeze–thaw cycles on the physicochemical and functional properties of ginger starch.

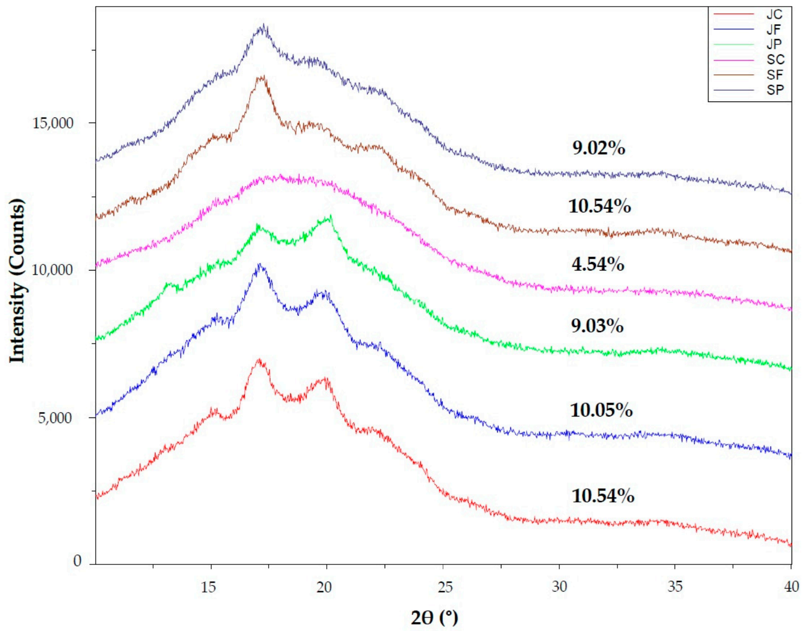


Figure 5. XRD patterns and crystallinity of rice samples (JC; Jasmine 105-control, JF; Jasmine 105-frozen and thawed; JP; Jasmine 105-PEF, SC; San Pa Tong 1-control; SF; San Pa Tong 1-frozen and thawed, and SP; San Pa Tong 1-PEF.

4. Conclusions

This study employed a pulsed electric field (PEF) as an alternative technique to produce quick-cooking rice. White rice treated with PEF required shorter processing and cooking durations by approximately 8.7 times compared to those that underwent freeze–thaw processing. Furthermore, the developed process improved rice's physicochemical properties, such as the water absorption capacity, while minimizing cooking losses and maintaining essential vitamins. Furthermore, it improved the in vitro digestibility of proteins and carbohydrates. The findings of this study might be helpful for promoting another novel quick-cooking rice process that serves consumer preferences and the rice industry's sustainability.

Author Contributions: Conceptualization, S.P.; data curation, S.T. and S.P.; formal analysis, S.T.; methodology, S.K., P.T., A.Y., W.K. and S.P.; supervision, S.P.; validation, S.K., Jaspreet Singh, P.T., A.Y., W.K., P.R., S.R. and S.P.; writing—original draft, S.T. and S.P.; writing—review and editing, S.K., J.S., P.T., A.Y., W.K., P.R. and S.R. All authors have read and agreed to the published version of the manuscript.

Funding: The present study was partially supported by the Thailand Research Fund (TRF) Research Team Promotion Grant, RTA, Senior Research Scholar (N42A671052).

Data Availability Statement: The data presented in this study and supporting data are available upon request from the corresponding author.

Acknowledgments: This study was partially supported by Chaing Mai University. The authors also acknowledge the supports from Mae Fah Luang University under the Reinventing University Program supported by The Office of the Permanent Secretary of the Ministry of Higher Education, Science, Research and Innovation.

Conflicts of Interest: 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.

References

1. Muthayya, S.; Sugimoto, J.D.; Montgomery, S.; Maberly, G.F. An overview of global rice production, supply, trade; consumption. *Ann. N. Y. Acad. Sci.* **2014**, *1324*, 7–14. [CrossRef] [PubMed]
2. Patindol, J.A.; Siebenmorgen, T.J.; Wang, Y. Impact of environmental factors on rice starch structure: A review. *Starch Stärke* **2015**, *67*, 42–54. [CrossRef]
3. Shahbandeh, M. Top rice exporting countries worldwide 2023/2024. Available online: https://www.statista.com/statistics/255947/top-rice-exporting-countries-worldwide-2011/ (accessed on 31 January 2024).
4. Boluda-Aguilar, M.; Taboada-Rodríguez, A.; López-Gómez, A.; Marín-Iniesta, F.; Barbosa-Cánovas, G.V. Quick cooking rice by high hydrostatic pressure processing. *LWT-Food Sci. Technol.* **2013**, *51*, 196–204. [CrossRef]
5. Thongkong, S.; Yawootti, A.; Klangpetch, W.; Fashakin, O.O.; Tangjaidee, P.; Rawdkuen, S.; Phongthai, S. A novel application of pulsed electric field as a key process for quick-cooking rice production. *Innov. Food Sci. Emerg. Technol.* **2023**, *90*, 103494. [CrossRef]
6. Rewthong, O.; Soponronnarit, S.; Taechapairoj, C.; Tungtrakul, P.; Prachayawarakorn, S. Effects of cooking, drying and pretreatment methods on texture and starch digestibility of instant rice. *J. Food Eng.* **2011**, *103*, 258–264. [CrossRef]
7. Kaur, B.; Ranawana, V.; Henry, J. The glycemic index of rice and rice products: A review.; table of GI values. *Crit. Rev. Food Sci. Nutr.* **2016**, *56*, 215–236. [CrossRef]
8. Tao, K.; Yu, W.; Prakash, S.; Gilbert, R.G. High-amylose rice: Starch molecular structural features controlling cooked rice texture and preference. *Carbohydr. Polym.* **2019**, *219*, 251–260. [CrossRef]
9. Zhu, D.; Fang, C.; Qian, Z.; Guo, B.; Huo, Z. Differences in starch structure, physicochemical properties and texture characteristics in superior and inferior grains of rice varieties with different amylose contents. *Food Hydrocoll.* **2021**, *110*, 106170. [CrossRef]
10. Dollete, U.G.; Azanza, M.P. Structural, Textural, and Thermal Properties of Freeze-thawed Quick-frozen Cooked Rice PSB Rc 18 (*Oryza sativa* L.). *Philipp. J. Sci.* **2020**, *149*, 279–284. [CrossRef]
11. Lang, G.H.; Timm, N.d.S.; Neutzling, H.P.; Ramos, A.H.; Ferreira, C.D.; de Oliveira, M. Infrared radiation heating: A novel technique for developing quick-cooking rice. *LWT* **2022**, *154*, 112758. [CrossRef]
12. Ho, S.Y.; Mittal, G.S. Electroporation of cell membranes: A review. *Crit. Rev. Biotechnol.* **1996**, *16*, 349–362. [CrossRef] [PubMed]
13. Kotnik, T.; Rems, L.; Tarek, M.; Miklavčič, D. Membrane electroporation and electropermeabilization: Mechanisms and models. *Annu. Rev. Biophys.* **2019**, *48*, 63–91. [CrossRef] [PubMed]

14. Thongkong, S.; Klangpetch, W.; Unban, K.; Tangjaidee, P.; Phimolsiripol, Y.; Rachtanapun, P.; Jantanasakulwong, K.; Schönlechner, R.; Thipchai, P.; Phongthai, S. Impacts of electroextraction using the pulsed electric field on properties of Rice bran protein. *Foods* **2023**, *12*, 835. [CrossRef] [PubMed]
15. Liu, Z.-W.; Zeng, X.-A.; Ngadi, M. Enhanced extraction of phenolic compounds from onion by pulsed electric field (PEF). *J. Food Process. Preserv.* **2018**, *42*, e13755. [CrossRef]
16. Lončarić, A.; Celeiro, M.; Jozinović, A.; Jelinić, J.; Kovač, T.; Jokić, S.; Babić, J.; Moslavac, T.; Zavadlav, S.; Lores, M. Green extraction methods for extraction of polyphenolic compounds from blueberry pomace. *Foods* **2020**, *9*, 1521. [CrossRef]
17. Chang, C.K.; Tsai, S.Y.; Gavahian, M.; Cheng, K.C.; Hou, C.Y.; Yudhistira, B.; Lin, S.H.; Santoso, S.P.; Hsieh, C.W. Direct and alternating current electric fields affect pectin esterase and cellulase in tomato (*Solanum lycopersicum* L.) fruit during storage. *Postharvest Biol. Technol.* **2023**, *205*, 112495. [CrossRef]
18. Syahariza, Z.; Sar, S.; Hasjim, J.; Tizzotti, M.J.; Gilbert, R.G. The importance of amylose and amylopectin fine structures for starch digestibility in cooked rice grains. *Food Chem.* **2013**, *136*, 742–749. [CrossRef] [PubMed]
19. Van Hung, P.; Chau, H.T.; Phi, N.T.L. Phi, In vitro digestibility and in vivo glucose response of native and physically modified rice starches varying amylose contents. *Food Chem.* **2016**, *191*, 74–80. [CrossRef]
20. Zhu, L.-J.; Liu, Q.-Q.; Wilson, J.D.; Gu, M.-H.; Shi, Y.-C. Digestibility and physicochemical properties of rice (Oryza sativa L.) flours and starches differing in amylose content. *Carbohydr. Polym.* **2011**, *86*, 1751–1759. [CrossRef]
21. Association of Official Analytical Chemists (AOAC). *Official Methods of Analysis*, 18th ed.; Association of Official Analytical Chemists (AOAC): Arlington, VA, USA, 2005.
22. Jiamyangyuen, S.; Wichaphon, J.; Boonmeejoy, J. Classification of rice cultivars by using chemical, physicochemical, thermal, hydration properties.; cooking quality. *Food Appl. Biosci. J.* **2019**, *7*, 42–62.
23. Inprasit, C.; Noomhorm, A. Effect of drying air temperature and grain temperature of different types of dryer and operation on rice quality. *Dry. Technol.* **2001**, *19*, 389–404. [CrossRef]
24. Jiao, A.; Xu, X.; Jin, Z. Modelling of dehydration–rehydration of instant rice in combined microwave-hot air drying. *Food Bioprod. Process.* **2014**, *92*, 259–265. [CrossRef]
25. Chin, L.; Therdthai, N.; Ratphitagsanti, W. Effect of microwave cooking on quality of riceberry rice (*Oryza sativa* L.). *J. Food Qual.* **2020**, *2020*, 4350274. [CrossRef]
26. Jaroenkit, P.; Matan, N.; Nisoa, M. Microwave drying of cooked brown rice and the effect on the nutrient composition and trace elements. *Int. Food Res. J.* **2013**, *20*, 351–355.
27. Van Wyk, J.; Dolley, L.; Mshicileli, N. *HPLC Analysis of Vitamin B1, B2, B3, B6, B9, B12 and Vitamin C in Various Food Matrices*; Nova Science Publishers: New York, NY, USA, 2014.
28. Kraithong, S.; Theppawong, A.; Lee, S.; Huang, R. Understanding of hydrocolloid functions for enhancing the physicochemical features of rice flour and noodles. *Food Hydrocoll.* **2023**, *142*, 108821. [CrossRef]
29. Moretti, R.; Thorson, J.S. A comparison of sugar indicators enables a universal high-throughput sugar-1-phosphate nucleotidyltransferase assay. *Anal. Biochem.* **2008**, *377*, 251–258. [CrossRef]
30. Butterworth, P.J.; Warren, F.J.; Grassby, T.; Patel, H.; Ellis, P.R. Analysis of starch amylolysis using plots for first-order kinetics. *Carbohydr. Polym.* **2012**, *87*, 2189–2197. [CrossRef]
31. Phongthai, S.; D'Amico, S.; Schoenlechner, R.; Homthawornchoo, W.; Rawdkuen, S. Fractionation and antioxidant properties of rice bran protein hydrolysates stimulated by in vitro gastrointestinal digestion. *Food Chem.* **2018**, *240*, 156–164. [CrossRef]
32. Ignat, A.; Manzocco, L.; Brunton, N.P.; Nicoli, M.C.; Lyng, J.G. The effect of pulsed electric field pre-treatments prior to deep-fat frying on quality aspects of potato fries. *Innov. Food Sci. Emerg. Technol.* **2015**, *29*, 65–69. [CrossRef]
33. Toepfl, S.; Heinz, V. Application of pulsed electric fields to improve mass transfer in dry cured meat products. *Fleischwirtschaft Int.* **2007**, *22*, 2007.
34. Rizk, L.F.; Doss, H.A. Preparation of improved quick cooking rice. *Food/Nahrung* **1995**, *39*, 124–131. [CrossRef]
35. Lu, L.; Zhu, K.-X. Physicochemical and fermentation properties of pre-fermented frozen dough: Comparative study of frozen storage and freeze–thaw cycles. *Food Hydrocoll.* **2023**, *136*, 108253. [CrossRef]
36. Ye, J.; Hu, X.; Zhang, F.; Fang, C.; Liu, C.; Luo, S. Freeze-thaw stability of rice starch modified by improved extrusion cooking technology. *Carbohydr. Polym.* **2016**, *151*, 113–118. [CrossRef] [PubMed]
37. Angersbach, A.; Heinz, V.; Knorr, D. Effects of pulsed electric fields on cell membranes in real food systems. *Innov. Food Sci. Emerg. Technol.* **2000**, *1*, 135–149. [CrossRef]
38. Asavasanti, S.; Stroeve, P.; Barrett, D.M.; Jernstedt, J.A.; Ristenpart, W.D. Enhanced electroporation in plant tissues via low frequency pulsed electric fields: Influence of cytoplasmic streaming. *Biotechnol. Prog.* **2012**, *28*, 445–453. [CrossRef]
39. Qiu, S.; Abbaspourrad, A.; Padilla-Zakour, O.I. Changes in the glutinous rice grain and physicochemical properties of its starch upon moderate treatment with pulsed electric field. *Foods* **2021**, *10*, 395. [CrossRef] [PubMed]
40. Polachini, T.C.; Norwood, E.-A.; Le-Bail, P.; Le-Bail, A.; Cárcel, J.A. Pulsed electric field (PEF) application on wheat malting process: Effect on hydration kinetics, germination and amylase expression. *Innov. Food Sci. Emerg. Technol.* **2023**, *86*, 103375. [CrossRef]
41. Wang, S.; Li, C.; Yu, J.; Copeland, L.; Wang, S. Phase transition and swelling behaviour of different starch granules over a wide range of water content. *LWT-Food Sci. Technol.* **2014**, *59*, 597–604. [CrossRef]

42. Hrubša, M.; Siatka, T.; Nejmanová, I.; Vopršalová, M.; Krčmová, L.K.; Matoušová, K.; Javorská, L.; Macáková, K.; Mercolini, L.; Remião, F.; et al. Biological properties of vitamins of the B-complex, part 1: Vitamins B1, B2, B3.; B5. *Nutrients* **2022**, *14*, 484. [CrossRef]
43. Contardo, I.; James, B.; Bouchon, P. Microstructural characterization of vacuum-fried matrices and their influence on starch digestion. *Food Struct.* **2020**, *25*, 100146. [CrossRef]
44. Eelderink, C.; Noort, M.W.J.; Sozer, N.; Koehorst, M.; Holst, J.J.; Deacon, C.F.; Rehfeld, J.F.; Poutanen, K.; Vonk, R.J.; Oudhuis, L.; et al. The structure of wheat bread influences the postprandial metabolic response in healthy men. *Food Funct.* **2015**, *6*, 3236–3248. [CrossRef]
45. Jane, J.-L. Structure of starch granules. *J. Appl. Glycosci.* **2007**, *54*, 31–36. [CrossRef]
46. Magallanes-Cruz, P.A.; Flores-Silva, P.C.; Bello-Perez, L.A. Starch structure influences its digestibility: A review. *J. Food Sci.* **2017**, *82*, 2016–2023. [CrossRef] [PubMed]
47. Tao, K.; Yu, W.; Prakash, S.; Gilbert, R.G. Investigating cooked rice textural properties by instrumental measurements. *Food Sci. Hum. Wellness* **2020**, *9*, 130–135. [CrossRef]
48. Bertoft, E. Understanding starch structure: Recent progress. *Agronomy* **2017**, *7*, 56. [CrossRef]
49. Htoon, A.; Shrestha, A.; Flanagan, B.; Lopez-Rubio, A.; Bird, A.; Gilbert, E.; Gidley, M. Effects of processing high amylose maize starches under controlled conditions on structural organisation and amylase digestibility. *Carbohydr. Polym.* **2009**, *75*, 236–245. [CrossRef]
50. Bhat, Z.; Morton, J.D.; Mason, S.L.; Bekhit, A.E.-D.A. Pulsed electric field improved protein digestion of beef during in-vitro gastrointestinal simulation. *LWT* **2019**, *102*, 45–51. [CrossRef]
51. Liu, K.; Zheng, J.; Chen, F. Effect of domestic cooking on rice protein digestibility. *Food Sci. Nutr.* **2019**, *7*, 608–616. [CrossRef]
52. Zhang, W.; Liu, S.; Wang, Y.; Zheng, L.; Liu, F.; Han, X.; Ren, Y.; Long, Q.; Zhao, Z.; Jiang, L.; et al. A study of the in vitro protein digestibility of indica and japonica cultivars. *Food Chem.* **2010**, *122*, 1199–1204. [CrossRef]
53. Kraithong, S.; Lee, S.; Rawdkuen, S. Physicochemical and functional properties of Thai organic rice flour. *J. Cereal Sci.* **2018**, *79*, 259–266. [CrossRef]
54. Wu, C.; Wu, Q.-Y.; Wu, M.; Jiang, W.; Qian, J.-Y.; Rao, S.-Q.; Zhang, L.; Li, Q.; Zhang, C. Effect of pulsed electric field on properties and multi-scale structure of japonica rice starch. *LWT* **2019**, *116*, 108515. [CrossRef]
55. Wang, Y.-C.; Liang, Y.-C.; Huang, F.-L.; Chang, W.-C. Effect of freeze–thaw cycles on physicochemical and functional properties of ginger starch. *Processes* **2023**, *11*, 1828. [CrossRef]