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Application of Microwave-Assisted Technology for Single-Pass Drying of Rough Rice

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Application of Microwave-Assisted Technology for Single-Pass Drying of Rough Rice

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy in Food Science

by

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This dissertation is approved for recommendation to the Graduate Council.

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ABSTRACT

The 915 MHz industrial microwave is a novel technology that has the potential to achieve one-pass drying of rice within a short drying duration and reduce rice drying losses. However, processing recommendations for the commercialization of this technology for rice drying is lacking. The goal of this research is to provide processing conditions that are useful for the commercialization of the 915 MHz industrial microwave technology for rice drying. This was achieved by studying the impact of microwave specific energy and processing conditions such as harvest moisture content, milling duration, and aging on the physicochemical properties of a 915 MHz microwave-dried rice. Two rice cultivars, a medium grain cultivar Titan and long grain hybrid cultivar XL753 with harvest moisture contents of 16%, 18% and 20% (wet basis) were used for the study. The rice samples were treated with two different drying methods, natural air drying as control and microwave heating at 915 MHz frequency (specific energies ranging from 360-720 kJ/kg-grain) followed by tempering and natural air cooling. The rice samples were dehulled and milled for 30 s, 45 s, and 60 s. Physicochemical and functional properties of the head rice samples were analyzed. Furthermore, some head rice samples were stored for 6 months at 4°C and 25°C representing non-aged and aged samples respectively. Physicochemical properties of the aged and non-aged rice samples were determined. Results indicate that microwave specific energy had a significant effect (p-value <0.0001) on moisture removal and head rice yield. The most desirable specific energy for moisture removal that maintains rice quality characteristics (relative to control samples) was 525 kJ/kg-grain. Statistical models predicted harvest moisture content of 20% and milling durations of 45 s and 42 s for processing microwave-dried rice cultivars Titan and XL753 respectively, to obtain rice with good quality characteristics. Furthermore, aging/storage significantly increased the setback viscosity, cooked rice hardness and gumminess, and significantly decreased the peak viscosity and solid loss of microwave-dried rice. Aged microwave dried rice that was treated at 360 and 525 kJ/kg-grain were practically equivalent in terms of hardness and solid loss. Therefore, microwave specific energy of 525 kJ/kg-grain is recommended for rice drying because it produces rice with desirable drying, physicochemical properties and functional properties. This research provides science-based information that is vital for optimizing processing conditions of rice dried using the 915 MHz industrial microwave and for selecting microwave parameters that will achieve desirable physicochemical characteristics required for different rice products.

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DEDICATION

This dissertation is dedicated to my yet-to-be-born daughter, Delanyo Adelaide Bruce-Gotah, for her constant joyous kicks and for enjoying the writing process with me.

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Bruce, R. M., Atungulu, G. G., Sadaka, S., & Smith, D. (2021). Impact of specific energy input of a 915 MHz microwave dryer on quality, functional, and physicochemical properties of different rice cultivars. *Cereal Chemistry, 98*(3), 557-570. Published. (Chapter 1)

Bruce, R. M., Atungulu, G. G., Sadaka, S., & Mauromoustakos, A. (2022). Influence of harvest moisture content and milling duration on microwave-dried rice physicochemical properties. *Cereal Chemistry,* 1-15. Published. (Chapter 2)

Bruce, R. M., Atungulu, G. G., Sadaka, S., & Mauromoustakos, A. (2022). Aging characteristics of rice dried using microwave at 915 MHz frequency. *Cereal Chemistry*. Accepted for publication. (Chapter 3)

INTRODUCTION

Rice drying by using the 915 MHz industrial microwave is a novel technology that is being explored to improve head rice yield and reduce the energy cost of drying. Previous works have investigated the feasibility of one-pass drying, physicochemical properties, and energy characteristics of medium grain rice dried using the 915 MHz industrial microwave dryer (Atungulu et al, 2016; Olatunde et al, 2017; Smith et al, 2018). However, there remain many questions about the processing conditions, functional, physicochemical, and aging properties of different rice cultivars dried with the 915 MHz industrial microwave. The goal of this research is to provide processing conditions that are useful for the commercialization of the 915 MHz industrial microwave technology for rice drying by evaluating the functional, physicochemical, and aging properties of different rice cultivars dried with the 915 MHz industrial microwave.

Rice is generally dried using natural air at ambient temperatures or heated air. The current methods of rice drying have not been successful in preventing rice breakage. This results in a reduction in rice quality since rice is usually eaten as head rice or whole kernels. Head rice is the high-value portion of dried rice that refers to the mass of milled rice kernels that are at least 3/4th of the original kernel length after milling of brown rice. Revenue losses related to head rice yield recovery in the U.S. in 2019 using conventional rice drying methods was approximately $234 million (Childs, 2019). Microwave heating has a great potential for rice drying and reducing rice breakage because of its unique heating mechanism. During microwave heating, heat is evenly distributed throughout the entire volume of the material, a process known as volumetric heating. The process contrasts with traditional heated-air processing which relies on conduction and convection from hot surfaces to deliver energy into the heated material.

Hypothesis

It is hypothesized that the volumetric heating associated with microwave technology will reduce moisture content and temperature gradients within individual rice kernels and result in better head rice yields compared to those achieved with air-drying (Olatunde et al., 2017). Additionally, the high heat fluxes associated with microwave heating will result in one-pass drying of rough rice, from harvest moisture contents to a safe storage moisture content (12.5%). The high heat flux of microwaves also has the potential to cause starch modifications which can be desirable in some food processes. Finally, because of the morphological differences (physical size and shape geometry) among long-grain hybrid, long-grain pureline, and medium-grain rice cultivars, it is hypothesized that different rice types dried with the 915 MHz industrial microwave may exhibit different drying responses.

Objectives

The goal of this research is to provide processing conditions for the single-pass drying of rough rice using the 915 MHz industrial microwave. This dissertation is presented in a “published/submitted papers” format. Each chapter is a stand-alone paper that has been published or is in preparation for submission to a peer-reviewed journal. Below are the chapter titles and objectives of the dissertation:

Chapter 1: Impact of specific energy input of a 915 MHz microwave dryer on quality, functional, and physicochemical properties of different rice cultivars.

Objectives

1. Determine the effect of microwave specific energy on the quality, functional and physicochemical properties of long grain hybrid and medium grain rice cultivars.

2. Develop models for prediction of desirable microwave specific energy to achieve one-pass drying of long grain hybrid and medium grain rough rice cultivars based on quality characteristics.
3. Determine the impacts of microwave specific energy on the physicochemical properties of long grain hybrid rice grown in different soil and environmental conditions.

Chapter 2: Influence of harvest moisture content and milling duration on microwave-dried rice physicochemical properties.

Objectives

1. Determine the effect of harvest moisture content on the physicochemical properties of microwave dried rice.
2. Determine the effect of milling duration on the physicochemical properties of microwave dried rice.
3. Determine desirable harvest moisture content and milling duration for rice dried using microwave at 915 MHz frequency.

Chapter 3: Aging characteristics of rice dried using microwave at 915 MHz frequency.

Objective

1. Determine the physicochemical properties of rice dried using a 915 MHz microwave and then aged.

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CHAPTER 1

IMPACT OF SPECIFIC ENERGY INPUT OF A 915 MHZ MICROWAVE DRYER ON QUALITY, FUNCTIONAL AND PHYSICOCHEMICAL PROPERTIES OF DIFFERENT RICE CULTIVARS

Rebecca M. Bruce, Griffiths G. Atungulu, Sammy Sadaka, Deandrae Smith

ABSTRACT

Background and objectives: The 915 MHz industrial microwave has a great penetration depth relative to the 2.45 GHz microwave and holds the potential to achieve one-pass drying of deeper rice beds within a short drying duration. The objective of this research is to determine the effect of microwave specific energy on the quality, functional and physicochemical properties of different rice cultivars. Two rice cultivars were used: a medium grain cultivar (Titan) and a long grain hybrid cultivar (XL753) from two different locations (Burdette and Carlisle). Rice samples at harvest moisture content of 20% wet basis were dried using the 915 MHz industrial microwave at specific energies ranging from 360-720 kJ per kg of initial wet grain mass (kJ.[kg-grain]$^{-1}$). Rice physicochemical and functional properties were analyzed.

Findings: Results indicate that specific energy had a significant effect (p-value <0.0001) on moisture removal and head rice yield. On average, increasing specific energy (drying duration 3-4 min, power 4-6 kW) resulted in increased moisture points removed from 2.5% to 7.3% and 3.7% to 7.5% for long grain hybrids and medium grain cultivars, respectively, while head rice yield decreased. Setback and final viscosities increased while peak viscosity decreased with increasing specific energies. Kernel surface lipid and protein content slightly decreased with increasing specific energies, although specific energy did not have a significant effect on these responses.

Resistant starch content decreased with increasing specific energy for hybrid rice. Water and oil absorption capacities varied at different specific energies. The most desirable specific energy for moisture removal that maintains rice quality characteristics (relative to control samples) was 525 kJ.[kg-grain]$^{-1}$.

Conclusions: The 915 MHz industrial microwave has the potential to achieve one-pass drying of rice. A study of the best specific energy for drying different cultivars of rice using this technology is essential to meet the diverse industrial needs for rice drying.

Significance and novelty: This study provides science-based information on the properties of different rice cultivars dried using the 915 MHz microwave and selection of desirable microwave parameters for rice drying. The technology has a great potential to transform the rice drying industry by decreasing rice drying duration, improving milling yield and energy efficiency.

Keywords: Rice cultivars, One-pass drying, Milling yields, Rice quality.

INTRODUCTION

Microwave energy is a type of electromagnetic energy with frequencies ranging from 300 MHz to 300 GHz and wavelengths of 1 m to 1 mm, respectively (Oghbaei & Mirzaee, 2010). The mechanism of microwave heating involves the alignment of the dipolar nature of water molecules and the ionic mechanism by the electric field. The vibration of water molecules at high amplitude leads to associated internal friction, which enables volumetric heating (Olatunde, Atungulu, & Smith, 2017). Typically, industrial microwaves operate at a frequency of 915 MHz, while domestic microwaves operate at 2.45 GHz (Olatunde et al., 2017; Oghbaei, & Mirzaee, 2010). Over the years, the 2.45 GHz microwave has been widely researched. However, the technology has not been successful in rice drying due to the limited penetration depth into products, which result in non-uniform heating (Kumar, 2015; Smith, Atungulu, Sadaka, & Rogers, 2018).

Recently, the 915 MHz industrial microwave with 3 times more penetration power than the 2.45 GHz microwave and higher energy efficiency has been explored for rice drying (Wang et al., 2003; Atungulu et al., 2016; Olatunde et al., 2017; Smith et al., 2018). The technology has a significant advantage of reducing rice drying duration. Existing rice drying technologies such as conventional heated-air dryers use long drying durations and several passes to dry rice leading to high energy cost, rice breakage and a reduction in quality. Atungulu et al. (2016) demonstrated that the 915 MHz industrial microwave has the potential of performing one-pass drying of rice within a short drying duration. They achieved this by drying a medium grain rice cultivar (*cv*) Jupiter from initial harvest moisture content of 23% to 14% using a specific energy of 600 kJ.[kg-grain]$^{-1}$ with 4 h tempering at 60°C. This breakthrough is significant in exploring energy and efficiency for future rice drying technologies because one-pass drying of rice reduces energy cost, rice breakage and improves rice quality.

Olatunde et al., (2017) studied the quality of medium-grain rice (*cv.* Jupiter) dried with the 915 MHz microwave at microwave specific energies of 450, 600 and 750 kJ.[kg-grain]$^{-1}$. The study reported that increasing rice bed thickness and specific energy reduced milling and head rice yields, increased final viscosity of milled rice, but marginally influenced peak viscosity, surface lipid and protein content of rice. Further studies by Smith et al., (2018) on the implications of microwave drying using 915 MHz frequency on physicochemical properties of the rice (*cv.* Jupiter) show that increasing microwave specific energy resulted in increased surface lipid content, peak and final viscosities. Protein content was inversely proportional to specific energy; significantly higher at lower specific energy of 533.33 kJ.[kg-grain]$^{-1}$ and decreased at a higher specific energy of 900 kJ.[kg-grain]$^{-1}$. Also, varying rice bed thickness up to a depth of 15 cm did not have a significant effect on peak and final viscosities of microwave dried rice.

The limitation of studies conducted so far on use of the 915 MHz frequency of microwave to dry rice lies in the inability to explore a much wider range of specific energies and cultivars, especially long grain hybrid cultivars. This study hypothesized that because of the morphological differences which include physical size and shape geometry among long-grain hybrid, long-grain pureline, and medium-grain rice cultivars, the rice types may exhibit different drying responses. The long-grain hybrid rice cultivars have pubescent characteristics that neither the long-grain pureline nor the medium-grain cultivars have. There are still many questions that need to be addressed to fully develop microwave drying technology using the 915 MHz frequency. Currently, parameters required (power, heating duration) to achieve one-pass drying of different cultivars of rice especially long grain hybrid rice cultivars are unknown. About 42% of rice grown in Arkansas, (largest rice producing state in USA) are long grain hybrids (Hardke, Moldenhauer, & Sha, 2018). Hybrid rice cultivars are characteristically blast resistant and have excellent yield potential. The influence of microwave specific energy on drying, physicochemical, and functional properties of long grain hybrid rice cultivars is vital for expansive use of the 915 MHz industrial microwave dryer for commercial rice drying purposes. Furthermore, rice growing location can influence the physicochemical properties of rice (Pitiphunpong, & Suwannaporn, 2009). It is therefore important to study the impacts of rice growing location on rice dried using the 915 MHz industrial microwave dryer. This research also hypothesized that the volumetric heating associated with microwave technology will reduce moisture content and temperature gradients within individual rice kernels and result in better head rice yields compared to those achieved with air-drying (Gowen, Abu-Ghannam, Frias, & Oliveira, 2006; Vadivambal & Jayas, 2007; Olatunde et al., 2017).

Additionally, the high heat fluxes associated with microwave heating will result in one-pass drying of rough rice, from harvest moisture contents to safe storage moisture content (12.5%).

This research seeks to; (1) Determine the effect of microwave specific energy on the quality, functional and physicochemical properties of long grain hybrid and medium grain rice cultivars. (2) Develop models for prediction of desirable microwave specific energy to achieve one-pass drying of long grain hybrid and medium grain rough rice cultivars based on quality characteristics. (3) Determine the impacts of rice growing location on the physicochemical properties of long grain hybrid rice dried using the 915 MHz industrial microwave dryer.

MATERIALS AND METHODS

Sample procurement and preparation

Fresh paddy rice from different geographical locations in Arkansas was used for this research. Titan, a medium grain cultivar from Pine Tree and two different sets of XL753, long grain hybrid cultivar from Burdette, and Carlisle were procured. Burdette and Carlisle are 150 miles apart. The two different sets of XL753 rice cultivar were used to study geographical properties of the same cultivar of rice. Henceforth, XL753-Carlisle and XL753-Burdette will mean XL753 sourced from Carlisle and Burdette respectively. All rice samples had initial harvest moisture content of 20%±0.5 (wet basis). Paddy rice moisture content was measured using a grain moisture tester (AM 5200, Perten Instruments, Hagersten, Sweden). The rice samples were treated with two different drying methods; natural air drying as control compared to microwave heating followed by tempering and natural air cooling. For control, approximately 2000 g of each rice cultivar in duplicates were exclusively dried using an equilibrium moisture content (EMC) chamber at 25°C and 65% relative humidity (RH) to a safe moisture content of 12.5% (henceforth the moisture content will be in wet basis). The experimental design is shown in Table 1. A flow chart of the methodology is shown in Figure 1.

Microwave treatment

Exactly 2000 g of each rough rice sample placed in a polypropylene microwave blind tray fitted with Teflon mesh was dried in an industrial microwave system (AMTek, Applied Microwaves Technology Inc., Cedar Rapids, IW, USA) at 915 MHz using specific energies ranging between 360-720 kJ per kg of the initial wet mass of the grain (henceforth the units are indicated as kJ.[kg-grain]$^{-1}$). Rice bed thickness was 2-3 inch. Microwave specific energy is the energy transferred per unit mass of product (Smith et al., 2018). Parameters for calculation of specific energy are shown in Table 2. Following microwave treatment, samples were immediately transferred into glass jars and tightly sealed. The samples were tempered in an incubator at 60˚C for 4 h. After tempering, evenly spread samples were allowed to cool in the EMC chamber at 25˚C and 65% relative humidity (RH). The moisture content of the samples were analyzed using AM 5200 Grain Moisture Tester (PERTEN Instruments). Samples that did not attain required moisture content of 12.5% were further dried in the EMC chamber.

Milled rice and head rice yield determination

All samples were milled on the same day. Exactly 150 g of each rice sample was dehulled using a huller (THU-35A, Satake Engineering, Tokyo, Japan) and milled using a laboratory mill (McGill Number 2, Rapsco, Brookshire, TX, USA) for 60 s to obtain surface lipid content standardized at 0.4%. The milled rice was separated into head rice and broken rice using a grain separating device (Grain Machinery Manufacturing Miami, FL, USA). Milled kernels of at least

75% of the length of whole kernels are considered as head rice. Head rice yield was calculated as the mass percentage of rough rice that remained as head rice. The head rice was used for all analyses in this research. For analysis that required the use of flour, samples were grinded using UDY cyclone sample mill (UDY Corp., Ft. Collins, CO) fitted with a 0.50-mm screen (Bruce, Atungulu, & Sadaka, 2019b).

Surface lipid content

The surface lipid content of milled rice was determined as an indicator of the degree of milling. About 50 g of milled rice was scanned using a near infrared reflectance (NIR, DA7200, Perten Instrument, Hagersten, Sweden). The NIR equipment was calibrated using AACC International Approved Method (39-25.01) prior to the analysis (Matsler, & Siebenmorgen, 2005; Saleh, Meullenet, & Siebenmorgen, 2008). The calibration curve is as follows.

$$SLC = 0.871 \text{ x } SLC_{NIR} - 0.092 \ldots\ldots\ldots\ldots (1)$$

Where SLC is surface lipid content (approved method) (%) and SLC_{NIR} is surface lipid content (NIR method).

Crude protein content

The percentage crude protein content of milled rice was determined by scanning about 50 g of milled rice using a near infrared reflectance (NIR, DA7200, Perten Instrument, Hagersten, Sweden), following the AACC International Approved Method (39-25.01). Prior to the analysis, the NIR equipment was calibrated using AACC International Approved Method (46-16.01). The equipment converted sensor data to crude protein through the following calibration equation;

$$\text{Crude protein (CP)} = 0.747 \text{ x } CP_{NIR} + 1.893 \ldots\ldots\ldots\ldots\ldots (2)$$

CP_{NIR} is the crude protein determined using the NIR method. Crude protein was reported on wet basis. (Bruce, Atungulu & Sadaka, 2020).

Whiteness index

Whiteness index was determined according to the method described by Pruengam, Soponronnarit, Prachayawarakorn, & Devahastin, (2014). The color of milled rice samples were measured using a near infrared reflectance (NIR, DA7200, Perten Instrument, Hagersten, Sweden). The sample color was described based on International Commission on Illumination (CIE) L^*, a^*, b^* color system. Whiteness index (WI) was calculated as follows:

$$WI = 100 - [(100-L^*)^2 + (a^*)^2 + (b^*)^2]^{0.5} \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

Pasting property

Pasting viscosities of rice flour were determined according to the AACC international approved method 61-02.01. The viscosities were determined on the paste of 3 g rice flour and 25 mL water using a viscometer (RVA-Super 4, Newport Scientific, Warriewood, NSW, Australia), which adjusts for moisture content. The flour paste was held at 50°C for 1.5 min, ramped to 95°C at 12.2°C /min, held for 2 min and then cooled to 50°C at 12.2°C /min and held for 1.5 min (Bruce et al., 2019b). The paste viscosities were recorded in centipoises, the peak time was recorded in seconds and the pasting temperature was recorded in degrees Celsius.

Water absorption capacity (WAC)

Water absorption capacity of rice flour samples was determined using the method described by Onwuka (2005) with modifications. About 1 g of the flour sample in a 15mL centrifuge tube was suspended in 10 mL of water and shaken for 1 minute at room temperature. The sample was allowed to settle for 30 min and centrifuged at 1200 x g for 30 min. The volume of supernatant was read directly from the centrifuge tube.

$$\text{WAC}\ (\%) = \frac{\text{Amount of water added} - \text{Free water}}{\text{Weight of sample}} \times \text{ density of water } \times 100 \ldots\ldots\ldots (4)$$

Oil absorption capacity (OAC)

Oil absorption capacity was measured to study how microwave dried rice interact with other lipophilic foods. About 1 g of the flour was mixed with 10 mL refined corn oil in a centrifuge tube and allowed to stand at room temperature for 1 h. The samples were centrifuged at 1600 x g for 20 min. The volume of free oil was recorded and decanted (Onwuka, 2005). The oil absorption capacity was expressed as mL of oil bound by 100 g dried flour**.**

$$\text{OAC}\ (\%) = \frac{\text{Amount of oil added} - \text{Free oil}}{\text{Weight of sample}} \times \text{ density of corn oil } \times\ 100 \ldots\ldots\ldots (5)$$

Digestible starch and resistant starch determination

Rice flour digestible starch and resistant starch content were determined using the Megazyme resistant starch assay procedure rapid format kit which is a modification of AOAC Method 2002.02 and AACC Method 32-40.

Hydrolysis and solubilization of digestible (non-resistant) starch

Exactly 100 mg of each rice flour sample was weighed directly into screw capped polypropylene tubes. About 3.5 mL of sodium maleate buffer (pH 6.0) was added to each sample and vortexed for 5 s. The samples were equilibrated in a water bath at 37°C for over 5 min. Exactly

0.5 mL of PAA/AMG (pancreatic α-amylase/amyloglucosidase) solution was added to each tube and further incubated at 37°C with continuous shaking (200 strokes/min) for 4 h. After incubation, the reaction was stopped by addition of 4.0 mL of 95% v/v ethanol with vigorous vortexing. The samples were centrifuged at 4,000 rpm for 10 min in a bench centrifuge and the supernatant was carefully decanted and retained for “digestible starch” analysis. The pellet was re-suspended in 2 mL of 50% v/v ethanol with vigorous vortexing. An additional 6 mL of 50% v/v ethanol was added to the samples and mixed thoroughly by inversion. The samples were centrifuged at 4,000 rpm for 10 min and the supernatant was decanted. The suspension and centrifugation process were repeated twice. Both supernatants were combined with the previously obtained supernatant for determination of “digestible starch”. The tubes with the pellets were inverted on absorbent paper to remove excess liquid.

Measurement of resistant starch

Each sample pellet was re-suspended in 2 mL of cold 1.7 M NaOH and stirred for 20 min in an ice/water bath. Exactly 8 mL of 1.0 M sodium acetate buffer (pH 3.8) was added to each tube with continuous stirring. Immediately, 0.1 mL of AMG was added, mixed well and tubes were incubated at 50°C for 30 min with intermittent vortexing. Aliquots (2 mL) of the tube contents were centrifuged at 13,000 rpm for 5 min. Exactly 0.1 mL aliquots (in duplicate) of the supernatants were transferred into glass test tubes. About 3.0 mL of GOPOD reagent (Glucose Determination Reagent) was added to the samples and incubated at 50°C for 20 min. The absorbance of each solution was measured at 510 nm against the reagent blank. The resistant starch content was calculated.

Measurement of digestible (non-resistant) starch

The supernatant obtained upon centrifugation of the initial incubation was combined with the supernatants obtained from the subsequent two 50% v/v aqueous ethanol washings and the volume was adjusted to 100 mL with distilled water in a volumetric flask. The contents were mixed well. Duplicate 0.1 mL aliquots of this solution were transferred to the bottom of glass test tubes. Exactly 0.1 mL of dilute AMG was added and incubated at 50°C for 30 min. Next, 3.0 mL of GOPOD reagent was added and incubated for 20 min at 50°C. The absorbance was measured at 510 nm against a reagent blank. The digestible starch was calculated as follows:

$$\text{Resistant Starch (g/100g)} = \Delta A \times F \times (EV/W) \times 0.90 \ldots\ldots\ldots (6)$$

$$\text{Digestible Starch (g/100g)} = \Delta A \times F \times (EV/W) \times 0.90 \ldots\ldots\ldots (7)$$

where:

ΔA = absorbance of sample solution read against reagent blank.

F = factor to convert absorbance values to mg glucose (100 mg glucose divided by the absorbance value obtained for 100 mg of glucose).

EV = sample extraction volume (10.3 mL or 100 mL).

W = sample weight in mg.

Statistical analysis

All quality, functional, and physicochemical properties of rice samples were determined in duplicates. Simple linear regression, analysis of variance, Tukey’s honest significant difference test, and response surface analysis were performed using statistical software (JMP Pro 15, SAS Institute, Cary N.C.) to determine significant differences between samples. The level of significance was set at 5% for mean comparison.

RESULTS AND DISCUSSION

Effect of microwave specific energy on drying and milling properties

A plot of drying and milling properties of control samples and rice dried using the 915 MHz microwave is shown in Figure 2. Generally, head rice yield decreased at higher specific energies for all cultivars. There were specific energies (360, 420 and 450 kJ.[kg-grain]$^{-1}$) that had slightly higher or comparable head rice yield with the control samples. Specific energy had a significant effect and a moderate negative correlation (-0.5544) with head rice yield (Table 3). The control samples were gently dried with natural air (at 25˚C and 65% RH) to maintain high head rice yields and are represented in the graph as samples with microwave specific energy = 0. Head rice yield is an acceptable commercial index of rice physical quality characteristics (Ondier, Siebenmorgen, & Mauromoustakos, 2010). It determines the value for rice produced; therefore, higher head rice yield is desirable. The low head rice yield at higher specific energies may be due to rapid drying with high temperatures which causes fissure formation in rice kernels. High specific energies are characterized by high power and longer drying durations (Table 2). High temperature and rapid moisture removal may be associated with increased fissure formation leading to lower head rice yield (Siebenmorgen, Yang, & Sun, 2004).

In terms of moisture removal, higher specific energies resulted in more moisture removal from rice kernels (Figure 2). Specific energy had significant influence and a strong positive correlation (0.9450) with moisture points removed (Table 3). The results are consistent with the findings of Olatunde et al. (2017) who also reported significant impact of specific energy on percent point moisture reduction for medium grain (Jupiter) rice. High specific energy is associated with high surface temperature of rice (95˚C surface temperature for rice dried at 5 kW and 4 min) and high entropy of water molecules, hence moisture loss (Atungulu et al., 2016). The ideal microwave heating process needs to maximize moisture removal and maintain high head rice yield.

Effect of microwave specific energy on physicochemical properties

Generally, whiteness index of microwave dried rice was slightly higher than the control samples (Figure 3). Specific energy did not have a significant effect on the whiteness index, surface lipid content and protein content of microwave dried rice (Table 3). There were very weak correlations between specific energy and physicochemical properties (Table 3). Samples dried at high specific energies had lower surface lipid contents. The trends observed in the physicochemical properties of microwave dried rice can be attributed to the ease of bran removal during milling. Rice bran is rich in oils and proteins and impact kernel color (Puri, Dhillon, & Sodhi, 2014). More rice bran removal during rice milling is associated with higher kernel whiteness, lower surface lipid, and protein content. The lower protein content of cultivar XL753 grown in Carlisle may be due to differences in edaphic factors such as soil nitrogen content during rice production (Prakash, Bhadoria, Amitava & Rakshit, 2002).

Previous literature has various reports on the effect of microwave heating on the physicochemical properties of cereals and grains. An obvious trend in this current study and works done by Olatunde et al., (2017) and Smith et al., (2018) is that different microwave specific energies impact product characteristics differently, especially specific energies above 600 kJ.[kg-grain]$^{-1}$. Characteristics of microwave-dried maize did not alter the protein content (measured by Kjeldahl's method) of maize though some structural changes in starch and protein were noticed (Velu, Nagender, Prabhakara Rao, & Rao, 2006). Smith et al. (2018) reported a significant increase in the protein content of microwave dried rice at specific energy of 533.33 kJ.[kg-grain]$^{-1}$ but a significant decrease at 900 kJ.[kg-grain]$^{-1}$ relative to control samples. This was attributed to possibility of protein denaturation at higher specific energies. The report also shows significantly higher surface lipid contents with increasing specific energy which is contrary to the present study. The upsurge in surface lipid was attributed to the hardening of rice bran upon microwave heating (Smith et al., 2018). The classical difference in the current study and the work done by Smith et al. (2018) is the milling duration (30 s) and rice cultivar (medium grain Jupiter). Therefore, it is possible that cultivar or milling duration is responsible for the disparities since milling duration of 60 s and different rice cultivars were used in this research. In summary, changes in physicochemical properties of microwave dried rice using 915 MHz frequency are greater at higher specific energies (above 600 kJ.[kg-grain]$^{-1}$) and it is possible to dry rice using microwave at 915 MHz frequency and optimize rice physicochemical characteristics by selecting the right specific energy.

Effect of microwave specific energy on starch and pasting properties

Specific energy had a significant impact (p-value<0.05) on most pasting properties; final viscosity, peak viscosity, setback viscosity, pasting temperature and peak time (Table 3). Peak viscosity is the highest viscosity of a food product during cooking (Bruce et al., 2019b). It decreased with increasing specific energy and a weak negative correlation between peak viscosity and specific energy was observed (Figure 4). Final viscosity which is an index of the final nature of a food product and a measure of the ability of starch to form a viscous paste upon cooking and cooling (Maziya-Dixon, Dixon, & Adebowale, 2007; Bruce & Atungulu, 2018) was found to increase with increasing specific energy. The increase might be due to increased retrogradation of amylose-like molecules. Similar results on medium grain rice (*cv.* Jupiter) dried at different bed thickness (1 m x10^{-2} and 5 m x10^{-2}) and specific energy of 450-600 kJ.[kg-grain]$^{-1}$ with significantly higher final viscosity (EMC dried) has been reported by Olatunde et al., (2017). Setback viscosity also increased with increasing specific energy. Starch with higher setback viscosity has higher tendency of retrogradation (Zaidul, Norulaini, Omar, Yamauchi, & Noda, 2007). It is desirable in the production of lower calorie products through formation of type 3 resistant starches (retrograded starches).

Changes in viscosity profile may be due to modifications in the starch structure during microwave drying. They may result in formation of damaged starch affecting the amylographic/ pasting characteristics of rice (Pinkrova, Hubackova, Kadlec, Prihoda, & Bubnik, 2003). Starch damage is likely to modify the surface properties of starch granules by increasing the hydrophilic bonds and fragmented amylopectin molecules, thereby decreasing viscosity parameters relative to intact granules (Tester, Patel, & Harding, 2006; Stevenson, Jane, & Inglett, 2007). High damage starch content indicates greater degree of granule disintegration and a smaller occupied volume fraction of the dispersion and a continuous phase-enriched amylopectin (Ma et al., 2016). Consequently, the higher degree of free water and a lower proportion of swollen granules occupying space at a lower starch concentration can contribute to lower viscosity (Ma et al., 2016).

Resistant starches are indigestible by amylases in the small intestines. Higher resistant starch content is preferable because foods with high resistant starch content have low glycemic index; thus, they can protect against health conditions such as type 2 diabetes, obesity, and cardiovascular diseases (Kendall, Emam, Augustin, & Jenkins, 2004). Titan, a medium grain rice had a lower resistant starch and higher digestible starch content than XL753 (Figure 6) thereby revealing cultivar effect (Table 4). Generally, resistant starch content decreased with decreasing specific energy. The digestible starch content trend was different for XL753 cultivars. The XL753 grown in Burdette had a slight decrease in digestible starch content with increasing specific energy, while XL753 from Carlisle had increased digestible starch with increasing specific energy. Specific energy and cultivar had significant effects on resistant starch with significant interactions between cultivar and specific energy (Table 4). The model explains 98% of the variability in resistant starch content. It was hypothesized that the increase in setback viscosity with increasing specific energy might lead to formation of type 3 resistant starches (retrograded starches). Although higher setback viscosities were recorded at higher specific energies, resistant starch did not increase with increasing specific energy. It is possible that the resistant starch content of the microwave dried samples may change upon cooking and cooling since that process is conducive for formation of retrograded starches (Marson & Topping, 1993).

Effect of microwave specific energy on functional properties

Functional properties describe the behavior of ingredients during cooking and how they interact with other food ingredients in a food system. They determine the application and end-use of food ingredients (Adeleke & Odedeji, 2010). The functional properties of control samples and rice dried using the 915 MHz microwave is shown in Figure 6. Different specific energies had varied oil and water absorption capacities. Specific energy had no significant effect on oil and water absorption capacities of microwave dried rice (Table 3). The variation in the functional properties of Titan is different from XL753, showing cultivar effect. Though specific energy did not have a significant impact on the functional properties (oil and water absorption capacities) of microwave-dried rice, the slight variations observed in the functional properties of control samples and rice samples dried at different microwave specific energies may be due to changes in starch and protein structure during microwave heating. Walde, Balaswamy, Velu, & Rao, (2002) in their work on microwave drying of wheat reported that although the total protein content of microwave-dried samples of wheat was not significantly different from the control (9.9%), there were changes in structural and functional characteristics of wheat protein–gluten. Functional properties are influenced by protein content and structure. Protein is the major chemical component that affects oil absorption capacity (Chandra, Singh, & Kumari, 2015). Hydrocarbon chains of lipids can form hydrophobic interactions with non-polar amino acid side chains of proteins (Jitngarmkusol et al., 2008). Therefore, changes in protein structures during microwave drying may impact water and oil absorption capacities.

Influence of cultivar

Cultivar, growing location, soil properties, climate, and post-harvest handling influence physicochemical and functional properties of rice (Bruce, Atungulu, Hettiarachchy, & Horax, 2019a; Bruce et al., 2019b). Cultivar had little impact on the rate of moisture removal from rice during microwave drying as both long grain hybrids and medium grains lost moisture with increasing specific energy. Additionally, cultivar had a significant impact on head rice yield, final viscosity, water absorption capacity, oil absorption capacity, resistant and digestible starches (Table 5). The slender structure of long grain hybrid rice makes it more susceptible to breakage than medium grain rice during milling, hence the cultivar effect reported in head rice yield. From the Tukey's honest significant difference test, in most cases, medium grain Titan was significantly different from the long grain hybrid XL753 cultivars in terms of milling, pasting, starch and functional properties. On the contrary, the water absorption capacity of Titan was not different from XL753 (Carlisle). The long grain hybrids had varied resistant starch content and water absorption capacity possibly due to rice growing location.

Effect of rice growing location

The impacts of location and specific energy on the physicochemical properties of long grain hybrid rice dried using the 915 MHz microwave is shown in Table 6. This is to study exclusively the behavior of long grain hybrid cultivar grown at different locations and dried using the 915 MHz microwave. Location had impact on moisture points removal, whiteness index, surface lipid content, water absorption capacity, peak viscosity, final viscosity, protein content and resistant starch content of long grain hybrid rice but not head rice yield. This is an indication that same cultivar grown at different locations with similar growth parameters, rice milling conditions and quality characteristics such as head rice yield can exhibit different functional and cooking properties. The growth history of rice influences its physicochemical properties. The effects of rice growing location can be attributed to differences in cultural practices such as irrigation, nitrogen application, and environmental factors such as pH, nighttime ambient temperature during grain development and essential soil elements like nitrogen, phosphorus, and potassium (Pitiphunpong, & Suwannaporn, 2009).

The models shown in Table 6 explain the effect of a change in location as well as the effect of varying microwave specific energy on rice quality characteristics. At a constant specific energy, a change in location from Carlisle to Burdette may result in the following: 0.522% decrease in moisture points removed, 0.527% decrease in head rice yield, 0.509 decrease in whiteness index, 0.082% increase in surface lipid content, 5.556% decrease in water absorption capacity, 130.167cP decrease in peak viscosity, 67.556cP increase in final viscosity, 1.569% increase in protein content and 0.813% decrease in resistant starch content. Therefore, changes in the properties of rice dried using the 915 MHz microwave should not only be attributed to the effect of microwave drying parameters (power and drying duration) but also the growth history of the rice. Ahn, Won, Rico,

& Lee (2010) noted that locations, varieties, and interactions between locations and varieties had a significant effect on the total phosphorus and phytate-phosphorus contents in rice. Location had a higher effect than variety. Hence, rice growing location is vital in influencing rice composition and functionality. Additionally, models for rice quality and physicochemical properties (Table 6) show that effect of rice growing location result in higher numerical changes in response variables than the effect of microwave specific energy. Consequently, the use of microwave technology is an effective method of drying rice with regard to rice quality and physicochemical properties because the numerical impact of specific energy on rice properties is smaller than that of a change in rice growing location. A major setback of the current study's experimental design was the small number of locations analyzed. It is recommended that more locations should be studied and variations in cultural practices be measured to fully understand the effect of rice growing location on the physicochemical properties of long grain hybrid rice dried using microwave 915MHz frequency.

Desirable specific energy for microwave drying of rice

Specific energy of 525 kJ.[kg-grain]$^{-1}$ (power-5kW, duration-3.5min) has been predicted as the most suitable for drying medium grain rice Titan and long grain hybrid XL753 based on physicochemical properties. Optimized rice characteristics for microwave drying at 525 kJ.[kg-grain]$^{-1}$ is shown in Table 7. This specific energy reduces on average the moisture content of freshly harvested rice (at 20% moisture content) by 5 moisture points, making one-pass drying of rough rice with harvest moisture content of 18-16% achievable. The head rice yields of samples dried at this specific energy are slightly lower than the control samples but provides a faster way of drying rice (Olatunde et al., 2017) which may compensate for the loss in head rice yield. The desirability column in Table 7 indicates the percentage success achieved in optimizing each rice physicochemical property.

Olatunde et al., (2017) and Smith et al., (2018) recommended a specific energy of 600 kJ.[kg-grain]$^{-1}$ for drying a medium grain rice (*cv.* Jupiter). In this study, although the specific energy of 600 kJ.[kg-grain]$^{-1}$ led to more moisture removal and rapid drying of rice kernels, the integrity of the kernels, as well as physicochemical and functional properties, significantly deviate from rice dried at ambient temperatures. Most physicochemical properties of the microwave dried rice at specific energy of 525 kJ.[kg-grain]$^{-1}$ match the control samples. However, pasting properties such as peak viscosity, final viscosity and setback viscosity are slightly different from the control samples. It is recommended that the cooking, sensory and storage properties of microwave dried rice at 525 kJ.[kg-grain]$^{-1}$ be analyzed to fully understand the effect of this technology on rice eating quality.

CONCLUSION

This is the first study to assess quality, physicochemical and functional characteristics of long grain hybrid rice and medium rice cultivar using the 915 MHz industrial microwave dryer. The significant findings of this research are:

(1) Microwave specific energy had a significant impact on rice quality and physicochemical properties such as moisture removal, head rice yield, pasting properties and resistant starch content.

    - Setback and final viscosity increased while peak viscosity decreased with increasing specific energies.

  - Kernel surface lipid content and protein content slightly decreased with increasing specific energies although specific energy did not have a significant effect on these responses.
  - Resistant starch content decreased with increasing specific energy for hybrid rice.
  - In terms of functional properties, specific energy had no significant effect on oil and water absorption capacities of microwave dried rice.

(2) Specific energy of 525 kJ.[kg-grain]$^{-1}$ (power-5kW, heating duration-3.5min) was predicted as the most suitable for drying medium grain rice Titan and long grain hybrid XL753 based on physicochemical properties relative to the control samples.

(3) Rice growing location had a significant effect on the physicochemical properties of long grain hybrid rice dried using the 915 MHz industrial microwave dryer. Therefore, changes in the properties of rice dried using the 915 MHz microwave should not only be attributed to the effect of microwave drying parameters (power and drying duration) but also the growth history of the rice.

It is recommended that the cooking, storage, and sensory properties of rice dried at the desirable specific energy of 525 kJ.[kg-grain]$^{-1}$ (power 5 kW, heating duration 3.5 min) be investigated to fully understand the effects of this technology on rice eating characteristics and consumer preference.

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TABLES AND FIGURES

Table 1. Experimental design.

Drying strategy	**Rice cultivars**	**Microwave treatment power (kW)**	**Microwave heating duration (min)**
1. Control treatment: natural air drying (temperature at 25°C and relative humidity at 65%) 2. Microwave heating followed by tempering at 60°C for 4 h and natural air cooling	XL 753 (Carlisle) XL 753 (Burdette) Titan	4 5 6	3 3.5 4

Table 2. Parameters for calculation of specific energy.

Power (kW)	**Mass (kg)**	**Duration (min)**	**Specific energy (kJ.[kg-grain]$^{-1}$)**
4	2	3	360
4	2	3.5	420
4	2	4	480
5	2	3	450
5	2	3.5	525
5	2	4	600
6	2	3	540
6	2	3.5	630
6	2	4	720

Table 3. Summary of linear associations between specific energy, physicochemical and functional properties for all rice cultivars dried using microwave at 915 MHz frequency.

Test	**Correlation**	**Parameter P-value**
Specific energy vs. Final viscosity	0.5976	<0.0001*
Specific energy vs. Peak viscosity	-0.4581	0.0005*
Specific energy vs. Setback viscosity	0.5229	<0.0001*
Specific energy vs. Pasting temperature	0.6632	<0.0001*
Specific energy vs. Peak time	0.6095	<0.0001*
Specific energy vs. Head rice yield	-0.5544	<0.0001*
Specific energy vs. Whiteness index	0.0449	0.7469
Specific energy vs. Surface lipid	-0.2633	0.0540
Specific energy vs. Protein content	-0.1987	0.1499
Specific energy vs. Moisture points removed	0.9450	<0.0001*
Specific energy vs. Water absorption capacity	-0.0756	0.5869
Specific energy vs. Oil absorption capacity	0.1503	0.2780

Sample size (n) =54

*Indicates statistical significance, $p<0.05$

Table 4. Effect summary table showing the effects of cultivar and specific energy on resistant and digestible starches.

Response	Source	P-value	R^2
Resistant starch	Cultivar	<0.0001*	0.9814
	Specific energy (kJ.[kg-grain]$^{-1}$)	<0.0001*	
	Cultivar*Specific energy (kJ.[kg-grain]$^{-1}$)	0.0134*	
Digestible starch	Cultivar	0.0000*	0.6389
	Specific energy (kJ.[kg-grain]$^{-1}$)	0.8031	
	Cultivar*Specific energy (kJ.[kg-grain]$^{-1}$)	0.4322	

*Indicates statistical significance, $p<0.05$

Table 5. Effect of cultivar on physicochemical and functional properties of microwave dried rice.

Test	**P-value**	**Tukey's honest significant difference test**		
		Titan	**XL753(Burdette)**	**XL753(Carlisle)**
Cultivar vs. Head rice yield	<0.0001*	A	B	B
Cultivar vs. Moisture points removed	0.2283	A	A	A
Cultivar vs. Final viscosity	<0.0001*	B	A	A
Cultivar vs. Water absorption capacity	0.0065*	A	B	A
Cultivar vs. Oil absorption capacity	0.0019*	B	A	A
Cultivar vs. Resistant starch	<0.0001*	C	B	A
Cultivar vs. Digestible starch	<0.0001*	A	B	B

*Indicates statistical significance, $p<0.05$. Sample size (n) =54
Levels not connected by the same letter in a row are statistically significant

Table 6. Impacts of location and specific energy on the physicochemical properties of long grain hybrid rice dried using microwave at 915 MHz frequency.

Model	**Whole model P-value (ANOVA)**	**R-square**	**P-values (parameter estimates)**	
			Specific energy	**Location**
MPR = -2.120-0.522L(B) +0.014SE	0.0010*	0.954	<0.0010*	<0.0010*
HRY = 76.494-0.527L(B) -0.067SE	<0.0010*	0.823	<0.0010*	0.6480
WI = 71.110-0.509L(B) -0.0002SE	0.0010*	0.342	0.7640	0.0000*
SLC = 0.405+0.082L(B)-0.0002SE	<0.0001*	0.790	<0.0001*	<0.0001*
WAC = 147.235-5.556L(B) +0.006SE	0.0037*	0.288	0.3988	0.0120*
PV = 3161.039-130.167L(B) -1.162SE	<0.0001*	0.602	<0.0001*	0.0023*
FV = 2953.417+67.556L(B) +1.034SE	<0.0001*	0.669	<0.0001*	0.0219*
PC = 4.987+1.569L(B) -0.001SE	<0.0001*	0.963	<0.0001*	<0.0001*
RS = 11.484-0.813L(B) -0.005SE	<0.0001*	0.547	<0.0001*	0.0009*

*Indicates statistical significance, p<0.05. Sample size (n) =36

Abbreviations

*ANOVA- Analysis of variance, MPR- Moisture points removed, SE- Specific energy, L(B)- Location (Burdette), HRY- Head rice yield, WI- Whiteness index, SLC- Surface lipid content, WAC- Water absorption capacity, PV- Peak viscosity, FV- Final viscosity, PC- Protein content and RS- Resistant starch.

Table 7. Summary of prediction profiler results for optimized specific energy of 525 kJ.[kg-grain]$^{-1}$. Sample size (n) =54. Rice harvest moisture content = 20%.

Response	**Cultivar**	**Optimized response**			**Control sample**	**Desirability (%)**
		Average	**Minimum**	**Maximum**		
Moisture points removed (%)	XL753(Burdette)	4.67	4.50	4.83	n/a	43.66
	XL753(Carlisle)	5.19	5.03	5.35	n/a	47.86
	Titan	5.51	5.35	5.67	n/a	67.34
Head rice yield (%)	XL753(Burdette)	40.76	39.19	42.32	44.90±0.24	43.66
	XL753(Carlisle)	41.29	39.72	42.85	50.87±0.47	47.86
	Titan	59.81	58.24	61.37	64.53±0.00	67.34
Final viscosity (cP)	XL753(Burdette)	3564.00	3523.98	3604.02	3126.50±9.19	52.79
	XL753(Carlisle)	3496.44	3456.42	3536.47	3007.50±75.66	52.72
	Titan	3215.00	3174.98	3255.02	2672±36.77	43.52
Peak viscosity (cP)	XL753(Burdette)	2420.83	2308.63	2533.03	2959.50±9.19	52.79
	XL753(Carlisle)	2551.00	2438.80	2663.20	2790.50±94.05	52.72
	Titan	3115.11	3002.91	3227.31	3326.00±29.70	43.52
Setback viscosity (cP)	XL753(Burdette)	1143.17	1011.19	1275.14	167.00±0.00	52.79
	XL753(Carlisle)	945.44	813.47	1077.42	217.00±18.38	52.72
	Titan	99.89	-32.09	231.87	-654.00±66.47	43.52
Whiteness index	XL753(Burdette)	70.51	70.32	70.70	69.57±0.30	47.74
	XL753(Carlisle)	71.02	70.83	71.21	70.23±0.86	48.45
	Titan	69.02	68.83	69.21	68.52±0.03	54.56

Table 7 Cont'd. Summary of prediction profiler results for optimized specific energy of 525 kJ.[kg-grain]$^{-1}$. Sample size (n) =54. Rice harvest moisture content = 20%.

Response	**Cultivar**	**Optimized response**			**Control sample**	**Desirability (%)**
		Average	**Minimum**	**Maximum**		
Surface lipid content (%)	XL753(Burdette)	0.39	0.38	0.41	0.38±0.01	47.74
	XL753(Carlisle)	0.31	0.30	0.32	0.34±0.02	48.45
	Titan	0.28	0.26	0.29	0.29±0.03	54.56
Protein content (%)	XL753(Burdette)	5.81	5.71	5.89	5.99±0.36	47.74
	XL753(Carlisle)	4.24	4.16	4.32	4.44±0.08	48.45
	Titan	6.04	5.96	6.13	6.37±0.01	54.56
Water absorption capacity (%)	XL753(Burdette)	145.00	142.38	147.62	145.00±7.07	59.61
	XL753(Carlisle)	150.56	147.93	153.18	145.00±7.07	81.42
	Titan	150.00	147.38	152.62	165.00±7.07	82.58
Oil absorption capacity (%)	XL753(Burdette)	136.4	134.03	138.77	134.85±6.58	59.61
	XL753(Carlisle)	138.47	136.10	140.83	130.20±0.00	81.42
	Titan	132.27	129.90	134.63	130.20±0.00	82.58
Resistant starch (%)	XL753(Burdette)	7.84	7.56	8.13	7.70±0.00	60.91
	XL753(Carlisle)	8.66	8.38	8.94	9.99±0.00	64.56
	Titan	0.29	0.01	0.57	0.34±0.00	15.88
Digestible starch (%)	XL753(Burdette)	70.46	69.00	71.92	71.46±0.00	60.91
	XL753(Carlisle)	70.16	68.70	71.62	71.80±0.00	64.56
	Titan	78.44	76.99	79.90	79.60±0.00	15.88

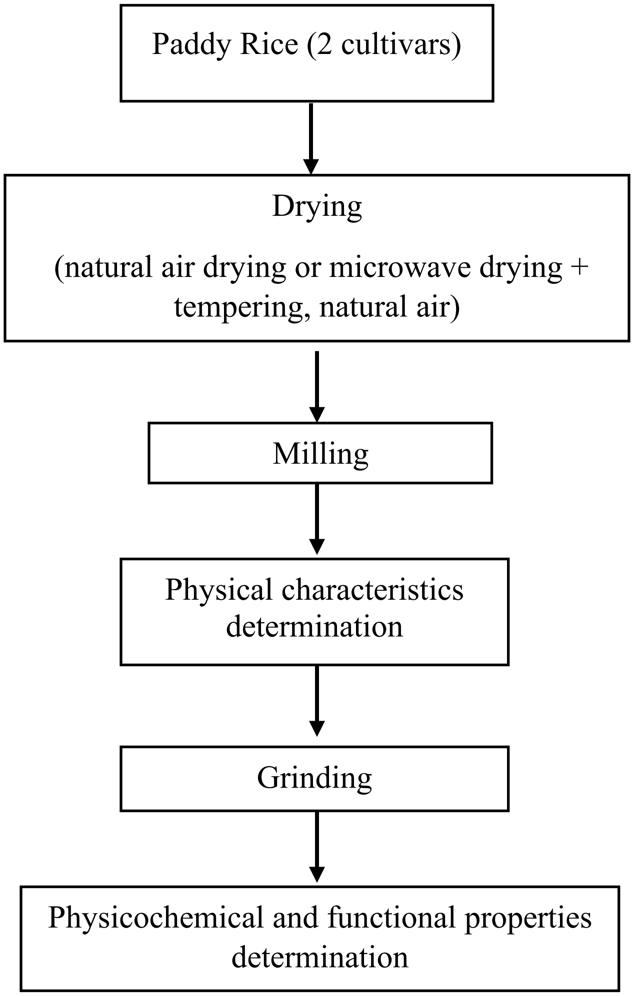

Figure 1. A flow chart of the methodology.

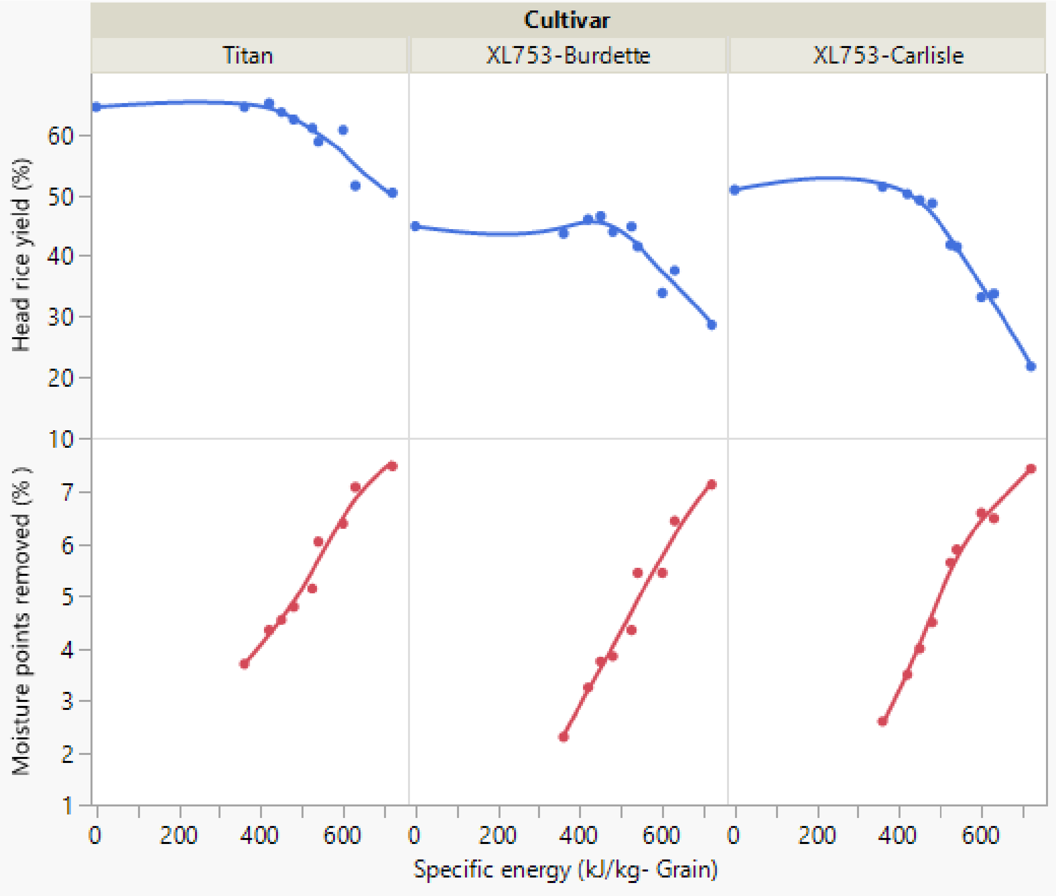

Figure 2. A plot of drying and milling properties of control samples and rice dried using microwave at 915 MHz frequency. Control samples were dried using the equilibrium moisture content chamber at 25˚C and 65% relative humidity (RH) and have microwave specific energy = 0. Burdette and Carlisle are the locations in Arkansas, where XL753 rice was grown.

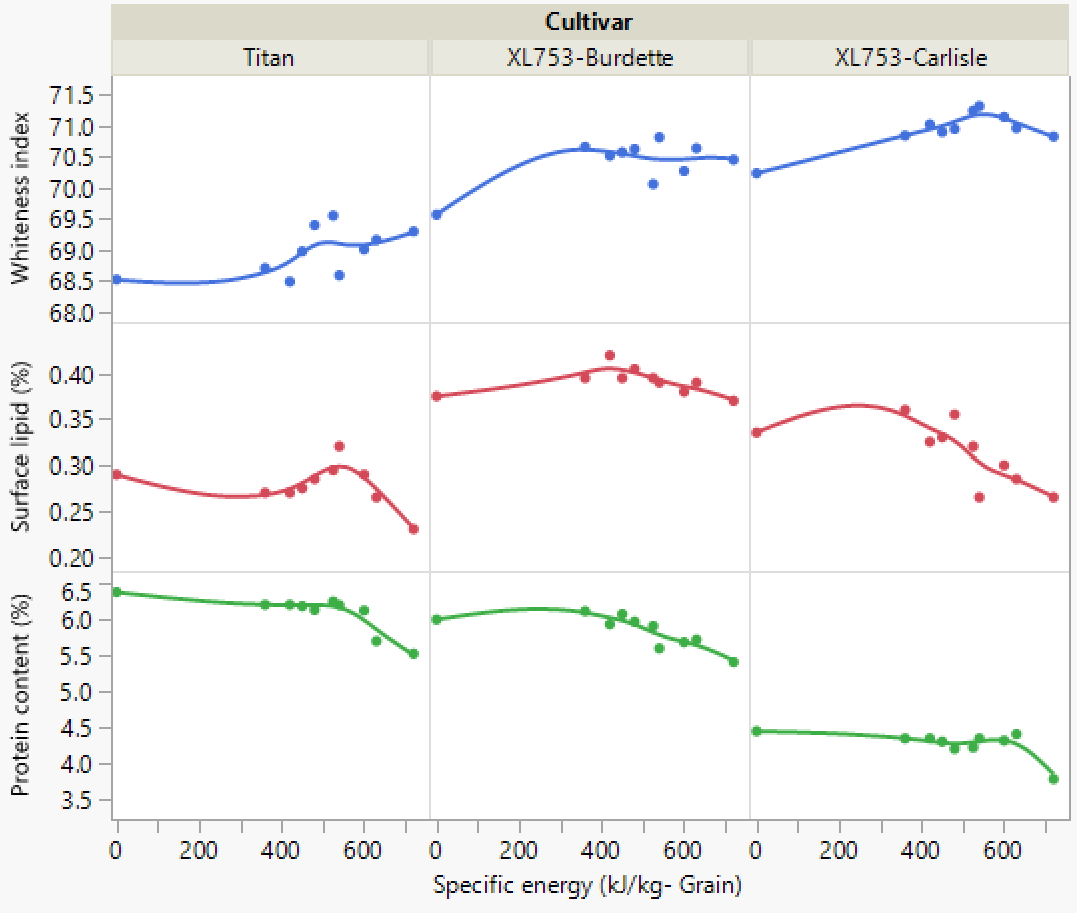

Figure 3. A plot of physicochemical properties of control samples and rice dried using microwave at 915 MHz frequency. Control samples were dried using the equilibrium moisture content chamber at 25˚C and 65% relative humidity (RH) and have microwave specific energy = 0.

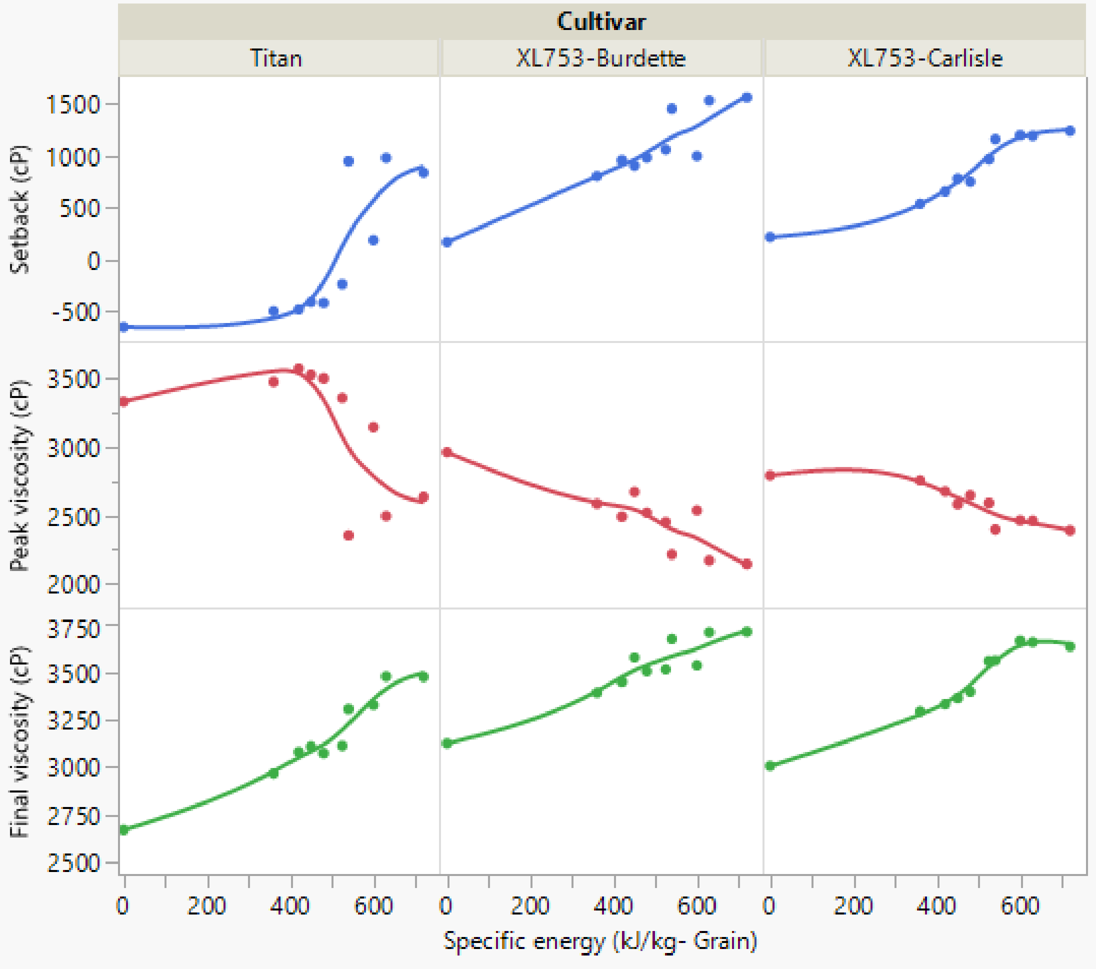

Figure 4. A plot of pasting properties of control samples and rice dried using microwave at 915 MHz frequency. Control samples were dried using the equilibrium moisture content chamber at 25˚C and 65% relative humidity (RH) and have microwave specific energy = 0.

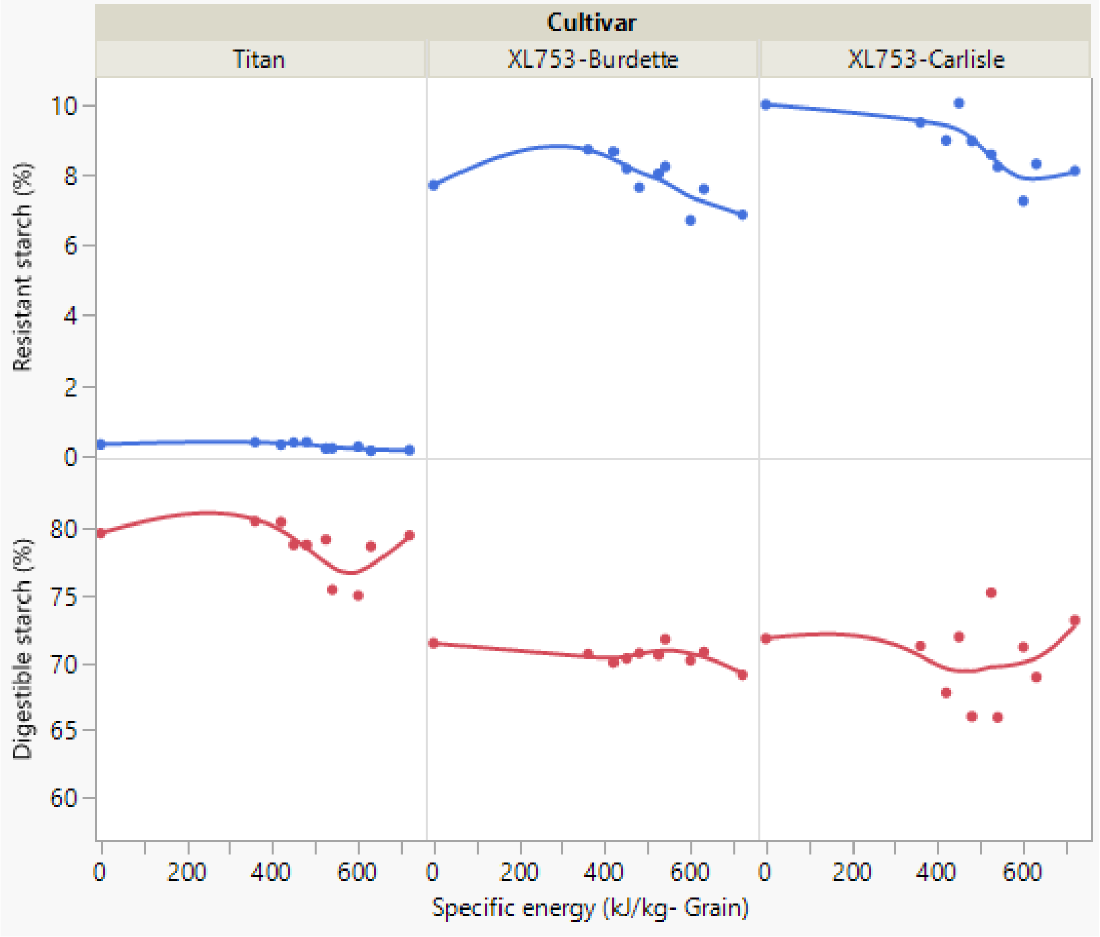

Figure 5. A plot of starch properties of control samples and rice dried using microwave at 915 MHz frequency. Control samples were dried using the equilibrium moisture content chamber at 25°C and 65% relative humidity (RH) and have microwave specific energy = 0.

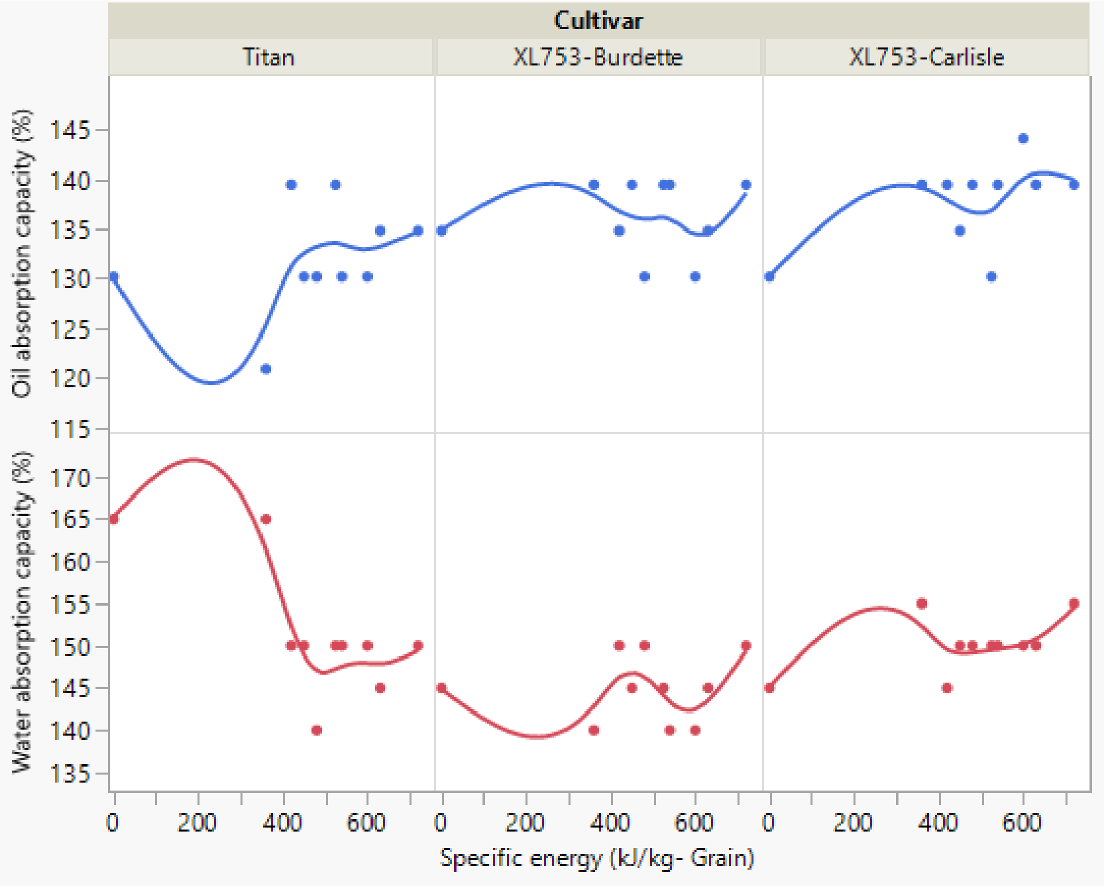

Figure 6. A plot of functional properties of control samples and rice dried using microwave at 915 MHz frequency. Control samples were dried using the equilibrium moisture content chamber at 25˚C and 65% relative humidity (RH) and have microwave specific energy = 0.

CHAPTER 2

INFLUENCE OF HARVEST MOISTURE CONTENT AND MILLING DURATION ON MICROWAVE-DRIED RICE PHYSICOCHEMICAL PROPERTIES

Rebecca M. Bruce, Griffiths G. Atungulu, Sammy Sadaka, Andy Mauromoustakos

ABSTRACT

Background and objectives: Harvest moisture content (HMC) and milling duration are important factors that influence milled rice quality. The goal of this research is to determine the effect of HMC and milling duration on the physicochemical properties of long grain and medium grain microwave-dried rice. A long-grain hybrid rice cultivar (XL753) and a medium grain rice cultivar (Titan) with initial HMCs of 16%, 18% and 20% (wet basis) were sourced from rice farms in Arkansas, USA. The rice samples were dried with the 915 MHz industrial microwave at a specific energy of 525 kJ/[kg-grain]. The control samples were dried with natural air in an equilibrium moisture content chamber set at 25°C and 56% relative humidity. Following drying, the samples were milled at milling durations of 30 s, 45 s, and 60 s, and physicochemical properties were determined.

Findings: HMC had significant ($p<0.05$) impacts on head rice yield, crude protein content and final viscosity of microwave-dried rice for both cultivars. There were strong positive correlations (Titan: 0.86, XL753: 0.88) between HMC and head rice yield and negative correlations (Titan: -0.85, XL753: -0.62) between HMC and final viscosity of microwave-dried rice. Milling duration significantly influenced the surface lipid content and whiteness index of microwave-dried rice for both cultivars. Furthermore, milling duration had significant impacts on the starch damage content and trough viscosity of microwave-dried rice cultivar XL753 but no significant impact on cultivar

Titan. Statistical models predicted HMC of 20% and milling durations of 45 s and 42 s for processing microwave-dried rice cultivars Titan and XL753 respectively, to obtain rice with superior characteristics.

Conclusions: HMC and milling duration significantly influenced some physicochemical properties of microwave-dried rice. We recommend that further studies should be conducted on the cooking, sensory, and storage properties of microwave-dried rice, to provide information on end-use and consumer acceptability.

Significance and novelty: This study provides science-based information that is vital for optimizing the harvesting and processing conditions of rice dried using the 915 MHz industrial microwave.

Keywords: Rice milling, 915 MHz microwave, Physicochemical properties, Harvest moisture content, Milling degree.

INTRODUCTION

Current convective heated-air rice drying technologies have not been successful in preventing rice breakage and reducing the cost of rice drying, leading to huge losses in revenue. According to the USDA economic research data, estimated revenue losses related to head rice yield (HRY) recovery using conventional rice drying methods in the U.S. in 2020 were approximately $388.7 million (Childs, 2021). This has created a critical need for the engineering of new rice drying technologies that will reduce rice drying induced losses.

The 915 MHz industrial microwave is a novel technology that has a great potential for rice drying (Olatunde, Atungulu, and Smith, 2017; Atungulu et al., 2016). Microwave heating is unique due to the ability of microwaves to evenly distribute heat throughout the entire volume of a material, a process known as volumetric heating (Kalla and Devaraju, 2017). This process contrasts with traditional heated air drying which relies on conduction and convection from hot surfaces to deliver energy into the heated material. The volumetric heating associated with microwave technology is hypothesized to reduce moisture content and temperature gradients within individual rice kernels and result in better HRYs compared to those achieved with air-drying (Olatunde et al., 2017). Additionally, the high heat fluxes of microwaves enable one-pass drying of rough rice from harvest moisture contents (HMCs) to a safe storage moisture content of 12.5% (wet basis) (Atungulu et al., 2016). Previous works on the use of the 915 MHz microwave for rice drying focused on understanding drying characteristics, physicochemical properties, microwave parameters and energy cost of rice drying (Bruce, Atungulu, Sadaka, and Smith, 2021; Smith, Atungulu, Sadaka, and Rogers, 2018; Olatunde et al., 2017; Atungulu et al., 2016). However, information is lacking on the influence of rice HMC and milling duration on the physicochemical properties of long grain and medium grain rice cultivars dried using microwaves at 915 MHz frequency.

The moisture content at which rice is harvested is an important factor that influences rice quality. Rice is generally harvested at 14-24% moisture content before drying to a safe moisture content of 12.5%. A strategy used by some farmers to reduce the energy cost of rice drying is harvesting rough rice at low moisture contents (Calderwood, Bollich, and Scott, 1980). HMC has a dramatic effect on the final gross income of rice producers. According to Calderwood et al. (1980), the energy for drying may be reduced to about 50% by harvesting rice at 16% rather than at 22% moisture content. Another study showed that there is the likelihood to incur significant losses in gross income when rice is harvested at moisture contents below 15% or above 22% (Lu, Siebenmorgen, Costello, and Fryar Jr, 1995). The HMC of rice can also affect rice physicochemical properties. Decreasing HMC from 23% to 15% increased chalkiness, decreased kernel dimension, crude protein content and HRY (Grigg, Siebenmorgen, and Norman, 2016). Furthermore, a decrease in HMC resulted in increased peak viscosity which is the highest viscosity during cooking and an indicator of rice functionality and performance in end-use product applications (Wang, Siebenmorgen, Matsler, and Bautista, 2004). Previous studies on the quality and physicochemical properties of rice dried with the 915 MHz industrial microwave focused on rice harvested at 20-24% moisture content. Because rice can be harvested at lower moisture contents than previously studied, understanding the impact of HMC on the physicochemical properties of microwave-dried rice is vital for the successful commercialization of the 915 MHz industrial microwave.

Rice is mostly consumed as milled whole kernels. Rice milling involves the removal of rice bran from the kernel surface. Degree of milling is the measure of how much bran is removed during the milling process. In convectional rice drying and processing, longer milling durations are generally associated with greater bran removal and higher degrees of milling. The degree of milling impacts the physicochemical properties of milled rice. Lower levels of components such as lipid, thiamin, phosphorus, dietary fiber, protein, and ash/minerals were reported for rice samples with a greater degree of milling (Fernandes Monks et al., 2013; Saleh and Meullenet, 2007; Lamberts et al., 2007; Perdon, Siebenmorgen, Mauromoustakos, Griffin, and Johnson, 2001; Siebenmorgen and Sun, 1994; Desikachar, 1955). The degree of milling has also been positively correlated with the degree of whiteness in milled rice (Saleh and Meullenet, 2007). Consequently, the whiteness or surface lipid content has been used to objectively measure the degree of milling of rice (Perdon et al., 2001). The degree of milling also influences the textural properties of cooked rice. Park, Kim, and Kim (2001) showed that the adhesiveness of cooked rice increased, while hardness decreased with increasing degree of milling. Olatunde and Atungulu (2018) studied the milling behavior and microstructure of medium grain rice dried using the 915 MHz industrial microwave at specific energies of 450, 600 and 750 kJ/kg. They reported that more than 80% of the surface lipid content was removed by 30 s of milling for both microwave and convective heated air-dried samples. Their study did not provide information on the effects of milling of microwave-dried rice on physicochemical properties such as kernel color, starch damage, and pasting properties. Information was also lacking on the milling behavior of long grain rice cultivars, especially long grain hybrid rice cultivars which are popularly grown in the United States of America and have excellent yield potential. It is also essential to study long grain hybrid rice cultivars because they may exhibit different drying responses due to their shape, size, and pubescent feature (Bruce et al., 2021).

During rice drying with the microwave, rice kernels undergo material state changes. The magnitude of the state change corresponds to heat fluxes during drying. It is unclear how the changes that occur during microwave drying will affect the subsequent process of bran detachment during milling of rice, especially long grain hybrid rice cultivars. To effectively commercialize the 915 MHz microwave drying approach, it is necessary to identify the milling ability of a wide range of rice kernels that have been subjected to microwave heating and recommend desirable rice processing parameters for microwave-dried rice. This study seeks to; (1) Determine the effect of HMC (and if it depends on milling duration) on the physicochemical properties of long grain and medium grain microwave-dried rice. (2) Determine the effect of milling duration (and if it depends on HMC) on the physicochemical properties of long grain and medium grain microwave-dried rice. (3) Determine suitable HMC and milling duration that maximizes the desirability of the physiological properties of long grain and medium grain microwave-dried rice.

MATERIALS AND METHODS

Sample procurement and preparation

Two rice cultivars were used for this study. A long grain hybrid cultivar XL753 and a medium grain cultivar Titan were sourced from rice farms in Burdette Arkansas and Pine Tree Arkansas, respectively. The rice cultivars were chosen based on their high yielding and disease resistant properties. XL753 is a short-season long-grain hybrid with excellent yield potential that is commonly grown in the US Midsouth. XL753 is highly cold and heat tolerant than other long grain pureline and hybrid cultivars (Jumaa, 2019). Titan is an early-maturing and short-statured medium-grain rice cultivar. It has a much larger kernel size and a 4% yield advantage over the predominant commercial medium grain cultivar Jupiter. Titan has a better resistance to both leaf and neck blast than other medium grain cultivars (Sha et al., 2018). The rice was harvested at HMCs of 16% ± 0.47, 18% ± 0.51, and 20% ± 0.53 (henceforth, moisture contents will be in wet basis). It took 35-45 days and 45-55 days after heading to reach the desired HMC ranges for XL753 and Titan respectively. The moisture content of samples was analyzed using AM 5200 Grain Moisture Tester (PERTEN Instruments). The samples were dried using two different drying methods; natural air drying which represents the control group and microwave heating which depicts the treatment group. For natural air-dried/control samples, 2000 g of each rice cultivar in duplicates were dried to a safe moisture content of 12.5% using an equilibrium moisture content (EMC) chamber at 25°C and 56% relative humidity (RH). The experimental design and methodology are shown in Table 1 and Figure 1 respectively.

Microwave treatment

Approximately 2000 g of each rough rice sample was weighed into polypropylene microwave blind trays fitted with Teflon mesh. The trays containing the samples were dried in an industrial microwave system (AMTek, Applied Microwaves Technology Inc., Cedar Rapids, IW, USA) at 915 MHz frequency using microwave specific energy of 525 kJ/[kg-grain] (power-5kW, heating duration-3.5min). Microwave specific energy is defined as the energy transferred per unit mass of the product (Smith et al., 2018). The choice of microwave specific energy was based on the findings and recommendations of Bruce et al., (2021). After the microwave treatment, samples were immediately placed into glass jars, sealed tightly, and tempered in an incubator at 60˚C for 4 h. After tempering, the samples were evenly spread on trays and cooled in the EMC chamber at 25˚C and 56% RH. The moisture content of samples was analyzed using AM 5200 Grain Moisture Tester (PERTEN Instruments). Samples that did not attain the required moisture content of 12.5% were further dried in the EMC chamber. All samples were milled after 24 h of drying.

Head rice yield (HRY)

Exactly 150 g of each rice sample was dehulled using a huller (THU-35A, Satake Engineering, Tokyo, Japan). Following dehulling, the samples were milled using a laboratory mill (McGill Number 2, Rapsco, Brookshire, TX, USA) at different milling durations of 30 s, 45 s, and 60 s. The milled rice was fractionated into head rice and broken rice using a grain separating device (Grain Machinery Manufacturing Miami, FL, USA). Head rice is defined as milled rice kernels that are at least ¾ the length of whole kernels. The average length of whole milled Titan and XL753 rice are 5.86 mm and 6.78 mm respectively. Therefore, kernels that were at least 4.40 mm and 5.09 mm for Titan and XL753 respectively were considered as head rice. HRY was calculated as the mass percentage of rough rice that remained as head rice. About 30 g of head rice of each sample was ground into flour using a cyclone sample mill (UDY Corp., Ft. Collins, CO) fitted with a 0.50-mm screen, and reserved for analyses that require the use of flour (Bruce, Atungulu, and Sadaka, 2020).

Surface lipid content, Crude protein content and Whiteness index determination

The surface lipid content, crude protein content and whiteness index of milled rice were determined following methods described by Bruce et al. (2021). The analyses were carried out by scanning 50 g of head rice with a near infrared reflectance instrument (NIR, DA7200, Perten Instrument, Hagersten, Sweden).

Pasting property

The pasting properties of rice flour samples were determined according to the AACC International Approved method 61-02.01 and as described by Bruce et al. (2021) using a Rapid Visco Analyzer (RVA-Super 4, Newport Scientific, Warriewood, NSW, Australia). The peak, final and trough viscosities were recorded in centipoises.

Starch damage determination

The starch damage content of rice samples was analyzed with a starch damage assay kit (Megazyme International Ireland, Bray, Ireland), following the Approved Method 76-31.01 (AACC International 2010) (Gibson, Kaldor, and McCleary, 1993). About 100 ± 10 mg of flour sample was weighed into a thick-walled glass centrifuge tube (16 x 120 mm; 12 mL capacity). The tubes containing the samples were pre-equilibrated at 40°C for 5 min. The enzyme, fungal α-amylase (from *A. oryzae*) solution (50 U/mL) was pre-equilibrated at 40°C for 5 min in a small glass beaker. Exactly 1.0 mL pre-equilibrated fungal α-amylase solution (50 U/mL) was added to each tube and the tubes plus content were stirred on a vortex mixer for approximately 5 s. The tubes plus content were then incubated at 40°C for exactly 10 min (from the time of addition of the enzyme). Exactly 8.0 mL of dilute sulphuric acid solution (0.2% v/v) was added to each tube after 10 min from the time of addition of the fungal α-amylase and the tubes were stirred vigorously for approximately 5 s. The tubes plus content were then centrifuged at 3,000 rpm (1,000 x g) for 5 min. A 0.1 mL aliquots of the supernatant solutions were carefully and accurately transferred to the bottom of two test tubes. Exactly 0.1 mL of amyloglucosidase (from *A. niger*) solution (2 U) was added to each tube followed by stirring on a vortex mixer and incubation at 40°C for 10 min. Exactly 4.0 mL of GOPOD reagent solution was added to each tube (including glucose standards and reagent blank tubes) and the tubes plus content were incubated at 40°C for 20 min. Absorbances of all solutions was measured at 510 nm against a reagent blank (0.2 mL of acetate buffer + 4.0 mL glucose oxidase/peroxidase reagent). The starch damage content was calculated as follows:

$$\textit{Starch Damage (\%)} = \Delta E \times \frac{F}{W} \times 8.1 \ldots\ldots\ldots\ldots (1)$$

Where, ΔE = Absorbance (reaction) read against the reagent blank.

$$F = \frac{150\ (\mu\text{g of glucose})}{\text{absorbance of } 150\ \mu\text{g of glucose}} \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

W = The weight in milligrams (“as is” basis) of the flour analyzed

Statistical analysis

All analysis were performed in duplicates. Analysis of variance of the 3X3 factorial treatment design were carried out in the Fit Model platform using JMP Pro 15.2 (SAS Institute, Cary N.C.) to determine significant main effects and interaction of the two factors, and maximize the overall desirability of several physicochemical properties.

RESULTS AND DISCUSSION

Effect of harvest moisture content (HMC) on physicochemical properties of microwave-dried rice

The two factors, HMC and milling duration, did not exhibit significant interaction in any of the physicochemical properties analysis. HRY is an accepted commercial measure of rice physical quality characteristics (Ondier, Siebenmorgen, and Mauromoustakos, 2010). Table 2 shows the linear associations between HMC and physicochemical properties of microwave-dried rice. HMC had a significant impact (p-value <0.05) on the HRY of microwave-dried medium grain rice (Titan) and long grain hybrid rice (XL753). There were strong positive correlations between HMC and HRY of microwave-dried rice for both cultivars (Table 2). Although the HRY of control samples did not change significantly with increasing HMC, the HRY of microwave-dried rice increased with increasing HMC for both rice cultivars (Figure 2a). This is because paddy rice harvested at lower moisture content may have existing fissures that could increase during microwave drying due to the high heat and entropy of water molecules within the rice kernel (Olatunde and Atungulu, 2018; Siebenmorgen, Counce, Lu, and Kocher, 1992). Grigg et al. (2016) also reported significant effects of HMC on HRY. They attributed the decreased HRY to increased brown rice fissured-kernel percentage and chalkiness. The highest HRY for microwave-dried rice in this study was recorded in samples with HMC of 20% for both cultivars (Figure 2a). This suggests that for the sole purpose of maximizing HRY, rice intended for drying with the 915 MHz industrial microwave should be harvested at a high moisture content of 20%. Differences were also observed in the HRY patterns of the two cultivars at 20% HMC. The HRY of microwave-dried Titan rice with 20% initial HMC was slightly higher than that of the control sample. Contrarily, for XL753, the HRY for microwave-dried rice with 20% initial HMC was significantly lower than the control sample. The differences in the two cultivars may be due to their inherent biological variations in size, shape, morphology, and kernel composition (Bruce et al., 2021; Prakash and Siebenmorgen, 2018). The pubescent nature (hair-like microstructure on the hull) of long grain hybrids may also influence their drying property and HRY (Atungulu, Zhong, Thote, Okeyo, and Couch, 2015).

The surface lipid content of rice indicates the degree of milling of rice kernels. HMC had a significant influence on the surface lipid content of microwave-dried rice cultivar Titan and no significant impact on XL753 (Table 2). For cultivar Titan, the surface lipid content of microwave-dried samples increased with increasing HMC although the differences between the means of surface lipid contents across HMCs were not significantly different (Figure 2b). Additionally, for both cultivars, the surface lipid content of the control samples and microwave-dried samples were not significantly different within and across all HMCs. It can therefore be inferred that the ease of bran removal from the kernel surface of microwave-dried rice was not affected by HMC for the long grain hybrid rice cultivar XL753 but was affected in the medium gain cultivar Titan. Again, the morphological differences of the two cultivars may impact their responses to environmental and harvesting factors which may influence their processing characteristics (Bruce et al., 2021; Ahn, Won, Rico, and Lee, 2010).

HMC had a significant impact on the crude protein content of microwave-dried rice for both cultivars (Table 2). The crude protein content increased with increasing HMC for microwave-dried rice cultivar Titan (Figure 2c). On the contrary, crude protein content decreased with increasing HMC for microwave-dried rice cultivar XL753. There were also no significant differences between the crude protein contents of the control and microwave-dried samples within all HMCs for rice cultivar XL753 (Figure 2c). For cultivar Titan, the crude protein contents of the control samples were significantly higher than that of the microwave-dried rice samples at 16% and 18% HMCs. The decreasing trend in the crude protein result for the microwave-dried rice XL753 is consistent with the finding of Grigg et al. (2016) who determined the impact of HMC on three long-grain rice cultivars dried with natural air (26°C and 56% relative humidity). They reported significantly higher crude protein contents for rice harvested at 15% moisture content than rice harvested at 19% and 23% moisture content for all cultivars. They explained that the delay in harvest causes a shift in kernel population to more late-maturing kernels which may have different compositions than the early maturing kernels. Chrastil (1993) also showed that the average molecular weight of oryzenin (rice storage protein) decreased significantly (by 27%) during the preharvest maturation of rice grains. The crude protein content trend for microwave-dried rice cultivar XL753 may be due to a shift in kernel population to more late-maturing kernels and changes in the molecular weight of rice proteins during kernel maturation. The different crude protein trends reported for the medium grain rice Titan may be due to the varietal effect and differences in kernel composition. Additionally, delaying the harvest of medium grain rice may not produce the same rate of change in the molecular weight of proteins and shift in kernel population as proposed for the long grain rice.

HMC did not significantly affect the whiteness index and starch damage content of microwave-dried rice for both cultivars (Table 2). The whiteness index is mostly influenced by the degree of milling and the color of the rice endosperm (starch being the largest component). The starch damage content is a measure of the mechanical disruption of starch granules during grinding and it is impacted by the physicochemical properties of starch (Bruce et al., 2020). Previous studies showed that the molecular weight of starch increased only slightly during rice kernel maturation (Chrastil, 1993). The minimal change in the molecular weight of starch during rice kernel maturation may not be significant in modifying the characteristics of starch that influence the rice color and starch granule damage. The lack of effect of HMC on the whiteness index and starch damage content may be advantageous to rice producers since they will have fewer parameters to control during rice processing.

Peak viscosity is the maximum viscosity attained during cooking and it depicts the viscous load likely to be encountered by a mixing cooker. The trough viscosity indicates the ability of a paste to withstand breakdown during cooking (Ayo-Omogie and Ogunsakin, 2013). HMC had a significant effect on the peak and trough viscosities of microwave-dried rice cultivar Titan and no significant effect on XL753 (Table 2). Both peak and trough viscosities had inverse correlations with the HMC of microwave-dried samples indicating decreasing viscosities with increasing HMC. The trough viscosity of microwave-dried samples for both cultivars was generally significantly higher than the control samples (Figure 2d). The result is consistent with the findings of Wang et al. (2004) who also reported inverse correlations between peak viscosity and HMC for rice samples dried with natural air (22°C and 65% relative humidity). They also observed that the rate of decrease in peak viscosity as HMC increased, varied with the cultivar and location. This is also similar to the current findings of this study where different rates of decrease (correlations of -0.61 and -0.24) in peak viscosity were reported for Titan and XL753.

The impact of HMC on the peak and trough viscosity may be due to changes in starch and protein molecular structure and amylase activity during kernel maturation (Baun, Palmiano, Perez, and Juliano, 1970; Chrastil, 1993). According to Jongkaewwattana, Geng, Hill, and Miller, (1993), rice kernels develop nonuniformly on a panicle. The kernels on the top portion of panicles mature about 10-15 days earlier than those on the bottom portion. Rice that is harvested early has high moisture content but may have a greater proportion of immature kernels. Chrastil (1993) reported that as kernels matured (up to 50 days after flowering), the average molecular weight of starch increased only slightly, while the average molecular weight of oryzenin decreased significantly. Baun et al. (1970) also showed that during kernel development, amylase activity which is related to starch synthesis was maximized at 14 days after flowering and then gradually decreased as kernels matured. It is possible that rice harvested at higher moisture contents may have greater proportions of immature kernels with greater amylase activity which may be responsible for the decreasing trend of peak and trough viscosities as HMC increased. Wang et al. (2004) argued that the dependence of peak viscosity on HMC could affect end-use processing operations. Therefore, the lack of dependence of peak viscosity on the HMC of the microwave-dried rice cultivar XL753 may be advantageous to end-use processing operations. The higher trough viscosities recorded in the microwave-dried rice compared to control samples may be due to starch and protein modifications during microwave drying (Olatunde and Atungulu, 2018).

Final viscosity is the viscosity of the rice product after cooking and cooling. It depicts the final nature of the product, and it is a common parameter that is used to define rice quality. The HMC had a significant impact on the final viscosity of microwave-dried rice cultivar Titan and

XL753 (Table 2). Based on the p-values and correlations, the impact of HMC on the final viscosity was greater in the medium grain rice cultivar than the long grain cultivar. The final viscosity of microwave-dried rice decreased with increasing HMC for both cultivars (Figure 2e). Similar to the discussions for peak and trough viscosities, the decreasing final viscosity with increasing HMC (i.e., early harvesting), may be due to a shift in kernel population to more late maturing kernels, and changes in amylase activity, starch, and protein contents (Grigg et al., 2016; Chrastil, 1993; Baun et al., 1970). In general, the influence of HMC on the physicochemical properties of microwave-dried rice is similar to the trends observed in rice dried using conventional drying methods by different researchers. These trends are vital for the identification of parameters for rice processing using the novel 915 MHz industrial microwave.

Effect of milling duration on physicochemical properties of microwave-dried rice

Milling duration had no significant impact on the HRY of microwave-dried rice (Table 3). There were no significant differences between the HRYs of microwave-dried rice across all milling durations for both cultivars. However, HRY significantly decreased with increasing milling duration for control samples (Figure 3a). The control samples also had significantly higher HRY than microwave-dried samples at all milling durations. The results for control samples in this study are similar to the findings of other authors. For instance, Meng et al. (2019) also reported linearly decreased HRYs with increased milling durations for rice dried using a convective heated air dryer. They explained that when rice is milled at longer durations, collision and collision power accumulate between the kernels and they break once the destructive force is attained (Meng et al., 2019; Han et al., 2016). The lack of a significant effect of milling duration on the HRY of microwave-dried rice may be due to changes in the starch structure during microwave drying.

Olatunde and Atungulu (2018) in their study of the microstructure of microwave-dried rice reported reduced roughness of the starch surface and disappearance of starch granules with increased microwave specific energy. They attributed the disappearance of starch granules to the high heat flux of microwaves. Li, Han, Xu, Xiong, and Zhao, (2014) also reported greater swelling and shrinkage of gaps between rice starch granules heated by microwave, than those heated with an electric cooker. These changes in the starch structure of microwave-dried rice can influence the strength of the rice kernels and reduce the effect of milling duration on HRY. Although control samples had higher HRY than microwave-dried samples, convective heated air rice drying methods use longer drying durations than the 915 MHz industrial microwave (Bruce et al., 2021; Olatunde et al., 2017). Therefore, the reductions in the HRY of microwave-dried rice may pay off by reductions in drying duration (Olatunde and Atungulu, 2018).

Milling duration had a significant impact on the surface lipid content of microwave-dried rice for both cultivars (Table 3). Surface lipid content decreased with increasing milling duration for the control and microwave-dried rice samples (Figure 3b). There were generally no significant differences between the surface lipid content of the control and microwave-dried rice samples within each milling duration, except for XL753 microwave-dried rice milled for 60 s, which was significantly higher than that of the control sample. Milling durations above 30 s resulted in surface lipid contents that meet the 0.4% limit set by industries. The slightly higher surface lipid contents observed in the microwave-dried rice milled for 30 s may be due to case hardening of the rice bran during microwave heating (Olatunde and Atungulu, 2018). Milling duration had a significant effect on the surface lipid content because increasing milling duration increases bran removal from the kernel surface and decreases the surface lipid content. The similar milling trends of the two drying methods are an indication that extra cost may not be required for the milling of microwave-dried rice.

Milling duration had a significant impact on the whiteness index of microwave-dried rice cultivars Titan and XL753 (Table 3). The whiteness index increased with increasing milling duration for both control and microwave-dried rice samples (Figure 3c). In general, microwave-dried rice samples had a significantly higher whiteness index across different milling durations than control samples. The whiteness index of rice increased with increasing milling durations because longer milling durations correlate with greater bran removal from the kernel surface, making the kernels whiter (Siebenmorgen, Matsler, and Earp, 2006). The higher whiteness index of microwave-dried rice may be due to faster moisture content reduction and inactivation of enzymes responsible for yellowing or browning reactions during microwave heating (Okeyo et al., 2017).

Milling duration had no significant effect on the crude protein content, final viscosity, and peak viscosity of microwave-dried rice for both cultivars (Table 3). On the contrary, milling duration had a significant impact on the trough viscosity of microwave-dried rice cultivar XL753 but no significant impact on cultivar Titan. Trough viscosity increased with increasing milling duration for both control and microwave-dried samples (Figure 3d). Furthermore, the trough viscosity of microwave-dried rice samples was significantly higher than the control samples within each milling duration for both rice cultivars. The influence of milling duration on the trough viscosity of microwave-dried rice cultivar XL753 can be attributed to variations in chemical constituents (protein, amylose, and total starch) due to different degrees of milling (Wang et al., 2021). Rice milled at a longer milling duration has less residual bran on the kernel surface than rice milled at a shorter milling duration. There are therefore possible variations in the compositions of kernels milled at different milling durations, which may affect the ability of starch granules to withstand breakdown. The higher trough viscosity of the microwave-dried rice may be due to modifications in the starch structure during microwave heating. Milling duration did not have a significant impact on the crude protein content of microwave-dried rice because the majority of the crude proteins present in the rice bran may have been removed within the first 30 s of milling. Generally, rice kernels have about 7% total protein content, with about 80% of the proteins concentrated in the starchy endosperm and the remaining 20% in the bran layer (Verma and Srivastav, 2017; Olatunde and Atungulu, 2018). In this study, the removal of over 90% of SLC within the first 30 s of milling could have facilitated enough removal of proteins concentrated in the bran layer, thereby preventing variations in crude protein content upon a further increase in milling duration.

Milling duration had a significant effect on the starch damage content of microwave-dried rice cultivar XL753 and no significant influence on cultivar Titan (Table 3). There were no significant differences in the starch damage contents of control and microwave-dried rice cultivar Titan (Figure 3e). The starch damage contents of microwave-dried rice cultivar XL753 were lower than the control samples across all milling durations. Generally, rice samples that were milled at longer milling durations (45 s and 60 s) had higher starch damage contents than those milled at a shorter milling duration (30s). The trend was different for the control medium grain rice. The starch damage content of the control rice cultivar Titan samples milled at 30 s was slightly higher than those milled at 45 s. The effect of milling duration on the starch damage content of the microwave-dried rice cultivar XL753 may be due to the intense friction and pressure that kernels undergo during longer milling durations which can disrupt the starch granules. Additionally, the lower starch damage content of microwave-dried rice may be due to starch modifications that occur during microwave drying and it may be advantageous for many end-use processes (Olatunde and Atungulu, 2018). Morphological and compositional differences in the two cultivars may also account for the variations seen in the impact of milling duration on the starch damage content. Milling durations need to be skillfully selected to reduce the formation of starch damage during milling.

Prediction of desirable harvest moisture content (HMC) and milling duration for processing microwave-dried rice

Table 4 shows models for predicting the physicochemical properties of microwave-dried rice. At a constant milling duration and cultivar, a unit change in HMC may lead to 4.58% increase in HRY, 0.016% increase in surface lipid content, 0.12 decrease in whiteness index and 53.67 cP decrease in final viscosity. At a constant HMC and cultivar, a unit change in milling duration may result in a 0.24% decrease in HRY, 0.004% decrease in surface lipid content, 0.05 increase in whiteness index and 0.009% increase in starch damage. Furthermore, keeping milling duration and HMC constant, a change in cultivar from XL753 to Titan may result in 11.13% increase in HRY, 0.04% decrease in surface lipid content, 0.87 decrease in whiteness index, 285.39 cP decrease in final viscosity and 0.46% increase in starch damage. The R^2 of the model ranged from 0.60-0.82, indicating an explanation of 60%-82% of the physicochemical properties. These models provide a quantitative overview of the impact of HMC and milling duration for each cultivar, on the physicochemical properties of rice. The models are also vital in understanding the impact of a change in one variable on the resulting property of rice. Therefore, the models should serve as a guide in preharvest and postharvest decision making for rice that will be dried using the 915 MHz industrial microwave.

Figures 4 and 5 show the prediction profilers for estimating desirable HMCs and milling durations for microwave-dried rice Titan and XL753 respectively. Four parameters including HRY, final viscosity, surface lipid content and whiteness index were used in a statistical model to predict the desirable variables. Because HRY is the most important factor for rice quality, it was set at an importance of 3 while the final viscosity, surface lipid content and whiteness index were set at an importance of 1. For the prediction profiler desirability settings, the HRY, final viscosity, and whiteness index were maximized, while the surface lipid content was matched at a set target of 0.4% (common industrial surface lipid content value). The statistical model predicted a desirable HMC of 20% for both Titan and XL753 rice cultivars. The statistical model also predicted milling durations of 45s and 42s for processing microwave-dried medium grain rice cultivar Titan and long grain rice cultivar XL753 respectively. About 66% and 64% desirabilities were achieved for Titan and XL753 respectively. This means that our goal to maximize HRY, final viscosity, and whiteness index, and match surface lipid content at a target of 0.4% was achieved by 66% and 64% for Titan and XL753 respectively. The recommended HMC of 20% will provide excellent HRY and physicochemical properties that are similar to the control method.

The medium grain rice kernels were thicker in size than the long grain rice kernels. The higher milling duration predicted for the medium grain rice compared to the long grain rice is consistent with the reports of Pomeranz and Webb (1985) and Webb (1980) who proposed that more milling pressure should be used for cultivars with thicker kernel sizes because of their thicker aleurone layer within the bran morphology. Most convectional rice processing methods use milling durations between 30 s and 60 s depending on the rice cultivar. The adoption of the 915 MHz industrial microwave will not require significant changes in milling duration, thereby maintaining the energy cost of rice milling. We recommend that further research should be performed on the cooking, sensory and storage or aging properties of rice dried using the 915 MHz industrial microwave, to provide details on the processing properties and consumer acceptability of microwave-dried rice.

CONCLUSION

The effect of HMC and milling duration did not interact significantly for any of the key physicochemical properties of long grain (XL753) and medium grain (Titan) microwave-dried rice that were analyzed. HMC had significant impacts on the HRY, crude protein content and final viscosity of microwave-dried rice for both cultivars. The HMC also significantly influenced the surface lipid content, peak and trough viscosities of microwave-dried rice cultivar Titan but did not significantly impact cultivar XL753. The differences in the response of the two cultivars to varying HMC may be due to morphological disparities in size, shape and composition. Milling duration had significant impacts on the surface lipid content and whiteness index of microwave-dried rice for both cultivars. Statistical models predicted HMC of 20% and milling durations of 45 s and 42 s for the processing of microwave-dried rice Titan and XL753 respectively. This study provides vital information for the optimization of processing conditions of rice dried using the 915 MHz industrial microwave. We recommend that further studies should be conducted on the cooking, sensory, and storage properties of microwave-dried rice, to provide information on end-use and consumer acceptability.

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TABLES AND FIGURES

Table 1. Experimental design

Drying strategy	Rice cultivars	Rough rice harvest moisture content (%, wet basis)	Milling duration (s)
1. Control treatment: natural air drying at 25°C and 56% relative humidity.	XL 753	20 ± 0.53	30
2. Microwave heating followed by tempering at 60°C for 4 h and natural air cooling.	Titan	18 ± 0.51	45
			60
		16 ± 0.47	

Table 2. Linear associations between harvest moisture content (HMC) and physicochemical properties of microwave dried rice

Associations	**Titan**		**XL753**	
	P-value	**Correlation**	**P-value**	**Correlation**
HMC vs. head rice yield	<0.0001*	0.8623	<0.0001*	0.8813
HMC vs. surface lipid content	0.0288*	0.5147	0.9354	0.0206
HMC vs. crude protein content	0.0063*	0.6179	0.0237*	-0.5298
HMC vs. whiteness index	0.2186	-0.3049	0.6342	-0.1204
HMC vs. starch damage	0.9584	-0.0133	0.1918	-0.3225
HMC vs. peak viscosity	0.0069*	-0.6126	0.3422	-0.2377
HMC vs. trough viscosity	0.0035*	-0.6500	0.1392	-0.3626
HMC vs. final viscosity	<0.0001*	-0.8482	0.0055*	-0.6255

*Indicates statistical significance, $p<0.05$. Sample size (n) =36

Table 3. Linear associations between milling duration (MD) and physicochemical properties of microwave dried rice

	Titan		**XL753**	
Associations	**P-value**	**Correlation**	**P-value**	**Correlation**
MD vs. head rice yield	0.2213	-0.3032	0.0780	-0.4259
MD vs. surface lipid content	0.0015*	-0.6908	<0.0001*	-0.9462
MD vs. crude protein content	0.2269	0.2997	0.0515	0.4657
MD vs. whiteness index	0.0004*	0.7478	<0.0001*	0.8948
MD vs. starch damage	0.2941	0.2617	0.0132*	0.5717
MD vs. peak viscosity	0.3097	0.2537	0.1363	0.3651
MD vs. trough viscosity	0.0837	0.4188	0.0260*	0.5228
MD vs. final viscosity	0.9970	-0.0010	0.3570	0.2307

*Indicates statistical significance, $p<0.05$. Sample size (n) =36

Table 4. Models for predicting the physicochemical properties of microwave dried rice

Model *	**R^2**
Head rice yield = -37.8250 - 0.2374MD + 11.1296C(T) + 4.5819HMC	0.7938
Surface lipid content = 0.2768 - 0.0041MD - 0.0400C(T) + 0.0160HMC	0.6042
Whiteness index = 68.7184 + 0.0503MD - 0.8702C(T) - 0.1197HMC	0.8007
Final viscosity = 4352.4444 - 285.3889C(T) - 53.6667HMC	0.8171
Starch damage = 4.6289 + 0.0095MD + 0.4580C(T)	0.7930

*Parameters that are not included in some of the models were not significant. Sample size (n) = 36. MD = milling duration, C(T) = Cultivar (Titan), HMC = harvest moisture content.

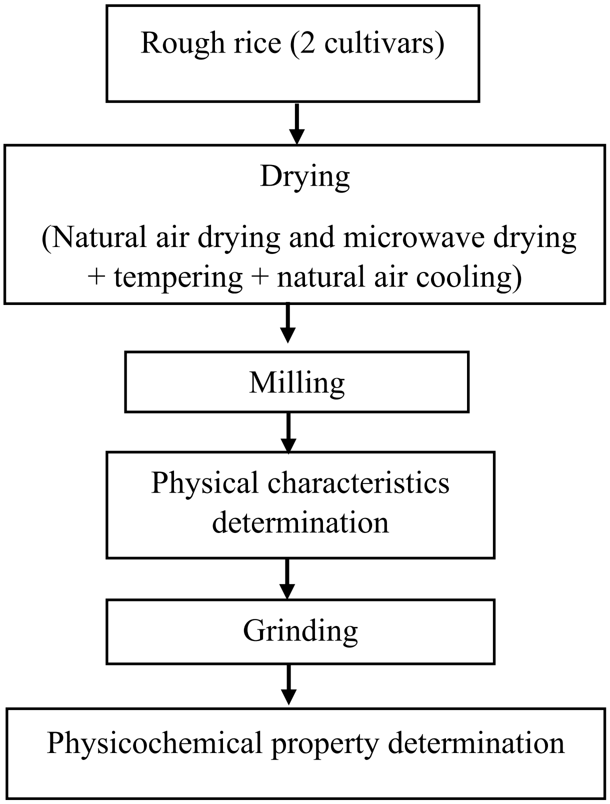

Figure 1. A flow chart of the methodology.

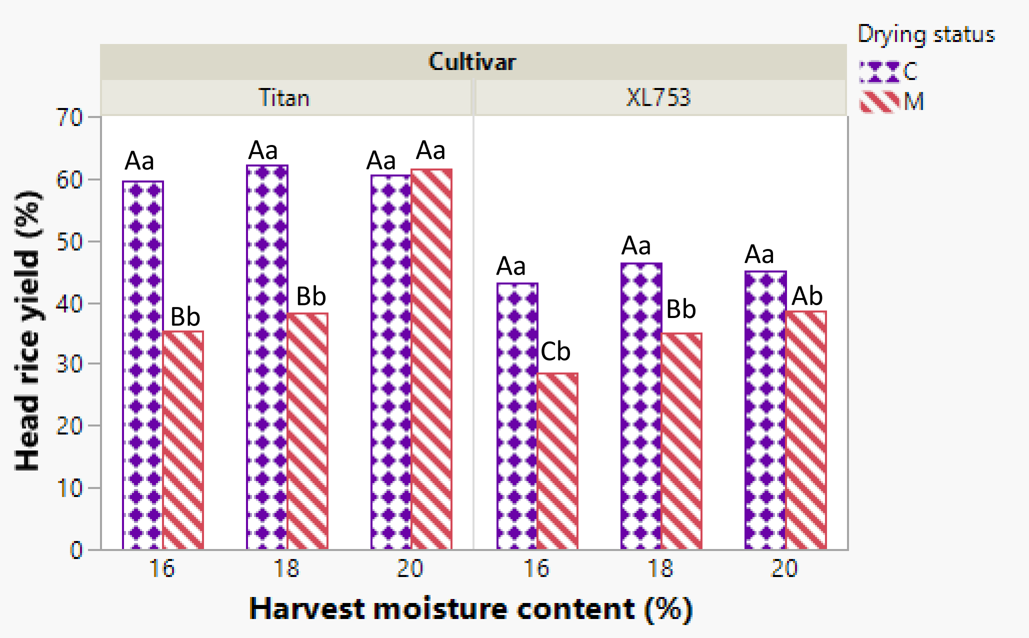

Figure 2a. Effect of harvest moisture content (wet basis) on head rice yield. Sample size (n) =72. Uppercase letters (A, B, C) show statistical differences within drying status. Lowercase letters (a, b, c) indicate statistical differences within harvest moisture content. Drying status C represents control samples and M represents microwave dried samples. Head rice yield shown above is an average for rice milled at 30 s, 45 s and 60 s.

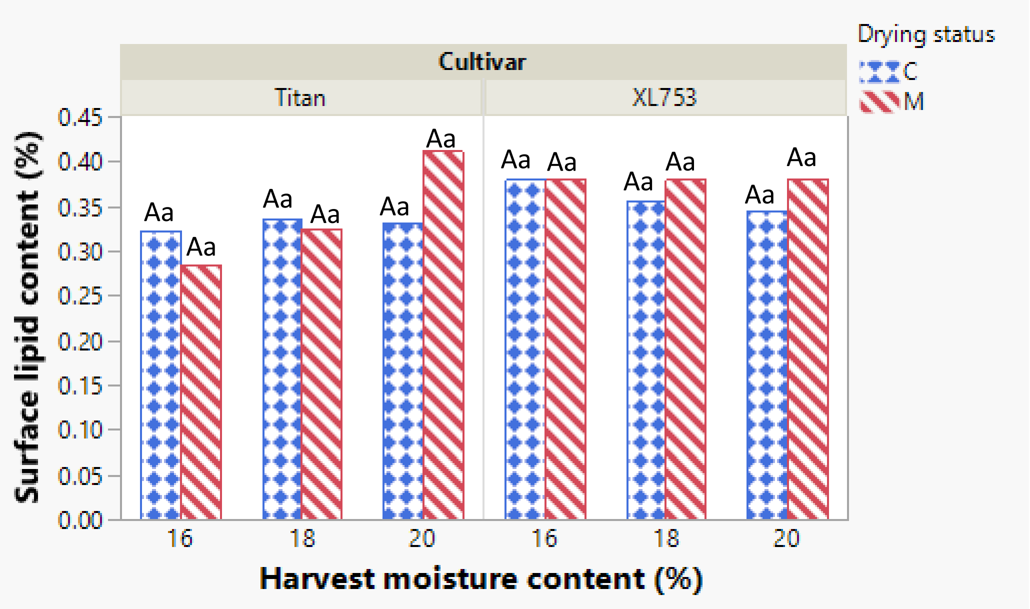

Figure 2b. Effect of harvest moisture content (wet basis) on the surface lipid content of rice. Sample size (n) =72. Uppercase letters (A, B, C) show statistical differences within drying status. Lowercase letters (a, b, c) indicate statistical differences within harvest moisture content. Drying status C represents control samples and M represents microwave dried samples. The surface lipid content shown above is an average for rice milled at 30 s, 45 s and 60 s.

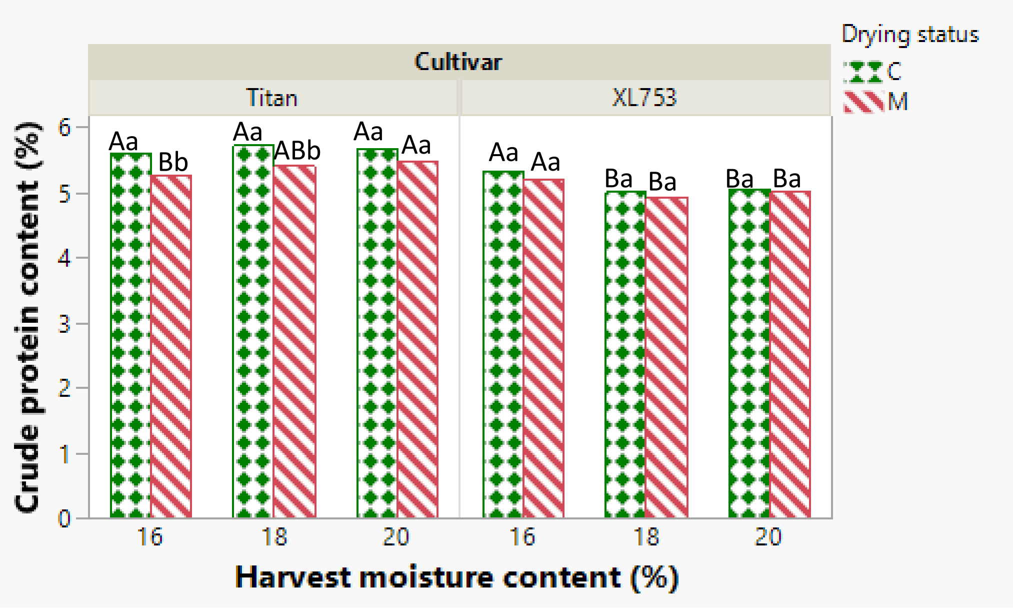

Figure 2c. Effect of harvest moisture content (wet basis) on the crude protein content of rice. Sample size (n) =72. Uppercase letters (A, B, C) show statistical differences within drying status. Lowercase letters (a, b, c) indicate statistical differences within harvest moisture content. Drying status C represents control samples and M represents microwave dried samples. The crude protein content shown above is an average for rice milled at 30 s, 45 s and 60 s.

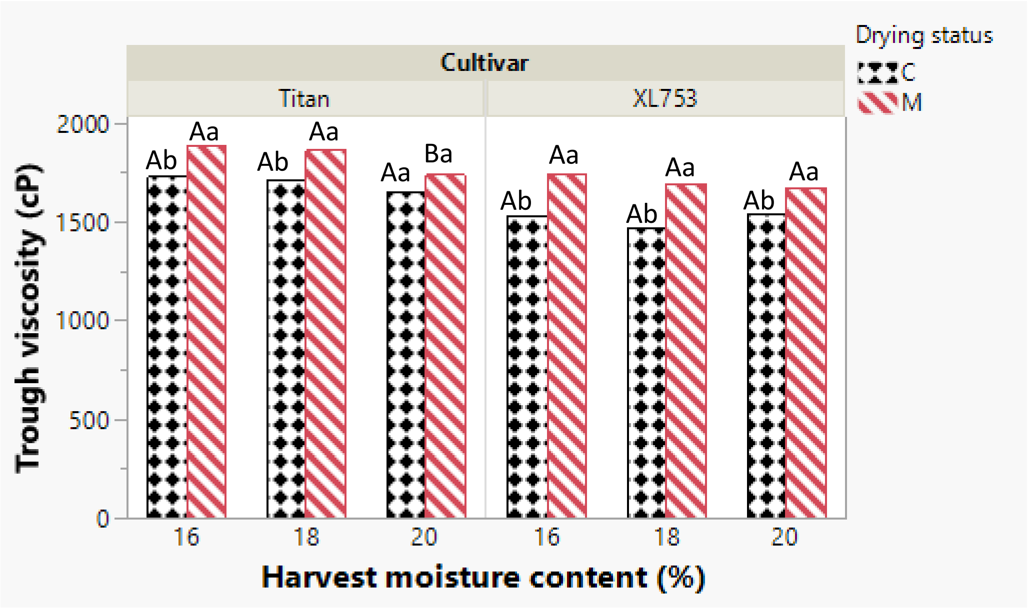

Figure 2d. Effect of harvest moisture content (wet basis) on the trough viscosity of rice. Sample size (n) =72. Uppercase letters (A, B, C) show statistical differences within drying status. Lowercase letters (a, b, c) indicate statistical differences within harvest moisture content. Drying status C represents control samples and M represents microwave dried samples. The trough viscosity shown above is an average for rice milled at 30 s, 45 s and 60 s.

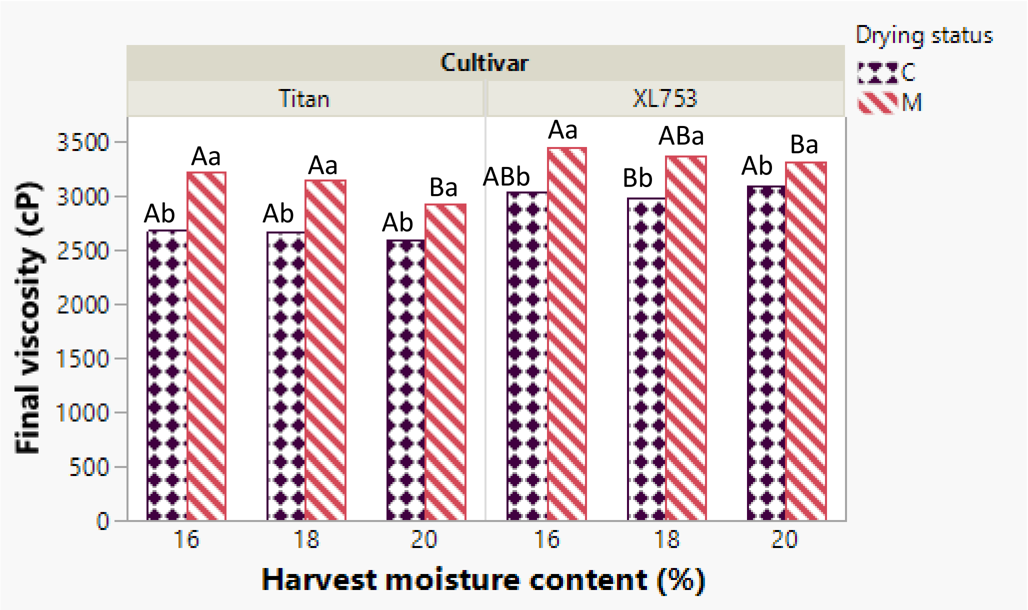

Figure 2e. Effect of harvest moisture content (wet basis) on the final viscosity of rice. Sample size (n) =72. Uppercase letters (A, B, C) show statistical differences within drying status. Lowercase letters (a, b, c) indicate statistical differences within harvest moisture content. Drying status C represents control samples and M represents microwave dried samples. The final viscosity shown above is an average for rice milled at 30 s, 45 s and 60 s.

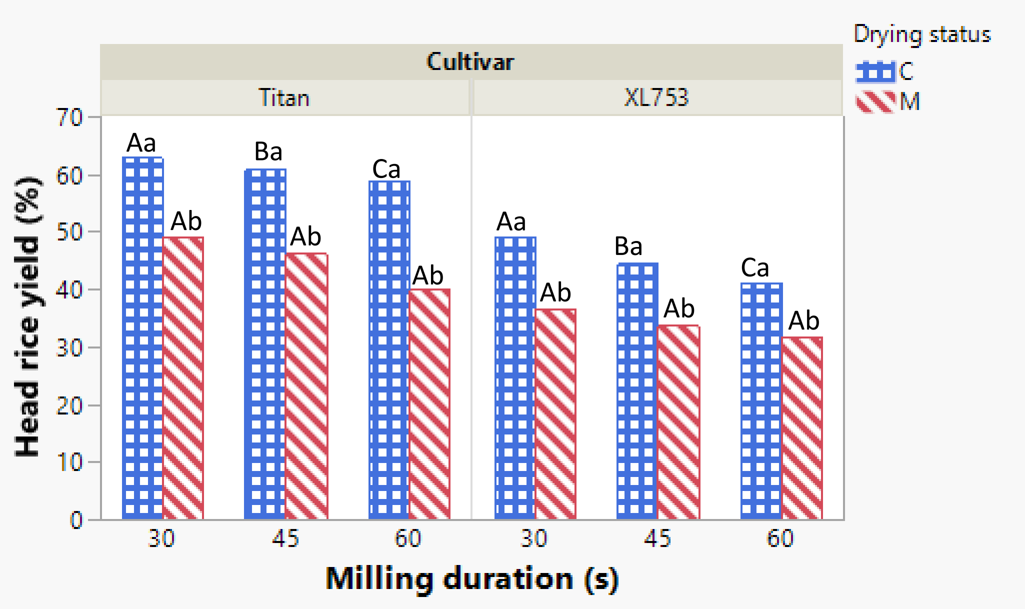

Figure 3a. Effect of milling duration on head rice yield. Sample size (n) =72. Uppercase letters (A, B, C) show statistical differences within drying status. Lowercase letters (a, b, c) indicate statistical differences within milling duration. Drying status C represents control samples and M represents microwave dried samples. The head rice yield shown above is an average for rice harvested at 16%, 18% and 20% moisture contents (wet basis).

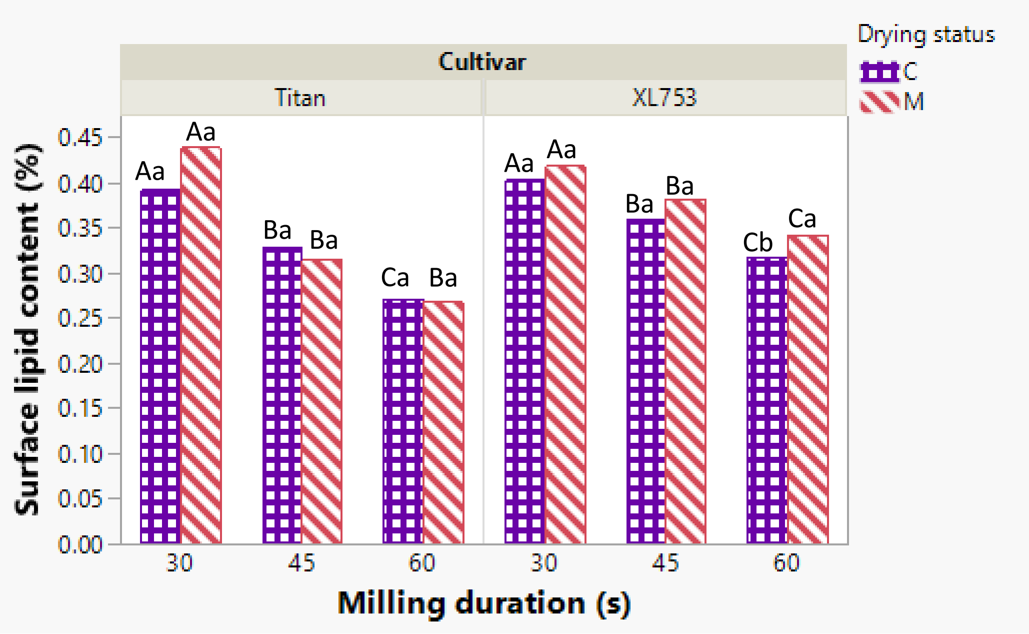

Figure 3b. Effect of milling duration on the surface lipid content of rice. Sample size (n) = 72. Uppercase letters (A, B, C) show statistical differences within drying status. Lowercase letters (a, b, c) indicate statistical differences within milling duration. Drying status C represents control samples and M represents microwave dried samples. The surface lipid content shown above is an average for rice harvested at 16%, 18% and 20% moisture contents (wet basis).

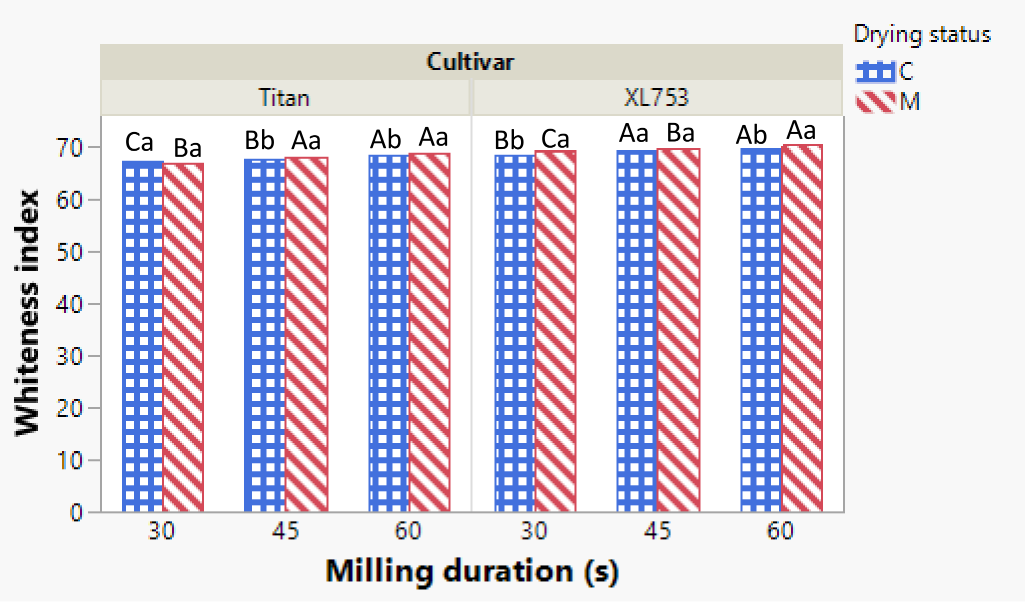

Figure 3c. Effect of milling duration on the whiteness index of rice. Sample size (n) = 72. Uppercase letters (A, B, C) show statistical differences within drying status. Lowercase letters (a, b, c) indicate statistical differences within milling duration. Drying status C represents control samples and M represents microwave dried samples. The whiteness index shown above is an average for rice harvested at 16%, 18% and 20% moisture contents (wet basis).

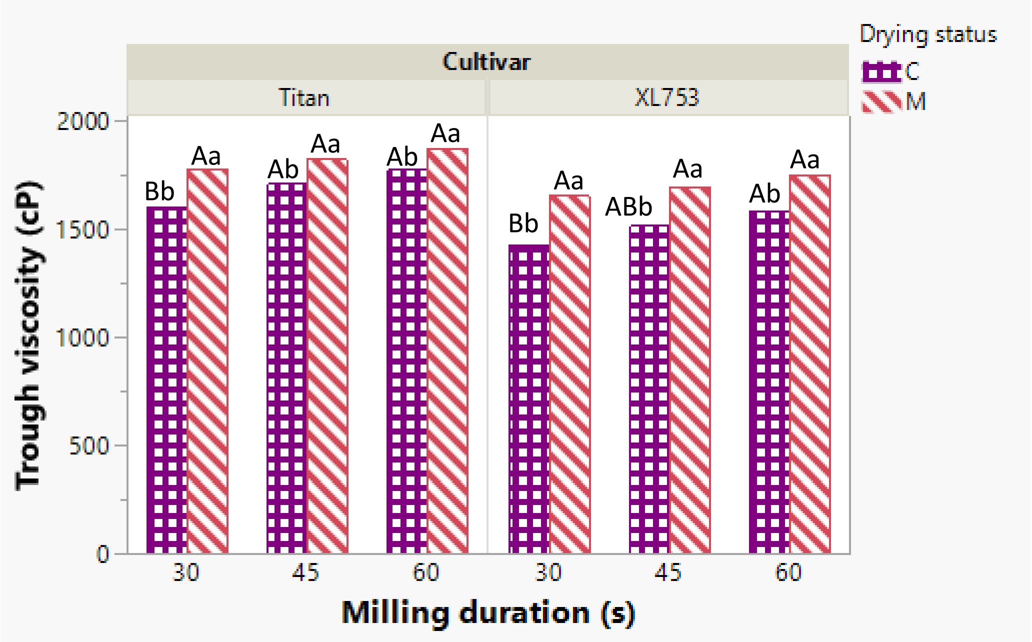

Figure 3d. Effect of milling duration on the trough viscosity of rice. Sample size (n) = 72. Uppercase letters (A, B, C) show statistical differences within drying status. Lowercase letters (a, b, c) indicate statistical differences within milling duration. Drying status C represents control samples and M represents microwave dried samples. The trough viscosity shown above is an average for rice harvested at 16%, 18% and 20% moisture contents (wet basis).

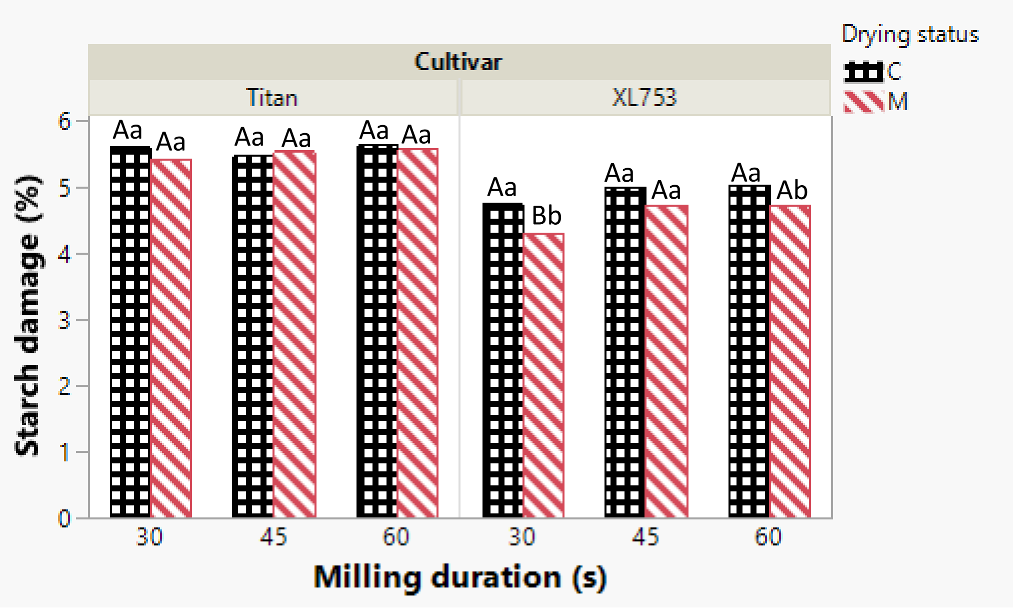

Figure 3e. Effect of milling duration on the starch damage content of rice. Sample size (n) = 72. Uppercase letters (A, B, C) show statistical differences within drying status. Lowercase letters (a, b, c) indicate statistical differences within milling duration. Drying status C represents control samples and M represents microwave dried samples. The starch damage content shown above is an average for rice harvested at 16%, 18% and 20% moisture contents (wet basis).

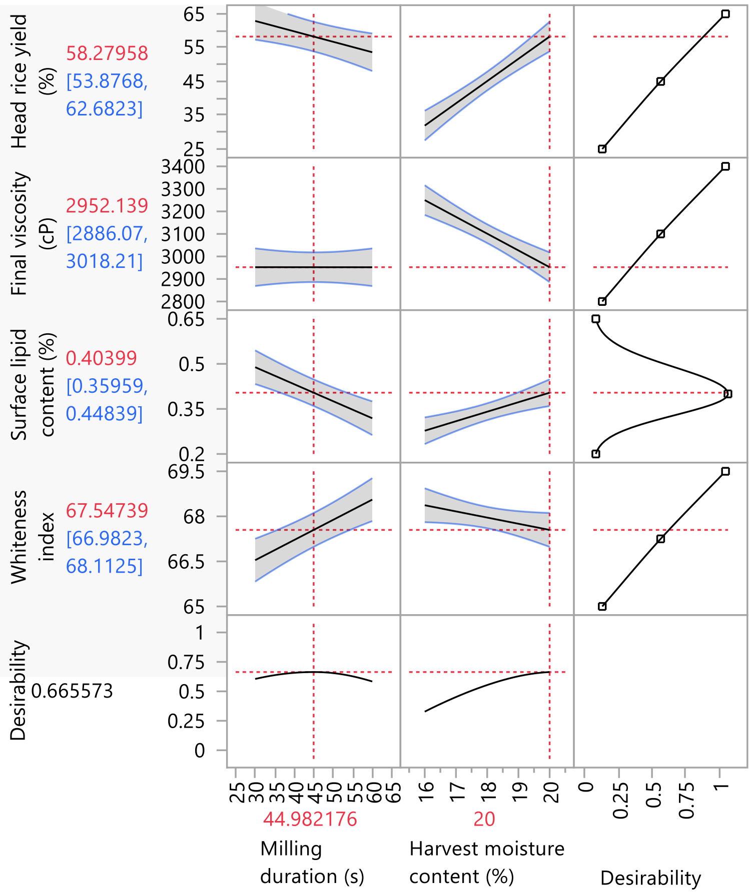

Figure 4. Prediction profiler for microwave dried rice using medium grain rice cultivar Titan. Sample size (n) =18; Harvest moisture content was measured on wet basis.

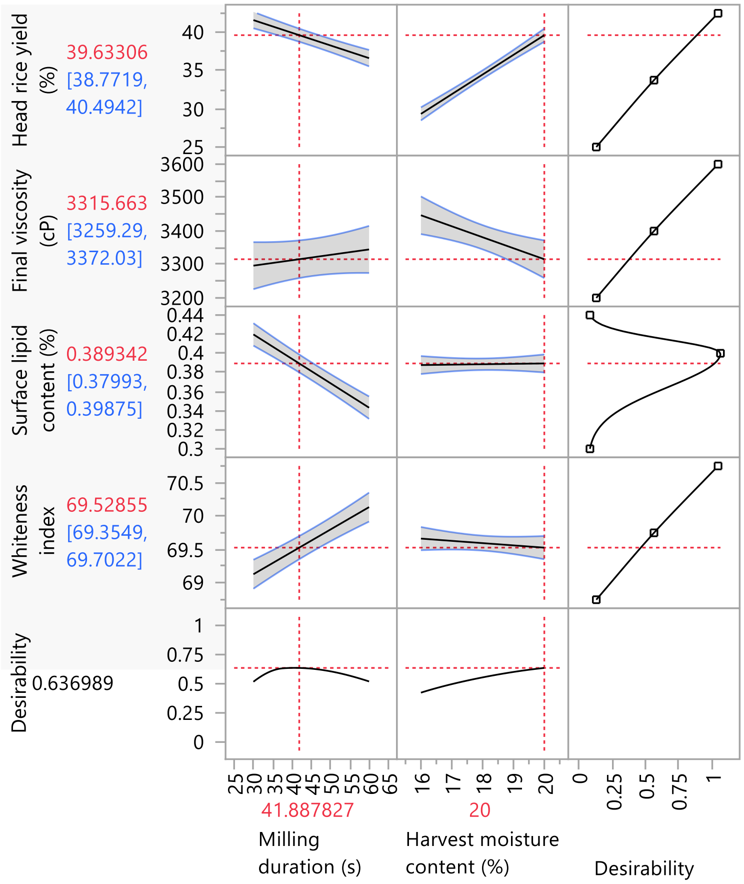

Figure 5. Prediction profiler for microwave dried rice using long grain rice cultivar XL753. Sample size (n) =18; Harvest moisture content was measured on wet basis.

CHAPTER 3

AGING CHARACTERISTICS OF RICE DRIED USING MICROWAVE AT 915 MHZ FREQUENCY

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ABSTRACT

Background and objectives: Rice aging is an intrinsic phenomenon that begins at preharvest and lasts until consumption. Aging leads to physicochemical changes in rice kernels. The goal of this research is to determine the physicochemical properties of rice dried using a 915 MHz microwave and then aged. Two rice cultivars, a medium grain cultivar Titan and long grain hybrid cultivar XL753, with a harvest moisture content of 20% ± 1% (wet basis) were used for the study. The rice samples were treated with two different drying methods, natural air drying as control and microwave heating at 915 MHz frequency followed by tempering and natural air cooling at 25°C and 56% relative humidity (RH). Microwave-dried samples were treated at specific energies ranging from 360 to 630 kJ/kg of initial wet grain mass (kJ/kg-grain). The rice samples were dehulled and milled for 60 s. Head rice samples were stored for 6 months at 4°C and 25°C representing non-aged and aged samples respectively. Physicochemical properties of the samples were determined.

Findings: Aged microwave-dried rice had significantly higher setback viscosity, cooked rice hardness and gumminess, and significantly lower peak viscosity and solid loss than non-aged rice. The final viscosity of aged microwave-dried rice significantly increased for Titan rice dried at 360 and 450 kJ/kg-grain microwave specific energies but was not significantly different in XL753. The changes in the viscosity profiles of aged microwave-dried rice were generally similar to the trends recorded for aged control rice. Furthermore, aging significantly increased the water uptake and kernel elongation ratio of microwave-dried rice cultivar XL753 but had no significant impact on rice cultivar Titan. Statistical models indicate that the solid loss of microwave-dried rice decreases by 0.083% while the final viscosity, kernel elongation ratio and hardness increases by 30 cP, 0.014 and 41 g respectively, with every degree Celsius increase in aging temperature, when all other variables are kept constant. Also, aged microwave dried-rice that were treated at 360 and 525 kJ/kg-grain were practically equivalent in terms of hardness and solid loss.

Conclusions: Natural aging of microwave-dried rice (dried at 915 MHz frequency) led to changes in some physicochemical properties which were generally similar to the aging patterns of the control rice. Microwave specific energy of 525 kJ/kg-grain is recommended for rice drying because it produces rice with desirable drying and aging properties.

Significance and novelty: This project provides processing recommendations that are useful for the selection of microwave parameters that will achieve desirable rice products.

Keywords: Rice aging, 915 MHz microwave, Physicochemical properties, Rice quality, Rice drying.

INTRODUCTION

Rice kernels undergo changes in cooking, textural, pasting, and thermal properties during storage (Saikrishna et al., 2018; Guo et al., 2015; Park et al., 2012; Parnsakhorn & Langkapin, 2013; Zhou et al., 2007). This process is known as rice aging. The physicochemical changes are usually noticed after six months of rice storage at ambient temperature (25°C) (Thanompolkrung, Yongsawatdigul, & Tongta, 2017). External factors such as temperature, moisture content, storage duration and packaging impacts aged rice physicochemical characteristics (Zhou et al. 2007; Chrastil, 1990a). Aged rice is mostly preferred over freshly harvested rice by consumers because of its enhanced cooking and sensory properties such as increased cooked rice kernel elongation, volume expansion, water uptake, hardness, and cohesiveness (Saikrishna et al., 2018; Chrastil, 1990a).

Rice aging mechanisms have been proposed to be related to qualitative changes in lipids, starch, and protein. There are two possible pathways of lipid modification during rice aging. Firstly, triglycerides could be hydrolyzed forming free fatty acids. This could result in an increase in the proportion of amylose-lipid complex which may cause increased kernel hardness. Secondly, there could be autooxidation of lipids yielding hydroperoxides (Saikrishna et al., 2018). The hydroperoxides may accelerate protein oxidation which eventually affect rice functional properties (Jungtheerapanich et al., 2017). In terms of changes that occur to proteins during rice aging, some researchers reported that the disulphide cross-linking of glutelin in rice is the main reason for aging (Chrastil 1990b; Chrastil & Zarins 1992; Tang et al. 2002). Other researchers also suggested that albumin and globulin are predominantly responsible for changes in pasting properties of rice during storage (Guo et al., 2015).

In recent times, a novel and efficient technology, the 915 MHz industrial microwave is being explored for rice drying (Atungulu et al., 2016). The technology has a significant advantage of reducing rice drying duration from days to minutes (Bruce, Atungulu, Sadaka, & Smith, 2021; Smith, Atungulu, Sadaka, & Rogers, 2018; Atungulu et al., 2016). Additionally, the microwave has other advantages such as volumetric heating, rapid heating, non-contact heating, quick start-up and stopping, and portability of equipment (Menéndez et al., 2010). The volumetric heating property of microwaves allows heat to be evenly distributed throughout the entire volume of the material (rice) leading to a reduction in the moisture content and temperature gradients within individual rice kernels and result in better head rice yields than other conventional rice drying methods (Olatunde et al., 2017).

So far, studies have been conducted to determine the 915 MHz microwave's drying potential, energy consumption, microbial load reduction, and impacts on rice physicochemical properties (Smith & Atungulu, 2018; Olatunde et al., 2017; Atungulu et al., 2016). Furthermore, Bruce et al., (2021) determined microwave parameters for drying different rice cultivars with the 915 MHz microwave. They reported that microwave specific energy of 525 kJ/kg-grain (power-5kW, heating duration-3.5min) was suitable for drying freshly-harvested (harvest moisture content of 20% (wet basis)) medium grain rice Titan and long grain hybrid rice XL753 based on physicochemical properties relative to the natural air-dried control samples. Although there have been great advances in research on the commercialization of the 915 MHz microwave for rice drying, the effects of the process on characteristics of aged rice are unknown; such knowledge is vital for the selection of microwave processing parameters that will result in desirable rice products.

Natural aging occurs during the post-harvest storage of rice, and it is a time-consuming process (takes a minimum of 3-4 months) (Saikrishna et al., 2018). An alternative and less time-consuming approach (takes seconds to few hours), artificial aging which is also known as "accelerated aging of rice", can be carried out by heat treatment, microwave heating, hydrothermal treatment, and radio frequency treatment. Because of the ability of microwave heating to induce artificial aging of rice, the purpose of previous research on microwave treatment of rice has been to accelerate the aging property of rice and not to dry the rice. Consequently, past studies on microwave aging of rice analyzed the use of microwaves for accelerating the aging properties of already dried rice (12-14% moisture content) and not the natural storage/aging characteristics of high moisture content rice that has been purposely dried using the microwave (Nayak & Mohapatra, 2019; Le, & Songsermpong, 2014; Le, Songsermpong, Rumpagaporn, Suwanagul, & Wallapa, 2014; Nguyen, & Goto, 2009). These studies also used microwave dryers at 2450 MHz frequency to treat rice at microwave powers ranging from 540-2000 W and short heating durations of 23-180 s. They reported that aged samples had increased cooking time, kernel elongation, cooked rice hardness and stickiness, and decreased head rice yield and gel consistency than control samples (Nayak, & Mohapatra, 2019). Other researchers also investigated the effect of microwave power level, exposure durations, and heating passes on accelerated rice aging properties. They reported decreased peak viscosity and final viscosity and slightly increased breakdown and setback viscosity with increased microwave heating passes and microwave power level. They also observed that the hardness and stickiness of cooked rice did not have a significant correlation with microwave heating (Le & Songsermpong, 2014). The goal of this research is to determine the physicochemical properties of rice dried using a 915 MHz microwave and then aged.

MATERIALS AND METHODS

Sample procurement and preparation

Fresh rough rice from different geographical locations in Arkansas was used for this research. Titan, a medium grain cultivar from Pine Tree, and XL753, a long grain hybrid cultivar from Burdette were procured. All rice samples had initial harvest moisture content of 20% ± 1% (wet basis). The rice samples were treated with two different drying methods; natural air drying as control, compared to microwave heating followed by tempering and natural air cooling. For the control, approximately 2000 g of each rice cultivar in duplicates was exclusively dried using an equilibrium moisture content (EMC) chamber at 25˚C and 56% relative humidity (RH) to a safe moisture content of 12.5%.

For microwave treatment, about 2000 g of each rough rice sample was placed in a polypropylene microwave blind tray fitted with Teflon mesh and dried in an industrial microwave system (AMTek, Applied Microwaves Technology Inc., Cedar Rapids, IW, USA) at 915 MHz using specific energies ranging between 360-630 kJ/kg-grain. Microwave specific energy is the energy transferred per unit mass of product (Smith et al., 2018). Parameters for calculation of specific energy are shown in Table 1. The choice of specific energy used was based on the findings of previous research which showed that the use of 360-630 kJ/kg-grain microwave specific energy for rice drying does not cause damage to the rice kernels (Bruce et al., 2021; Smith & Atungulu, 2018; Olatunde et al., 2017). Following microwave treatment, samples were immediately transferred into glass jars and tightly sealed. The samples were tempered in an incubator at 60˚C for 4 h. After tempering, evenly spread samples were allowed to cool in the EMC chamber at 25˚C and 56% relative humidity (RH). The moisture content of the samples was analyzed using a grain moisture tester (AM 5200-A, PerkinElmer, Hagersten, Sweden). Samples that did not attain the required moisture content of 12.5% were further dried in the EMC chamber.

All dried rice samples from both treatment methods were dehulled using a huller (THU-35A, Satake Engineering Co., Tokyo, Japan). The brown rice was milled using a laboratory mill (McGill Number 2, Rapsco, TX, U.S.A.) for 60 s to obtain surface lipid content standardized at 0.4%. The head rice was separated from the broken rice using a grain separating device (Grain Machinery Mfg. Corp., FL, U.S.A.). The head rice was used for the experiment. About 300 g of head rice samples from all drying treatments were stored in airtight glass jars at 25°C in a forced air general laboratory incubator (VWR International Radnor, Korea) for 6 months.

Simultaneously, another 300 g of the head rice samples were stored at 4°C in a refrigerator (TFR725, Thomson, China) for 6 months. Samples stored at 25°C represent aged rice samples and those stored at 4°C represent non-aged samples. After storage, about 50 g of each sample was milled into flour using a cyclone sample mill (UDY Corp., CO, U.S.A.) fitted with a 0.50-mm screen for pasting properties determination. Physicochemical properties of the samples were determined. All experiments were duplicated. A flow chart of the methodology is shown in Figure 1 and the experimental design is shown in Table 2.

Surface lipid content

The surface lipid content of milled rice was determined by scanning about 50 g of milled rice using a near infrared reflectance meter (NIR, DA7200, Perten Instrument, Hagersten, Sweden). The NIR equipment was calibrated using AACC International Approved Method (39-25.01) prior to the analysis (Matsler, & Siebenmorgen, 2005; Saleh, Meullenet, & Siebenmorgen, 2008). The equipment converted sensor data to surface lipid content via the following calibration equation:

$$SLC\ (\%) = 0.871 \times SLC_{NIR} - 0.092 \ldots\ldots\ldots\ldots (1)$$

Where SLC is the surface lipid content for the approved method and SLC_{NIR} is the surface lipid content for the NIR method.

Whiteness index

Whiteness index was determined according to the method described by Pruengam, Soponronnarit, Prachayawarakorn, & Devahastin, (2014). The color of about 50 g of head rice samples was measured using a near infrared reflectance meter (NIR, DA7200, Perten Instrument, Hagersten, Sweden). The sample color was described based on the International Commission on Illumination (CIE) L^*, a^*, b^* color system. Color parameter L^* represents lightness and ranges from 100 (light) to 0 (dark), parameter a^* represents red-green color with $+a^*$ values for redness and $-a^*$ values for greenness, parameter b^* signifies yellow-blue color with $+b^*$ values for yellowness and $-b^*$ values for blueness. The a^* and b^* parameters range from −120 to 120 (Khir et al., 2014). The whiteness index (*WI*) was calculated using the following equation:

$$WI = 100 - [(100-L^*)^2 + (a^*)^2 + (b^*)^2]^{0.5} \ldots\ldots\ldots\ldots (2)$$

Crude protein content

The percentage crude protein content of milled rice was determined according to the AACC International Approved Method (39-25.01). A near infrared reflectance meter (NIR, DA7200, Perten Instrument, Hagersten, Sweden) was used to scan about 50 g of milled rice. Prior to the analysis, the NIR equipment was calibrated using AACC International Approved Method (46-16.01). The equipment translated sensor data to percentage crude protein using the following calibration equation:

$$CP\ (\%) = 0.747 \text{ x } CP_{NIR} + 1.893 \ldots\ldots\ldots\ldots\ldots (3)$$

Where CP is the crude protein using the approved method and CP_{NIR} is the crude protein determined using the NIR method (Bruce, Atungulu, & Sadaka, 2020a).

Pasting properties

The pasting properties of rice flour were analyzed according to the AACC international approved method 61-02.01. The paste viscosities were determined on the paste of 3 g rice flour and 25 mL water using a viscometer (RVA-Super 4, Newport Scientific, Warriewood, NSW, Australia), which adjusts for moisture content. The flour paste was first held at 50˚C for 1.5 min, ramped to 95˚C at 12.2˚C /min, held for 2 min and then cooled to 50˚C at 12.2˚C /min and finally held for 1.5 min (Bruce et al., 2020a). The peak, setback and final viscosities were recorded in centipoises.

Kernel elongation ratio and water uptake capacity

The kernel elongation ratio and water uptake capacity of rice were determined following methods described by Nayak and Mohapatra (2019) with some modifications. Exactly 8 g of head rice was weighed. The length of 10 randomly selected raw head rice kernels were measured using a digital vernier caliper and added back to the weighed sample. The 8 g rice sample was placed in an aluminum canister and 40 g of water was added. The canister containing the rice sample and water was then placed in boiling water inside a rice cooker (ARC-363NG, Aroma Housewares Co., China) and cooked for 20 min. After cooking, the excess water from the rice was drained into a pre-weighed Erlenmeyer flask using a 2 mm sieve placed in a funnel. After draining off the water, the cooked rice was weighed and the length of 10 randomly selected cooked kernels were measured. Kernel elongation and water uptake were calculated as follows:

$$\text{Kernel elongation ratio} = \frac{\text{Length of 10 cooked rice kernels}}{\text{Length of 10 uncooked rice kernels}} \ldots\ldots\ldots.. (4)$$

$$\text{Water uptake (\%)} = \frac{\text{Weight of the cooked rice} - \text{Weight of the uncooked rice}}{\text{Weight of the uncooked rice}} \times 100 \ldots\ldots\ldots (5)$$

Volume expansion ratio

The volume expansion ratio is the change in volume of rice after cooking. Using the toluene displacement method, exactly 8 g of raw rice was placed in a measuring cylinder containing 30 mL of toluene solution. The volume of the raw rice was measured as the difference between the final volume and the initial volume of the toluene solution. The same procedure was used to determine the volume of cooked rice. The volume expansion ratio was calculated as follows:

$$\text{Volume expansion ratio} = \frac{\text{Volume of cooked rice}}{\text{Volume of uncooked rice}} \ldots\ldots\ldots\ldots (6)$$

Solid loss

The excess water that was drained from the cooked rice into the pre-weighted Erlenmeyer flask was evaporated at 105°C for 24 h in a forced air general laboratory incubator (VWR International Radnor, Korea). The Erlenmeyer flask containing dehydrated solids was cooled in a desiccator for 1 h and weighed. Solid loss is defined as the increase in weight of the Erlenmeyer flask divided by the weight of the rice sample expressed as a percentage. The solid loss was calculated as follows:

$$\text{Solid loss (\%)} = \frac{\text{Increase in weight of Erlenmeyar flask}}{\text{Weight of rice sample}} \times 100 \ldots\ldots\ldots\ldots (7)$$

Textural properties

Cooked rice texture was analyzed using a texture analyzer (Plus-upgrade, Stable Microsystems, UK). About 1 g of cooked rice sample was compressed with a 35 mm cylinder probe using a two-cycle, force-versus-distance compression program. The texture analyzer settings are as follows: Pre-Test Speed, 1.00 mm/s; Test Speed, 5.00 mm/s; Post-Test Speed, 5.00 mm/s; Strain, 80%; Time, 5.00 s; Trigger Force (auto), 0.049 N. The cooked rice hardness and cohesiveness were computed with the Exponent Stable Micro Systems software. Four texture measurements were taken for each cooked rice sample.

Statistical analysis

All properties of rice samples except texture analysis (quadruplicates) were determined in duplicates. Analysis of variance, Tukey's honest significant difference test and Equivalence Two One-Sided Tests were performed using statistical software JMP Pro 16 (SAS Institute, Cary N.C.) to determine significant differences between samples. The level of significance was set at 5% for mean comparison.

RESULTS AND DISCUSSION

Surface lipid, whiteness index, and crude protein content of aged microwave-dried rice

Surface lipid content and the whiteness index of control samples and microwave-dried rice at all specific energies for aged and non-aged rice of the studied cultivars were not statistically different (Table 3). The highest whiteness index of 70.231 ± 0.44 was recorded in rice cultivar XL753 that was microwave-dried at 450 kJ/kg-grain and aged. On the other hand, the lowest whiteness index of 67.616 ± 1.07 was reported in the non-aged control Titan rice. Surface lipid content of rice refers to the quantity of lipids remaining on the rice kernel surface after milling, and it is an indicator of the degree of milling. Significantly higher surface lipid contents in rice can lead to early rancidity of the rice. The whiteness index is also an indicator of the color or visual appeal, and degree of milling of rice. The more rice bran that is removed from a rice kernel surface during milling, the higher the kernel whiteness, and the lower the surface lipid and protein contents (Puri, Dhillon, & Sodhi, 2014; Bruce et al., 2021). The lack of significant impact of aging on the whiteness index of rice suggests that there was limited Maillard-type non-enzymatic browning during the aging process. Although the surface lipid content was not impacted by aging for both drying methods, it is possible that changes like hydrolysis and oxidation may have occurred in the non-starch lipids (free lipids) within the kernel which can affect some cooking properties of the rice (Zhou et al., 2002). The advantage in having a lack of significant influence of aging on the whiteness index and surface lipid content of both control rice and microwave-dried rice is that the storability, and visual appeal of the rice to consumers will not be negatively impacted. Therefore, microwave-dried rice which is already advantageous due to the use of shorter drying duration of about 3.5 min relative to the control/ natural air-drying duration of about 7 days will also not suffer marketability upon aging because it has similar physical properties as the control rice.

The crude protein content of the aged and non-aged control rice samples of both cultivars were not significantly different (Table 3). Furthermore, aging did not have a significant effect on the crude protein content of all microwave-dried rice samples for both rice cultivars. This finding is consistent with the reports of other researchers that no change in protein content occurs during storage of conventionally dried rice (Bruce, Atungulu, & Sadaka, 2020b; Thanompolkrung, et al., 2017; Zhou, Robards, Helliwell, & Blanchard, 2002). On the contrary, during storage or aging of rice, structural changes such as the protein oxidation (formation of di-sulphide linkages from sulphydryl groups), increase in free amino acid content of rice, decrease in lower molecular weight peptides, increase in higher molecular weight peptides, and decrease in solubility of inherent albumin may occur leading to textural and cooking property changes in the rice (Bhattacharya, 2011; Zhou et al., 2002; Dhaliwal, Sekhon, & Nagi, 1991; Chrastil 1990a). The slight variations in the level of change in the protein content across the different microwave specific energies during aging in this study suggests the variability in the degree of starch and protein modifications during microwave drying of rice at different specific energies as indicated by other researchers (Bruce et al., 2021, Olatunde & Atungulu, 2018; Smith et al., 2018).

Pasting properties of aged microwave-dried rice

The pasting properties of the control and microwave-dried rice are shown in Table 3. Peak viscosity refers to the highest attainable viscosity during cooking of starch. Final viscosity is the viscosity after cooking and cooling the starch paste. The setback viscosity is the gain or a bounce back in viscosity during the cooling of the starch paste. Generally, aged microwave dried rice had similar pasting property trends as aged control rice. Aging had a significant impact on the peak viscosity of microwave dried rice. The peak viscosity of microwave-dried rice decreased upon aging. Increasing the microwave specific energy from 360 to 630 kJ/kg-grain resulted in a 975 cP decrease and a 166 cP decrease in the peak viscosity of aged Titan and aged XL753 rice respectively. For the control samples, aging significantly decreased the peak viscosity of XL753 but had an insignificant impact on Titan. In addition, aging resulted in significantly increased final viscosity and setback viscosity of the control rice for both cultivars. For microwave-dried rice, the final viscosity of aged rice significantly increased for Titan rice dried at 360 and 450 kJ/kg-grain microwave specific energies but was not significantly different in XL753. Increasing the microwave specific energy from 360 to 630 kJ/kg-grain decreased the final viscosity of Titan and XL753 aged rice by 102.5 cP and 367.5 cP respectively. Statistical models for predicting the physicochemical properties of microwave-dried rice are shown in Table 4. The models indicate that final viscosity increases by 30 cP with every degree Celsius increase in the aging temperature of microwave-dried rice when all other variables are kept constant. There were interactions between aging status and microwave specific energy with regards to the final viscosity of rice. The R-square indicates that the model accounts for 77.5% of the variability in final viscosity. Regarding variable importance, cultivar had a greater total effect (0.798) on the final viscosity of microwave-dried rice than microwave specific energy (total effect = 0.588) and aging status (total effect = 0.380). Aging also significantly increased the setback viscosity of microwave dried rice. These findings are consistent with the viscosity profiles of aged control rice reported by other researchers (Guo et al., 2015; Katekhong & Charoenrein, 2012; Zhou et al., 2003). They explained that the decrease in peak viscosity shows that starch granules of aged rice were more resistant to swelling than those of fresh rice (Katekhong & Charoenrein, 2012). They also attributed the decrease in peak viscosity to the interaction between starch and non-starch components of the rice (Zhou et al., 2003). The formation of starch-lipid complexes during aging may also impact the rice pasting behavior (Kaur & Singh, 2000, Keawpeng & Venkatachalam, 2015). Le and Songsermpong (2014) in their work on the acceleration of rice aging properties using microwave observed changes in the viscosities of microwave treated rice samples. They explained that the increase in setback viscosity indicates a higher degree of retrogradation and leads to increased cooked rice firmness (Soponronnarit, Chiawwet, Prachayawarakorn, Tungtrakul, & Taechapairoj, 2008). The differences in the effects of aging on the pasting properties of the two rice cultivars in this study may be due to genotypic variation. The similar pasting property changes or trends exhibited by the control rice and microwave dried rice during aging may be useful in the easy prediction of cooking properties of microwave dried rice during storage.

Kernel elongation ratio of aged microwave-dried rice

Figure 2 shows the kernel elongation ratio of rice samples. An increase in the cooked rice kernel length without increase in width is considered a highly desirable trait in some high-quality rice (Rosniyana, Hashifah, & Shariffah Norin, 2004). Aging significantly increased the kernel elongation ratio of rice cultivar XL753 that was microwave dried at 360 kJ/kg-grain specific energy but had no significant impact on those dried at other specific energies. Generally, across both cultivars and drying methods, the kernel elongation ratio of aged rice was slightly higher than those of non-aged rice. It is also interesting to note that the kernel elongation ratio of aged control rice samples was not significantly different from those of aged microwave dried samples across both cultivars. This implies that regarding marketability, the aged microwave dried rice can compete with aged control rice and will not suffer low marketability due to lower kernel elongation when cooked. Statistical models indicate that kernel elongation ratio increases by 0.014 with every degree Celsius increase in aging temperature, when all other variables are kept constant (Table 4). Aging status had a greater total effect (0.542) on the kernel elongation ratio than cultivar (total effect = 0.441) and microwave specific energy (total effect = 0.378). Increase in the kernel elongation ratio of aged conventionally dried rice has been reported by other researchers (Soponronnarit et al., 2008; Rosniyana et al., 2004). During rice aging, the oxidation of the ferulate ester of the hemicellulose fraction of the cell contributes to crosslinking and increases the strength of the cell walls of starch. This leads to greater resistance of grains to disintegration during cooking; hence kernel elongation is increased without breakage of the rice (Soponronnarit et al., 2008; Mod, Conkerton, Chapital, & Yatsu, 1983).

The equivalence test for kernel elongation ratio, solid loss, and hardness of rice is shown in Table 5. The equivalence two one-sided test method is used to analyze practical differences between means (Schuirmann, 1987). The choice of the values for the *difference considered practically zero* was based on an understanding of the properties of rice and a physical observation of the rice for different physicochemical properties. Using a value of 0.09 as the *difference considered practically zero* for kernel elongation ratio, five pairs and two pairs of samples were identified as practically equivalent for Titan cultivar and XL753 respectively. For instance, Titan rice cultivar that was microwave dried at 450 kJ/kg-grain and aged was practically equivalent in terms of kernel elongation ratio to Titan rice cultivars that was microwave dried at 525 kJ/kg-grain and aged. The same finding was also observed in rice cultivar XL753. Consequently, rice producers can choose the higher microwave specific energy of 525 kJ/kg-grain for rice drying because it provides higher moisture removal from rice kernels, and it has been shown by other researchers to be suitable for drying freshly harvested rice based on physicochemical properties relative to the natural air-dried control samples (Bruce et al., 2021).

Water uptake, volume expansion ratio and solid loss of aged microwave-dried rice

The water uptake and volume expansion ratio of rice samples are shown in Figures 3 and 4 respectively. The water uptake of control rice for both cultivars significantly increased after aging. For microwave drying, aging significantly increased the water uptake of rice cultivar XL753 but had no significant impact on rice cultivar Titan. The difference between the maximum and minimum water uptake for cultivar XL753 was 87.5%. The maximum water uptake for XL753 was recorded in the control aged rice while the minimum was recorded in rice that was microwave-dried at 525 kJ/kg-grain and non-aged. In addition, across both cultivars and drying methods, aged rice had slightly higher water uptake than non-aged rice. Aging had no significant impact on the volume expansion ratio of control and microwave dried rice across both cultivars. Generally, aged rice had slightly higher volume expansion ratio than non-aged rice. In rice cultivar Titan, the volume expansion ratios of aged microwave dried rice at 525 and 630 kJ/kg-grain specific energies were significantly lower than the aged control rice. However, this was not observed in XL753. The varying response of the two cultivars in terms of water uptake and volume expansion ratio may be an influence of variations in the rice genotypes. Other researchers also reported increased water uptake and volume expansion ratio of rice during storage (Soponronnarit et al., 2008; Rosniyana et al., 2004; Chrastil, 1990a). They explained that aged rice was more resistant to disintegration during cooking because of the formation of a more strengthened cell wall during storage, which maintains the hexagonal shape that provides higher water adsorption and subsequent volume increase.

Aged rice had significantly lower solid loss than non-aged rice for both cultivars and drying methods (Figure 5). Furthermore, microwave drying at 630 kJ/kg-grain provided a higher solid loss reduction in rice than the control drying method. Increasing the microwave specific energy from 360 to 630 kJ/kg-grain decreased the solid loss of aged Titan rice by 0.74% and that of aged XL753 rice by 0.21%. Statistical models indicate that the solid loss decreases by 0.083% with every degree Celsius increase in aging temperature, when all other variables are kept constant (Table 4). The model accounts for 95.8% of the variability in solid loss. Aging status had a greater total effect (0.655) on the solid loss of microwave-dried rice than microwave specific energy (total effect = 0.372) and cultivar (total effect = 0.011). The equivalence test using a value of 0.28 as the *difference considered practically zero* for solid loss identified six pairs and two pairs of samples as practically equivalent for Titan cultivar and XL753 respectively (Table 5). For instance, both rice cultivars that were microwave dried at 360 kJ/kg-grain and aged were practically equivalent in terms of percent solid loss to rice that was microwave dried at 525 kJ/kg-grain and aged. This further reinforces the point that the choice of a higher microwave specific energy of 525 kJ/kg-grain over lower microwave specific energies by rice producers may not negatively impact rice cooking properties. The reduction in the solid loss content of aged rice may be due to structural changes in starch granules like strengthened cell walls during storage, which leads to greater resistance of the grain to disintegration during cooking. (Soponronnarit et al., 2008).

Hardness and cohesiveness of aged microwave-dried rice

Figure 6 shows a plot of cooked rice hardness of control samples and microwave-dried rice. The cooked rice hardness is the force required to compress food between the molar teeth on the first chew (Pandey, MR, & A, 2016). It is technically defined as the force exhibited in first bite at maximum compression (Pandey et al., 2016). Aging had a significant impact on the hardness of control samples and microwave-dried rice samples for both rice cultivars. Aged rice was significantly harder than non-aged rice. All aged microwave-dried samples were significantly harder than the aged control rice samples for both rice cultivars. Additionally, hardness significantly increased with increasing microwave specific energy for both aged and non-aged samples. For medium grain cultivar Titan, the hardness of aged control rice was not significantly different from those of non-aged rice that were microwave treated at 360, 450 and 525 kJ/kg-grain. Similarly, for XL753, the hardness of the control aged rice was not significantly different from those of non-aged rice that were microwave treated at 360 and 450 kJ/kg-grain. This indicates that the use of microwaves to dry freshly harvested rice accelerates rice aging and improves the cooked rice hardness which is desirable to consumers. Furthermore, the statistical model for the prediction of rice physicochemical properties indicates that in both cultivars, irrespective of the microwave specific energy, hardness increases by 41 g with every degree Celsius increase in aging temperature (Table 4). In terms of variable importance, cultivar had a greater total effect (0.378) on hardness than microwave specific energy (total effect = 0.345) and aging status (total effect = 0.293).

Testing for equivalence with a value of 300 g as the *difference considered practically zero* for hardness, the Titan non-aged microwave-dried rice at specific energies 360, 450 and 525 kJ/kg-grain were identified as practically equivalent (Table 5). The Titan aged microwave-dried rice at specific energies 360 and 525 kJ/kg-grain were also practically equivalent. For XL753, non-aged microwave-dried rice at specific energies 360 and 450, and 525 and 630 kJ/kg-grain were practically equivalent. These findings imply that when specific energies of 360-630 kJ/kg-grain are used to dry medium and long grain rice, the cooked rice firmness may not be easily distinguishable. Consequently, rice processes can choose the higher microwave specific energy for rice drying since it is characterized by higher moisture removal from the rice kernel (Bruce et al., 2021). Other researchers also reported increased cooked rice hardness of microwave accelerated aged rice and aged conventionally dried rice (Nayak & Mohapatra, 2019; Le & Songsermpong, 2014; Tananuwong & Malila, 2011; Wiset, Laoprasert, Borompichaichartkul, Poomsa-ad, & Tulyathan, 2011; Zhou et al., 2002). During rice aging, the increased retrogradation of starch (as seen in increased setback viscosity) leads to increased cooked rice hardness (Villareal, Resurreccion, Suzuki, & Juliano, 1976). Also, the increased disulfide linkages in proteins during storage may cause starch granules in rice kernels to become stronger, leading to an increase in rice hardness (Le & Songsermpong, 2014; Wiset et al., 2011; Chrastil, 1990b). Another explanation is that structural modifications of starch and protein gels (formation of stronger network of oryzenin gel) during aging may increase the hardness of the cooked aged rice. (Tananuwong & Malila, 2011).

Cohesiveness is defined as the internal force holding a grain together before it breaks when compressed between the teeth (Pandey et al., 2016). There was no significant effect of aging on the cooked rice cohesiveness of the control and microwave dried rice (Figure 7). Across both cultivars, the cohesiveness of the control aged rice was not significantly different from those of the microwave-dried rice at different specific energies. Gumminess is the denseness that persist throughout mastication of food. It is defined as the energy required to disintegrate cooked food to a state, ready for swallowing (Pandey et al., 2016). Aging had a significant impact on the gumminess of microwave-dried rice (Figure 8). Across both drying methods and cultivars, aged rice had higher gumminess than non-aged rice. The highest gumminess was recorded in the aged microwave-dried rice at 630 kJ/kg-grain specific energy for both cultivars. Increasing the microwave specific energy from 360 to 630 kJ/kg-grain resulted in 1094.83 g and 648.26 g increases in the gumminess of aged Titan and aged XL753 rice respectively. In addition, all non-aged microwave-dried rice had significantly higher gumminess than non-aged control rice for both cultivars. This implies that microwave dried rice generally has greater denseness that persist throughout mastication than the control rice. The impact of aging on the gumminess of microwave dried rice may be due to structural changes like the protein oxidation, and the formation of starch-lipid complexes during rice aging (Keawpeng & Venkatachalam, 2015; Bhattacharya, 2011; Zhou et al., 2002).

CONCLUSION

This study explored the physicochemical properties of rice dried using a 915 MHz microwave and then aged. Generally, the aging trends of the microwave-dried rice were like the patterns of the control rice. This indicates that aged microwave-dried rice can provide the beneficial physicochemical properties that aged control rice provides consumers. Aged microwave-dried rice had significantly higher setback viscosity, cooked rice hardness and gumminess, and significantly lower peak viscosity and solid loss than non-aged rice. Aging significantly increased the water uptake and kernel elongation ratio of microwave-dried rice cultivar XL753 but had no significant impact on rice cultivar Titan. On the other hand, aging had no significant impact on the surface lipid content, whiteness index, crude protein content, volume expansion ratio and cohesiveness of control, and microwave-dried rice for both rice cultivars. Statistical models indicate that the solid loss of microwave-dried rice decreases by 0.083% while the final viscosity, kernel elongation ratio and hardness increases by 30 cP, 0.014 and 41 g respectively, with every degree Celsius increase in aging temperature, when all other variables are kept constant. Regarding variable importance, aging status had a greater total effect on the kernel elongation ratio and solid loss of microwave dried rice than cultivar and microwave specific energy. Furthermore, rice dried at microwave specific energies 360 and 525 kJ/kg-grain were practically equivalent in terms of solid loss and cooked rice hardness. Therefore, we recommend the use of the 525 kJ/kg-grain microwave specific energy for rice drying because it provides higher moisture removal from rice kernels than lower specific energies and it does not negatively impact rice physicochemical properties.

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TABLES AND FIGURES

Table 1. Parameters for calculation of specific energy

Power (kW)	Mass (kg)	Duration (min)	Microwave specific energy (kJ/kg-grain) [*]
4	2	3	360
5	2	3	450
5	2	3.5	525
6	2	3.5	630

[*] kJ/kg-grain means kJ per kg of initial wet grain mass.

Table 2. Experimental design[*]

Drying strategy	Rice cultivars	Microwave treatment power (kW)	Microwave heating duration (min)
1. Control treatment: natural air drying (temperature at 25°C and relative humidity at 56%)	XL753	4	3
2. Microwave heating followed by tempering at 60°C for 4 h and natural air cooling	Titan	5	3.5
		6	

[*] This is not a full factorial design

Table 3. Some physicochemical properties of aged and non-aged rice

Sample name[*]	Surface lipid content (%)	Whiteness index	Crude protein content (%)	Peak viscosity (cP)	Final viscosity (cP)	Setback viscosity (cP)
T0A	0.340 ± 0.00 a	67.945 ± 0.31 a	6.780 ± 0.10 a	3348.0 ± 1.41 ab	3485.0 ± 66.47 a	183.0 ± 0.00 d
T0N	0.335 ± 0.04 a	67.616 ± 1.07 a	6.620 ± 0.16 abc	3525.0 ± 22.63 a	2772.5 ± 44.55 d	-752.5 ± 21.92 g
T360A	0.380 ± 0.01 a	68.492 ± 0.72 a	6.705 ± 0.11 ab	2934.5 ± 33.23 c	3511.0 ± 83.44 a	659.0 ± 0.00 c
T360N	0.320 ± 0.03 a	68.069 ± 0.12 a	6.335 ± 0.04 bcde	3317.0 ± 45.25 ab	3010.0 ± 21.21 c	-307.0 ± 24.04 f
T450A	0.350 ± 0.03 a	68.819 ± 0.00 a	6.620 ± 0.04 abc	2692.5 ± 54.45 c	3415.5 ± 2.12 ab	723.0 ± 52.33 c
T450N	0.310 ± 0.01 a	68.018 ± 0.64 a	6.330 ± 0.01 cde	3237.0 ± 16.97 b	3087.5 ± 37.48 c	-149.5 ± 20.51 g
T525A	0.380 ± 0.03 a	68.756 ± 0.18 a	6.540 ± 0.11 abcd	2310.0 ± 45.25 d	3357.5 ± 10.61 ab	1047.5 ± 34.65 b
T525N	0.325 ± 0.02 a	68.067 ± 0.33 a	6.180 ± 0.07 de	3392.5 ± 133.64 ab	3206.5 ± 48.79 bc	-126.0 ± 0.00 g
T630A	0.390 ± 0.06 a	68.460 ± 0.25 a	6.030 ± 0.14 ef	1959.5 ± 75.66 d	3408.5 ± 65.76 ab	1449.0 ± 9.90 a
T630N	0.365 ± 0.02 a	68.096 ± 0.28 a	5.705 ± 0.04 f	2275.5 ± 103.94 e	3414.0 ± 77.78 ab	1138.5 ± 26.16 b

[*] The first letter of the sample name indicates the rice cultivar; T represents Titan and X represents XL753. The number following the first letter indicates the microwave specific energy. Zero microwave specific energy refers to control rice samples that were exclusively dried with the equilibrium moisture camber. The last letter in the sample name represents the aging status of the rice; A represents aged, and N represents non-aged. For instance, T0A refers to Titan rice that was dried with the equilibrium moisture camber and then aged. X450N represents XL753 rice that was dried with the 915 MHz industrial microwave at 450 kJ/kg-grain and non-aged. Levels not connected by the same letter in a column are statistically significant, $p<0.05$. kJ/kg-grain means kJ per kg of initial wet grain mass.

Table 3 Cont'd. Some physicochemical properties of aged and non-aged rice

Sample name[*]	Surface lipid content (%)	Whiteness index	Crude protein content (%)	Peak viscosity (cP)	Final viscosity (cP)	Setback viscosity (cP)
X0A	0.345 ± 0.01 a	69.645 ± 0.63 a	6.125 ± 0.12 ab	2141.5 ± 31.82 cd	3714.0 ± 24.04 a	1572.5 ± 7.78 bc
X0N	0.335 ± 0.04 a	69.551 ± 0.05 a	6.280 ± 0.00 a	2986.0 ± 35.36 a	3169.5 ± 24.75 b	183.5 ± 10.61 g
X360A	0.395 ± 0.05 a	69.543 ± 0.37 a	6.120 ± 0.06 ab	1715.0 ± 9.90 a	3504.5 ± 169.00 ab	1677.0 ± 0.00 a
X360N	0.415 ± 0.04 a	69.000 ± 0.18 a	6.125 ± 0.18 ab	2619.0 ± 18.38 b	3533.0 ± 121.62 ab	815.0 ± 0.00 f
X450A	0.420 ± 0.01 a	70.231 ± 0.44 a	6.185 ± 0.16 a	1855.0 ± 39.60 de	3499.5 ± 4.95 ab	1644.5 ± 34.65 ab
X450N	0.380 ± 0.06 a	69.554 ± 0.45 a	6.080 ± 0.06 ab	2352.5 ± 173.24 bc	3391.5 ± 54.45 ab	1123.0 ± 0.00 e
X525A	0.420 ± 0.00 a	70.077 ± 0.18 a	6.130 ± 0.01 ab	1624.0 ± 155.56 a	3226.0 ± 216.37 b	1602.0 ± 60.81 ab
X525N	0.410 ± 0.07 a	69.249 ± 0.58 a	5.965 ± 0.16 ab	2259.5 ± 105.36 c	3425.5 ± 21.92 ab	1256.0 ± 0.00 d
X630A	0.410 ± 0.00 a	70.058 ± 0.43 a	5.875 ± 0.02 ab	1549.0 ± 0.00 a	3137.0 ± 0.00 b	1588.0 ± 0.00 abc
X630N	0.385 ± 0.01 a	69.642 ± 0.44 a	5.760 ± 0.04 b	1813.0 ± 89.10 de	3322.0 ± 96.17 ab	1509.0 ± 7.07 c

[*] The first letter of the sample name indicates the rice cultivar; T represents Titan and X represents XL753. The number following the first letter indicates the microwave specific energy. Zero microwave specific energy refers to control rice samples that were exclusively dried with the equilibrium moisture camber. The last letter in the sample name represents the aging status of the rice; A represents aged, and N represents non-aged. For instance, T0A refers to Titan rice that was dried with the equilibrium moisture camber and then aged. X450N represents XL753 rice that was dried with the 915 MHz industrial microwave at 450 kJ/kg-grain and non-aged. Levels not connected by the same letter in a column are statistically significant, $p<0.05$. kJ/kg-grain means kJ per kg of initial wet grain mass.

Table 4. Models for predicting the physicochemical properties of microwave-dried rice

Model[*]	R-square	Variable Importance		
		Variable	Main Effect	Total Effect
Final viscosity (cP) = 3096.206 - 529.299C(T) + 529.299C(X) + 0.412MSE + 30.352AS + 0.835C(T)*MSE - 0.835C(X)*MSE + 6.398C(T)*AS - 6.398C(X)*AS - 0.055MSE*AS	0.775	Cultivar	0.130	0.798
		Microwave specific energy (kJ/kg-grain)	0.053	0.588
		Aging status (°C)	0.054	0.380
Kernel elongation ratio = 1.831 + 0.101C(T) - 0.101C(X) + 0.0003MSE + 0.014AS - 0.0002C(T)*MSE + 0.0002C(X)*MSE - $2.177\text{x}10^{-5}$MSE*AS	0.574	Aging status (°C)	0.442	0.542
		Cultivar	0.194	0.441
		Microwave specific energy (kJ/kg-grain)	0.027	0.378
Solid loss (%) = 1.537 - 0.072C(T) +0.072C(X) + 0.017MSE - 0.083AS - $2.114\text{x}10^{-5}(\text{MSE})^2$ + 0.006C(T)*AS - 0.006C(X)*AS + $7.723\text{x}10^{-5}$MSE*AS	0.958	Aging status (°C)	0.609	0.655
		Microwave specific energy (kJ/kg-grain)	0.332	0.372
		Cultivar	0.004	0.011
Hardness (g) = 9386.539 + 345.843C(T) - 345.843C(X) - 13.784MSE + 41.321AS + $0.018(\text{MSE})^2$	0.905	Cultivar	0.352	0.378
		Microwave specific energy (kJ/kg-grain)	0.319	0.345
		Aging status (°C)	0.267	0.293

[*] C(T) = Cultivar (Titan), C(X) = Cultivar (XL753), MSE = Microwave specific energy (kJ/kg-grain), AS = Aging status (°C).

Table 5. Equivalence test report for kernel elongation ratio, solid loss, and hardness of rice [*]

	Kernel elongation ratio	Solid loss (%)	Hardness (g)
Difference considered practically zero	0.09	0.28	300
Practically equivalent samples (Cultivar Titan)	T450A and T525A T360N and T630A T450A and T450N T360A and T0N T450N and T525A	T360A and T525A T360A and T630N T360N and T450N T360N and T0N T450N and T0N T525A and T630N	T360A and T525A T360N and T450N T360N and T525N T450N and T525N
Practically equivalent samples (Cultivar XL753)	X450A and X525A X630A and X630N	X360A and X525A X360N and X525N	X360N and X450N X525N and X630N

[*] The first letter of the sample name indicates the rice cultivar; T represents Titan and X represents XL753. The number following the first letter indicates the microwave specific energy. Zero microwave specific energy refers to control rice samples that were exclusively dried with the equilibrium moisture camber. The last letter in the sample name represents the aging status of the rice; A represents aged, and N represents non-aged. For instance, T0A refers to Titan rice that was dried with the equilibrium moisture camber and then aged. X450N represents XL753 rice that was dried with the 915 MHz industrial microwave at 450 kJ/kg-grain and non-aged. kJ/kg-grain means kJ per kg of initial wet grain mass.

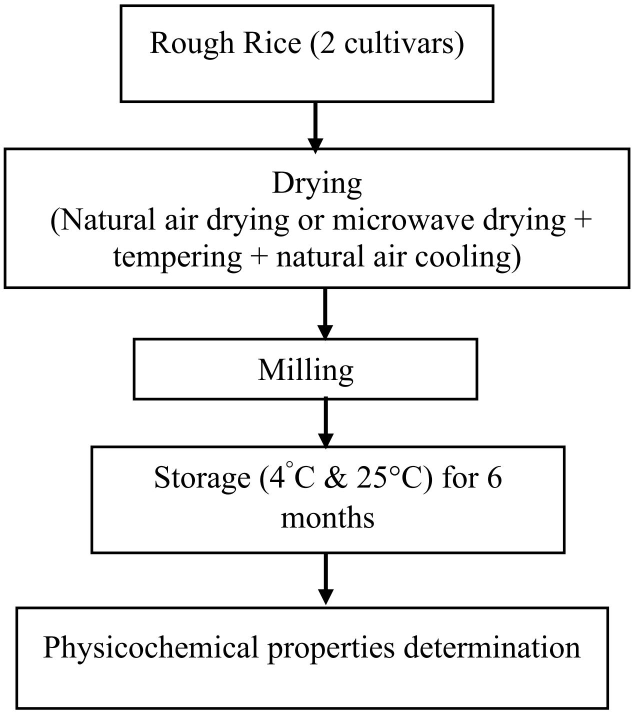

Figure 1. A flow chart of the methodology for all samples.

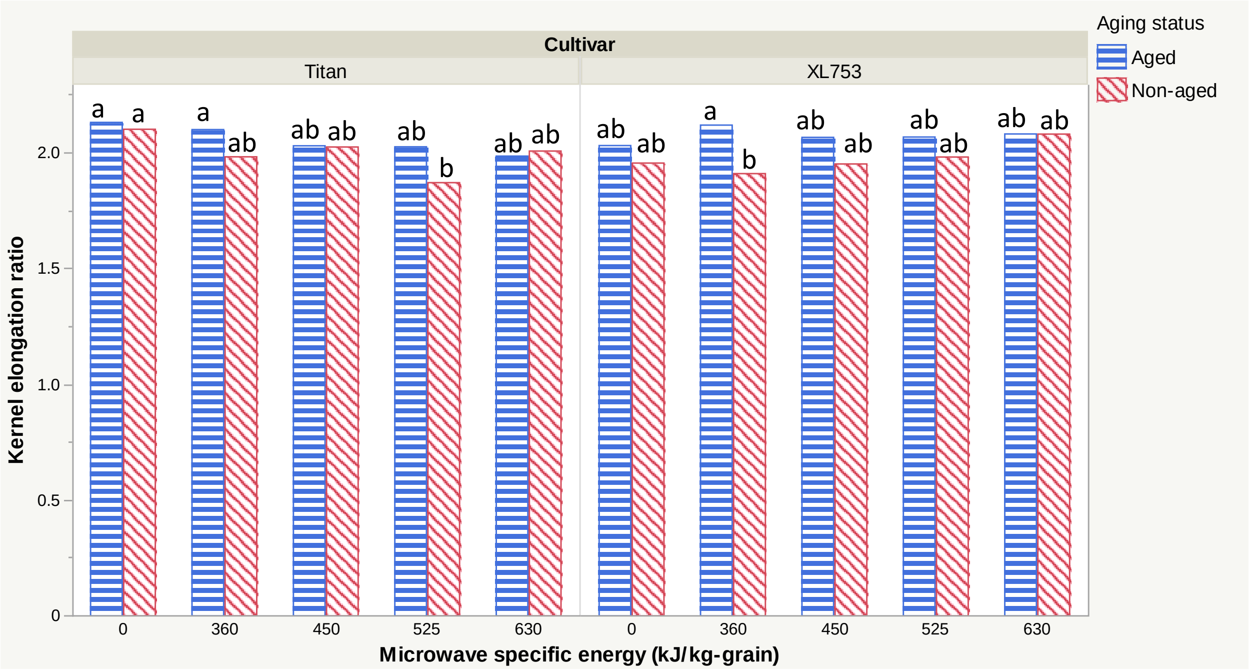

Figure 2. A plot of kernel elongation ratio against control samples and rice dried using microwave at 915 MHz frequency. Control samples were dried using the equilibrium moisture content chamber at 25°C and 65% relative humidity (RH) and have microwave specific energy = 0. Levels not connected by the same letter are statistically significant, $p<0.05$. kJ/kg-grain means kJ per kg of initial wet grain mass.

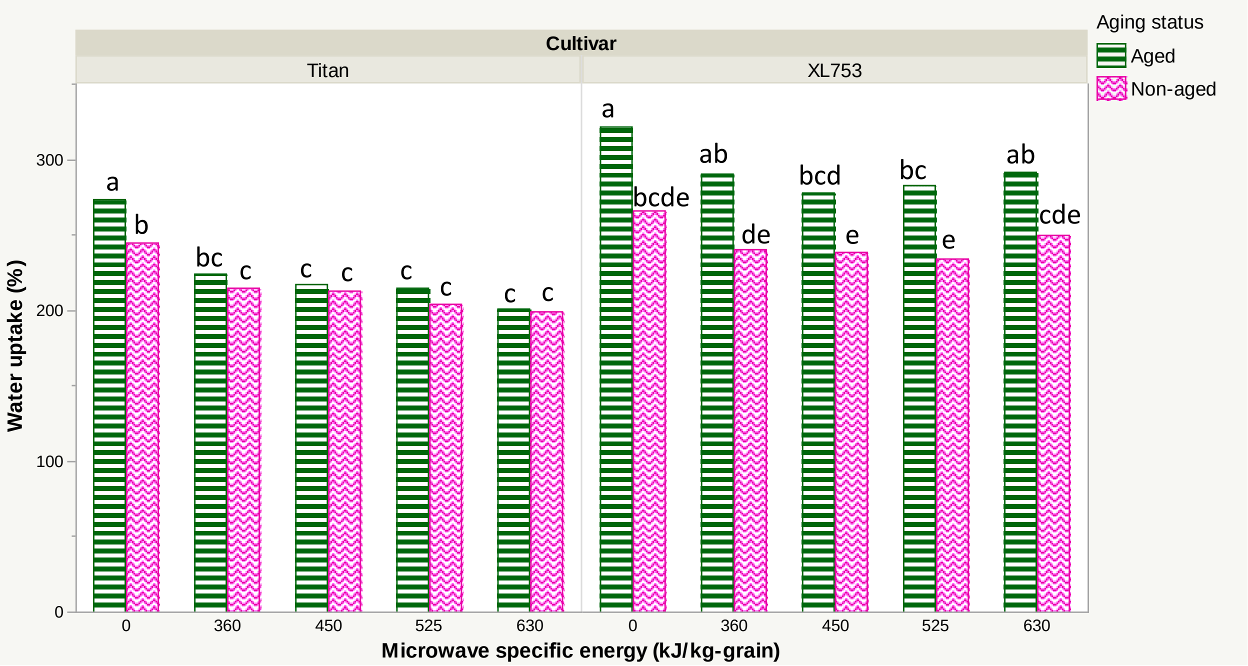

Figure 3. A plot of water uptake against control samples and rice dried using microwave at 915 MHz frequency. Control samples were dried using the equilibrium moisture content chamber at 25˚C and 65% relative humidity (RH) and have microwave specific energy = 0. Levels not connected by the same letter are statistically significant, $p<0.05$. kJ/kg-grain means kJ per kg of initial wet grain mass.

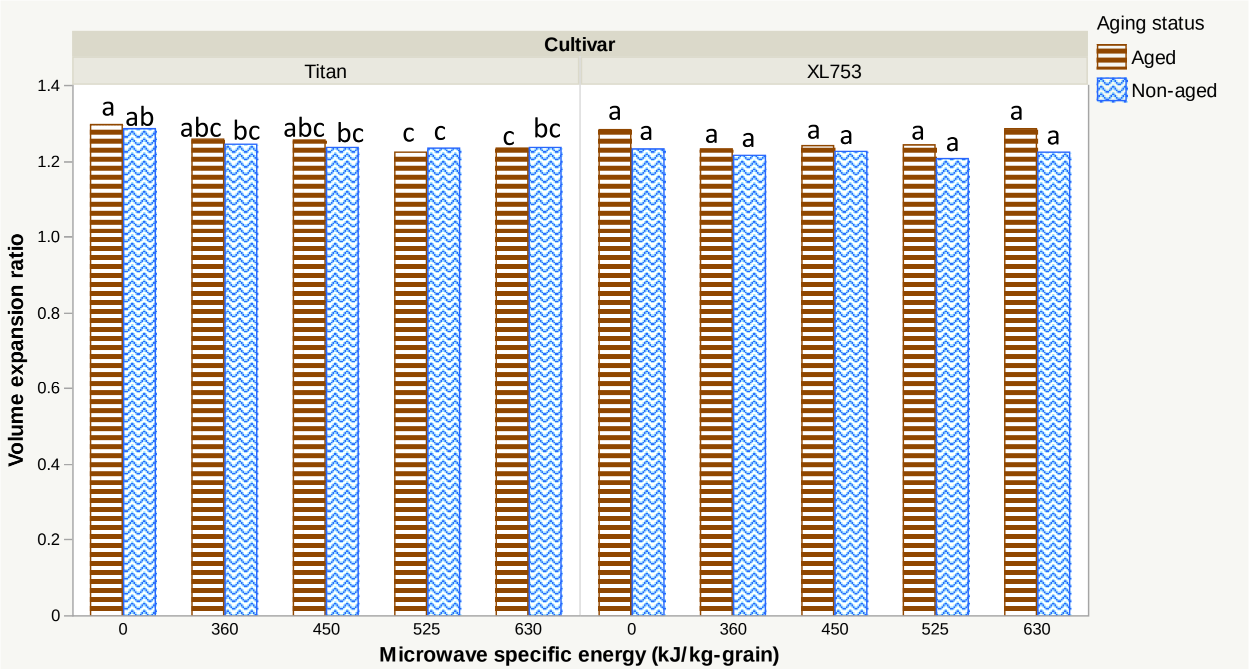

Figure 4. A plot of volume expansion ratio against control samples and rice dried using microwave at 915 MHz frequency. Control samples were dried using the equilibrium moisture content chamber at 25°C and 65% relative humidity (RH) and have microwave specific energy = 0. Levels not connected by the same letter are statistically significant, $p<0.05$. kJ/kg-grain means kJ per kg of initial wet grain mass.

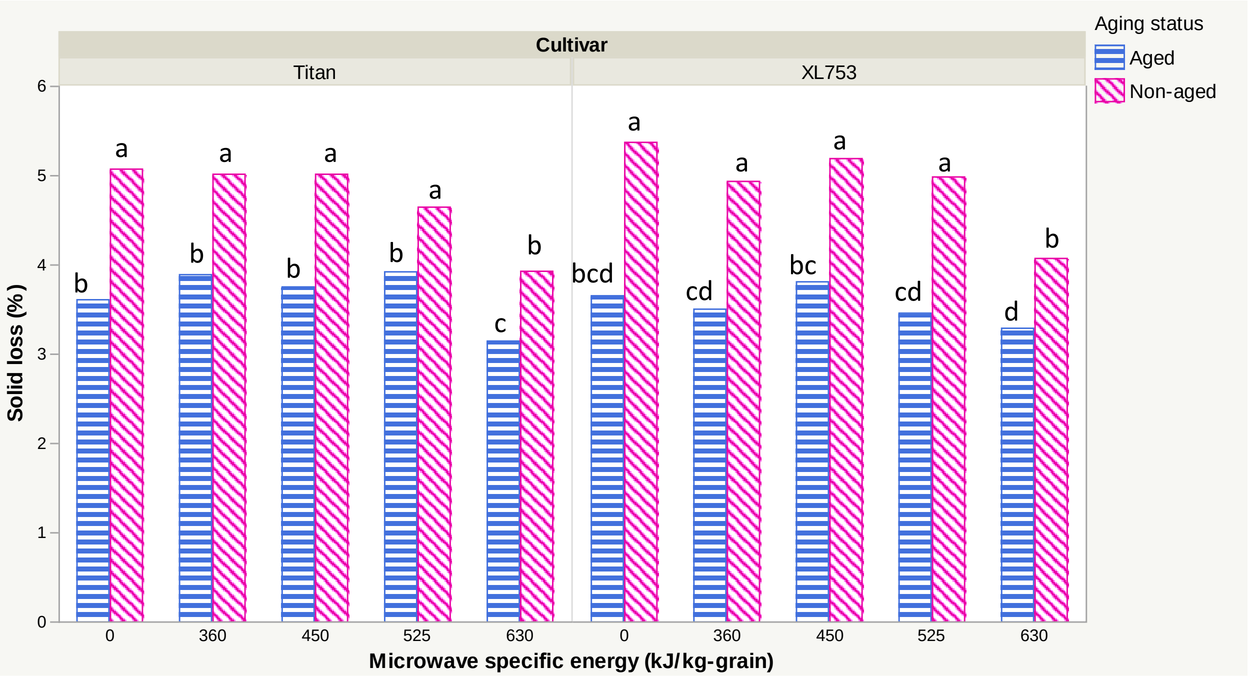

Figure 5. A plot of solid loss against control samples and rice dried using microwave at 915 MHz frequency. Control samples were dried using the equilibrium moisture content chamber at 25˚C and 65% relative humidity (RH) and have microwave specific energy = 0. Levels not connected by the same letter are statistically significant, $p<0.05$. kJ/kg-grain means kJ per kg of initial wet grain mass.

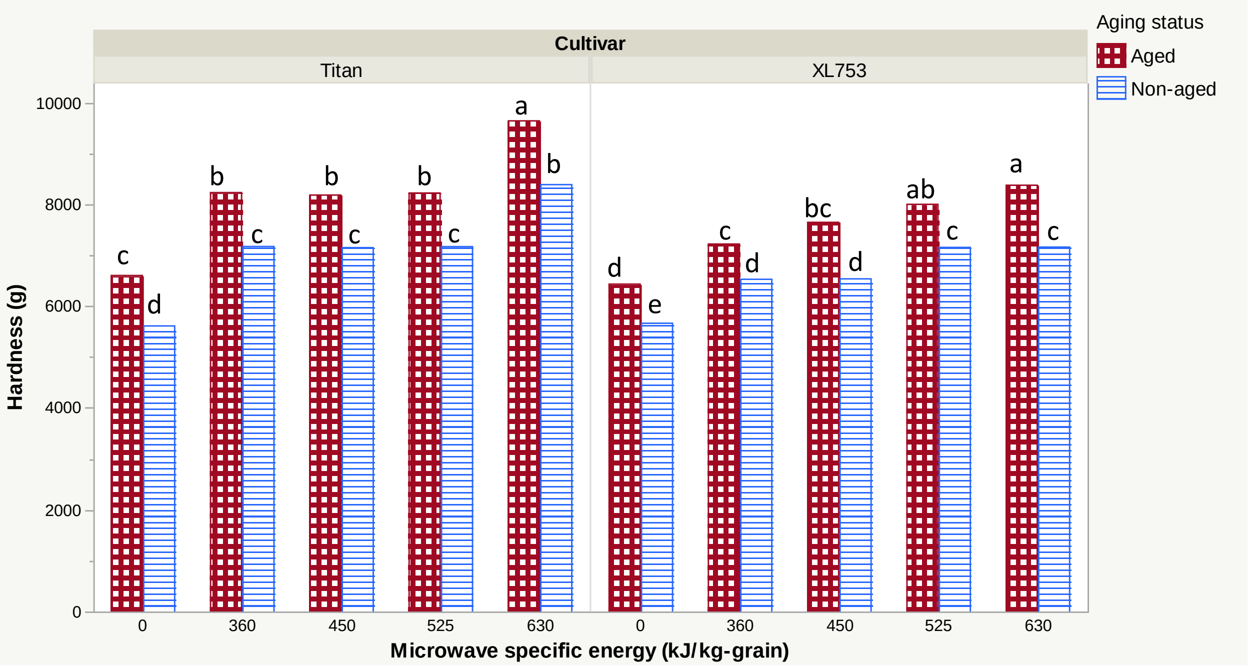

Figure 6. A plot of hardness against control samples and rice dried using microwave at 915 MHz frequency. Control samples were dried using the equilibrium moisture content chamber at 25˚C and 65% relative humidity (RH) and have microwave specific energy = 0. Levels not connected by the same letter are statistically significant, $p<0.05$. kJ/kg-grain means kJ per kg of initial wet grain mass.

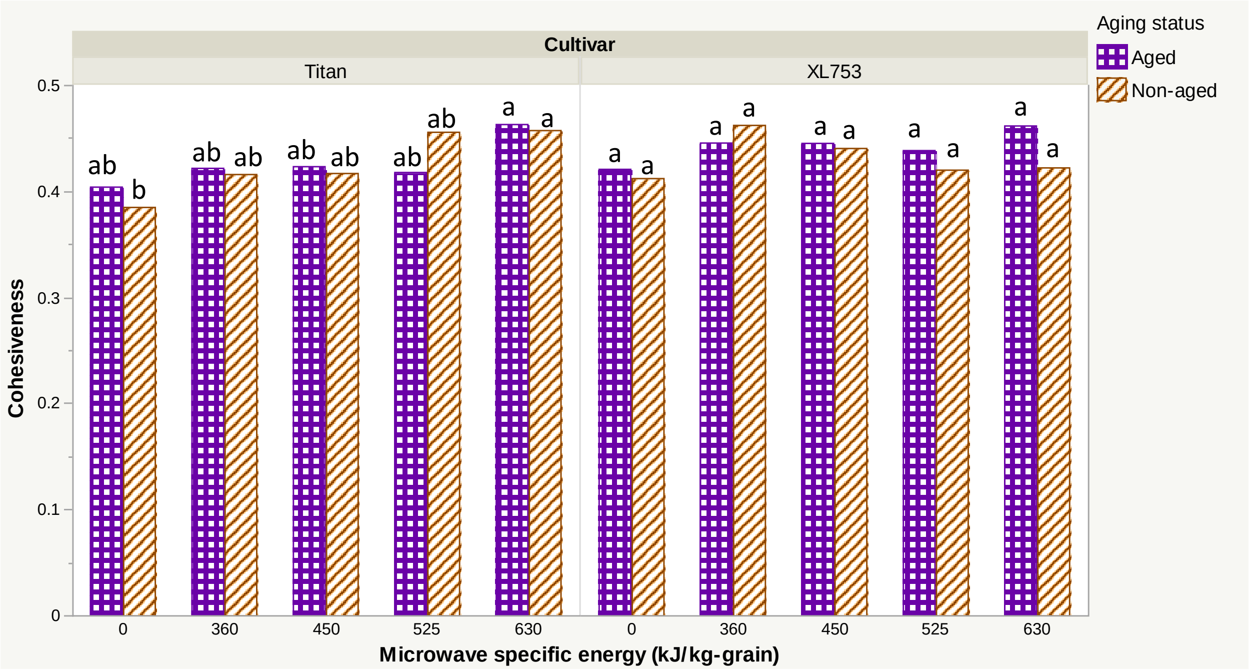

Figure 7. A plot of cohesiveness against control samples and rice dried using microwave at 915 MHz frequency. Control samples were dried using the equilibrium moisture content chamber at 25°C and 65% relative humidity (RH) and have microwave specific energy = 0. Levels not connected by the same letter are statistically significant, $p<0.05$. kJ/kg-grain means kJ per kg of initial wet grain mass.

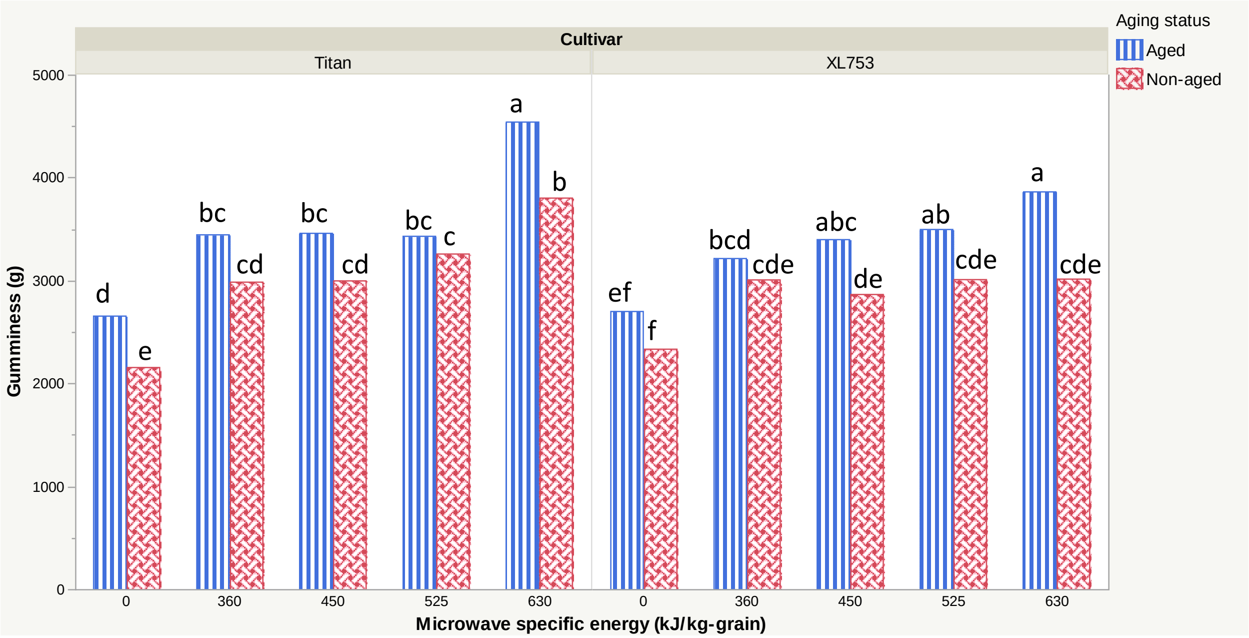

Figure 8. A plot of gumminess against control samples and rice dried using microwave at 915 MHz frequency. Control samples were dried using the equilibrium moisture content chamber at 25˚C and 65% relative humidity (RH) and have microwave specific energy = 0. Levels not connected by the same letter are statistically significant, $p<0.05$. kJ/kg-grain means kJ per kg of initial wet grain mass.

OVERALL CONCLUSIONS

This research sought to provide processing conditions that are useful for the commercialization of the 915 MHz industrial microwave technology for rice drying. The goal was achieved by studying the impact of microwave specific energy and processing conditions such as harvest moisture content, milling duration, and aging on the physicochemical properties of a 915 MHz microwave-dried rice.

The study showed that microwave specific energy had a significant impact on rice quality and physicochemical properties such as moisture removal, head rice yield, pasting properties and resistant starch content. Specific energy of 525 kJ/kg-grain (power-5kW, heating duration-3.5min) was predicted as the most suitable for drying medium grain rice cultivar Titan and long grain hybrid XL753 based on physicochemical properties relative to the control samples. In terms of harvesting and processing conditions, the harvest moisture content had significant impacts on the head rice yield, crude protein content and final viscosity of microwave-dried rice. Milling duration also had significant impacts on the surface lipid content and whiteness index of microwave-dried rice. Statistical models predicted harvest moisture content of 20% and milling durations of 45 s and 42 s for the processing of microwave-dried rice cultivars Titan and XL753 respectively. Regarding the storage properties of microwave-dried rice, aging significantly increased the setback viscosity, cooked rice hardness and gumminess, and significantly decreased the peak viscosity and solid loss of microwave-dried rice. Statistical models indicate that the solid loss of microwave-dried rice decreases by 0.083% while the final viscosity, kernel elongation ratio and hardness increases by 30 cP, 0.014 and 41 g respectively, with every degree Celsius increase in aging temperature, when all other variables are kept constant. In addition, aged microwave dried rice that was treated at 360 and 525 kJ/kg-grain were practically equivalent in terms of hardness and solid loss.

Overall, we recommend the use of the 525 kJ/kg-grain microwave specific energy for rice drying because it provides higher moisture removal from rice kernels than lower specific energies and it does not negatively impact rice physicochemical properties. The use of the 915 MHz industrial microwave technology will transform the rice processing industry by decreasing rice drying duration, improving milling yield, and physicochemical properties.