Impacts of Postharvest Temperature Exposure Profiles on Rice Physicochemical Properties

Seth Graham-Acquaah

University of Arkansas, Fayetteville

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Impacts of Postharvest Temperature Exposure Profiles on Rice Physicochemical Properties

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

by

Seth Graham-Acuah
University of Ghana, Legon
Bachelor of Science in Nutrition and Food Science, 2007
University of Ghana, Legon
Master of Philosophy in Food Science, 2010

December 2020
University of Arkansas

This dissertation is approved for recommendation to the Graduate Council.

________________________________________________________________________

Terry J. Siebenmorgen, Ph.D.
Dissertation Director

________________________________________________________________________

Ya-Jane Wang, Ph.D.
Committee Member

Andronikos Mauromoustakos, Ph.D.
Committee Member

________________________________________________________________________

Ruben O. Morawicki, Ph.D.
Committee Member

Scott Osborn, Ph.D.
Committee Member

________________________________________________________________________

Han-Seok Seo, Ph.D.
Committee Member
ABSTRACT

Heated-air drying followed by tempering (HAT) is effective for increasing rough-rice drying rates without compromising head rice yield (HRY). However, heat exposure could affect rice end-use properties. Hypothesizing that the total amount of heat exposure incurred by rice during heated-air drying determines the trend and magnitude of changes in end-use properties, this dissertation sought to 1) characterize the effects of drying and tempering regimen on changes in end-use properties, 2) derive an index to quantify and compare the amount of heat exposure that rice kernels incur during active drying and, 3) relate values of this index to changes in rice end-use properties. A series of drying experiments were conducted on a long-grain rice cultivar. Paste viscosities and texture of rice gels prepared from flour obtained from dried (12.5% MC) rice samples were evaluated. A theoretical framework was developed and employed alongside time-temperature data collected from drying experiments to derive an index for quantifying thermal exposure, Graham-Acquaah’s Thermal Exposure (GATE) value, during drying. Paste viscosities and gel texture were not only dependent on drying air temperature but also on how long the rice was exposed to a given temperature during drying and tempering. Air relative humidity (rh) had an indirect effect on end-use properties. Using different HAT regimens, peak viscosity was altered by 16%, breakdown by 24%, and setback by >500% compared to control samples. Gel strength was increased by approximately 40% with HAT regimens. The GATE values had strong and significant (p<0.05) correlations (0.82 – 0.93) with end-use properties. Practical changes (≥10% change) in end-use properties occurred when GATE values were ≥ 40 min. The results suggest that HAT regimens must be carefully selected, not only to minimize HRY reductions but also to minimize variations in the functional properties of rice for end-use applications. The proposed GATE values would be useful for predicting changes in rice properties during heated-air drying.
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DEDICATION

To the memory of Dr Terry Siebenmorgen. You light shone brightly as a guide…
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I. INTRODUCTION

Rice grain quality is a composite of several characteristics – appearance, milling, cooking and eating characteristics. Appearance attributes such as color, kernel dimensions and chalkiness often determine whether rice is first purchased or not; milling yields, particularly head rice yield, (HRY) is a primary measure of the economic value of rice; cooking and organoleptic characteristics, such as the swelling ratio, together with texture and taste, determine rice marketability; end-use properties, such as paste viscosities and gel texture, determine the utility of rice flour for food applications. Industry requirements for physical quality traits such as HRY and chalkiness are universal: premium rice should have high HRY, have uniform color and be translucent (Fitzgerald et al., 2009; Lyman et al., 2013; Nelson et al., 2012). On the contrary, consumer preferences for cooking and organoleptic attributes and industry requirements for end-use applications vary widely (Calingacion et al., 2014; Champagne et al., 2010; Bhattacharya et al., 1999).

Genotype and environmental conditions during rice cultivation are regarded as the principal determinants of rice grain quality. Planting cultivars that consistently produce desired rice quality has thus been recommended for minimising quality variation (Sreenivasalu et al., 2015; Liu et al., 2015; Graham-Acquaah et al., 2018). Regardless of intrinsic cultivar characteristics and suitability of growth conditions, postharvest management practices could affect quality. Most rice is harvested at greater moisture contents (MC ≥18% wet-basis) and dried to about 12-13% MC before milling. This makes drying a critical postharvest operation that has major implications on rice physicochemical properties.

The principal objective in commercial drying is to reduce moisture content to safe levels as quickly as possible without compromising HRY. This is often achieved with heated-air drying
followed by tempering (HAT) (Cnossen and Siebenmorgen, 2000; Ondier et al., 2010). Various HAT regimens are employed in commercial rough-rice drying in the Mid-South US depending on the logistics or experience of dryer operators. Such differences in HAT regimens could affect the physicochemical and functional properties of rice (Champagne et al., 1998; Patindol et al., 2003; Zheng et al., 2011; Ambardekar and Siebenmorgen, 2012; Ondier et al., 2013) and contribute to the reported inconsistencies in rice end-use properties that hamper the rice industry’s capability to exploit the emerging market for gluten-free food products (Teo et al., 2000; Pearce et al., 2001; Qiu et al., 2015). Moreover, the fact that post-drying heat treatments are sometimes employed to modify the physicochemical properties of rice for end-use applications (Puncha-anorm and Uttapap, 2013; Arns et al., 2015) imply that HAT regimens could, likewise, be used to alter rice properties for specified end-uses.

Most research on rice drying focus on accurate prediction of moisture content with several thin-layer and deep-bed drying models developed for that purpose. Substantial reports on the effects of drying conditions on fissuring and head rice yields also exist but relatively few reports on the effects of drying on rice end-use properties. Where the effects of drying on end-use properties have been studied, the focus has been on air temperature with contrasting outcomes. Champagne et al. (1998) and Ondier et al. (2013) reported increases in peak and final viscosities with increasing drying temperature. Daniels et al. (1998), however, observed that peak viscosity decreased as drying temperature increased. Hypothesizing that the total amount of heat (cumulative temperature-duration) exposure incurred during HAT regimens would determine the trend and magnitude of changes in end-use properties, the objectives of this dissertation were to:
1. characterize the effects of drying conditions (air temperature and relative humidity) and tempering duration on changes in rice end-use properties (i.e. paste viscosities and gel texture)

2. derive an index for quantifying and comparing thermal exposure incurred during active drying and

3. ascertain the relationship between values of the derived index and changes in rice properties during drying.

The dissertation is organized in the “published/submitted papers” format with each chapter being a manuscript that has been published or under review in a peer-reviewed journal.

In Chapter One, the relative impacts of heated-air drying conditions (air temperature and relative humidity) and tempering duration on changes in rice end-use properties (i.e. paste viscosities and gel texture) were characterized to ascertain the effects of specific combinations of heated-air conditions (air temperature and relative humidity) and tempering durations on rice end-use properties. Such process characterization studies are essential for ensuring that manufacturing processes deliver products of consistent quality. Chapter Two presents a theoretical framework, based on the $F_0$-value concept used in thermal sterilization, for quantifying and comparing thermal exposure incurred during rough-rice drying. Further, the derivation and application of a novel thermal exposure index, is demonstrated. In Chapter Three, thermal exposure incurred by rough rice during drying under varying conditions are quantified and the values of thermal exposure related to changes in rice properties.
LITERATURE CITED


II. CHAPTER 1

Rice paste viscosities and gel texture resulting from varying drying and tempering regimen

Graham-Acquaah, S. and Siebenmorgen, T.J.

ABSTRACT

Background and objectives: Heated-air drying followed by tempering (HAT) is effective for increasing rough-rice drying rates without compromising head rice yield (HRY). However, relatively little is known about the specific nature of the effects of HAT regimens on end-use properties of rice. This study determined the effects of drying air conditions (air temperature and relative humidity) and tempering durations on changes in rice paste viscosities and gel texture.

Findings: Rice paste viscosities and gel texture were not only dependent on drying air temperature but also on how long the rice was exposed to a given temperature during drying and tempering. Air relative humidity (rh) had an indirect effect on rice end-use properties. Using different HAT regimens, peak viscosity was altered by 16%, final viscosity by 21%, breakdown by 24%, and setback by >500% compared to control samples. Gel strength was increased by approximately 40% with HAT regimens.

Conclusions: Heated-air drying and tempering conditions must be carefully selected, not only to minimize HRY reductions but also to minimize variations in the functional properties of rice intended for specified end-uses. Likewise, HAT regimens could be selected to produce desired properties for specified end-uses.

Significance and novelty: Inconsistencies in rice flour functionality is a hindrance to an expansive use of rice in end-use, gluten-free product development. This study shows that drying, a critical postharvest operation, could introduce variations in rice flour quality, which also implies that HAT regimens could deliberately be utilized to produce flour for various end-use applications.
INTRODUCTION

Rice is usually harvested at a greater (16-22%†) moisture content (MC) than it is stored and milled (12-13% MC). Drying of rough rice is thus a critical postharvest operation and must be accomplished quickly to prevent the growth of moulds that could affect the quality and safety of rice as food. Drier designs, air conditions (air temperature and relative humidity), cultivar types (long, medium and short grains) and initial (harvest) moisture contents of rice to be dried may differ among operations and situations but the primary objective of drying remains the same - to reduce moisture content to safe levels as quickly as possible without compromising head rice yield (HRY). Due to the volumes of rice that must be dried during the harvest season, most commercial drying operations in the Mid-South region of the United States employ heated air at various temperatures to dry rough rice.

Greater air temperatures, while effective for increasing drying rate, must be accompanied by a tempering step in order to prevent HRY reduction (Cnossen & Siebenmorgen, 2000; Ondier Siebenmorgen & Mauromoustakos, 2013). Tempering reduces intra-kernel moisture and material state gradients during heated-air drying, the occurrence of which can cause fissuring in rice kernels, which in turn results in kernel-breakage during milling (Mukhopadhay, 2017). Although tempering for 1-3 hours has been shown to be sufficient for preserving HRYs (Steffe & Singh, 1980; Cnossen & Siebenmorgen, 2000; Ondier et al., 2013), tempering durations in commercial drying operations vary widely depending on the experience of the operators or logistics (Steffe & Singh, 1980; Mukhopadhay, 2017).

Emphasis on HRYs in the rice industry is prompted by the fact that, traditionally, rice is consumed as cooked intact kernels. However, the growth of the gluten-free market presents an

† All moisture content values are expressed as percent wet-basis unless otherwise stated.
opportunity to expand the use of rice beyond its conventional consumption to include its use in food product development. The rice industry’s capability to exploit this emerging gluten-free market is hampered by inconsistencies in rice end-use properties (Teo, Karim, Cheah, Norziah & Seow, 2000; Pearce, Marks & Meullenet, 2001; Qiu, Cao, Xiong & Sun, 2015). Differences among end-use properties of various cultivars aside, for any particular cultivar, postharvest operations could alter functional properties (Pearce et al., 2001). For instance, post-drying heat treatments such as annealing and heat-moisture treatments (HMT) may alter the functional properties of rice (Puncha-anorm & Uttapap, 2013; Arns et al., 2015; Qiu et al., 2015); annealing and HMT are physical methods for modifying starch properties by heat treating flour/starch samples in the presence of water for varying durations. Ageing, a phenomenon that occurs during rice storage and purportedly produces rice with superior cooking and end-use characteristics compared to freshly harvested rice (Perdon, Siebenmorgen, Mauromoustakos, Griffin, & Johnson, 1997), could be accelerated with heat treatments (Gujral & Kumar, 2003; Amberdarkar & Siebenmorgen, 2012). The aforementioned suggests that heated-air drying operations could, likewise, alter rice end-use properties; and while useful for preserving HRYs from rough rice dried using heated air, tempering could also affect rice end-use functionality.

Previous studies on the effects of drying on rice end-use properties have focused, primarily, on drying air temperature and have produced contrasting results. Champagne et al. (1998) and Ondier et al. (2013) observed that increasing drying air temperatures increased peak and final viscosities. Daniels et al. (1998), on the other hand, reported that increasing drying air temperatures decreased the peak viscosity of rice. There is a need, therefore, for further studies to characterize the effects of heated-air drying and tempering regimens on rice end-use characteristics. Process characterization studies are essential for ensuring that manufacturing processes deliver products
of consistent quality (Garretson, Mani, Leong, Lyons & Haapala, 2016). This study characterizes the individual and interactive effects of drying conditions (air temperature and relative humidity) and tempering durations on changes in rice end-use properties with a focus on paste viscosities and gel texture. Rice paste viscosities and gel texture are considered the most important determinants of the suitability of cereal grains for food applications (Bhattacharya, Zee & Cork, 1999; Collado, 2001; Malumba, Massaux, Deroanne, Masimango, & Béra, 2009). It is hypothesized that drying and tempering regimens could cause variations in paste viscosities and gel texture, and thus, could be utilized to produce rice with desired end-use characteristics.

MATERIALS AND METHODS

Raw material

A long-grain rice cultivar (CLXL745), harvested at a moisture content of 18.5%, was procured from a commercial rice farm near Pocahontas, AR during the 2018 crop year. The rough rice was cleaned using a dockage tester (XT4, Carter-Day, Minneapolis, MN, USA), placed in a plastic tub and stored (approximately 12 weeks) in a cold room (4°C) until used. Prior to conducting an experiment, 4-kg samples of rough rice were removed from cold storage, placed in a sealed bag and allowed to equilibrate over a 24-h period to ambient temperature (22°C) in a laboratory. Afterwards, five 15-g subsamples were dried for 24 h in a convection oven that was set at 130°C (Jindal & Siebenmorgen, 1987) in order to measure the initial moisture content of the rice prior to drying.
Drying and tempering experiment

The experiment was a 3×2×2 full-factorial design (Figure 1). The experimental factors were drying air temperature (40°C, 60°C, 80°C), drying air relative humidity (10% and 50%), and tempering duration (2 and 6 h). Rough rice was dried inside a 0.91-m³ controlled-environment chamber (Platinous Sterling Series, ESPEC North America, Hudsonville, MI, USA) that produced the desired drying air temperature and relative humidity conditions. For each experimental run, approximately 220 g of rough rice were spread in a uniform thin layer (2-3 kernels deep) in a drying basket (25 cm × 15 cm × 5 cm) and then dried for 30 minutes.

Immediately after drying, rice samples were transferred into airtight bags, sealed and tempered for either 2 or 6 h (Figure 1) in an oven (Model OV702G, Thermo-Scientific, Dubuque, Iowa, USA) that was preheated to the same temperature that was used for drying; in order to obtain the MC of the rough rice prior to tempering, approximately 15 g of each dried sample was removed and dried for 24 h in a convection oven that was set at 130°C. When tempering durations had elapsed, the rough rice samples were removed from the oven, spread in a uniform thin layer on mesh trays and conditioned to 12.5% MC in an equilibration chamber maintained at 25°C and 56% relative humidity. Each drying run (representing a combination of drying air temperature, relative humidity and tempering duration) was conducted in duplicate. Two 200-g rough rice samples (18.5% MC) were spread in a uniform thin layer on mesh trays and gently conditioned in the equilibration chamber to 12.5% MC and used as control samples. A total of 24 experimental runs, 12 drying and tempering runs (in duplicate), were conducted. Thus, in addition to the control samples, 26 rough-rice samples were milled, the head rice ground to flour and paste viscosities and gel textures determined.
After drying, tempering and conditioning to 12.5% MC, 150-g rough rice samples were dehulled using a laboratory sheller (THU, Satake, Tokyo, Japan) with a clearance of 0.048 cm (0.019 in) between the rollers. The resultant brown rice samples were milled for 30 s using a laboratory mill (McGill No. 2, RAPSCO, Brookshire, TX). Head rice, milled kernels having length equal to or greater than three-fourths of the original kernel length, were then separated from broken kernels using a double-tray sizing device (Seedburo Equipment Co., Chicago, IL). The surface lipid contents of the head rice samples were estimated using a diode array NIR analyzer (DA 7200, Perten instruments, SE-141 05, Huddinge, Sweden) to provide an indication of the degree of milling.

**Pasting properties of rice flour**

Pasting properties were measured as described by Ambardekar & Siebenmorgen (2012). For each measurement, 20 g of head rice was ground into flour using a cyclone mill with a 0.5-mm screen (UDY, Fort Collins, CO). The MCs of the flour samples were determined by placing duplicate, 2-g samples in an oven at 130°C for 1 h. Peak, trough and final viscosities of rice flour were determined with a viscometer (RVA Super 4, Newport Scientific, Warriewood, Australia) by mixing 3 ± 0.01 g of flour at approximately 12% MC with 25 ± 0.05 mL of deionized water. Breakdown viscosity was calculated as the difference between peak and trough viscosities. Setback viscosity was calculated as the difference between final and peak viscosities. The viscometer used a 12.5 min cycle (1.5 min at 50°C, heating to 95°C at 12°C/min, 2.5 min at 95°C, and cooling to 50°C at 12°C/min) according to AACC International Approved Method 61-02.01 (2010). Duplicate RVA determinations were conducted on each of the 26 drying and tempering run
samples and the two control samples. Paste viscosities are expressed as rapid visco-units (RVU; 1 RVU = 12 cP).

**Rice gel texture**

Rice paste generated from each RVA run was formed into a 20-mm diameter × 20-mm-high gel and the hardness (strength) of the gel measured using a texture analyzer (TA-XT2i, Texture Technologies, Scarsdale, NY). Plastic containers for forming the gels were fabricated by placing two cylindrical tubes (each with a diameter of 20 mm and a height of 20 mm) end-to-end and fastening them together with adhesive tape to obtain a 20-mm diameter × 40-mm-high tube. A detachable base was then placed on one end of the tube to serve as the bottom of the container (Figure 2). Immediately upon completing an RVA run, the rice paste was transferred from the RVA canister into the gel-forming container (Figure 2) and placed in a refrigerator (5°C). After an 18-h storage period, the containers with gels were removed from the refrigerator, the adhesive tape that fastened the two 20-mm diameter × 20-mm-high cylinders, which constituted the gel-forming container, was peeled off and a knife was used to cut through the gel at the joint between the cylinders. Subsequent to this, the detachable base of the gel-forming container was removed and a 20-mm diameter × 20-mm-high gel from the bottom cylinder was allowed to slide unto the horizontal platform of the texture analyzer. This procedure ensured that uniformly-sized and well-formed gels with flat surfaces were used for texture analyses.

The test sequence shown in table 1 was then followed to perform uni-axial compression of the gel using a 35-mm diameter probe. The maximum force measured (in Newton) during the compression of the gel to reach 40% deformation was recorded as its hardness (strength). The

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† Gels that formed in top cylinders did not have consistent sizes or flat surfaces when flour pastes were transferred from the RVA canisters.
deformation of 40% was used because greater deformations tend to break gels and produce erroneous results (Pons & Fiszman, 1996).

**Data analyses**

Data were analyzed using statistical software (JMP Pro 14, SAS Institute, Cary, NC). Analyses of variance were conducted to determine the individual and interactive effects of drying air conditions (air temperature and relative humidity) and tempering durations on paste viscosities and gel texture. Rice paste viscosities are influenced by surface lipid content (Perdon et al., 2001). As such, the possible effects of SLC on rice paste viscosities and gel texture were considered by including SLC as a factor in the analyses of variance. This provided an adjustment for varying SLCs and permitted the effects of drying and tempering regimen to be compared without the influence of degree of milling (SLC). Further, changes in paste viscosities and gel texture due to heated-air drying and tempering regimen were expressed in percentages relative to the control samples as follows:  

\[ \text{Change in property (\%) = \left( \frac{V_t - V_c}{V_c} \right) \times 100} \]

Where \( V_t \) is the numerical value for the specified end-use property of a given drying and tempering regimen; \( V_c \) is the numerical value for the specified end-use property of the control sample.

**RESULTS AND DISCUSSION**

The results of the analyses of variance showed that in addition to the individual effects of air temperature and tempering duration, there were significant (p<0.05) interactive effects of air temperature and relative humidity (rh) as well as air temperature and tempering duration on paste viscosities and gel texture (Table 2). These significant (p<0.05) interactive effects suggest that changes in rice paste viscosities and gel texture cannot be attributed solely to the impact of any
individual factor. Rather, changes in these end-use properties are dependent on combinations of drying conditions (air temperature and rh) and tempering durations. These results offer a possible explanation for contrasting reports from previous investigations into the effects of drying air temperature on rice paste viscosities. For instance, while Champagne et al. (1998) and Ondier et al. (2013) observed that increasing drying air temperatures increased peak and final viscosities, Daniels et al. (1998) reported that increasing drying air temperatures decreased peak viscosity of rice. Those studies focused on drying temperature and likely had inherent differences in rh of the drying air; also, tempering, when conducted in those studies, was used solely for minimizing HRY reductions.

The significant interactive effects between drying air temperature and tempering duration, alongside the trends described in the succeeding sections, suggest that changes in paste viscosities and gel texture depend on the total amount of thermal exposure (cumulative time-temperature treatment) incurred by rough rice during heated-air drying. This suggests the need for an index for quantifying and comparing thermal exposures incurred during heated-air drying as proposed by Graham-Acquaah and Siebenmorgen (2020). The interactive effects of air temperature and rh, on the other hand, could be due to the effects of rh on the MC of rough rice attained after drying and thus, during tempering. As shown in Figure 3, at any given drying air temperature, the greater the rh, the greater the MC of the rough rice after drying for 30 min, which implies that the rough rice was tempered at a greater MC. The greater the MC of rough rice, the greater the expected changes in physicochemical properties during heat treatments (Pearce et al., 2001; Gujral & Kumar, 2003). Longer heating durations, especially at greater temperatures, exacerbate changes in physicochemical properties. Ambardekar & Siebenmorgen (2012) observed greater PVs when rough rice with 17% MC was heat-treated in comparison to rough rice with 12.5 % MC.
Effects of heated-air drying conditions on paste viscosities of rough rice tempered for varying durations after drying.

Figure 4 shows the effects of drying air conditions (air temperature and rh) on the peak viscosities of rice samples tempered for 2 h and 6 h after drying. When drying was followed by tempering for 2 h, increasing air temperature increased peak viscosity (PV); greater PVs were observed when air temperatures were combined with 10% rh than 50% rh. An approximate 16% increase in PV (relative to the control samples) was observed when rice was dried using air that was conditioned at 80°C and 10% rh compared to a 7% increase when 80°C|50% rh air condition was used (Figure 4b). At a longer (6 h) tempering duration, air temperatures of 40°C and 60°C increased PV regardless of air rh. Combining air temperature at 80°C with 10% rh produced a similar increment in PV as that observed at an air temperature of 60°C. However, combining 80°C air temperature with 50% rh reduced PV.

These trends in PV could be due to the effects of heat on the structure of protein layers on the surface of starch granules (Patindol, Wang, Siebenmorgen, & Jane, 2003; Puncha-arnnon and Uttapap, 2013). Peak viscosity indicates the extent to which starch granules swell in the presence of water, heat, and shear. The relatively mild heat treatments received by samples that were dried and tempered for 2 h may have loosened the structure of the protein layers and allowed them to absorb more water (Groot & Bakker, 2016), which facilitates starch granule swelling, thereby increasing PV. At 80°C|50% rh air conditions, rough rice MC after drying and during tempering was greater (15%) compared to the MC (12.5%) of rough rice dried using 80°C|10% rh air conditions (Figure 3). Moisture content increases molecular interactions in proteins during heat treatments (Damodaran, 2015). Therefore, during prolonged heating (tempering for 6 h) of rough rice with a greater MC (15%) at a greater temperature (80°C), intra-molecular interactions within
proteins may promote disulphide bonding and formation of higher molecular-weight proteins (Opstvedt, 1984; Chrastil, 1990) that restrict water uptake and starch granule swelling, thereby reducing PV (Little & Dawson, 1960; Hamaker & Griffin 1993; Baxter, Zhao & Blanchard, 2010).

Breakdown viscosity (BD) increased (Figure 5) by approximately 13-14% relative to control samples when rough rice was dried using 80°C|10% rh air conditions followed by tempering for 2 h or 60°C|50% rh air conditions followed by tempering for 6 hours. Tempering for a longer (6 h) duration following drying at 80°C, on the other hand, decreased BD regardless of air rh (Figure 5); however, BDs were less when 80°C air temperature was combined with 50% rh (24% decrease in BD) than 10% rh (15% decrease in BD). Breakdown viscosity provides a measure of the stability of starch granules to heat and shear during processing; the lesser the BD, the more stable the starch. In rice-noodle production, for example, Collado (2001) suggested that the ideal flour must have restricted swelling and a low peak viscosity that remains constant during continuous heating and shearing (indicative of low breakdown) such as those observed when rice was dried using 80°C|50% rh air conditions and tempered for 6 h. An increase in disulphide bonding, formation of higher molecular-weight proteins and starch-protein complexes formed during heat treatments tend to strengthen starch granules and prevent them from rupturing in the presence of heat and shear during rapid-visco analyses (da Cruz, da Silva, dos Santos, da Rosa Zavareze & Elias, 2015; Silva et al., 2017).

As regards final viscosity (FV), the greater the temperature and the longer the tempering duration, the greater the FV of rice (Figure 6). An approximate 21% increase in FV was observed when samples were dried using 80°C|10% rh air conditions and tempered for 6 hours. During an RVA cooling cycle, high molecular-weight proteins in heat-treated samples form stronger gel
networks in rice pastes and increase FV (Cham & Suwannaporn, 2010; Puncha-arnon & Uttapap, 2013).

The greatest magnitude of change in paste viscosities due to experimental conditions was observed for setback (SB) viscosity (Figure 7); when 80°C at both 10% rh and 50% rh air conditions were followed by tempering for 6 h, SB increased by over 500% in relation to control samples. Since SB is calculated from the difference between final and peak viscosities, treatments that increase final viscosity while limiting peak viscosity would increase SB.

**Effects of heated-air drying conditions on gel strength of rough rice tempered for varying durations after drying.**

Rice gel texture, similar to paste viscosities, is a practical method for predicting flour quality for end-use applications. Hardness (strength) of rice flour gels, for instance, is a dominant factor in rice noodle quality (Bhattacharya et al., 1999; Horndok & Noomhorm, 2007). When samples were tempered for 2 h, the only significant change, an approximate 19% increase, in gel strength was observed for samples that were dried using air that was conditioned at 80°C and 50% rh. When samples were dried using air that was conditioned at 80°C and 50% rh followed by tempering for 6 h, an approximate 40% increase in gel strength was observed compared to a 27% increase when samples were dried using 80°C|10% rh air conditions and tempered for 6 h. The greater gel strengths observed when 80°C air temperature was combined with 50% air rh could be related to the impact of rh on rough rice MC after drying and during tempering (Figure 3). Cham & Suwannaporn (2010) reported that the greater the MCs of rice flour samples and the greater the treatment temperature and treatment duration, the greater the hardness of rice gels that were produced from the heat-treated flour. Similar to paste viscosities, this could be attributed to the
effect of heat treatments on intra and inter-molecular interactions among starch and protein molecules that stabilize rice gel structure.

CONCLUSIONS

Changes in rice paste viscosities and gel texture were impacted by drying air temperature but were compounded by how long the rice was exposed to a given temperature during drying and tempering. Drying air relative humidity (rh) indirectly influenced end-use characteristics of rice through its effect on moisture content (MC) of dried rough rice during tempering. These changes in viscosity profiles and gel texture with drying and tempering regimen imply that heated-air drying and tempering conditions could impact physicochemical properties of rice intended for specified end-uses. These findings also suggest that heated-air drying and tempering (HAT) could be exploited in producing functional properties of rice for food applications; however, additional research is required to optimize HAT regimens for particular products. Furthermore, these results justify the need for an index, such as the drying process values proposed by Graham-Acquaah and Siebenmorgen, for quantifying and comparing thermal exposure incurred during rough rice drying.

ACKNOWLEDGEMENT

The authors acknowledge the financial support from the corporate sponsors of the University of Arkansas Rice Processing Program, and the rice farmers in Arkansas with funding provided through the Arkansas Rice Checkoff Program that is administered by the Arkansas Rice Research and Promotion Board. The authors also thank Mr. Greg Baltz of Running Lake Farms, Pocahontas, AR, for providing rough rice.
LITERATURE CITED


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Figure 6: Effects of air temperature, relative humidity and tempering duration on (a) final viscosity and (b) percentage change in final viscosity in relation to control samples.

Figure 7: Effects of air temperature, relative humidity and tempering duration on (a) setback viscosity and (b) percentage change in setback viscosity in relation to control samples.

Figure 8: Effects of air temperature, relative humidity and tempering duration on (a) rice gel hardness (b) percentage change in rice gel hardness in relation to control samples.
Long-grain rough rice lot (CLXL745); initial moisture content = 18.5%.

<table>
<thead>
<tr>
<th>Air temperatures</th>
<th>Relative humidities</th>
<th>Tempering durations</th>
</tr>
</thead>
<tbody>
<tr>
<td>40°C</td>
<td>10% 50%</td>
<td>2 h 6 h</td>
</tr>
<tr>
<td>60°C</td>
<td>10% 50%</td>
<td>2 h 6 h</td>
</tr>
<tr>
<td>80°C</td>
<td>10% 50%</td>
<td>2 h 6 h</td>
</tr>
</tbody>
</table>

Grain quality evaluations
- Pasting properties of rice flour using a viscometer;
- Texture of rice gel using a texture analyzer.

Control samples were gently dried at 25°C and 56% RH without tempering

Number of drying and tempering runs = 12; conducted in duplicate; total number of experimental runs = 24
Total number of samples evaluated = 24 samples from experimental runs + 2 control samples = 26 samples.

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Table 1: Test sequence for texture profile analyses of rice gels.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probe starting position (height)</td>
<td>40 mm</td>
</tr>
<tr>
<td>Pre-test speed</td>
<td>1.0 mm/s</td>
</tr>
<tr>
<td>Test (compression) speed</td>
<td>5.0 mm/s</td>
</tr>
<tr>
<td>Compression strain (deformation)</td>
<td>40%</td>
</tr>
<tr>
<td>Holding time after compression</td>
<td>5.0 s</td>
</tr>
<tr>
<td>Post-test (retraction) speed</td>
<td>5.0 mm/s</td>
</tr>
</tbody>
</table>
Table 2: Individual and interactive effects of drying conditions (air temperature and relative humidity) and tempering durations on rice paste viscosities and gel texture.

<table>
<thead>
<tr>
<th>Source of variance</th>
<th>Paste viscosities</th>
<th>Gel texture (hardness)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Peak</td>
<td>Breakdown</td>
</tr>
<tr>
<td>Model</td>
<td>**</td>
<td>***</td>
</tr>
<tr>
<td>Temperature (A)</td>
<td>**</td>
<td>***</td>
</tr>
<tr>
<td>Relative humidity (B)</td>
<td>ns</td>
<td>**</td>
</tr>
<tr>
<td>Tempering duration (C)</td>
<td>ns</td>
<td>**</td>
</tr>
<tr>
<td>Interactions:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A×B</td>
<td>*</td>
<td>ns</td>
</tr>
<tr>
<td>A×C</td>
<td>**</td>
<td>***</td>
</tr>
<tr>
<td>B×C</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>A×B×C</td>
<td>ns</td>
<td>ns</td>
</tr>
</tbody>
</table>

*** significant at p<0.001; ** significant at p<0.01; * significant at p<0.05; ns- not significant
III. CHAPTER 2

A Proposed Method for Quantifying Thermal Exposure Incurred During Rough-Rice Drying

Graham-Acquaah, S and Siebenmorgen, T.J.

ABSTRACT

Heated air is used to dry most rice in the United States. Thus, commercial rice drying can be considered as a thermal process that aims to remove moisture from rough rice until a desired moisture content is reached. Parallels can be drawn between rice drying and thermal sterilization that is targeted at reducing microbial load since moisture content reduction during drying follows similar decay rate kinetics as reduction in microbial load during thermal sterilization. Given the different combinations of drying air conditions (air temperature and relative humidity), as well as drying and tempering durations, employed in various drier designs for rice drying and the impact that these conditions have on rice end-use functionality, this study sought to derive a thermal treatment index (drying-process-value), based on the $F_0$-value concept used in thermal sterilization, for quantifying and comparing thermal exposure incurred by rice during drying under various scenarios. Using data collected from rough rice drying experiments, a decimal desorption value ($D_{mv}$) that represents the duration required to cause a 90% reduction in moisture ratio during drying at a specified temperature was determined, from which a thermal desorption constant ($Z_{mv}$) that represents the increase in temperature necessary to cause a 90% reduction in $D_{mv}$ during drying was established. Subsequently, a thermal desorption value ($F_{mv}$) was derived to express the duration that a rice lot would have been heat treated at a reference temperature during drying to produce an equivalent effect on moisture content as that produced by the actual drying process.
INTRODUCTION

A more extensive use of rice in food product development is limited by inconsistencies in end-use functionality (Teo et al., 2000; Pearce et al., 2001; Qiu et al., 2015). Planting cultivars that have consistent physicochemical properties across production environments has been recommended for minimizing some of the quality variation in rice (Sreenivasalu et al., 2015; Liu et al., 2015). However, regardless of the cultivar used and the growth conditions, postharvest practices, such as drying, can affect quality.

It is recommended that rice in the Mid-South region of the United States be harvested at a moisture content (MC) of 18% - 21% for long-grain cultivars and 19% - 20% for medium-grains in order to maximize milling yields (Bautista et al., 2009). Once harvested, rice is dried to MCs between 12 and 13% for storage and milling. The volumes of rough rice that must be dried during the harvest season necessitate the use of heated air in commercial rice drying operations (Ondier et al., 2010; Wiset et al., 2005; Inprasit and Noomhorm, 2001). Different air conditions (air temperature and relative humidity), as well as drying and tempering durations, are employed, with the choice of drying conditions being dependent on logistics and experience of drier operators.

The various heated-air conditions used to dry rough rice determine the rate of drying and affect rice quality. Greater air temperatures and lesser relative humidities increase drying rate, which in turn, increase head rice yield (HRY) reduction; the longer the drying duration, the more pronounced the magnitude of HRY reduction (Chen et al., 2007). As regards end-use characteristics, Champagne et al. (1998) associated increases in peak and final viscosities, which resulted from high-temperature drying, to changes in cooked rice texture. Ondier et al. (2013) explored the prospects of single-pass, high-temperature drying of rice and reported similar effects

Moisture contents are expressed as wet basis unless otherwise stated.
on peak and final viscosities. Wiset et al. (2005) also observed that increasing air temperature during fluidised bed drying, while maintaining HRY, also increased peak and breakdown viscosities. Daniels et al. (1998), on the other hand, reported that greater drying air temperatures reduced peak viscosity. Dillahunty et al. (2001) observed an interactive effect between temperature and duration of heat treatment and concluded that the extent to which drying temperature influenced paste viscosities depended on the duration of exposure. The foregoing suggests that rice quality changes during heated-air drying may depend on the total amount of thermal exposure (cumulative temperature-duration) incurred by rough rice. Despite the extensive research on predicting the drying process with respect to the effects of air conditions on drying rate and MC, there has been little research on quantifying thermal exposure incurred by rough rice during drying under various conditions.

In thermal processing of foods, indices such as the $D$, $Z$, and $F_0$ values are often used to show adequacy of heat treatment with respect to inactivation of microorganisms (Fellows, 2000). The $F_0$ value, for instance, represents the duration equivalence of a heating process to destroy microorganisms compared to that at a reference temperature of 121.1°C. The $F_0$ value, therefore, serves as a standard to compare sterilization values for different processes. Although its primary role is to indicate the adequacy of heat treatment in inactivating microorganisms, differences in $F_0$ values are also often associated with differences in the physical, nutritional and sensory characteristics of thermally-processed foods (Mohan et al., 2006; Van-Loey et al., 1994; Hagen-Plantinga et al., 2017).

Since heated air is used to dry most rice in the United States, rice drying could be considered a thermal process that aims to remove moisture from rough rice until a desired MC is attained. Furthermore, the rate of moisture loss during drying follows similar decay rate kinetics
as reduction in microbial load during thermal sterilization. As such, parallels could be drawn between drying and thermal sterilization to derive an index for quantifying and comparing thermal exposure incurred by rough rice during drying. This is necessary given the different combinations of air conditions (air temperature and relative humidity), as well as drying durations, employed in various drier designs for rice drying and the impact that these conditions have on rice quality. Therefore, the objectives of this study are to:

(a) present a theoretical framework, which is based on the F₀-value concept used in thermal sterilization, for defining and calculating drying process values (DPVs), namely, decimal desorption value (D<sub>mv</sub>), thermal desorption constant (Z<sub>mv</sub>) and thermal desorption duration (F<sub>mv</sub>) that could be used to quantify thermal exposure incurred by rice lots during drying and
(b) demonstrate the application of thermal desorption durations (F<sub>mv</sub>) for comparing thermal exposure incurred by rough rice during drying.

**MATERIALS AND METHODS**

**Theoretical framework for development of drying process values**

In food processing, microbial survival curves are represented as follows (Fellows, 2000):

\[ \log N = -kt + \log N_o \]  \hspace{1cm} (1)

Where \( N \) is the number of live microorganisms after processing for a specified duration, \( t \); \( N_o \) is the initial number of microorganisms; \( k \) is the kinetic constant (absolute value of the slope of a linear plot of \( \log N \) versus \( t \)). The kinetic constant is related to the decimal reduction time (D value) as follows:

\[ k = \frac{1}{D} \]  \hspace{1cm} (2)

Decimal reduction time represents the duration needed for a 90% reduction in the microbial
population and provides a measure of a microbe’s heat resistance. The D value can be obtained from a plot of \( \log \frac{N}{N_0} \) against t, in which case the D value is the inverse of the absolute value of the slope.

Rice drying is often expressed as

\[
MR = \frac{M_t - M_e}{M_o - M_e} = e^{-kt}
\]

(3)

Where MR is the moisture ratio; \((M_t - M_e)\) is the moisture content differential between the rice moisture content after drying for duration, t, and the equilibrium moisture content (EMC); \((M_o - M_e)\) is the moisture content differential between the initial moisture content and EMC.

Equation (3) could be expressed as follows:

\[
\log(MR) = -kt
\]

(4)

From equation 4, a decimal desorption value \((D_{mv})\) at a specified drying temperature can be obtained as the inverse of the absolute value of the slope \((k)\) of the linear curve obtained by plotting \(\log(MR)\) against t. This \(D_{mv}\) would represent the duration required to reduce the MR of rough rice by 90% under specified drying conditions.

Again, in food processing, the D value is used to derive a Z value (thermal resistance constant) that refers to the increase in temperature necessary to cause a 90% reduction in the decimal reduction time (D value). The Z value is obtained by plotting the logarithm of the D value as a function of temperature (T) and taking the inverse of the absolute value of the slope of the fitted curve (Fellows, 2000). Similar to thermal sterilization, a thermal desorption constant \((Z_{mv})\) for drying would refer to the increase in temperature necessary to cause a 90% reduction in the decimal desorption value \((D_{mv})\) and would be determined by plotting \(\log D_{mv}\) against T and finding the inverse of the absolute value of the slope of the linear curve obtained.

The third important parameter in thermal processing calculations is the F value, which is
used for comparing heat sterilization procedures. The F value of a thermal treatment process represents the overall impact of temperature and duration of treatment on microorganisms in the food. It may also be thought of as the duration needed to reduce microbial numbers by a multiple of the D value at a specified temperature and is expressed as:

\[ F = D_T (\log N_o - \log N) \]  

(5)

Similarly, for drying, a thermal desorption duration at a given temperature can be expressed as:

\[ F_{mv} = D_{mvT} (\log MR_o - \log MR_t) \]  

(6)

Where \( F_{mv} \) is the thermal desorption duration; \( D_{mvT} \) is the decimal desorption value at a temperature, T; \( MR_o \) is the moisture ratio at the start of drying; \( MR_t \) is the moisture ratio after drying for duration, t.

Different combinations of temperature and duration can have the same lethal effect on microorganisms during sterilization. As temperature increases, there is a logarithmic reduction in the duration needed to destroy the same number of microorganisms (Fellows, 2000). Lethality (L), a dimensionless number, is often used to express the integrated effect of temperature and duration on microorganisms. Lethality provides an indication of the fraction of microbes that are killed during a unit duration at a temperature, T, and refers to a portion of the thermal death time at temperature \( T \) with respect to the thermal death time at reference temperature \( T_R \). Lethality is calculated as:

\[ L = 10^{\frac{T - T_R}{Z}} \]  

(7)

Taking the integral of equation 7 gives the \( F_o \) value (accumulated lethality)

\[ F_o = \int L \, dt \]  

(8)

Thus:
\[ F_o = \int 10 \frac{T(\xi) - T_R}{z} \, dt \]  

Similarly, during drying, different temperature and duration combinations can produce same MC reductions. As such, \( F_{mv} \) could be calculated as follows:

\[ F_{mv} = \int 10 \frac{T_k - T_a}{z_{mv}} \, dt \]  

Where \( T_k \) is the temperature of rice kernels; \( T_a \) is the drying air temperature.

This \( F_{mv} \) value could be used to provide an indication of the duration that a rice lot has been heat treated at a specified temperature in order to bring its moisture content to a desired level. \( F_{mv} \) at a particular temperature, \( T \), could be related to \( F_{mv} \) at a reference temperature, \( T_{ref} \), as follows:

\[ F_{mv(T)} = F_{mv(T_{ref})} \times 10^{\frac{T_{ref} - T}{z_{mv}}} \]  

Drying experiments

Rough rice (CLXL745) was harvested at a moisture content of 18.5% from a commercial farm near Pocahontas, AR during the 2018 crop year. The rough rice lot was cleaned using a dockage tester (XT4, Carter-Day, Minneapolis, MN, USA), placed in plastic tubs, and stored in a cold room (4°C) until used. Prior to conducting experiments, approximately 4 kg of rough rice was removed from cold storage, placed in a sealed bag and kept in a laboratory for 24 h to equilibrate to room temperature (22°C). The initial moisture content of the rough-rice sample was determined by drying five 15-g subsamples for 24 h in a convection oven that was set at 130°C (Jindal and Siebenmorgen, 1987).

Figure 1 shows the layout of the drying experiment that was conducted. Rice samples were dried inside a 0.91-m³, controlled-environment chamber (Platinous Sterling Series, ESPEC North
America, Hudsonville, MI, USA) that produced desired drying air temperature and relative humidity conditions. Drying air temperatures ranging from 30 to 80°C in 5°C increments (Figure 1) were selected to reflect the wide range of air temperatures that are used in thin layer and fluidized bed drying experiments, which also coincide with drying temperatures used in on-farm and industrial dryers in the Mid-South U.S. (Prakash and Siebenmorgen, 2018; Ondier et al., 2013). Relative humidity (rh) was mostly maintained at 50% to control for the effect of rh on drying rates. However, in order to ascertain the possible effects of rh on drying process values, three temperatures (40, 60 and 80°C) were selected and additional drying runs conducted at those temperatures with rh maintained at 10%. For each drying run (representing a specific combination of drying air temperature, relative humidity and drying duration), approximately 200 g of rough rice were spread in a uniform thin layer (2-3 kernels deep) inside a rectangular drying basket (25 cm × 15 cm × 5 cm) and then dried for specified durations (5, 10, 15, 20, 25, 30, 45 and 60 min). Since typical drying durations range between 20 and 30 min in industrial dryers in the Mid-South U.S, it was deemed unnecessary to dry samples for longer than 60 min. At the end of each drying run, rough rice was removed from the drying chamber and quickly transferred into an air-tight and insulated container that had two k-type thermocouple probes imbedded at the top and bottom in order to obtain a measure of rice kernel temperature after drying. Afterwards, the sample was weighed to determine the amount of moisture loss during drying. Drying runs were conducted in duplicate. Average moisture contents determined from the duplicate drying runs were used for calculating drying process values. In total, 224 drying runs were conducted.

**Determination of peak viscosity**

Selected samples from drying runs (samples dried for 10, 20- and 30-min using air
temperatures of 40, 60 and 80°C with rh maintained at 50%) were conditioned to 12.5% MC in an equilibration chamber maintained at 25°C and 56% relative humidity. Following this, 150-g samples of rough were dehulled using a laboratory sheller (THU, Satake, Tokyo, Japan) with a clearance of 0.048 cm (0.019 in) between the rollers. The resultant brown rice samples were milled for 30 s using a laboratory mill (McGill No. 2, RAPSCO, Brookshire, TX). Head rice, milled kernels having length equal to or greater than three-fourths of the original kernel length, were then separated from broken kernels using a double-tray sizing device (Seedburo Equipment Co., Chicago, IL). Subsequently, 20-g head-rice samples were ground into flour using a cyclone mill with a 0.5-mm screen (UDY, Fort Collins, CO). The MCs of the flour samples were determined by placing duplicate, 2-g samples in an oven at 130°C for 1 h. Afterwards, 3 ± 0.01 g of flour at approximately 12% MC was mixed with 25 ± 0.05 mL of deionized water and the peak viscosity of the flour determined with a viscometer (RVA Super 4, Newport Scientific, Warriewood, Australia) using a 12.5 min cycle (1.5 min at 50°C, heating to 95°C at 12°C/min, 2.5 min at 95°C, and cooling to 50°C at 12°C/min) according to Approved Method 61-02.01 (AACC International, 2010). For each sample, duplicate measurements of peak viscosity were conducted and the average reported.

**Data analyses**

Data were analyzed using statistical software (JMP Pro 14, SAS Institute, Cary, NC). Linear models were fit to the drying datasets to derive drying process values as outlined in the theoretical framework and to ascertain the relationship between thermal desorption durations (also referred to as thermal exposure values) and peak viscosity. The adequacies of fitted models were evaluated using R-square values.
RESULTS AND DISCUSSION

Effects of drying conditions on the moisture contents of rough rice dried for various durations

The effect of increasing air temperature at a constant relative humidity (50%) on the moisture contents (MCs) of rough rice dried for various durations is shown in Figure 2. At all drying air temperatures, MC generally decreased with longer drying durations. The magnitude of the reductions in MC with drying durations were more pronounced at greater air temperatures. These typical trends during drying are attributed to the effect of increasing air temperature on rice kernel temperature and mobility of water molecules inside kernels. As air temperature increases, rice kernel temperature likewise increases and enhances water mobility inside the kernels resulting in a faster rate of water removal from kernels.

The results, however, also show that when samples were dried for 5 minutes, greater air temperatures at a constant relative humidity of 50% produced rough rice with greater MCs (Figure 2). In fact, the MC of samples increased when dried for 5 minutes using air at a temperature of 80°C and 50% rh (Figure 2). During drying, heat transfer from the air to the kernel could cause a decrease in the temperature of the air that is in contact with the kernels. If the temperature of the air in contact with kernels decreases to its dew point (Table 1) as rice kernels absorb heat, condensation could occur on the surface of the kernels and cause a momentary increase in the MC of the rough rice (Pixton and Warburton, 1971; Casada and Alghannam, 1999; Bala, 2017). This would be more likely to occur in greater-MC rice, such as that used.

Figure 3 shows the effect of rh on the MC of samples dried for various durations using air at 40, 60 and 80°C. At a lesser rh (10%), the apparent increase in MC after 5 minutes of drying at 80°C is not evident. Also, at all temperatures, MC reductions with duration of drying were greater
at 10% rh than at 50% rh (Figure 3). These results affirm previous reports on the effect of rh on the MC of rough rice during drying (Agrawal and Singh, 1977; Ondier et al., 2011; Prakash and Siebenmorgen, 2018).

**Estimating $D_{mv}$ and $Z_{mv}$ values for rough rice drying**

Equilibrium moisture contents (EMCs) for the various drying conditions used in the experiment were estimated by incorporating drying parameters reported by Ondier (2011) into the modified Chung-Pfost equation (ASABE, 2014) as shown in equation 12.

\[
M_e = \frac{1}{0.2316} \times \ln \left[ \frac{-511.7649}{(T+22.1226) \times \ln(RH_d)} \right]
\]  

(12)

Having estimated EMCs, equation 3 was used to calculate the moisture ratios (MRs) of samples during drying (Supplementary data 1). Figure 4 shows plots of the logarithm of MR against drying duration for samples dried at air temperatures of 30, 40, 50, 60, 70 and 80°C and 50% rh. The absolute value of the slopes of the fitted curves increased with increasing drying temperature. This is expected as drying rate is known to increase with increasing air temperature. Since decimal moisture desorption values ($D_{mv}$) were determined by taking the reciprocals of the absolute values of the slopes of the fitted curves, as air temperatures increased from 30 to 80°C, $D_{mv}$ values decreased from 427 to 101 minutes. The $D_{mv}$ value represents the number of minutes, at a specified temperature and rh, required to reduce MR of samples by 90% during drying.

A thermal desorption constant ($Z_{mv}$), analogous to the $Z$-value (thermal resistance constant) used in thermal sterilization, was determined by taking the inverse of the absolute value of the slope of a plot of the logarithm of $D_{mv}$ against drying temperature (Figure 5). The results indicate that a 77.5°C increase in temperature is required to decrease $D_{mv}$ by 90%. All the fitted

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\* Me refers to equilibrium moisture content (EMC) expressed on a dry basis
models were adequate as each explained greater than 95% of the variation observed in the dataset as depicted by R-square values (Figures 4 and 5).

**Effect of air relative humidity (RH) on drying process values**

Drying occurs due to differences in vapor pressure between rice kernels and the surrounding drying environment. Vapor pressure is dependent on both air temperature and rh. Additionally, EMC, which is an important factor in the determination of moisture ratios and drying rates, is affected by rh (Ondier et al., 2011). Results of this study also affirm the impact of rh on MC of rough rice dried for various durations. Therefore, the effect of rh (10% and 50%) on $D_{mv}$ was ascertained by plotting the logarithm of MR against drying duration for samples dried in a controlled-environment chamber at 40, 60 and 80°C (Figure 6). At any specified temperature, the slope of the fitted curve and for that matter the rate of drying was slightly greater for samples dried at the lesser (10%) rh. Since $D_{mv}$ has an inverse relationship with drying rate, $D_{mv}$ values were greater at 50% rh than at 10% rh (Table 2). The results also show that as air temperature increased, the magnitude of the difference between $D_{mv}$ at the two rhs reduced (Table 2). This implies that increasing air temperature minimizes the impact of rh on $D_{mv}$.

Despite the apparent effect of rh on drying rate and $D_{mv}$, the impact that rh has on decimal desorption constant ($Z_{mv}$) is minimal (Figure 7). Less than a 1°C difference in $Z_{mv}$ was observed despite the 40 percentage-point difference in rh. This suggests that $Z_{mv}$ is robust to changes in drying conditions. This implies that $Z_{mv}$ is appropriate as an index for estimating thermal exposure during drying; temperature measurements, which are usually easier to monitor compared to relative humidity, could be used solely and reliably to quantify thermal exposure during drying, although additional experiments to verify this conclusion are warranted. The utility of the Z value,
which is analogous to $Z_{mv}$, in thermal sterilization calculations, is grounded in its stability to varying conditions within processing equipment during sterilization (Buschaert et al., 1978).

**Relationship between thermal desorption durations ($F_{mv}$) and peak viscosity**

Thermal desorption durations ($F_{mv(60)}$) were calculated for selected drying runs using equation 10 and a reference drying temperature (60°C) alongside kernel temperatures (Supplementary table 2). Table 3 shows the drying conditions and their corresponding $F_{mv(60)}$ values. At any given drying temperature, $F_{mv(60)}$ values increased with drying duration. When samples were dried for the same duration, $F_{mv(60)}$ increased as temperature increased. The results also show that a sample dried at a lesser temperature for a longer duration could incur greater thermal exposure than a sample that is dried at a greater temperature for a shorter duration. For instance, a sample dried using an air temperature of 40°C for 30 min would incur greater thermal exposure than a sample dried at 60°C for 10 min as typified by their respective $F_{mv(60)}$ values (Table 3).

Figure 8 shows the relationship between $F_{mv(60)}$ values and peak viscosity. As thermal exposure increased, peak viscosity increased. Peak viscosity, provides a measure of the capacity of starch granules to swell in the presence of water, heat and shear and is an important indicator of end-use functionality. Heat exposure loosens the structure of protein layers on the surface of starch granules and allow them to absorb more water (Groot & Bakker, 2016) to facilitate starch granule swelling, thereby increasing peak viscosity (Patindol et al., 2003; Puncha-arnon and Uttapap, 2013).
CONCLUSIONS

A theoretical framework, which is based on the $F_0$-value concept used in thermal sterilization has been developed and implemented in deriving drying process values (DPVs) that could be used in quantifying and comparing thermal exposure incurred by rough rice during drying. The robustness of the thermal desorption constant ($Z_{mv}$) to changes in drying conditions, particularly relative humidity of the drying environment, makes it appropriate as an index for estimating thermal exposure during drying as it would allow temperature measurements to be used solely and reliably for calculating thermal desorption durations ($F_{mv}$ values), which could also be referred to as thermal exposure values. Thermal exposure values had a positive correlation with peak viscosity. The proposed methodology for calculating thermal exposure could facilitate comparisons of the effects of drying regimens on rice end-use functionality. Future experiments could compare the impact of cultivars and initial moisture content on DPVs in order to establish thermal desorption constants $Z_{mv}$ that are typical for cultivar classes over a wide range of harvest moisture contents.

ACKNOWLEDGEMENT

The authors acknowledge the financial support from the corporate sponsors of the University of Arkansas Rice Processing Program and Arkansas Rice Checkoff Program, administered by the Arkansas Rice Research and Promotion Board.
### Definition of terms in manuscript equations

**Terms in equations related to heat sterilization**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(k)</td>
<td>kinetic constant</td>
</tr>
<tr>
<td>(t)</td>
<td>duration</td>
</tr>
<tr>
<td>(N)</td>
<td>number of microorganisms after processing for a specified duration</td>
</tr>
<tr>
<td>(N_o)</td>
<td>initial number of microorganisms</td>
</tr>
<tr>
<td>(T)</td>
<td>temperature</td>
</tr>
<tr>
<td>(D)</td>
<td>D value (decimal reduction time)</td>
</tr>
<tr>
<td>(Z)</td>
<td>thermal resistance constant</td>
</tr>
<tr>
<td>(F)</td>
<td>thermal death time</td>
</tr>
<tr>
<td>(L)</td>
<td>lethal rate</td>
</tr>
<tr>
<td>(F_0)</td>
<td>Lethality (Thermal process value)</td>
</tr>
</tbody>
</table>

**Terms in equations related to proposed drying process indices**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(T_k)</td>
<td>temperature of rice kernel</td>
</tr>
<tr>
<td>(T_a)</td>
<td>air temperature</td>
</tr>
<tr>
<td>(rh)</td>
<td>relative humidity</td>
</tr>
<tr>
<td>(M)</td>
<td>MC of kernels (kg water/kg dry solids)</td>
</tr>
<tr>
<td>(M_o)</td>
<td>Initial MC of kernels (kg water/kg dry solids)</td>
</tr>
<tr>
<td>(M_e)</td>
<td>EMC (kg water/ kg dry solids)</td>
</tr>
<tr>
<td>(k)</td>
<td>drying constant (s(^{-1}))</td>
</tr>
<tr>
<td>(M - M_e)</td>
<td>the moisture differential relative to EMC during drying</td>
</tr>
<tr>
<td>(M_o - M_e)</td>
<td>moisture differential between initial moisture content and EMC</td>
</tr>
<tr>
<td>(D_{mv})</td>
<td>Decimal desorption value</td>
</tr>
<tr>
<td>(Z_{mv})</td>
<td>Thermal desorption constant</td>
</tr>
<tr>
<td>(F_{mv})</td>
<td>Thermal desorption duration/ thermal exposure value</td>
</tr>
</tbody>
</table>
LITERATURE CITED


Qiu, C., Cao, J., Xiong, L., & Sun, Q. (2015). Differences in physicochemical, morphological, and


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Figure 1: Experimental layout

Figure 2: Moisture contents of rough rice dried for various durations at the indicated air temperatures and relative humidity of 50%.

Figure 3: Effects of air temperature and relative humidity on moisture contents of rough rice dried for various durations.

Figure 4: Plots of the logarithm of moisture ratio against drying duration for rough rice dried at the indicated air temperature and a relative humidity of 50%. The $D_{mv}$ values are the reciprocals of the absolute values of the slopes of the fitted lines. Plots for 35, 45, 55, 65 and 75°C air temperatures are not shown.

Figure 5: A plot of the logarithm of decimal desorption value ($D_{mv}$) against air temperature. Thermal desorption constant ($Z_{mv}$) is the reciprocal of the absolute value of the slope of the fitted line.

Figure 6: Plots of the logarithm of moisture ratio against drying duration for rough rice dried at the indicated drying air temperatures and two relative humidities (10% and 50%)

Figure 7: Effect of relative humidity on thermal desorption constant ($Z_{mv}$) of rice

Figure 8: Relationship between thermal desorption durations (thermal exposure values) at a reference temperature of 60°C ($F_{mv(60)}$) and peak viscosity of rice.

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Supplementary Table 2: Rice kernel temperature (°C) after drying rough rice for various durations using the indicated drying conditions
Figure 1: Experimental layout (Graham-Acquaah and Siebenmorgen, 2020b)
Figure 2: Moisture contents of rough rice dried for various durations at the indicated air temperatures and relative humidity of 50% (Graham-Acquaah and Siebenmorgen, 2020b).
Figure 3: Effects of air temperature and relative humidity on moisture contents of rough rice dried for various durations (Graham-Acquaah and Siebenmorgen, 2020b).
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Figure 7: Effect of relative humidity on thermal desorption constant ($Z_{mv}$) of rice (Graham-Acquaah and Siebenmorgen, 2020b).
Figure 8: Relationship between thermal desorption durations (thermal exposure values) at a reference temperature of 60°C ($F_{mv(60)}$) and peak viscosity of rice (Graham-Acquaah and Siebenmorgen, 2020b).

\[ y = 7.2725x + 2870 \]
\[ R^2 = 0.8689 \]
\[ r = 0.9321 \]
Table 1: Dew point temperatures associated with the indicated drying air conditions

<table>
<thead>
<tr>
<th>Drying conditions</th>
<th>Relative humidity</th>
<th>Dew point temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30°C</td>
<td>50%</td>
<td>18.4</td>
</tr>
<tr>
<td>35°C</td>
<td>50%</td>
<td>23.0</td>
</tr>
<tr>
<td>40°C</td>
<td>10%</td>
<td>2.60</td>
</tr>
<tr>
<td>40°C</td>
<td>50%</td>
<td>27.6</td>
</tr>
<tr>
<td>45°C</td>
<td>50%</td>
<td>32.1</td>
</tr>
<tr>
<td>50°C</td>
<td>50%</td>
<td>36.7</td>
</tr>
<tr>
<td>55°C</td>
<td>50%</td>
<td>41.2</td>
</tr>
<tr>
<td>60°C</td>
<td>10%</td>
<td>17.4</td>
</tr>
<tr>
<td>60°C</td>
<td>50%</td>
<td>45.8</td>
</tr>
<tr>
<td>65°C</td>
<td>50%</td>
<td>50.3</td>
</tr>
<tr>
<td>70°C</td>
<td>50%</td>
<td>54.8</td>
</tr>
<tr>
<td>75°C</td>
<td>50%</td>
<td>59.3</td>
</tr>
<tr>
<td>80°C</td>
<td>10%</td>
<td>31.9</td>
</tr>
<tr>
<td>80°C</td>
<td>50%</td>
<td>63.8</td>
</tr>
</tbody>
</table>

Dew point temperatures were estimated from a psychometric chart.
Table 2: Estimated equilibrium moisture contents and decimal desorption values ($D_{mv}$) associated with the indicated drying air conditions.

<table>
<thead>
<tr>
<th>Drying air conditions</th>
<th>Equilibrium moisture content (% dry-basis)</th>
<th>Decimal desorption value ($D_{mv}$) (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40°C</td>
<td>10%</td>
<td>5.50</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>10.7</td>
</tr>
<tr>
<td>60°C</td>
<td>10%</td>
<td>4.30</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>9.48</td>
</tr>
<tr>
<td>80°C</td>
<td>10%</td>
<td>3.36</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>8.54</td>
</tr>
</tbody>
</table>
Table 3: Thermal desorption durations (thermal exposure values) at reference temperature of 60°C ($F_{mv(60)}$) for rice samples dried under varying conditions.

<table>
<thead>
<tr>
<th>Drying conditions</th>
<th>Relative humidity</th>
<th>Drying duration (min)</th>
<th>Thermal exposure durations ($F_{mv(60)}$) at reference temperature of 60°C (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40°C</td>
<td>50%</td>
<td>10</td>
<td>4.6</td>
</tr>
<tr>
<td>40°C</td>
<td>50%</td>
<td>20</td>
<td>9.5</td>
</tr>
<tr>
<td>40°C</td>
<td>50%</td>
<td>30</td>
<td>14.7</td>
</tr>
<tr>
<td>60°C</td>
<td>50%</td>
<td>10</td>
<td>6.9</td>
</tr>
<tr>
<td>60°C</td>
<td>50%</td>
<td>20</td>
<td>14.5</td>
</tr>
<tr>
<td>60°C</td>
<td>50%</td>
<td>30</td>
<td>22.4</td>
</tr>
<tr>
<td>80°C</td>
<td>50%</td>
<td>10</td>
<td>10.1</td>
</tr>
<tr>
<td>80°C</td>
<td>50%</td>
<td>20</td>
<td>20.9</td>
</tr>
<tr>
<td>80°C</td>
<td>50%</td>
<td>30</td>
<td>32.7</td>
</tr>
</tbody>
</table>
Supplementary Table 1: Estimated equilibrium moisture contents (emcs) associated with the indicated drying air conditions and moisture ratios (decimal) of rice samples dried for various durations in a controlled-environment chamber.

| Air conditions (temperature| relative humidity) | Equilibrium moisture content (% dry basis) | Moisture ratio (decimal) at various drying durations |
|--------------------------|------------------------------------------|---------------------------------------------------|
|                          |                                           | 5 min     | 10 min | 15 min | 20 min | 25 min | 30 min | 45 min | 60 min |
| 30°C| 50%                           | 11.45                                              | 0.92     | 0.89   | 0.85   | 0.84   | 0.80   | 0.78   | 0.73   | 0.68   |
| 35°C| 50%                           | 11.05                                              | 0.93     | 0.88   | 0.84   | 0.82   | 0.80   | 0.78   | 0.70   | 0.67   |
| 40°C| 50%                           | 10.69                                              | 0.93     | 0.88   | 0.86   | 0.81   | 0.78   | 0.76   | 0.70   | 0.66   |
| 45°C| 50%                           | 10.35                                              | 0.93     | 0.92   | 0.82   | 0.79   | 0.74   | 0.72   | 0.66   | 0.55   |
| 50°C| 50%                           | 10.04                                              | 0.98     | 0.91   | 0.82   | 0.79   | 0.78   | 0.71   | 0.63   | 0.54   |
| 55°C| 50%                           | 9.75                                               | 0.97     | 0.90   | 0.85   | 0.81   | 0.71   | 0.66   | 0.57   | 0.48   |
| 60°C| 50%                           | 9.48                                               | 1.01     | 0.92   | 0.82   | 0.77   | 0.74   | 0.67   | 0.56   | 0.49   |
| 65°C| 50%                           | 9.23                                               | 0.99     | 0.91   | 0.79   | 0.75   | 0.74   | 0.69   | 0.50   | 0.40   |
| 70°C| 50%                           | 8.99                                               | 1.01     | 0.96   | 0.84   | 0.74   | 0.68   | 0.63   | 0.49   | 0.38   |
| 75°C| 50%                           | 8.76                                               | 1.03     | 0.94   | 0.87   | 0.75   | 0.65   | 0.56   | 0.52   | 0.37   |
| 80°C| 50%                           | 8.54                                               | 1.06     | 0.94   | 0.87   | 0.75   | 0.66   | 0.57   | 0.43   | 0.30   |
Supplementary Table 2: Rice kernel temperature (°C) after drying rough rice for various durations using the indicated drying conditions

<table>
<thead>
<tr>
<th>Drying conditions</th>
<th>Rice kernel temperature (°C) after drying for a specified duration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Air temperature</td>
</tr>
<tr>
<td>30°C 50%</td>
<td>26.4</td>
</tr>
<tr>
<td>35°C 50%</td>
<td>31.2</td>
</tr>
<tr>
<td>40°C 10%</td>
<td>30.6</td>
</tr>
<tr>
<td>40°C 50%</td>
<td>32.9</td>
</tr>
<tr>
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<td>37.1</td>
</tr>
<tr>
<td>50°C 50%</td>
<td>38.4</td>
</tr>
<tr>
<td>55°C 50%</td>
<td>43.0</td>
</tr>
<tr>
<td>60°C 10%</td>
<td>41.6</td>
</tr>
<tr>
<td>60°C 50%</td>
<td>46.6</td>
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<td>65°C 50%</td>
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<td>70°C 50%</td>
<td>54.8</td>
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<td>58.7</td>
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<tr>
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<td>51.9</td>
</tr>
<tr>
<td>80°C 50%</td>
<td>60.7</td>
</tr>
</tbody>
</table>
CHAPTER 3

Thermal exposure values for predicting changes in rice end-use properties during drying.

Graham-Acquaah, S., Siebenmorgen, T.J., Mauromostakos, A., Wang, Y.J.

ABSTRACT

Background and objectives: Rough rice may incur degrees of thermal exposure during heated-air drying, which may cause variations in end-use properties. This study employed a recently proposed method to quantify thermal exposure incurred during drying and its effects on rice milling and end-use properties.

Findings: Greater drying-air temperatures and longer drying durations increased thermal exposure (GATE**) values; the higher the GATE value, the more moisture lost during drying. Increasing GATE values increased HRY-reductions. The most practical (≥10%) reductions in HRY occurred when GATE values were ≥ 30 min. Additionally, increasing GATE values increased peak and breakdown viscosities of rice but decreased both setback viscosity and rice gel strength; the impact of drying on end-use properties was of most practical importance (≥10% change) when GATE values were ≥ 40 min.

Conclusions: The proposed GATE values would permit comparisons of the effects of thermal exposure on rice milling and end-use properties to facilitate predictions of changes in these properties due to heated-air drying.

Significance and novelty: Differences in heated-air drying conditions contribute to the inconsistencies in rice flour functionality that hinder the wide use of rice in end-use, gluten-free product development. This study shows that thermal exposure (GATE) values could be useful for quantifying and comparing cumulative heat-exposure during drying to facilitate predictions of changes in rice properties.

** GATE means Graham-Acquaah’s Thermal Exposure
INTRODUCTION

Rough rice must be dried promptly after harvesting to prevent mold growth that affects the safety of rice as food. Commercial drying of rough rice in the Mid-South US involves the use of heated air to enhance productivity and ensure prompt drying of the large volumes of rice that are available during the harvest season. Heated-air conditions (air temperature and relative humidity) and drying durations that are employed in industrial dryers vary depending on the experience of drier operators or logistics. Such differences in heated-air drying conditions could affect rice physicochemical and functional properties.

The fact that rice, predominantly, is consumed as cooked whole kernels makes head rice yield (HRY) the key determinant of economic value. Previous studies report that drying conditions could cause fissures in rice kernels; fissured kernels break during milling leading to HRY reductions. Although greater air temperatures and lesser relative humidities increase drying rate, they promote fissuring and reduce HRYs. More pronounced HRY reductions occur when heated-air drying lasts for longer durations (Chen, Siebenmorgen & Marks, 2007).

While there continues to be a research emphasis on HRY, there is growing interest in the use of rice for food product development as a result of the emerging gluten-free market. However, reported inconsistencies in rice end-use functionality hamper a wide use of rice in product development. These inconsistencies are due to the notable differences in various cultivars’ properties and differences in postharvest handling practices. For instance, varying drying regimens cause significant differences in rice paste viscosities and gel texture, two critical determinants of cereal grains’ suitability for food applications (Bhattacharya, Zee & Cork, 1999; Malumba, Massaux, Deroanne, Masimango & Béra, 2009).
Research on rice drying has focused mostly on accurate prediction of moisture content and has yielded several thin-layer and deep-bed drying models. There are also reports on the effects of drying conditions on fissuring, HRY reductions, and end-use properties (Chen et al., 1997; Dillahunty, Siebenmorgen & Mauromoustakos, 2001; Ondier, Siebenmorgen & Mauromoustakos, 2013; Graham-Acquaah & Siebenmorgen, 2020a). These studies have shown that the extent of moisture removal and changes in rice physicochemical properties depend on interactions among drying conditions, particularly temperature and duration of exposure during drying and tempering. Based on these interactions, Graham-Acquaah & Siebenmorgen (2020b) hypothesized that the total amount of thermal (cumulative temperature-duration) exposure determines the trend and magnitude of changes in rice properties and proceeded to propose a method for quantifying thermal exposure incurred during drying. The relationship between the proposed thermal exposure values and changes in various rice properties is yet to be determined. This study quantifies thermal exposure incurred by rough rice during drying and relates the derived thermal exposure values to changes in HRY, paste viscosities (peak, breakdown, and setback viscosities) and gel texture during drying.

MATERIALS AND METHODS

Drying experiment

A lot of rough rice (CLXL745) that was harvested at a moisture content of 18.5% was procured from a commercial farm near Pocahontas, AR during the 2018 crop year. The rice lot was cleaned using a dockage tester (XT4, Carter-Day, Minneapolis, MN, USA), placed in plastic tubs, and kept in a cold room (4°C) until used. A day before conducting experiments, approximately 8 kg of rough rice was removed from cold storage and equilibrated to room
temperature (22°C). Afterwards, the initial moisture content of the rough-rice sample was determined by drying five 15-g subsamples for 24 h in a convection oven that was set at 130°C (Jindal & Siebenmorgen, 1987).

The layout of the experiment that was conducted is shown in Figure 1. Thin-layer drying experiments were conducted inside a 0.91-m³, controlled-environment chamber (Platinous Sterling Series, ESPEC North America, Hudsonville, MI, USA) that produced desired drying air conditions (40°C|30% rh, 50°C|30% rh and 60°C|30% rh). The drying temperatures were chosen to cover the range of temperatures mostly used in industrial dryers in the Mid-South U.S. Relative humidity (rh) was maintained at 30% in order to control for the effect of rh on drying rates. At each of the three stipulated drying conditions, four separate 220-g samples of rough rice were each spread in a uniform thin layer (2-3 kernels deep) inside a rectangular drying basket (25 cm × 15 cm × 5 cm) and dried for either 15, 30, 45 or 60 min. At the end of each drying run, rough rice was removed from the drying chamber and weighed to determine the amount of moisture loss during drying. After weighing, samples were transferred unto mesh trays and conditioned to 12.5% MC in an equilibration chamber maintained at 25°C and 56% relative humidity.

A total of 24 experimental runs were conducted: three air conditions, four (4) drying durations for each air condition, and duplicate runs for each combination of air conditions and drying duration. Two 200-g rough-rice samples were gently conditioned in the equilibration chamber to 12.5% moisture content and used as controls. Thus, milling, rapid visco-analyses (RVA) and texture analyses were conducted on 26 rough-rice samples.
Milling analyses

After drying and conditioning rough rice to 12.5% MC, 150-g samples were dehulled using a laboratory sheller (THU, Satake, Tokyo, Japan) with a clearance of 0.048 cm (0.019 in) between the rollers. The brown rice obtained were milled for 30 s using a laboratory mill (McGill No. 2, RAPSCO, Brookshire, TX). Head rice, milled kernels having length equal to or greater than three-fourths of the original kernel length, were then separated from broken kernels using a double-tray sizing device (Seedburo Equipment Co., Chicago, IL). The surface lipid contents (SLCs) of the head rice samples were estimated using a diode array NIR analyzer (DA 7200, Perten instruments, SE-141 05, Huddinge, Sweden) to indicate the degree of milling. The percentage point differences between the HRYs of samples from drying runs and the control sample was recorded as HRY reduction (HRYR).

Pasting properties of rice flour

Pasting properties were measured using the method described by Ambardekar & Siebenmorgen (2012). About 20 g of head rice from each sample was ground into flour using a cyclone mill with a 0.5-mm screen (UDY, Fort Collins, CO). The MCs of the flour samples were determined by placing duplicate, 2-g samples in an oven at 130°C for 1 h. Peak, trough and final viscosities of rice flour were determined with a viscometer (RVA Super 4, Newport Scientific, Warriewood, Australia) by mixing 3 ± 0.01 g of flour at approximately 12% MC with 25 ± 0.05 mL of deionized water. Breakdown viscosity was calculated as the difference between peak and trough viscosities. Setback viscosity was calculated as the difference between final and peak viscosities. The viscometer used a 12.5 min cycle (1.5 min at 50°C, heating to 95°C at 12°C/min, 2.5 min at 95°C, and cooling to 50°C at 12°C/min) according to Approved Method 61-02.01
Duplicate RVA determinations were conducted on each of the 26 samples.

**Rice gel texture**

Rice paste generated from each RVA run was formed into a 20-mm diameter × 20-mm-high gel and the hardness (strength) of the gel measured using a texture analyzer (TA-XT2i, Texture Technologies, Scarsdale, NY) as described by Graham-Acquaah and Siebenmorgen (2020a).

**Determination of thermal exposure values**

Thermal exposure values during drying, hereafter referred to as GATE (Graham-Acquaah’s Thermal Exposure) values were determined using data on rice kernel temperatures (Supplementary Table 1) alongside the thermal exposure equation proposed by Graham-Acquaah and Siebenmorgen (2020b) as follows:

\[
GATE = F_{mv(T_{ref})} = \int 10^{\frac{T_k-T_{ref}}{Z_{mv}}} dt
\]

(1)

GATE refers to the equivalent duration of heat treatment at a reference temperature of 60°C that a rice lot would have received in order to achieve the same magnitude of moisture removal as the actual drying conditions. \(T_k\) is the temperature of rice kernels; \(T_{ref}\) is the reference drying air temperature (60°C); \(Z_{mv}\) - thermal desorption constant (i.e. 77.5°C).

Separate drying runs were conducted to generate data on rice kernel temperatures during drying at the three air conditions used in this study. This was necessary to avoid delays in measuring kernel temperature and moisture content on the same sample. Also, this permitted measurement of kernel temperatures over shorter intervals (5 min). Twenty-four (24) 220-g
samples of rough rice were spread in a uniform thin layer (2-3 kernels deep) inside rectangular drying baskets (25 cm × 15 cm × 5 cm). At each drying temperature, a sample was dried in the environmental chamber for a specified duration (i.e. 5, 10, 15, 20, 25, 30, 45, or 60 min). Once the drying duration elapsed, the rough rice was removed from the drying chamber and quickly transferred into an air-tight and insulated container with two k-type thermocouple probes embedded at the top and bottom in order to measure the temperature of rice kernels after drying for the specified duration. The average temperature from the two probes was recorded as the temperature of the dried rice.

Data analyses

Data were analyzed using statistical software (JMP Pro 15.2.04, SAS Institute, Cary, NC). Analyses of variance were conducted to determine the individual and interactive effects of drying air temperature and drying durations on HRY reductions, paste viscosities and gel texture. The possible effect of SLC on end-use properties (Perdon, Siebenmorgen, Mauromoustakos, Griffin & Johnson, 2001) was considered by including SLC as a factor in the analyses of variance. This provided an adjustment for varying SLCs and permitted the effects of drying conditions to be compared without the degree of milling (SLC). Further, changes in paste viscosities and gel texture during drying were expressed in percentages relative to the control samples as follows:

\[
\text{Change in property} \, (\%) = \frac{V_t - V_c}{V_c} \times 100
\]

(2)

Where \( V_t \) is the numerical value for the specified property of a given dried sample; \( V_c \) is the numerical value for the specified property of the control sample.

Linear models were fitted to ascertain the relationship between GATE values and changes in HRY, paste viscosities and gel texture. Pearson’s correlation coefficient determined the strength of the
linear relationship between GATE and rice properties. F-test determined the significance of the fitted effects. Fit statistics, such as overall R-square values and RMSE, are also reported.

RESULTS AND DISCUSSION

A tempering step usually accompanies heated-air drying. Tempering helps to reduce moisture and material state gradients that occur during the actual drying process, which is also referred to as active drying in this manuscript. However, tempering durations affect rice end-use properties to different extents depending on the moisture content of the rice after active drying (Graham-Acquaah & Siebenmorgen, 2020a); this suggests that any form of tempering could mask the effects of active drying on rice properties. Therefore, in this study, dried samples were not tempered to permit the evaluation of changes in HRY, paste viscosities, and gel texture without the confounding effect of tempering.

Effects of drying conditions on GATE values, moisture content and head rice yields

Table 1 shows significant effects of air temperature, drying duration, and the interaction between the two factors on all the rice properties that were measured. These results, especially the observed interactive effects of air temperature and drying duration, suggest that notwithstanding the significant effects of air temperature and drying duration, neither can be used reliably to explain changes in rice properties during active drying. The results also reaffirm the need for temperature-duration effects on end-use properties to be considered in tandem while also re-emphasizing the importance of a methodology for quantifying and comparing thermal exposure during drying (Graham-Acquaah & Siebenmorgen, 2020b). Further, the results highlight the need for systematic characterization and optimization of rice drying processes for specified end-use applications.
Figure 2a shows that longer drying durations at any given drying air temperature increased GATE values implying that the longer a sample stays at a particular air temperature, the greater the heat exposure that it incurs. The results also show that a lot of rough rice dried at a lesser temperature could receive greater heat exposure if dried for a longer duration than another sample dried at a greater temperature for a shorter duration. For instance, rough rice dried at 40°C for 60 mins incurs greater thermal exposure than another dried at 50°C for 30 min or 60°C for 15 min (Figure 2a). The trend of MC reductions (Figure 2b) with drying conditions was very similar to that of GATE values - greater temperatures and longer durations produced greater MC-reductions in rough rice. Greater air temperatures increase rice kernel temperature to enhance water mobility inside the kernels resulting in a faster rate of water removal from kernels; the longer the duration of drying, the greater the number of water molecules that escape from samples.

When the GATE values were related to MC-reductions, a strong correlation (0.99) was observed (Figure 3). This implies that increasing cumulative temperature-duration exposure increases MC-reduction during active drying. These results further affirm the reliability and utility of GATE values for quantifying and expressing thermal exposure incurred during active drying.

The results (Figure 4a) of this study show that increasing drying temperatures and longer drying durations produced more percentage point reductions in HRY during active drying. There was a strong correlation (r = 0.91) between GATE values and change in HRY due to active drying (Figure 4b). Greater drying temperatures and longer drying durations create fissures in rice kernels during drying that break during milling and reduce head rice yields (Chen et al., 1997). Increasing air temperatures, as well as longer drying durations, increase GATE values; therefore, greater thermal exposure would cause more pronounced HRY reductions (Figure 4b). The strong correlation between GATE values and HRY reductions implies that GATE values could
adequately predict changes in HRY during active drying. The greatest changes (≥ 10% reduction) in HRY occurred when GATE values exceeded 30 min, suggesting that the impact of heated-air drying on HRY reductions would be minimal if cumulative temperature-duration exposure does not exceed about 30 min. Further research under more drying scenarios in different drying equipment is necessary to confirm these findings.

**Relationship between GATE values and end-use properties**

Drying samples at 40°C and 50°C for different durations (15 to 60 min) did not produce significant changes in peak viscosities. At an air temperature of 60°C, however, increasing drying durations increased peak viscosity; samples dried for longer than 30 min had significantly greater peak viscosities than those dried for 15 or 30 min (Figure 5). Changes in the peak viscosity of rice flour during drying is associated with the effect of temperature on the non-starch component of rice, especially proteins, and heat-induced interactions between starch and proteins (Tang, Hettiarachchy, Ju & Cnossen, 2002; Patindol, Wang, Siebenmorgen & Jane, 2003). According to Tang et al (2002), drying rough rice at 60°C increases the surface hydrophobicity of rice proteins. The longer the drying duration at 60°C, the more the increase in surface hydrophobicity. Increasing surface hydrophobicity enhances water absorption by rice proteins (Zhu, Lin, Ramaswamy, Yu & Zhang, 2017). Groot & Bakker (2016) also concluded that relatively mild heat treatments loosen protein structure, thereby allowing them to absorb more water. Peak viscosity reflects the capacity of starch granules to swell in the presence of water, heat, and shear; therefore, treatments that enhance water absorption by flour would facilitate starch granule swelling and increase peak viscosity. Changes in surface hydrophobicity and heat-induced interactions between starch and protein that could lead to increases in peak viscosity would be more likely to occur at 60°C since
it is the temperature at which the rough-rice lot used in the study, given its initial MC of approximately 18% wet-basis, could have undergone glass transition as postulated by Cnossen & Siebenmorgen (2003). Protein unfolding during glass transition affects surface hydrophobicity (Ju, Hettiarachchy, & Rath, 2001; Tang et al., 2002).

There was a significant (p<0.05) positive correlation (r = 0.86) between GATE values and peak viscosity (Figure 6a). Martin & Fitzgerald (2002) suggested that during rapid visco-analyses (RVA), the rate of pasting would reflect only the swelling of starch if proteins were absent. As such, rate of pasting could reflect the role of proteins in the formation of peak viscosity. In this study, rate of pasting was determined by dividing peak viscosity by the duration it took to observe peak viscosity (peak time) during RVA. Similar to peak viscosity, there was a significant correlation between thermal exposure values and rate of pasting (Figure 6b), affirming that the apparent relationship between GATE values and peak viscosity could be due to the effects of thermal exposure on rice proteins during drying. These results also suggest that for active drying to have a practical impact (≥10% change) on peak viscosity, thermal exposure must exceed a minimum threshold (GATE value ≥ 40) during drying.

The trends in the effects of active drying conditions on breakdown viscosity were similar to peak viscosity (data not shown). Moreover, like peak viscosity, a strong correlation was observed between breakdown viscosity and GATE values; as thermal exposure increased breakdown viscosity increased (Figure 7a). Again, the magnitude of changes in breakdown were of most practical importance (≥10% change) when GATE values exceeded 40 min. Graham-Acquaah & Siebenmorgen (2020a) observed increases in breakdown of rice samples dried and tempered at temperatures that did not exceed 60°C. Malumba et al. (2009) also observed that drying corn at 60°C increased peak and breakdown viscosities and concluded that flour samples
that swell to a high degree are also usually less resistant to breakdown. During the RVA holding phase, swollen starch granules disintegrate as the paste is stirred at a constant temperature. The more water released from the granules to the pasting medium, the lesser the minimum viscosity (Trough) and the greater the breakdown (the difference between peak and trough viscosities). In this study, there were no significant differences in trough viscosity; therefore, these changes (increase) in breakdown are likely due to the effects of active drying on peak viscosity. Drying conditions that increase peak viscosity without affecting trough will result in an increase in breakdown.

Setback viscosities, on the other hand, decreased with increasing thermal exposure (Figure 7b). Similar to peak and breakdown viscosities, changes in setback were more pronounced at 60°C than at 40 and 50°C. Thermal exposure values of about 40 min or more produced the greatest changes in setback during active drying.

Figure 8 shows the relationship between GATE values and rice gel strength; as thermal exposure increased, gel strength decreased. Practical reductions (≥ 10% change) in gel strength occurred when GATE values were ≥ 40 min. Martin and Fitzgerald (2002) suggested that changes in protein properties that resulted in a decrease in the concentration of the viscous phase of rice pastes during RVA and thus increased breakdown would reduce the ability of the rice paste to form stable gels.

CONCLUSIONS

Thermal exposure (GATE) values were determined to express the cumulative temperature-duration exposure incurred by rough rice during active drying. The GATE values increased with both air temperature and drying duration and had a strong correlation (0.99) with moisture
reduction during drying. Greater GATE values reduced HRY. The most notable (≥ 10%) reductions in HRY during active drying occurred when GATE values exceeded about 30 min. Regarding end-use properties, increasing GATE values increased peak and breakdown viscosities but decreased setback and gel strength. Changes in end-use properties were of most practical importance (≥10%) when GATE values were ≥ 40 min. The proposed GATE values could facilitate comparisons of the effects of thermal exposure during drying on rice physicochemical and functional properties. Additionally, GATE values would be useful for predicting changes in rice properties during heated-air drying. Future studies are necessary for determining the utility of GATE values under typical commercial drying scenarios.

ACKNOWLEDGEMENT

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LITERATURE CITED


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\[ y = -0.7947x + 16.24 \]

\[ R^2 = 0.8674 \]

\[ r = -0.9314 \]

\[ RMSE = 4.695 \]
Table 1: F-values from an analysis of variance of the effects of drying conditions and their interactions on moisture content (MC) reduction, head rice yield (HRY) reduction, paste viscosities and gel texture.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>MC-reduction</th>
<th>HRY reduction</th>
<th>Paste viscosities (cP)</th>
<th>Rate of pasting</th>
<th>Gel strength (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature (AT)</td>
<td>143***</td>
<td>34.5**</td>
<td>4.49*</td>
<td>14.6***</td>
<td>5.00*</td>
</tr>
<tr>
<td>Drying duration (DD)</td>
<td>383***</td>
<td>12.1*</td>
<td>7.39**</td>
<td>12.5***</td>
<td>9.92***</td>
</tr>
<tr>
<td>AT×DD</td>
<td>24.5***</td>
<td>4.46</td>
<td>4.71**</td>
<td>3.25*</td>
<td>2.20</td>
</tr>
<tr>
<td>SLC</td>
<td>na</td>
<td>na</td>
<td>0.724</td>
<td>0.508</td>
<td>0.262</td>
</tr>
<tr>
<td>Fitted model</td>
<td>146***</td>
<td>11.6*</td>
<td>5.35**</td>
<td>7.86***</td>
<td>5.70***</td>
</tr>
<tr>
<td>R-square</td>
<td>0.991</td>
<td>0.977</td>
<td>0.800</td>
<td>0.855</td>
<td>0.810</td>
</tr>
<tr>
<td>RMSE</td>
<td>0.176</td>
<td>3.44</td>
<td>48.9</td>
<td>38.5</td>
<td>44.7</td>
</tr>
</tbody>
</table>

*Significant at $p < 0.05$; **Significant at $p < 0.01$; ***Significant at $p < 0.001$; na-not applicable/effect not tested
IV. OVERALL CONCLUSIONS

Heated-air drying is an essential component of rice postharvest handling in the Mid-South US. While heated-air drying and tempering (HAT) regimens may enhance drying rate without compromising head rice yield, end-use properties could be affected. This dissertation evaluated the impacts of HAT regimens on rice end-use properties. Hypothesizing that the total amount of heat exposure determines the trend and magnitude of changes in rice end-use properties during drying, a theoretical framework based on the F0-value concept used in thermal sterilization was formulated to derive an index, Graham-Acquaah’s Thermal Exposure (GATE) value, for quantifying and comparing thermal exposure incurred during active drying of rough rice.

The three main objectives for this research were to (i) determine the impacts of varying drying and tempering regimens on rice end-use properties (ii) develop an index for quantifying thermal exposure incurred during rough rice drying and (iii) ascertain the relationship between values of thermal exposure and changes in rice end-use properties during active drying.

In fulfilling the first objective, rough rice samples were dried using varying air conditions (air temperature and relative humidity) and tempering durations. The effects of the varying HAT regimens, i.e. combinations of air conditions and tempering durations, on changes in rice paste viscosities and gel texture were determined. Results showed that rice paste viscosities and gel texture were not only dependent on drying air temperature but also on how long the rice was exposed to a given temperature during drying and tempering. Air relative humidity (rh) had an indirect effect on rice end-use properties as it affected the moisture content of rough-rice after drying and thus, during tempering. Using different HAT regimens, peak viscosity was altered by 16%, final viscosity by 21%, breakdown by 24%, and setback by >500% compared to control samples. Gel strength was increased by approximately 40% with HAT regimens. These results
signify that heated-air drying and tempering conditions ought to be carefully selected, not only to minimize HRY reductions but also to minimize variations in the physicochemical and functional properties of rice intended for specified end-uses. Furthermore, it shows that HAT regimens could be selected to produce desired properties for specified end-uses.

The second objective was addressed by drawing parallels between heated-air drying and thermal sterilization to formulate a theoretical framework for quantifying thermal exposure incurred by rough rice during drying. Subsequently, data collected from rough rice drying experiments were employed alongside the theoretical framework to derive a decimal desorption value ($D_{mv}$) that represents the duration required to cause a 90% reduction in moisture ratio during drying at a specified temperature. From the $D_{mv}$, a thermal desorption constant ($Z_{mv}$) that represents the increase in temperature necessary to cause a 90% reduction in $D_{mv}$ during drying was established. Finally, a thermal desorption value ($F_{mv}$), also referred to as Graham-Acquaah’s Thermal Exposure (GATE) value was derived to express the duration that a rice lot would have been heat treated at a reference temperature during drying to produce an equivalent effect on moisture content as that produced by the actual drying process.

To address the third objective, GATE values were determined and related to changes in rice end-use properties during active drying. Significant ($p<0.05$) correlations ($0.82 – 0.93$) were observed between GATE values and end-use properties. The most practical changes ($\geq10\%$ change) in end-use properties occurred when GATE values were $\geq 40$ min. The proposed GATE value could facilitate comparisons of the effects of thermal exposure during drying on rice physicochemical and functional properties. The GATE values would also be useful for predicting changes in rice properties during heated-air drying.
V.  RECOMMENDATIONS FOR FUTURE WORK

The findings of this dissertation suggest a need for systematic characterization and standardization of heated-air drying and tempering (HAT) regimen for specified end-uses. The mechanisms, such as changes to the structure and function of rice macromolecules (i.e. starch, proteins and lipids), that underlie the observed differences in end-use properties could also be studied to provide a fundamental understanding of how HAT regimens affect rice properties.

Regarding the novel methodology for quantifying thermal exposure, future experiments could determine the impact of cultivars and initial moisture content on drying rates in order to establish thermal desorption constants $Z_{mv}$ that are typical for cultivar classes over a wide range of harvest moisture contents. The utility of GATE values under drying scenarios that are typical in commercial operations could also be investigated.