Impact of Parboiling Processing Conditions on Rice Characteristics

by

Martha Hunt

B.S., Kansas State University, 2009

A REPORT

submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

Food Science

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2019

Approved by:

Major Professor
Dr. Fadi Aramouni

Copyright

Abstract

Parboiling rice is the process of soaking, steaming, and drying prior to milling. One of the primary advantages to parboiling is the potential to increase head rice yield. Head rice are the kernels that are at least three-fourths intact after milling and are more economically valuable than broken kernels. Parboiling also migrates of nutrients from the exterior bran layer to the interior of the rice kernel during soaking and steaming, thereby improving the nutritional value of the rice post-milling. Parboiling causes physical changes to the rice kernel, such as kernel hardening and pasting properties that lead to longer cook times and different eating texture. One quality of parboiled rice that is monitored and can be slightly disadvantageous is color. Parboiled rice is typically yellow and darker in color than unparboiled rice, and severity of parboiling conditions can increase the color to defect levels if not controlled. Soaking is the first stage of parboiling and the primary objective is to obtain uniform absorption of water to about 30%, which prepares the rice kernel for starch gelatinization. Steaming is the second stage of parboiling and targets fully gelatinizing the starch, sealing fissures in the kernel endosperm that might otherwise break apart during milling. Drying is the third stage of parboiling and requires lowering the moisture content gently to attain optimal quality for storage and milling (typically between 12-14%). Milling is the next stage of production after parboiling and removes the bran layer and hull, resulting in saleable rice products. Parboiling can result in advantages for millers, such as: improved head rice yields, improved nutritive content rice that can be marketed to customers, and different pasting properties that can make unique rice ingredients, like longer cooking times and firmer kernels. Research on the effectiveness of the rice parboiling process starts with understanding the rice qualities and structural composition going into processing, and then

applying that knowledge to optimize parboiling processing parameters. Research on adjusting processing methods compared to the traditional approach can focus on pre-processing applications, like heat-moisture treatment prior to parboiling or pre-steaming. Studies can also focus on modifying conditions during the parboiling process, such as; the application of IR heat during steaming and soaking, continuous steaming, and fluidized bed-drying. Ultimately, researchers seek to modify the traditional parboiling process to minimize processing time and energy requirements, while concurrently increasing head rice yields and desirable rice characteristics.

Table of Contents

List of Figures ... vi
List of Tables ... vii
Acknowledgements ... viii
Global Rice Production ... 1
Rice Varieties ... 3
Rice Structure ... 7
Nutritional Composition of Rice ... 9
Nutritional Quality and Glycemic Index ... 13
Rice Products ... 15
Rice Processing Overview ... 18
Parboiling Overview ... 21
Parboiled Rice Physiochemical Properties ... 25
Rice Composition Measurement Methods ... 31
Modifying Traditional Parboiling Methods ... 37
Conclusion ... 46
References ... 47

List of Figures

Figure 1. Longitudinal section of rice grain 7
Figure 2. Steps to convert raw rough rice to milled parboiled rice. 21

List of Tables

Table 1. Global Rice Market Summary for 2015 to 2018 2
Table 2. Chalk values[a] and peak head rice yields[b] for cultivars harvested from different locations in 2010[c] 5
Table 3. National Weekly Rice Summary March 2019..19
Table 4. Moisture content after steaming at various soaking conditions with three varieties (Chainat 1, Supanburi 1 and KDML 105) 25
Table 5. Effect of parboiling method on nutrient content and distribution in brown rice[a]............28
Table 6. Rapid Visco Analyser curves of heat-moisture treatment grain flours and flours of parboiled grain after heat-moisture treatment at different treatment times 40
Table 7. Qualities evaluation, pasting properties, and thermal property of IR-heated sample with 30% initial moisture content 43

Acknowledgements

I wish to acknowledge Dr. Aramouni, Dr. Smith, and Dr. Getty for their assistance in getting to the resolution of my Master's Degree. I would also like to acknowledge the encouragement and support of my family who always shared my excitement and frustrations, which helped me find my way to completing my degree.

Global Rice Production

Rice is a food staple for more than half the world's population (National Geographic Education Staff, 2014). According to the Food and Agricultural Organization of the United Nations (FAO), global paddy production was 751.9 million tons (499.2 million tons, milled basis) in 2016 (FAO, 2017). Asia was the largest producer of rice with 680.1 million tons and China produced the more rice in the world in 2016 with an estimate of 208.5 million tons. Africa and South America were second and third largest continent rice producers at 30.8 and 23.7 million tons, respectively. The United States produced 10.2 million tons in 2016, which makes it a small contributor compared to total global rice production.

As seen in table 1, world utilization of rice was estimated at 500.3 million tons in 2016/2017 and forecasted to increase to a total of 506.5 million tons in 2017/2018 (FAO, 2017). The discrepancy between rice production quantities and utilization is linked to the loss of material when processing from paddy rice collected in the field to useable ingredients. FAO forecasted an increase of 5.1 million tons of rice consumption as food to a total of 401.8 million tons in 2016/2017. Animal feed quantities were estimated at 80.2 million tons. Based on these calculations, the global per capita food use would be 54.1 kilos in 2017. There is also a significant discrepancy between imported/exported rice quantities compared to total rice utilized. Most countries consume a large portion of the rice produced in their own country, which limits the amount of rice exported or imported as it relates to the total production of rice per country.

Table 1. Global Rice Market Summary for 2015 to 2018

	2015-16	2016-17	2017-18	2017-18/ 2016-17
	Milled tonnes, milled esq			Var. %
Production	491.6	499.2	503.8	0.9
Supply	711.0	713.3	720.0	0.9
Utilization	495.3	500.3	506.5	1.2
Food Use	396.7	401.8	406.4	1.1
Feed Use	18.1	18.3	18.0	-1.8
Other Use	80.5	80.2	82.1	2.4
Trade 1/	41.6	43.3	44.2	2.0
Ending Stocks 2/	171.4	171.3	170.7	-0.3
	%			
Global stock-to-use ratio	34.3	33.8	33.2	-
Major exporters' stock-to-disappearance ratio 3/	19.2	18.6	16.9	-

1/ Data refer to the calendar year trade (Jan.-Dec.) of the second year shown.
2/ Stocks carried over in the second year shown.
3/ Defined as the sum of the five major rice exporters (India, Pakistan, Thailand, United States and Viet Nam) stocks divided by the sum of their domestic utilization plus exports

Adapted from http://www.fao.org/fileadmin/templates/est/COMM_MARKETS_MONITORING/Rice/Images/RMM/RMM_APR17_H.pdf. Copyright (2017) by Food and Agricultural Organization of the United Nations.

Rice production varies from year-to-year by many factors due to its nature as a crop-dependent source. For example, the improvement in rice supply from 2015 to 2016 (Table 1) was theorized to stem from the return of normal weather patterns after a El Niño affected year in 2015 that influenced the rain fall (or lack thereof). The phenomena caused negative effects in planting conditions and loss of useable land for paddy cultivation.

Rice Varieties

There are several rice varieties based on breeding method. According to International Rice Research Institute (IRRI) (2007), pureline rice varieties (also called pureline rice cultivars) are plants that will have "offspring or succeeding generations that will have same genetic make up." (IRRI, 2007). Pureline cultivars are also called "inbred" because most rice flowers have both male and female organs, allowing for self-pollination. Plants grown from seeds collected from pureline cultivars will have the same varietal identity as the parent plant, assuming the plant was self-pollinated. Most rice varieties grown today are pureline cultivars.

Hybrid rice cultivars are plants that come from the cross between two genetically distinct varieties (IRRI, 2007). Hybrid rice can have selected patent genes for key advantages in vigor (competitive advantages over weeds), yield, and increased resistance to disease and pests. However, there are disadvantages to choosing hybrid rice cultivars. The seeds are expensive and one-time use because of their selectively bred genetic make-up that will not maintain through future generations of the plant. Hybrid rice cultivars produce approximately 30% greater yield than pureline cultivars (Yuan, 1994). Hybrid rice was first used in China in the 1970s (Walton, 2003), but it is a relatively new technology in the U.S. The first commercially available hybrid rice cultivar in the United States was released in 2000 and more cultivars have been released in subsequent years (Walton, 2003).

Transgenic rice, typically referred to as genetically modified rice, is a rice plant that has any gene introduced through genetic engineering, primarily sourced from alternative life forms such as microorganisms or different plants. "The gene is introduced directly into the cultured cells and/or organs (immature embryo) using biolistic or agrobacterium methods of transformation." (IRRI, 2007). Desirable traits, such as good yields under less than optimal conditions like drought and photosynthesis efficiency from other types of plants (Khullar, 2017), and reduction of arsenic accumulation from fungi (Yogesh, 2018) are tested in the rice plants or the next generation of the rice plant after a genetically engineered modification has been implemented.

The improvement of rice cultivars through genetics are part of the approach that rice producers consider to counter varying factors from growing crops in various environments, which can affect rice processing properties such as milling characteristics (Webb, Bollich, Carnahan, & McKenzie, 1985; Ambardekar, Siebenmorgen, Counce, Lanning, & Mauromoustakos, 2011; Lanning, Siebenmorgen, Counce, Ambardekar, & Mauromoustakos, 2011). Authors Lanning et al (2011) published a study that analyzed three long-grain pureline cultivars (Cypress, LaGrue, Wells), two medium-grain pureline cultivars (Bengal and Jupiter), and one long-grain hybrid cultivar (XL723) in five locations staggered north to south throughout Arkansas (Keiser (35.7°N), Newport (35.6°N), Pine Tree (35.1°N), Stuttgart (34.5°N), and Rohwer (33.8°N)) in an effort to monitor the effect of night-time (between 8:00pm and 6:00am) air temperature during the growing season. Data was collected between 2007-2010 to include night-time air temperatures over the season and plotted for each stage of rice growth. For each combination of year, cultivar and location, quantile analysis identified the temperature below which 95% of all temperatures occurred. As a reference point in the study, 2010 was known to have record high night-time air temperatures and could be used to contribute verification to night-time air temperature effects from the prior three years. In particular, the frequency of night-time air temperatures reaching 26ºC or greater was particularly high in 2010, which was observed to drive the development of chalk from Fitzgerald and Resurreccion, (2009). Chalk is an opaque area of the rice kernel that is undesirable to consumers and delivers poor eating quality (Lanning et al, 2011).

Table 2. Chalk values[a] and peak head rice yields[b] for cultivars harvested from different locations in 2010[c]

Location [d]	Cultivars											
	Bengal		Jupiter		Cypress		LaGrue		Wells		XL723	
	Chalk (%)	pHRY (%)	Chalk (%)	pHRY (%)	Chalk (%)	pHRY (%)	Chalk (%)	pHRY (%)	Chalk (%)	pHRY (%)	Chalk (%)	pHRY (%)
Keiser	3.96	51.6	2.98	47.4	3.28	52.1	4.46	41.0	5.03	40.3	11.78	39.6
Newport	1.87	56.9	0.61	54.5	1.27	58.1	1.05	52.0	1.66	54.5	2.09	52.8
Pine Tree	3.99	60.4	3.41	55.8	2.87	60.9	4.82	45.0	4.61	49.5	9.88	51.3
Stuttgart	4.40	56.2	5.15	44.6	3.79	59.0	9.28	36.7	8.01	38.8	12.99	48.6
Rohwer	5.61	48.2	9.06	41.5	9.98	47.5	20.41	21.8	16.09	27.8	23.42	36.9
SE	0.37	1.26	0.83	1.42	0.82	1.56	1.82	2.80	1.35	2.52	1.86	1.73

[a] Chalk values were measured in duplicate brown rice samples and averaged across all harvest lots for each location/cultivar combinations.

[b] Head rice yields were measured in duplicate on samples harvested at optimal moisture content and averaged to attain pHRYs were adjusted to a 0.4% surface lipid content according to the method of Pereira et al. (2008).

[c] Similar data for 2007-2009 is published in Ambardekar et al. (2011).

[d] All locations are in AR, USA.

Adapted from “Extreme nighttime air temperatures in 2010 impact rice chalkiness and milling quality” by Lanning, S.B., Siebenmorgen, T.J., Counce, P.A., Ambardekar, A.A., & Mauromoustakos, A. 2011, *Field Crop Res, 124*(1), 134. Copyright 2011 by Elsevier.

Table 2 shows the data from the study that implies that chalk development and lesser peak head rice yields can be affected by high night-time air temperatures. Growing location also impacted rice quality observed as data was collected further south, the night-time air temperatures generally increased (Ambardekar et al, 2011); thereby influencing the final measured chalk and peak head rice yields. In Table 2, the authors determined that for all cultivars, the chalk levels and peak head rice yields had significant relationships ($\alpha = 0.05$) to the 95th percentile of night-time air temperature frequencies during the later half of the rice growing stages (R5-R8). Further analyzing the data, the authors found that each cultivar had a positive quadratic relationship between chalk and the 95th percentile of night-time air temperature frequency. However, long-grain cultivars appeared to have more susceptibility to chalk formation at the temperatures than the medium-grain cultivars based on this information. Long-grain hybrid cultivars did not appear to have as significant effect on chalk formation when compared to long-grain pureline cultivar behavior.

Rice Structure

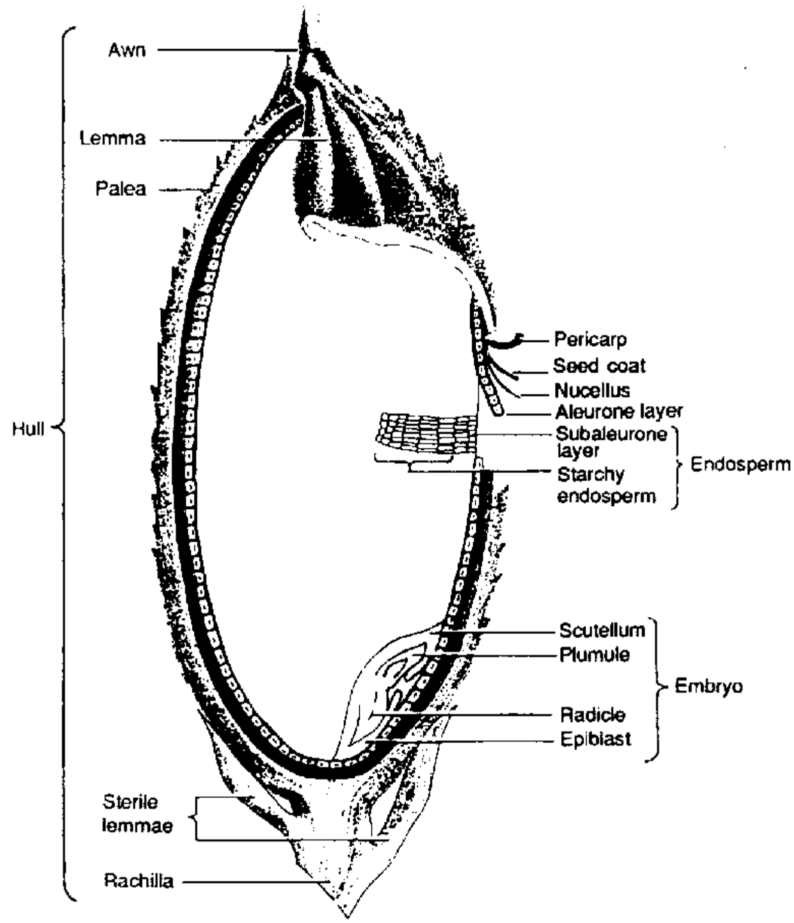

Figure 1. Longitudinal section of rice grain
FAO. (1993). Longitudinal section of rice grain. Retrieved from http://www.fao.org/3/t0567e /T0567E01.GIF

There are several terms to describe different forms of harvested rice (Juliano & Bechtel, 1985). Rough rice (or paddy rice) refers to the presence of a protective outer layer called a hull around the rice fruit or caryopsis (*Figure 1*). The rice caryopsis is often referred to as brown, cargo, dehulled or dehusked rice. The rice caryopsis includes three main components: the seed-coat and nucellus called the pericarp, the embryo called the germ, and the endosperm. Pigment, a component that influences the rice color, is located in the pericarp. The endosperm consists of the aleurone layer that protects the germ, the subaleurone layer, and the starchy, inner endosperm. The endosperm contributes around 90-91% of the total rice weight (Juliano, 1972). The aleurone layer and pericarp layer together are referred to as the bran of rice, which is important when referring to the milling process and nutritional composition.

Nutritional Composition of Rice

Paddy rice goes through an abrasive milling process to remove the hull, which is not edible and results in brown rice. When targeting milled rice products, the abrasive milling process is used to remove the "pericarp, seed-coat, testa, aleurone layer and embryo." (Juliano, 1993, p.1). The duration of milling required to yield the greatest amount of head rice (or kernels that are at least three-fourths intact post processing) is the degree of milling (DOM). The DOM is the amount of bran removed from the brown rice kernel during milling, which affects the surface lipid content located in that section of the grain and head rice yield (HRY) (Siebenmorgen, Matsler, & Earp, 2006). The standard approach to DOM is understanding that bran is typically about 20% oil or lipid; therefore, measuring the surface lipid content can indicate how much bran was removed from the surface of the kernel (Siebenmorgen, 2018). Milling durations chosen to yield a DOM with a specific surface lipid content can be affected by growth location, cultivars, and parboiling (Gujral, Singh, & Sodhi, 2002; Siebenmorgen et al 2006; Lanning & Siebenmorgen, 2011). The DOM also can affect rice color, which is a concern when comparing multiple cultivars (Siebenmorgen et al, 2006). In the process of removing the layers, there is a loss of "fat, protein, crude and neutral detergent fiber, ash, thiamine, riboflavin, niacin, and α-tocopherol." (Juliano, 1993, p.1).

According to Juliano (1993), starch is about 90% of the milled rice. The starch is typically in polymers of D-glucose linked at alpha-(1-4) and in the two forms of linear amylose and branched alpha (1-6) amylopectin. According to Juliano (1979) and Juliano (1985b), classification of rice can include starch composition such as waxy rice (1 to 2% amylose), very low amylose (2 to 12%), low amylose (12 to 20%), intermediate (20 to 25%) and high (25 to 33%). The percentage of starch that is not amylose is amylopectin. According to Juliano (1979), non-waxy rice has a visually transparent endosperm because of pores present between and within the starch granule. Waxy rice has a more compact starch structure and is visually opaque.

The bran layer contains the most dietary fiber in the rice kernel as well as a low density and concentrated amount of B vitamins. The location of specific vitamins affects the finished content of milled rice. About 95% of the total tocopherols and nearly one-third of the oil content are located in the embryo (Gopala Krishna, Prabhakar & Sen, 1984), which remains in milled rice. Locational gradient is also the cause of large reductions during processing because the composition of the bran layer compared to the endosperm layer will be almost all removed when milling to a white rice outcome. According to Juliano (1993):

> "65% of the thiamine of brown rice is in the bran, 13% in the polish and 22% in the milled rice fraction." [Riboflavin is calculated to have] "39% in bran, 8 % in polish, and 53% of the milled rice fraction. Niacin distribution is 54% in the bran, 13% in the polish, and 33% in the milled rice fraction." (p. 39).

Minerals (ash) such as phytin phosphorous, potassium, and magnesium, are also primarily concentrated in the bran layer. Therefore, removal of the bran layer during milling without pre-processing conditions will cause the reduction of the vitamins and minerals in the milled rice product. Resurreccion, Juliano, and Tanaka (1979) observed an ash distribution in brown rice around 51% in bran, 10% in germ, 10% in the polish, and 28% in the milled rice fraction. More evenly distributed minerals that are better retained in milled rice include 63% of sodium, 74% of calcium, and 83% of the Kjeldahl N content (Juliano, 1993).

According to Juliano (1993), milled rice protein is primarily composed of 15% albumin (water soluble) and globulin (salt soluble), 5 to 8% prolamin (alcohol soluble) and the rest glutelin (alkali soluble). Rice protein also contains one of the highest levels of lysine at 3.5 to

4.0% of the total rice protein content. Rice bran has greater quantities of albumin than endosperm proteins and can be identified in "distinct protein bodies containing globoids in the aleurone layer and the germ." (Juliano, 1993, p. 44). Endosperm protein is primarily in protein bodies, such as "crystalline (PB-II) protein bodies rich in glutelin and large spherical protein bodies (PB-I) rich in prolamin." (Juliano, 1993, p. 44-45).

The fat content of rice is primarily located in the bran layer (about 20%, dry basis), "specifically as lipid bodies or spherosomes in the aleurone layer and bran." (Juliano, 1993, p. 45). Only about 1.5 to 1.7% is in milled rice, mainly as non-starch lipids. Major fatty acids of lipids are linoleic, oleic, and palmitic acids (Hemavathy & Prabhaker, 1987). According to Jaiswal (1983), linoleic acid and linolenic acid are the essential fatty acids in rice oil (29-42% and 0.8-1.0%, respectively).

The endosperm or milled rice cell wall has low lignin but high pectin content, which has a higher uronic acid content than other grain tissues. Water soluble polysaccharides and insoluble dietary fiber can be found in rice grains primarily in the bran layer and have the capability to complex with starch. Normand, Ory and Mod (1981) suggest that this could have a hypocholesterolaemic effect. High-amylose starch, which can be found in some raw rice cultivars, can be classified as a resistant start type 2, which results in resistance to digestion because of the nature of the starch granule (Slavin, 2013). Resistant starch type 3 is a result of cooking and cooling starch, which causes retrogradation of amylose and amylopectin (Slavin, 2013) and can be developed through rice processing, or end-product cooking and cooling before consumer consumption. According to Maier et al (2017):

> [Resistant starch is a] "complex carbohydrate and prebiotic that is relatively resistant to degradation in the small intestine by α-amylase, a starch degradation enzyme produced

> by the host. The degree of resistance to degradation is largely dependent on the proportion of amylose to amylopectin that the starch molecule contains." (p. 2).

This effect allows fermentation by the gut microflora and can generate compounds (like butyrate) that are linked to positive gut health benefits.

Nutritional Quality and Glycemic Index

According to Arvidsson-Lenner et al (2004), glycemic index (GI) is the:

> "difference in blood glucose response after ingestion of the same amount of carbohydrates from different foods, and possible implications of these differences for health, performance and well-being. GI is defined as the incremental blood glucose area (0-2 h) following ingestion of 50g of available carbohydrates in the test product as a percentage of the corresponding area following an equivalent amount of carbohydrate from a reference point." (p. 85).

The implications of a high GI is typically associated with high insulin response.

The authors Miller, Pang, and Bamall (1992) organized a study in Australia to evaluate the glycemic index and insulin-index for 12 rice products using 8 healthy test subjects with normal glucose tolerance and ranging in age from 19 to 36 with BMIs between 18 and 25. Volunteers were given 50g of each sample and consumed within a timed period (12 min) with a set accompaniment of tea and milk. Samples were given 1 week apart to ensure no overlap and blood samples were collected in intervals after the meal began (0, 15, 30, 60, 90, and 120 min). GI and insulin index were calculated using 50-g portion of white bread as control, which is 70 when compared to a reference of pure glucose = 100. The mean of the 8 subjects were used in a two-way analysis of variance and Bonferroni adjustment of the Student's *t* test. Linear regression analysis was used to test for an association between glycemic and insulin responses. Typical GI of white rice can range from 54 to 121 when compared to bread (GI = 70). It is suggested that the range of GI observed in rice varieties comes from the proportion of starch in the form of amylose to amylopectin ratio. Rice with higher proportions of amylose (28%, Doongara cultivar) resulted in slower rate of digestion than rice with a standard amylose content (20%, Calrose and Pelde).

This led to Doongara cultivar having a statistically ($P < 0.01$) lower GI (64 ± 9 SE) and insulin responses (40 ± 10 SE) than Calrose and Pelde cultivars with GI at 83 ± 13 and insulin response at 67 ± 15, and GI at 93 ± 11 and insulin response at 67 ± 11, respectively (Table 3). Waxy rice (about 0-2% amylose), parboiled rice, quick-cooking brown rice, puffed rice cakes, rice pasta, and rice bran samples did not appear to statistically change the GI reaction compared to white rice cultivars. The study on healthy subjects was limited to only a few people and so larger studies are needed for validation. Rice bran was noted to have very low GI (around 19 ± 3) and insulin response (23 ± 4), which could be linked to its composition. The author concluded that only one of the rice varieties tested could be useful in low GI-diets (the Doongara high-amylose cultivar). Additionally, the rice bran could also be used as supplements in diabetic diets. However, one observation the author made was that the GI was correlated, but not directly connected to the insulin index values. The observation was that the insulin index values were usually lower than GI. The implications of the difference in GI and insulin index could be that the insulin response might be less impactful than indicated by a high GI value. Diets requiring a lower insulin response may be able to use rice varieties, despite the high GI values.

Rice Products

While rice processing primarily focuses on intact milled rice kernels as the end product, rice processing can generate many by-products (Rice Association, 2018). Rice bran is generated during milling when removing the outer bran layer and a rich source of vitamin B6, iron, phosphorus, magnesium, potassium, nicacin, thiamin, and fiber. According to Prakash (1996):

> "full-fat rice bran and defatted rice bran have been used incorporated into many bakery products, such as multigrain breads, doughnuts, pancakes, waffle mixes, muffins, specialty breads, and cookies, in breakfast cereals, and in deep-fried preparations. Deffated rice bran has been used in a wide variety of other products such as protein supplements, binder ingredient for meat and sausage products, and raw material for the production of hydrolyzed vegetable proteins. The commercial application of rice bran cereal, granola bar, and fruit and fiber bars." (p. 547).

Rice bran oil is extracted and filtered from the bran removed during milling and used as a cooking oil. Rice flour is produced from grinding white or brown rice, and is a gluten-free source of bakery flour (Rice Association, 2018).

Rice hulls are the inedible outer layer of the rice and removed by dehulling brown rice. The hulls can be used in non-food products, such as packaging material, fuel in power plants, or mulch. Rice starch is derived from the rice kernel endosperm and can be used as a thickener in food. Ash from hulls is primarily turned into cellulose products like rayon or rice fuel and can be used to clean discolored teeth. Broken rice are rice kernels that are less than ¾ of the full kernel generated during processing and can be used in a variety of food products, such as rice flour and pet food. Brewers rice is an ingredient used in brewing, beer in particular, where it is considered a premium ingredient. Brewers rice can also be used for dairy feed or in pet food when rice kernel quality expectation is not as stringent.

Rice can also be further processed into other products. One example is a puffed rice product, used in food items like breakfast cereal and rice snack cakes. Rice can be puffed through multiple methods, including hot sand puffing, canon gun puffing, and machine puffing (Ashwini, Robinson, Madhu, & Syed, 2016). These methods all balance high temperature and high pressure (typically applied by pressurized steam). A key characteristic of the starting rice material is internal moisture content (typically 13-14% as a market standard (Basavaraj, 2015)), which contributes to the rapid expansion of the rice structure that forms the airy, crunchy result. Another example of further processed products is rice syrup, which is considered a natural, clean label sweetener made from brown rice (Malt Products Corporation, 2019). There are different degrees of sweetness in the form of different dextrose equivalent options (30DE, 42DE, 60DE). Brown rice syrup is recommended by producers (Malt Products Corporation, 2019) as good as a binder for inclusions in products such as cereal bars and nutrition bars. The syrup is high in maltose and low in glucose (65–85% maltose, 10–15% maltotriose, 5–20% dextrins and only 2–3% glucose), which affects the sweetness level (Shaw & Sheu, 1992). Rice powders are also available in the same dextrose equivalent options as an alternative sweetener option.

The rice snack market is a growing business utilizing various forms of rice. The global market is expecting a 9% compound annual growth rate between 2018-2022 (Technavio, 2018). The market demand for rice-based snacks is partially driven by the growing demand for healthier snack foods. Additionally, the behavior of consumers has been migrating from three main meals a day to more snacking occasions, which drive the need for healthier and more variety in snack options. This desire for snacks using rice is also applicable to the gluten-free market, which has developed into a market with potential for some consumer bases. According to Zion Market Research (2018), the global gluten free market is around USD 4.72 billion in 2017 and predictions for this market have been set at USD 7.60 billion by 2024. While the reasons to pursue gluten-free foods vary from diets to “better-for-you” beliefs to allergies, the market for this type of product is growing and will require ingredients that can be used to meet the consumer demand.

Rice Processing Overview

Rice is a cereal grain primarily marketed and consumed as intact kernels in the U.S. (USDA, 2009). Prior to harvest and during post-harvest operations, rapid increases or decreases in moisture content (MC) can cause an imbalance of intra-kernel stress in the endosperm. Failure of kernels to adjust to these stresses can result in the formation of hairline cracks called fissures (Siebenmorgen, Nehus, & Archer, 1998). Fissures resulting from rapid increases in MC can occur in all stages of rice harvest to final production, including in the field, during harvesting, and during the drying stages of processing, such as before a column or deep bed dryer. (Chau & Kunze, 1982). Fissures from rapid decreases in MC can occur during high-temperature drying conditions without tempering, post-drying tempering, and rapid cooling immediately after drying (Schluterman & Siebenmorgen, 2007).

Fissured kernels generally break apart during the milling process, significantly decreasing head rice yield (HRY) (Sun & Siebenmorgen, 1993). Milling yield consists of the total milled rice, including broken and whole kernels, produced during the milling of rough rice to a well-milled degree (USDA, 2009). Head rice is comprised of milled kernels that are at least three-fourths the length of the original brown kernel (USDA, 2009a). Broken kernels are worth approximately 60% or less than head rice (Siebenmorgen, Bautista, & Counce, 2007). This significant price difference emphasizes an economic advantage to increasing HRY. Parboiling is one process employed by the industry to “fuse” endosperm fissures in rice kernels, thus increasing the number of kernels that can withstand the abrasive milling process and decreasing the number of broken kernels. Parboiling is also used to increase storage life, prevent nutritive loss during milling, and salvage damaged paddy. Parboiled rice is usually sold at a premium price. This pricing can be partially contributed to the cost of extra processing that occurs compared to brown or white rice, but the recovery of head rice and other advantages serve to off-set some of these costs.

Table 3. National Weekly Rice Summary March 2019

LR_GR410
Little Rock, AR   Mon Mar 25, 2019   USDA Market News Service

National Weekly Rice Summary
(Arkansas-Louisiana-Texas-California)

Domestic Trend

In the south, long and medium grain milled rice prices steady. Parboiled prices steady. Second heads and Brewers prices steady. Rice by-products: Rice Bran, Millfeed and Rice Hulls steady.

In California, medium grain milled rice prices steady. Second heads and Brewers steady. Rice by-products: Rice Bran and Rice hulls steady.

CME Rough Rice settlements for Monday 25th, May 19 closed .045 lower at 11.165; Jly 19 closed .02 lower at 11.30. US dollar index settled at 96.54.

	Arkansas	Texas	Louisiana	California
MILLED RICE				
Long white	23.50-25.00	24.50-26.75	22.50	-----
Long brown	25.50-25.75	28.75	NA	-----
Medium white	30.00-31.50	-----	31.50	37.00-39.00
Medium brown	NA	-----	NA	37.00-39.00
Short white	-----	-----	-----	NA
Parboiled	26.00	32.50	-----	-----
Second heads	18.00-19.00	13.50-15.00	17.00	18.00-19.00
Brewers	14.00-17.50	12.25-13.00	15.00	16.00-17.00

Domestic shipment: Offers, fob mills, milled rice, spot prices, dollars per cwt, bagged. (All milled rice grade No 2 not to exceed 4 percent broken, except California grade No 1. All second heads grade No 4 or better, second head and brewers are bulk.)

Rice by-products (spot prices, dollars per short ton, fob mills).

Rice fat bran	90.00-120.00	110.00-130.00	120.00-145.00	145.00-150.00
Rice millfeed	40.00	40.00-45.00	40.00	-----
Rice hulls	10.00	5.00	5.00	0.00-5.00

*NA = not available

Source: USDA Market News Service, Little Rock, AR
James M. Ward, (501)823-1711 JamesM.Ward@usda.gov
www.ams.usda.gov/mnreports/LR_GR410.txt
www.ams.usda.gov/lsmarketnews

Adapted from https://www.ams.usda.gov/mnreports/lr_gr410.txt. Copyright 2019 by USDA Market News.

As seen in Table 3 from the USDA Market News Service (2019), the price of long-grain milled white rice from Arkansas in March was $23.50-$25.00, long-grain brown rice was $25.50-$25.75, and parboiled rice was $26.00 per short ton. From Texas in the same month, long-grain milled white rice was $24.50-26.75, brown rice was $28.75, and parboiled rice was $32.50 per short ton. Rice is a commodity-based supply, which means variability in crop growth, crop supply, and consumer demand will influence the final costs monthly, if not weekly. Parboiled is still of more economic value compared to other forms of rice, however the extent of that value varies depending on location and the state of the market at the time.

Parboiling Overview

Parboiling is a traditional method of processing rice that has been around for a long time in countries such as India, Pakistan, Bangladesh, and Nigeria, but has also spread into many countries in Europe, North and South America (Bhattacharya, 2011). While improvements to the process have been explored to address improvements in technology and changes to rice cultivars, the basic principles of parboiling have remained primarily consistent with past research.

The parboiling process is generally applied to rough rice prior to hulling, although there have been a few cases of brown rice parboiling. The process consists of three steps: soaking, steaming, and drying (*Figure 2)*. According to Luh and Mickus (1991), the primary processing objectives of parboiling include increasing HRY, forcing bran layer nutrients into the endosperm to prevent loss during milling, and salvaging quality product from wet or damaged paddy.

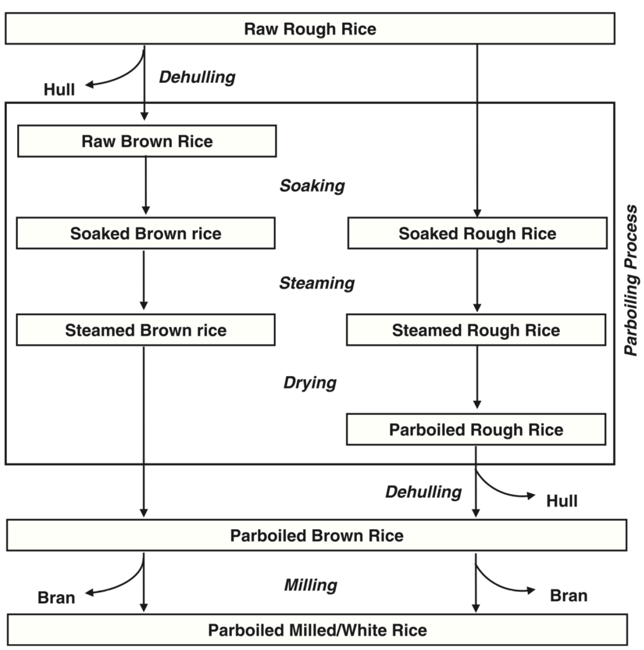

Figure 2. Steps to convert raw rough rice to milled parboiled rice.
Adapted from *Principles of Cereal Science and Technology* (3rd ed., p.137), by V. Derycke and L. Lamberts, 2010, St. Paul, MN: AACC. Copyright 2010 by AACC International Inc.

In the rice industry, parboiled rice is primarily found in applications like instant rice, frozen entrees, canned goods, and ready-to-eat meals because of its heat stability and retained nutrients. Parboiling is also used to extend the storage life of rice through resistance to spoilage from insect and mold infestation (Bhattacharya, 1966).

About 90% of the world's parboiled rice is produced and consumed in South Asia where it is a staple food (Bhattacharya, 2004). The United States produced approximately 1% of the parboiled rice worldwide in 2004, while Asia produced approximately 62% of the parboiled rice in that same year (Bhattacharya, 2004). According to the same study, parboiling is applied to about 20% of the rice produced worldwide. According to a market research company called IMARC, between 2010 and 2017, global consumption of parboiled rice increased compound annual growth rate by 1.8% (IMARC, 2018).

Soaking

The first step of parboiling is soaking. The purpose of the soaking step is to promote rapid and uniform water absorption (Wimberly, 1983). Rice kernels are soaked in water to increase moisture content (MC) (Miah et al, 2002) to approximately 30% (Bhattacharya, 1985). Soaking is advantageous in several ways, including the limitation of respiration, fermentation, and microbial growth (Wimberly, 1983). The soaking temperature is typically set within a few degrees below the gelatinization temperature of rice starch to ensure that the gelatinization process occurs during steaming. Rice starch gelatinization temperatures are typically between 55 and 79ºC (IRRI, 1979); however, the exact starch gelatinization temperature can vary between rice cultivars (Juliano, B.O. et al, 1964) and harvest years due to environmental factors such as weather patterns and growing locations (IRRI, 1979). These inconsistencies emphasize the importance of determining physiochemical properties of cultivars prior to processing. Bhattacharya and Rao (1966a) observed that soaking multiple cultivars of paddy rice (Bangara Sana, Ratna Chudi, S-139, Mysore Kaddi) at lower temperatures (50ºC and 60ºC) resulted in slow water absorption and an eventual equilibrium at 29% MC. At 75ºC and 80ºC (for Ratna Chudi as low as 65ºC), the rate of moisture absorption sharply increased after an initial slower phase and decreased the soaking time by several hours (up to 6 hours soaking duration reduction when increasing 50ºC soaking temperature to 75ºC). The exact temperature of optimal soaking duration and temperature was dependent on starch gelatinization temperatures of the particular cultivar. However, the author also observed that using soaking temperatures greater than the starch gelatinization temperature (80ºC for some cultivars) resulted in undesirable quality characteristics, such as hull splitting, starch leaching, and endosperm deformity. The caution is that soaking optimization is dependent on the rice composition and while soaking duration can be optimized, assumptions should be limited that similar rice cultivars will process the same way.

Steaming

The second parboiling step is steaming. Steaming temperatures (typically 100ºC) cause starch to gelatinize, which is a conversion of granular crystals to a melted amorphous form (Hua et al, 1990). The amorphous starch fills fissures in the endosperm and seals them when cooled (Kaddus Miah, Haque, & Paul, 2002). This process results in stronger kernels that generally remain intact during the rigors of milling, thereby increasing HRYs. The steaming process also inhibits enzymes and improves storage characteristics, kernel firmness, and eating quality (Bhattacharya & Rao, 1996a). Exact durations can vary depending on rice cultivars and prior processing parameters like soaking, but a standard duration is about 10 min at atmospheric pressure (Bhattacharya & Swamy, 1967).

Drying

The third and final parboiling step is drying. The moisture content of rice after soaking and steaming is usually between 30 and 40% (Kaddus Luh & Mickus, 1991; Wimberly, 1983). The drying step of the parboiling process reduces MC to 12-14% for storage and milling. Sun-drying in the shade outdoors with active stirring is a traditional method to dry the wet rice that can be a multiple day process (Bhattacharya, 1966a). In industrial settings, the parboiled rice is dried in temperature-controlled environments with regulated airflow and relative humidity to prevent fissuring caused by extreme loss of moisture in a short period of time (Luh & Mickus, 1991). Exact drying temperature can vary based on prior processing conditions and rice cultivars used in the process, but Bhattacharya and Swamy (1967) observed that drying the rice up to 80ºC until the rice was 15- 19%, and then tempering the parboiled rice for up to 2 hours in lesser temperatures (40ºC), or up to 8 hours in ambient temperature, improved the moisture gradient distribution throughout the kernel and aided the finished head rice quantity yields by preventing fissuring. After the tempering process, the rice would continue to dry to the target 12-14% moisture prior to milling. Relative humidity is also dependent on rice cultivar and drying temperatures, but there are rice equilibrium moisture charts available that can recommend relative humidity conditions based on drying temperature to reach the target kernel moisture content. In the case of up to 80ºC, relative humidity should range between 55 – 65% to achieve optimal finished moisture (Sadaka & Bautista, 2014).

Parboiled Rice Physiochemical Properties

There has been limited research published on rice cultivar properties that affect the parboiling process. One factor that influences the parboiling characteristics of rice cultivars is the amylose-to-amylopectin ratio. Parnsakhorn and Noomhorm (2008) focused on the effect a range of parboiling conditions (70ºC and 80ºC soaking for 1, 2, 3, and 4h; 100ºC steaming at 14.698 lb/in^2 for 10, 20, and 30 min) had on brown rice cultivars (KDML 105, Supanburi 1 and Chainat 1) with low and high-amylose contents (19.30%, 35.10%, and 37.2% respectively).

Table 4. Moisture content after steaming at various soaking conditions with three varieties (Chainat 1, Supanburi 1 and KDML 105)

Soaking conditions		Moisture content (% w.b.)								
Initial		Chainat 1			Supanpuri 1			KDML 105		
temperature	Time	Steaming time (min)			Steaming time (min)			Steaming time (min)		
(°C)	(hours)	10	15	20	10	15	20	10	15	20
70	1	33.96	34.91	35.78	34.02	34.62	35.67	37.70	38.33	38.72
	2	34.16	34.58	35.71	36.65	36.79	37.76	39.43	38.97	39.24
	3	36.52	37.21	37.64	36.96	37.23	38.30	39.85	39.54	40.08
	4	37.18	38.08	38.92	37.12	38.84	40.50	40.42	40.17	41.88
80	1	36.52	36.58	36.47	35.92	36.12	37.18	42.56	43.56	43.85
	2	37.28	37.80	37.89	37.59	38.00	38.26	46.25	47.49	48.99
	3	38.59	38.78	39.51	39.22	39.45	40.47	48.41	49.98	50.88
	4	39.55	40.06	40.34	40.64	41.27	41.73	51.16	51.47	52.24

Adapted from *"Changes in Physicochemical Properties of Parboiled Brown Rice During Heat Treatment"* by Parnsakhorn, S. & Noomhorm, A. 2008, *Ag Eng Int*, *X* (Manuscript FP08 009), 6. Copyright 2008 by CIGR.

Rice with low-amylose content absorbed more water in shorter durations than the high-amylose cultivars, as observed in Table 4. Under similar parboiling conditions, the lower amylose cultivar

(KDML 105) had greater moisture content than the other higher amylose cultivars (Chainat I and Supanpuri I). High-amylose cultivars absorbed water rapidly during initial stages, but subsequently exhibited a consistent and slower water absorption rate. Deformed kernel development was observed in KDML 105 when moisture content reached greater than 40%, but did not develop in the high-amylose cultivars at all. Chainat I had a significant ($p < 0.05$) increase in HRY 66% to 71% when soaked at 80ºC for increasing durations (1-4h); however, there was a slight decrease in HRY for Supanpuri I at similar conditions. Alternately, Supanpuri I had a directional increase of HRY from 64% to 71% when soaked at 70ºC for increasing time (1-4h), but Chainat I had varying HRY outcomes. Both cultivars had similar amylose content levels, so the specific cultivar does change the outcome of the HRY despite a key characteristic similarity. Soaking the low-amylose cultivar (KDML 105) at the greater temperature (80ºC instead of 70ºC) and steaming at the longer duration (20 min) decreased HRY as opposed to a gentler set of conditions (70ºC soaking for 1-2h and 10-15 min of steaming). The lowest HRY (54%) observed from KDML 105 was from soaking at 80ºC for 4h and steaming for 20 min, which lined up to the greatest moisture content of all samples (Table 6). The target moisture out of parboiling is 30%, so the kernels were extremely saturated in the most extreme conditions of the study. The high-amylose content cultivars had an increasing hardness overall as soaking duration increased (Chainat I cultivar 39.61 to 47.96 N after soaking at 70ºC for 1h and steaming for 10 min to soaking at 70ºC for 4h and steaming for 20 min). Hardness of high-amylose cultivar also increased when using similar conditions, but a greater initial soaking temperature, specifically 70ºC to 80ºC (39.61 to 42.15 N soaking for 1 h and steaming for 100ºC for 10 min). The low-amylose cultivar had slight increase in hardness at the lower soaking temperature (16.73 to 17.15 N at 70ºC for 1h to 4h, steaming 100ºC for 10 min), but decreasing hardness when soaking at the higher temperature (18.21 to 18.17 N at 80ºC for 1h to 4h, steaming 100ºC for 10 min to 10 min). The lowest hardness values were observed in the low-amylose content cultivar at the most extreme conditions (14.13 N at 80ºC soaking for 4 h, 100ºC for 20 min). The hardness reflects how well the kernels stay intact during milling and the resulting HRYs that drive profitability of final product. The color of all three cultivars were affected in similar patterns based on the parboiling conditions. The longer the soaking time at a single temperature (1-4h) and the higher the soaking temperature (70ºC to 80ºC), the greater the b-value, which is the yellow color measurement used in the rice industry from HunterLab. The b-values ranged from 9.23 – 11.33. The lower the b-value, the less yellow in appearance the kernels are and the more desirable the rice is to consumers from a visual expectation perspective. The whiteness of the kernel is also linked to quality of the final kernel and whiter kernels are more desirable. All three cultivars were affected under similar conditions to have lower whiteness values when soaking for longer durations, at higher temperatures, and longer steaming durations. The gentlest parboiling conditions (70ºC for 1h soaking, 100ºC for 10 min steaming) to harshest parboiling conditions (80ºC for 4h soaking, 100ºC for 20 min steaming) reflected this outcome in Chainat I (43.63 to 41.9 N), Supanpuri I (40.6 to 36.40 N), and KDML 105 (38.00 to 32.40%). Bhattacharya and Rao (1966b) suggested the color change that occurs during soaking is primarily because of the Maillard reaction, bran sticking to the endosperm, and possibly husk pigment coloring the endosperm. The color of the process rice kernels is important to consumer acceptance, but should also be balanced with the profitability of processing the rice (HRY and hardness) when selecting optimal parboiling conditions.

Protein, thiamin (or B1 vitamin), and lipids are other components that are affected during the parboiling process. Padua and Juliano (1974) explored the effect of parboiling on the protein, thiamin and lipid content of two types of Ceylonese varieties (H-4 & BG11-11) and three commercial U.S. varieties (Belle Patna, Dawn, and Starbonnet). Data was also collected from raw and rough rice of IR20 and IRRI line dried by IRRI engineers. Additional rough rice data was collected from IR20 and IR22 from the IRRI farm that was soaked for 6 h at 60ºC, steamed for 20 min at 100ºC or 10 min at 121ºC and air-dried.

Table 5. Effect of parboiling method on nutrient content and distribution in brown rice[a]

Treatment	Degree of milling (%)	Thiamin (μg/g) Brown rice	Thiamin (μg/g) Milled rice	Protein (%) Milled rice	Protein (%) Bran-polish	Bran-polish fat (%)
I. Modified traditional method (hot soak) (H-4 and BG11-11)						
Raw (check)	11.0	3.18	0.45	8.3	13.1	15.2
Treated	10.6	2.49	1.90	7.8	14.5	17.6
II. Conversion (Belle Patna, Dawn and Starbonnet)						
Raw (check)	12.2	3.91	0.54	6.6	14.0	18.1
Treated	12.6	2.78	2.10	6.2	15.3	22.4
III. Laboratory method (hot soak) (IR20 and IR22)						
Raw (check)	11.6	3.80	0.58	9.0	13.4	16.6
Treated 100 °C	11.1	3.60	0.95	8.7	13.6	17.4
Treated 121 °C	12.0	3.17	2.94	8.6	15.0	19.8
IV. Heated sand drying (IR20 and IRRI line)						
Raw (check)	10.5	3.72	0.56	8.2	13.6	16.8
Treated	10.2	3.61	1.80	7.8	13.8	18.4
S.E.M.	0.24	0.107	0.152	0.25	0.15	0.75
L.S.D. (5%)	0.85	0.388	0.551	0.92	0.55	2.73

[a] All at 14% moisture.

Adapted from "Effect of Parboiling on Thiamin, Protein, and Fat of Rice" by Padua, A.B., & Juliano, B.O. 1974. *J Sci Food Agr, 25*(6), 669. Copyright 1974 by John Wiley & Sons, Ltd.

As reflected in Table 5, thiamin content was less in parboiled brown rice compared to untreated brown rice (for example, H-4 and BG11 cultivars had 3.18 micrograms per gram of thiamin when untreated, but only 2.49 micrograms per gram of thiamin when parboiled). However, milling the brown rice to similar degrees of bran removal resulted in more thiamin retained in the parboiled rice than the untreated rice. Therefore, the migration of thiamin (a water-soluble vitamin) during parboiling might have resulted in some loss initially into the soaking water or degradation from the heat treatment, but overall more thiamin was retained in the endosperm and not removed during milling compared to milled white rice. Bran polish on parboiled rice was observed to have greater protein content and fat content than raw rice bran. The severity of the parboiling steaming condition appeared to continue directionally increasing the bran and protein % (IR20 and IR22 had 13.4% protein and 16.6% fat in the bran polish of raw rice, 13.6% protein and 17.4% fat in bran polish after 100ºC steam treatment, and 15.0% protein and 19.8% fat in bran polish after 121ºC steam treatment). Conversely, the milled rice with a similar degree of milling had directionally less protein and fat when parboiled compared to raw rice, which implies the protein and bran in the polish does not migrate into the endosperm during parboiling. Degree of milling describes the extent that bran is removed from the caryopsis layer during the milling the process (Graves, Siebenmorgen, & Saleh, 2009). Padua and Juliano (1974) suggested that protein had high molecular weights that prevented diffusion through the cell membrane during parboiling as evidenced by a starch-composed endosperm and rice protein located in the bran layer of parboiled rice kernels. Oil is not water-soluble and, therefore, did not migrate through the endosperm as the water-soluble vitamin did. Parboiled rice had directionally greater amounts of lipids in parboiled rice bran polish compared to raw rice (15.2% raw to 17.6% parboiled in H-4 and BG11-11, 18.1% raw to 22.1% parboiled in Belle Patna, Dawn, and Starbonnet, 16.6% raw IR20 and IR22 to 17.4% parboiled with 100ºC steam to 19.8% parboiled with 121ºC steam, and 16.8% raw to 18.4% parboiled in IR20 and IRRI line). The authors explained that the increased fat % in the bran polish was because parboiling hardens the endosperm kernel and resulted in a more effective removal of the bran layer during milling. The efficient removal of bran would result in more of the lipid, primarily located in the bran layer, to be removed and end up in the bran polish.

Other properties affected by parboiling include: ash content, gelatinization, and cooking properties. Author Damir (1985) observed that there was a slight increase in ash content of parboiled rice (0.49%) compared to milled, raw rice (0.39%). Water-soluble minerals spreading through the endosperm during the soaking and steaming steps of parboiling could have caused the ash to increase. It was also observed that the duration and temperature required to reach starch gelatinization were greater for parboiled rice compared to milled, raw rice. The differences in gelatinization properties were suggested by Damir (1985) to be from the limited swelling ability of starch granules in parboiled rice. The study also revealed that parboiled rice required a longer cooking duration to reach the equivalent softness as that of milled, raw rice. When overcooking samples, milled raw rice kernels became soggy and burst, while the parboiled rice kernels retained a distinctive shape after the same duration, associated with the harder kernels that result from gelatinized rice and retrogradation of the starch. A visual difference that occurred during parboiling as a result of lower water absorption and more swelling limitations was a shorter and wider kernel appearance of parboiled rice compared to raw-milled rice kernels. This is expected by consumers who are familiar with the product.

Rice Composition Measurement Methods

Color

Rice color is often quantified using a colorimeter. A colorimeter is used to determine the color of parboiled rice products (Bhattacharya, 1966). A white color tile is used to standardize the equipment. The white tile is centered over the sample port to establish a standard. Two readings are taken. If the two readings are within 0.4 units, the standard is considered established. Approximately 30 g of rice is poured into a petri dish and centered over the sample port. A black cover is placed over the petri dish to prevent variability due to outside light sources. Using the computer program, the first color reading is initiated. The sample is manually rotated 120-180 degrees and then the second color reading is initiated. If the sample readings are similar to each other, the data is accepted and an average of the two color readings is saved onto a spreadsheet. Essentially, light is applied to a rice sample and the resulting reflected light is passed through standardized red, green, and blue filters. A photodetector measures the amount of light passing through the filters and produces color values. A lightness value is also measured based on the intensity of lightness reflected off the sample (HunterLab, 2001). The lightness (L^*) and yellowness (b^*) of parboiled head rice using HunterLab (2011) is typically considered the relevant data to finished rice quality.

Chalk

Chalk can be measured in duplicate using a procedure from a previous study (Ambardekar et al, 2011). One hundred kernels of brown rice are counted manually and placed on a tray (152 mm x 100 mm x 20 mm) made from a 32 mm-thick, clear acrylic sheet. The kernels are spread apart, so that each kernel had space between every other kernel. Before measuring the sample, the imaging system is configured to color-classify chalk by selecting and scanning a brown rice kernel considered to be completely chalk. A digital image of kernels are created by placing the tray on the scanner of an image analysis system (such as a WinSeedle Pro 2005a™, Regent Instruments, Inc., Sainte-Foy, Quebec, Canada). The imaging system measures and records the number of pixels corresponding to those areas color-classified for chalk on a kernel. Percent chalk in a sample is determined as the ratio of the total chalky area (pixels) of the 100-kernel set to the total area of the kernels, multiplied by 100.

Surface Lipid Content and Total Lipid Content

Surface lipid content and total lipid content is measured using a standard AACC Soxtec method (AACC, 2000) modified by Matsler and Siebenmorgen (2005) and a standard lipid extraction system (typically a Soxtec instrument). Five g of brown rice kernels are weighed into a tared thimble and recorded as W_1. Clean, defatted cotton is placed on top of the thimble to prevent boiling out. Samples are dried at 103 ± 2°C for 1 h in a convection oven and cooled for approximately 10 min in a desiccator. Three to four glass boiling beads are placed in each extraction cup and weighed. The measurement is recorded as W_2. The thimbles are magnetically attached to the base of the Soxtec extraction units and 70 mL of petroleum ether is added to each extraction chamber. The Soxtec procedure is initiated. In phase one, the samples are boiled at 135°C for 20 min. In phase two, the samples are rinsed for 30 min and in phase three, the solvent is recovered for five min. After the procedure is complete and a five min allowance is given for evaporation, the cups are heated in a convection oven at 103 ± 2°C for 30 min and cooled in a desiccator for 30 min. The weight of the cup and sample are recorded as W_3 and the total % lipid content is calculated:

$$\% \text{ Lipid content} = [(W_3 - W_2)/W_1] \times 100$$

Total lipid content follows the same procedure using ground brown rice samples instead of brown rice kernels.

Amylose Content

Brown rice is milled for a set period of time using a weight to ensure even application of abrasion, and then the rice is aspirated for a set period of time. Head rice is separated from broken kernels manually and ground in a laboratory mill containing a desired screen.

Amylose content is determined using the Fitzgerald et al (2009) method. One hundred mg of milled rice flour is poured into a 100 mL volumetric flask and 1 mL of ethanol is added. Nine mL of 1 M sodium hydroxide solution is added to the flask and the sample is dissolved into a homogenous solution by gentle swirling. The sample is left to stand at room temperature for 24 ± 2 h. The solution is brought to 100 mL with de-ionized water and mixed by inverting the covered flask ten times. One-half mL is pipetted from each flask and distributed into two test tubes. Five mL of deionized water, 0.1 mL acetic acid, 0.2 mL iodine solution, and 4.2 mL deionized water are added to each test tube. A vortex is used to mix the solution for 10 s. Absorbance is measured at 720 nm using a spectrophotometer. The amylose content is determined using a potato starch standard curve and expressed as a dry basis percentage. Amylose content is measured in two replications.

Protein Content

Ground brown rice samples are used to determine protein content, which can be analyzed using the Kjeldahl method or standard combustion method. The authors Marco, Rubio, & Compaño, (2002) used the Kjeldahl method in the following way:

> “According to the N content, appropriate amounts of samples (0.2–1 g) are placed in the digestion tube. Twenty milliliter of sulfuric acid and a tablet containing 0.48 g of mercury

oxide as a catalyst and 4.52 g of potassium sulfate are added. Blanks containing all these reagents are simultaneously processed. The tubes are placed in the preheated digestion block at 420 °C for 2 h 30 min. The resulting solutions are cooled at room temperature and diluted by adding 30 ml of water. The tubes are placed in the distillation–titration unit. Then, 20 ml of sodium hydroxide solution are automatically added and the solutions are distilled (6 min). The ammonia collected in the receiving solution (30 ml) is automatically titrated against the standard 0.25 M hydrochloric acid with colorimetric end point detection. Ammonium dihydrogen phosphate standard (NIST SRM 194) is used to check the concentration of the titrating solution. The distillation–titration sequence is as follows: two blanks, two replicates of the ammonium dihydrogen phosphate standard, twelve samples, two replicates of this standard and two blanks. The analysis of recovery controls is recommended." (p. 1021)

The authors Marco, Rubio, & Compaño, (2002) used the combustion method in the following way:

"Fifty milligrams of solid sample are weighed in a tin capsule and then introduced into the autosampler. A continuous helium flow of 130 ml min−1 enters the system. The analysis cycle begins with an oxygen flow of 100 ml min−1 for the first 25 s. The sample is introduced into the heated combustion reactor (900 °C) in the third second of the cycle. The reactor consists of a stainless steel tube filled, from bottom to top, as follows, 4 cm of quartz wool; 14 cm of oxidation catalyst (about 25 g) and 2 cm of quartz wool. The gaseous mixture is carried by the helium flow through the reduction reactor (700 °C) filled with copper (about 50 g). The resulting gases are then carried through the carbon dioxide and water traps, finally reaching the GC column and the thermal conductivity detector (at 60 °C). The analysis cycle is completed in 6 min. Calibration of the instrument is carried out with three amounts (3, 30 and 60 mg) of acetanilide as standard. The analysis sequence is as follows: two blanks (empty tin capsules); the three acetanilide standards; ten samples (50 mg each); the three acetanilide standards again; and two blanks." (p. 1022). (Marco, Rubio, & Compaño, 2002)

Differential Scanning Calorimetry

Differential scanning calorimetry can be performed by a differential scanning calorimeter equipped with a thermal analysis data station. Differential scanning calorimetry measures thermal and gelatinization properties (Wang, White, & Pollack, 1992). Each cultivar is measured separately. Milled head rice is ground and the moisture content (MC) of the resulting flour is measured. The flour MC (wet basis) is used to calculate 4.0 mg (dry basis) of flour for the process.

$$MC_{wb} = (100 * MC_{db})/(100 + MC_{db}) \quad [2]$$

The 4.0 ± 0.5 mg (dry basis) is weighed in an aluminum DSC pan using an analytical scale. Eight µL of deionized water is then added to the sample using a 10 µL micro-syringe. A universal crimper press is used to seal the aluminum pan with an aluminum lid. The samples in the sealed pans are hydrated overnight for the same duration of at least 24 h. On the following day, the thermal analysis data station is turned on and set to 50°C, which allowed a 30-min warm-up period for the equipment. The nitrogen gas containers attached to the DSC are opened for the procedure. To prepare for the test, two processing stages are entered into the computer program. The first stage is held at 25°C for one min. The second stage increases the temperature from 25°C to 100°C at the rate of 10°C/min. A reference aluminum pan and the sample aluminum pan are set in furnace compartments. The reference aluminum pan is empty and will eliminate any “noise” that comes from the sample pan during the heating process. This procedure is employed to limit the thermogram record to sample responses only.

The furnace compartments are locked and appropriate labeling is entered into the computer. Before initializing the program, the instrument temperature is reduced to 25°C. Once the temperature reaches 25°C, the program is initiated. Following the run completion, the sample thermogram is adjusted to a horizontal orientation and the peak is analyzed. The bell-shaped gelatinization peak is identified (usually occurring between 60 and 90°C). The upper and lower temperature limits are marked near the peak inflection points. The onset, peak, endset, and enthalpy are calculated by the computer program and displayed on the screen. After recording the data, the sample and reference pans removed from the chamber and the DSC temperature is returned to 50°C. The nitrogen gas containers are closed within 4 h. DSC results will indicate gelatinization temperatures of samples.

Cooking Properties

A standard AACC method 61-02 (AACC International, 2009) and a Rapid Visco Analyzer can be used to measure the pasting properties of the rice samples.

Modifying Traditional Parboiling Methods

Parboiling is a process that takes time and energy to condition the rice prior to milling. Improvements to optimize the parboiling process can improve profitability while balancing the quality of the finished product. Competitive advantage for improved methods and rice quality characteristics has resulted in privatized research that is funded by key processing manufacturers and retained as part of trade secrets. However, some peer-reviewed research has begun to explore possible processing improvements and rice quality outcomes that optimize processing efficiency and address key processing issues.

With the increased popularity of hybrid rice cultivars globally, it is important to understand the impact of mixing hybrid with pureline rice on finished rice products. Leethanapanich, Mauromoustakos, and Wang (2016) studied the effect of comingling pureline and hybrid rice cultivars prior to processing. The comingling can occur during "harvesting, drying, storage, and distribution," and could result in a wide range of gelatinization temperatures (typically between 55 and 79ºC (IRRI, 1979)). Basutkar, Siebenmorgen, Wang, and Patindol (2015) observed that the gelatinization temperature target for comingled rice cases was the lowest value cultivar. As discussed, gelatinization is a key outcome that is targeted by the parboiling process in order to optimize the finished rice product. Identifying the variability of gelatinization temperature based on commingling rice cultivars leads to the conclusion that if not tested prior to processing or the commingled sample composition changes during processing time as new shipments of ingredients are accepted into a production facility, the resulting parboiling process could be under optimal conditions which would result in not fully gelatinized rice, or extreme conditions that over gelatinize rice and cause defects like hull splitting, starch leaching, and kernel deformity.

Another aspect of all varieties of rice is the age at processing. Recently harvested rice behaves different compared to rice that has aged several months, typically resulting in inferior rice quality post processing compared to aged rice post processing (Bhattacharya, 2013). Parboiling manages these inferior qualities to some degree, but concern for best quality rice post-processing and uniformity that varies based on mixed rice ages are still present by processors. One counter-measure employed by some millers is the use of pre-steaming, which artificially "ages" the rice to a degree that it can be processed more uniformly to a better quality outcome. Pre-steaming involves applying steam to the rice prior to parboiling and then holding the rice in a hot-tempering environment to optimize the rice prior to soaking. The exact time to temper the rice is dependent on the variety and the age of the rice being pre-steamed, but targeted moisture content should not exceed 14% to limit texture and color defects. Pre-steaming does tend to cause a browning discoloration to develop with long application, which can be further exacerbated by the following parboiling process. The target of this method, as a result, is to pre-steam as quickly as possible while still developing the benefits. One advantage to the pre-steaming process when applied properly is a reduction in soaking time. Bhattacharya (2013) cites an observation that Pusa Basmati 1 soak duration was 10h at 60ºC for optimal processing, but the use of pre-steaming decreased the necessary soaking duration to 8h. The theorized reasoning behind this decrease in soaking duration was that the pre-steaming off-set the air trapped on the surface of the grain which could come from the hair on the hulls and the crevices in the grain, which resulted in quicker wetting and initial hydration behavior. Improving the uniformity of rice helps prevent defects developing from over- or under-processed rice and reducing the soaking duration helps manage rice quality factors, like color that develops with longer soak times and durations, and off-set the extra time needed to pre-steam the rice prior to parboiling.

One method of improving the parboiling process was to explore the application of a heat moisture treatment to paddy rice (IRGA-424 cultivar with high-amylose content of 29%) prior to parboiling (Arns, Paraginski, Bartz, Almeida Schiavon, Elias, Rosa Zavareze, & Dias, 2014). The rice was held at a consistent temperature (120°C) and pressure (1kgf cm^{-2}) for increasing durations (10 min, 30 min, 60 min) and then parboiled. Control rice was parboiled, but not held under heat-moisture treatment and hydration curves were used to determine comparable soaking temperature and duration as related to moisture content percentage of the finished rice. The gelatinization temperatures of the rice increased (56.31 to 59.14ºC initial, 63.46 to 71.82ºC peak, and 72.07 to 80.39ºC conclusion) as heat-treatment (HMT) duration increased (from 10 min to 60 min). The author theorized that heat treatment prior to parboiling shifted the starch structure into a better crystalline structure, thereby increasing the temperature required to completely change the form of the starch from crystalline to amorphous during an optimal gelatinized process. In Table 6, application of HMT prior to parboiling overall significantly decreased peak viscosity (331.58 RVU after 10 min HMT to 51.89 RVU after 60 min HMT), final viscosity (631.61 RVU after 10 min HMT to 76.30 RVU after 60 min HMT) and setback (301.72 RVU after 10 min HMT to 38.03 RVU after 60 min HMT) with longer treatment durations. The breakdown value decreased significantly upon application of HMT when compared to no heat treatment (121.53 RVU untreated to 10.34 RVU after 10 min HMT), but increasing the duration of the treatment did not result in a consistent pattern and more data is needed for conclusive results. The study author attributed the decrease in peak viscosity to the early gelatinization process that occurs during parboiling as opposed to non-parboiled rice. Setback references the retrogradation and re-alignment of starch molecules when cooling during the drying stage, which results in the gel structure of the pre-cooked rice kernels. The decreased breakdown value observed when using HMT (compared to no HMT) is linked to hardier grains that are more resistant to negative effects from mechanical and heat agitation.

Table 6. Rapid Visco Analyser curves of heat-moisture treatment grain flours and flours of parboiled grain after heat-moisture treatment at different treatment times

Parameter	Flours	Treatments			
		Native	HMT time (min)		
			10	30	60
Pasting temperature (°C)	HMT grain	71.82 ± 1.68[d]	85.02 ± 0.56[c]	90.07 ± 0.52[b]	95.20 ± 0.48[a]
	Parboiled grain	88.10 ± 0.50[b]	93.25 ± 0.40[a]	nd	nd
Peak viscosity (RVU)	HMT grain	437.06 ± 6.25[a]	331.58 ± 11.30[b]	231.36 ± 18.11[c]	51.89 ± 4.00[d]
	Parboiled grain	19.58 ± 0.10[a]	12.46 ± 0.30[b]	11.17 ± 0.10[c]	5.75 ± 0.35[d]
Breakdown (RVU)	HMT grain	121.53 ± 4.57[a]	10.34 ± 3.21[c]	35.61 ± 2.56[b]	13.61 ± 1.37[c]
	Parboiled grain	3.17 ± 0.10[a]	0.67 ± 0.12[b]	0.67 ± 0.01[b]	0.71 ± 0.06[b]
Final viscosity (RVU)	HMT grain	627.70 ± 7.48[a]	631.61 ± 8.33[a]	394.53 ± 11.94[b]	76.30 ± 5.71[c]
	Parboiled grain	25.17 ± 0.10[a]	14.46 ± 0.30[b]	12.50 ± 0.10[c]	7.09 ± 0.47[d]
Setback (RVU)	HMT grain	312.17 ± 3.52[a]	301.72 ± 3.13[b]	210.03 ± 10.57[c]	38.03 ± 3.11[d]
	Parboiled grain	8.75 ± 0.10[a]	2.67 ± 0.47[b]	2.00 ± 0.10[b]	2.04 ± 0.06[b]

nd, value not determined; RVU, rapid visco units; HMT, heat–moisture treatment.
Different letters in the same row differ statistically ($P < 0.05$). Results are the means of three determinations ± the standard deviation.

Adapted from "The effects of heat-moisture treatment of rice grains before parboiling on viscosity profile and physicochemical properties" by Arns, B., Paraginski, R., Bartz, J., Almeida Schiavon, R., Elias, M.C., Rosa Zavareze, E., & Dias, A.R.G. 2014. *Int J Food Sci Tech, 49*(8), 1942. Copyright 2014 by Institute of Food Science and Technology.

A key measure of rice processing profitability is HRY, so analysis of the impact of the HMT treatment on HRY is an important factor to consider before implementation. Head rice yield decreased as HMT treatment was applied as a pre-treatment compared to no HMT; however, there was no significant difference between the untreated rice and the HMT at 10 and 30 min durations. Significant decrease in HRY was observed in rice with HMT for 60 min (68.95%) compared to untreated (72.07%) and HMT for 10 min (72.07%). Decreases in HRY were attributed to the requirement of longer milling time to meet degree of milling targets, which applies more friction and can drive more breakage in the finished yields. Color is a delicate balance with optimized parboiling processing outcomes (like HRY) as it can drive desirability for customers. The application of HMT consistently reduced the whiteness (or L* values) and increased the yellowness (b* values) as duration increased (10 min, 30 min, 60 min). The L* values were 90.97 untreated, 89.96 HMT for 10 min, 89.07 HMT for 30 min, and 88.40 for HMT 60 min. The b* values were 8.26 untreated, 9.39 with HMT for 10 min, 10.92 with HMT for 30 min, and 12.97 with HMT for 60 min. Cooking time of the treated rice significantly ($p \leq 0.05$) increased with as the HMT duration increased (27.1 min for untreated to 47.0 min for HMT after 60 min), possibly because of the increased mobility and restructuring of the starch from the additional heat step causing decreased internal spaces and increasing the grain resistance to moisture absorption. The results of this study emphasize the importance of balancing the increased efficiency parameters against rice quality and quantity outcomes.

Processing duration is a key factor that influences the cost of parboiling rice. The application of an infrared heat treatment during soaking has been explored with the intention of removing the steaming step completely and drying the gelatinized rice after the “enhanced” soaking step (Likitrattanaporn & Noomhorm, 2011). The removal of a separate steaming step reduces the parboiling process duration overall and removes the needs for steaming equipment. The ability to remove the steaming step while attaining gelatinization through heated soaking results in lower moisture rice which can be dried faster and saves time and money during full scale production. Infrared heating is used in industry to dry surface moisture from material, which was reflected in observation that a deep bed of rice causes moisture variability. However, using vibration systems to constantly shift the bed of rice allows for more uniform application of infrared (IR) heat. To study this method of drying, Pathumthani 60 variety was used, which is a long-grain, medium amylose content (26%). Rice samples were tempered, soaked in 55ºC until moisture content reached 30% wet basis, and then tempered for 1h before processed as controls. Control samples included untreated paddy rice and paddy rice that underwent standard parboiling with steaming at 100kPa for 10 min) and dried to 11% wet basis. Soaked rice at 30% wet basis was heated by IR (2100 W positioned 150mm above rice bed and resulted in 100ºC temperature) for 3, 5, 7, 9, 11, 12, 13, 14, 15, 16, 17, 19, 21, and 23 min. Moisture removal increased when IR treatment duration increased in the study. Within 19 min, at least 50% of the initial moisture was removed. With a target of 14% MC by the end of drying, the IR heating application did show promise to shorten the duration necessary to dry the paddy rice compared to standard parboiling processing.

As seen in Table 7, optimal IR heating for HRY appeared to between 5-14 min with the results between 66-67%, which was only 1% less than rice parboiled under the standard method. However, as IR treatment duration increased, HRY started to directionally decrease, resulting in the lowest HRY of treated rice in the study with 56.90% after 23 min of IR treatment).

Table 7. Qualities evaluation, pasting properties, and thermal property of IR-heated sample with 30% initial moisture content

Treatment	MC wb% after heating	HRY (%)	Yellowness (b-value)	Peak viscosity (rvu)	Breakdown viscosity (rvu)	Final viscosity (rvu)	Enthalpy (Jg^{-1})	Gelatinization (%)
Control sample (raw rice)	12.30 ± 0.07	34.66 ± 0.33	16.38 ± 0.29	361.67 ± 16.9	48.42 ± 42.5	476.92 ± 16.67	11.69	0.00
30%, 2,100 W, 10 min	24.60 ± 0.24	68.48 ± 0.28	19.72 ± 0.07	137.58 ± 7.3	13.97 ± 2.14	145.72 ± 9.79	7.34	37.21
30%, 2,100 W, 13 min	22.00 ± 0.56	67.19 ± 0.58	22.51 ± 0.62	123.88 ± 2.54	12.58 ± 3.00	128.25 ± 2.75	5.89	49.62
30%, 2,100 W, 15 min	20.03 ± 0.62	65.05 ± 0.34	23.67 ± 0.22	111.58 ± 0.58	13.67 ± 0.83	113.08 ± 1.41	5.24	55.18
30%, 2,100 W, 18 min	17.63 ± 0.02	62.76 ± 0.18	24.46 ± 0.05	106.33 ± 2.00	11.50 ± 2.08	110.17 ± 0.91	4.79	59.02
Control sample (steam 1 bar, 10 min)	34.11 ± 0.90	69.34 ± 0.24	28.80 ± 0.34	29.08 ± 48.29	3.29 ± 3.15	39.54 ± 45.60	1.95	83.32

Adapted from "Effects of simultaneous parboiling and drying by infrared radiation heating on parboiled rice quality" by Likitrattanaporn, C. & Noomhorm, A. 2011. *Dry Technol, 29*(9), 1071. Copyright 2011 by Taylor and Francis Ltd.

Chalkiness was not observed in the treated rice, which is a quality defect and can lead to reduced milling yields. However, the lack of chalkiness was considered partially due to the 100ºC temperature maintained in the IR equipment. When the cover of the equipment was removed and the temperature was only 70ºC, the 2-10% white belly (a form of chalkiness) was observed. Additionally, the yellow color of the rice increased with increased IR treatment duration to reach similar yellow color as a standard parboiled grain (29.7 b* value). Whiteness was compared to raw rice (45.35 L* value) and IR treated rice at any duration was observed at lower values (33.33 L* value). The rice treated to IR heat between 5 and 19 min were considered statistically similar to standard parboiled rice (29.53 to 31.20) and within expectation range for parboiled rice consumers. Pasting properties, which is linked to the cooking quality of rice, was also measured. Peak viscosity, breakdown viscosity, and final viscosity all directionally decreased as IR treatment duration increased, all of which were less than untreated raw rice, but greater than standard parboiled rice. The lower viscosities were assumed to be from the higher degree of starch gelatinization, which is linked to a loss of water-binding capacity. Breakdown viscosity is the breakdown of starch once swelled to maximum with water and the resulting loss of structure. The final viscosity is a result of the gel structure formed as a result of retrogradation and can indicate stickiness of cooked rice. Parboiled rice under standard conditions is known as a firmer, less sticky kernel, so the IR heat treatment conditioned the rice closer to parboiled rice cooking qualities, but not to the same extent. When applying IR heat technology, the balance of finished rice quality needs to be evaluated in the loss of profit compared less processing cost by decreasing the duration of soaking and removing the steaming step completely (which includes time and equipment).

Another step of parboiling that can be modified for optimized processing is drying. Bootkote, Soponronnarit, and Prachayawarakorn (2016) explored the effects of fluidized bed drying and tempering using Suphanburi 1 paddy rice with high amylose content between 25 and 30%. The drying process requires a gentle reduction over time to ensure that grains do not form fissures prior to milling with imbalanced moisture migration and cause less HRY. Tempering is often used to combat the effects of rapid moisture loss by improving the balance of moisture from internal to external areas of the kernel. Fluidized bed drying is an effective method of drying grains faster because heat and mass transfer between particles and drying medium is increased compared to standard drying methods. Surface moisture is dried faster because of exposure to drying air in a fluidized bed dryer. Isothermal drying is usually slower because inner kernel moisture migrates from the inside to the outside of the kernel before evaporation. Drying conditions were evaluated based on inlet air temperature 110-170ºC, relative humidity 1.5-0.2%, air velocity 3.5m/s, 1 cm bed height, and increasing the drying duration from 0.5, 1, 2, 4, and 6 min. Lower moisture final moisture contents were observed to result in less HRY. The lower moisture in the kernel can cause a greater gradient across the kernel area from internal to external location, thereby forming stress fissures and forming more brokens during milling. A way to improve HRY and take advantage of the fluidized bed drying process was to temper the rice after drying in an enclosed environment to trap the moisture in the air that is removed from the kernel slowly, which allows time for the rice moisture gradient to decrease through balancing with atmosphere air and the internal moisture. Tempering for at least 30 min statistically (ANOVA, $p < 0.05$) improved final HRY by increasing 8-10% compared to no tempering (69-71% HRY and 62-65% HRY respectively) and higher internal moisture after drying (27% db compared to 22% db) further increased HRY by 1-1.2%. There was a tempering limit where the effects reached a plateau and did not continue to increase beneficially with an effect on HRY (30 min to 60, 90, 120 min). The drying duration and temperature using fluidized bed equipment did not affect the whiteness (25.8 – 26.2) compared to standard parboiling color expectations (26.1) primarily because of the short duration necessary for drying (2-4 min). However, the increasing tempering duration and associated higher drying temperatures did cause a decrease in whiteness, which was theorized to be from Maillard browning occurring from the longer exposure to higher temperatures. Acceptable light brown color (24.8-26.2) and dark brown (22-24) were judged as the representative ranges. Drying rice at 110-170ºC and tempered 30 min resulted in light brown rice, while 130-170ºC drying temperature and tempering for 60-90 min resulted in dark brown rice. The best conditions were judged to be using the fluidized bed drying at 150ºC and tempering for 30 min for light brown and 60 min for dark brown parboiled rice with optimal conditions. Though fluidized air bed drying appears to optimize the drying process in terms of time and efficiency, the quality of the rice in terms of color and processing properties like HRY, are important outcomes to balance against processing advantages.

Conclusion

Parboiling rice is a traditional process that primarily improves head rice yields for millers, among other advantages, but there is also innovation in equipment and processing capabilities that can optimize the time and efficiency of these steps. Current research seeks to understand the physiochemical properties and cultivar characteristics that can affect rice processing properties and qualities post-parboiling. This understanding will lead to solutions that will allow millers to produce consistent product regardless of variability in the rice crop being processed by leveraging the adaptability of their processing parameters and equipment capabilities. Modifications to the parboiling method can include pre-treatments like heat-moisture application prior to parboiling and pre-steaming. Improved equipment, such as the use of a fluidized bed dryer or IR heat can optimize the time and energy efficiencies of the specific stages of the process. Publishing new research and updated information on parboiling helps to bring awareness of the nutritive advantageous version of rice and brings the potential for innovation. Research should continue to explore modifications to all aspects of rice processing to ensure the best process that produces good quality finished products that is advantageous to millers and consumers.

References

AACC International. (2000). *Approved Methods of Analysis: Method 30-20.01 Crude Fat in Grain and Stock Feeds* (10th ed). St. Paul, MN: AACC International.

AACC International. (2009). *Approved Methods of Analysis: Method 61-02.01 Determination of the Pasting Properties of Rice with the Rapid Visco Analyzer* (11th ed). St Paul, MN: AACC.

Ambardekar, A. A., Siebenmorgen, T. J., Counce, P. A., Lanning, S. B., & Mauromoustakos, A. (2011). Impact of field-scale nighttime air temperatures during kernel development on rice milling quality. *Field Crop Res, 122*(3), 179-185.

AOAC International. (1990). *Official Methods of Analysis: Method 990.03 Association of Official Analytical Chemists Protein (Crude) in Animal Feed*: *Combustion Method*. (15th ed). Gaithersburg, MD: AOAC.

Arns, B., Paraginski, R., Bartz, J., Almeida Schiavon, R., Elias, M.C., Rosa Zavareze, E., & Dias, A.R.G. (2014). The effects of heat-moisture treatment of rice grains before parboiling on viscosity profile and physicochemical properties. *Int J Food Sci Tech, 49*(8), 1939-1945.

Arvidsson-Lenner, R., Asp, N-G., Axelsen, M., Bryngelsson, S., Haapa, E., Jarvi, A., …Vessby, B. (2004). Glycemic Index. *Scand J Nutr*, *48*(2), 84-94.

Ashwini, M.V., Robinson, P., Madhu, G., & Syed, S. (2016). Design and Fabrication of Domestic Puffed Rice Making Machine, *IJERT, 5*(8), 428-432.

Barber, S. (1972). Milled rice and changes during aging. In D.F. Houston (Ed.), *Rice: Chemistry and Technology* (215-263). St. Paul, MN: AACC.

Basavaraj, Raviteja, G., & Deshpande, R. (2015). *Physical Properties of Rice for Puffing*, *IJLTET, 5*(3), 376-380.

Basutkar, N.N., Siebenmorgen, T.J., & Mauromoustakos, A. (2014). Milling properties of commingled rice-cultivar lots. *Trans. ASABE, 57*, 1717-1720.

Basutkar, N.N., Siebenmorgen, T.J., Wang, Y.-J., & Patindol, J.A. (2015). Functional properties of commingled rice-cultivar lots. *Cereal Chem, 92*, 114-119.

Bhattacharya, S. (1996). Kinetics on color changes in rice due to parboiling. *J Food Eng, 29*, 99-106.

Bhattacharya, K.R. & Swamy, M.I. (1967). Conditions of Drying Parboiled Paddy for Optimum Milling Quality. *Cereal Chem, 44*, 592 - 600

Bhattacharya, K.R. & Subba Rao, P.V. (1966a). Processing conditions and milling yield in parboiling of rice. *J Agr Food Chem*, *14*, 473–475.

Bhattacharya, K.R. & Subba Rao, P.V. (1966b). Effect of processing conditions on quality of parboiled rice. *J of Agr Food Chem*, *14*, 476–479.

Bhattacharya, K.R. (1985). Parboiling of rice. In B.O. Juliano (Ed.), *Rice Chemistry and Technology* (2nd ed, pp. 305-306). St. Paul, MN: AACC.

Bhattacharya, S. (1996). Kinetics on color changes in rice due to parboiling. *J Food Eng, 29*, 99-106.

Bhattacharya, K.R. (2004). Parboiling of Rice. In E. Champagne (Ed.), *Rice Chemistry and Technology* (3rd ed, pp. 329). St Paul, MN: AACC.

Bhattacharya, K.R. (2011). Rice Quality. In K. R. Bhattacharya (Ed.), *Rice quality: A guide to rice properties and analysis*. (pp. 21-25). Cambridge, UK: Woodhead Publishing.

Bhattacharya, K. (2013). Improvements in technology for parboiling rice. *Cereal Food World, 58*(1), 23-26.

Bootkote, P., Soponronnarit, S., & Prachayawarakorn, S. (2016). Process of producing parboiled rice with different colors by fluidized bed drying technique including tempering. *Food Bioprocess Tech, 9*(9), 1574-1586.

Chau, N.N. & Kunze, O.R. (1982). Moisture Content Variation Among Harvested Rice Grains. *Transactions of the ASAE, 25*(4), 1037-1040.

Damir, A.A. (1985). Comparative studies on the physiochemical properties and microstructure of raw and parboiled rice. *Food Chem, 16*(1), 1-14.

Delcour, J.A., & Hoseney, R.C. (2010). Rice and oat processing. In Principles of Cereal Science and Technology (3rd ed, pp. 137). St. Paul, MN: Hoseney, R.C.

Derycke, V., Veraverbeke, W.S., Vandeputte, G.E., Man, W.E., Hoseney, R.C., & Delcour, J.A., (2005). Impact of proteins on pasting and cooking properties of nonparboiled and parboiled rice. *Cereal Chem, 82*, 468-474.

Fitzgerald, M.A., Bergman, C.J., Ressurreccion, A.P., Moller, J., Jimenez, R., Reinke, R.F., … Mestres, C. (2009). Addressing the Dilemmas of Measuring Amylose in Rice. *Cereal Chem, 86*(5), 492-498.

Gopala Krishna, A.G., Prabhakar, J.V. & Sen, D.P. (1984). Effect of degree of milling on tocopherol content of rice bran. *J Food Sci Tech MYS*, *21*, 222-224.

Graves, A.M., Siebenmorgen, T.J., & Saleh, M.I. (2009). A comparative study between the McGill #2 Laboratory Mill and Commercial Milling Systems. *Cereal Chem, 86*(4), 470-476.

Gujral, H.S., Singh, J., & Sodhi, N.S. (2002). Effect of milling variables on the degree of milling of unparboiled and parboiled rice. *Intl J Food Prop, 5*(1), 193-204.

Hemavathy, J. & Prabhakar, J.V. (1987). Lipid composition of rice (Oryza sativa L.) bran. *J Am Oil Chem Soc, 64*, 1016-1019.

Hua, L., Lelievre, J., & Ayoung-Chee, W. (1991). A study of starch gelatinization using differential scanning calorimetry, X-ray, and birefringence measurements. *Carbohyd Res, 210*, 79-87.

HunterLab. (2001). *Color Theory: Basics of Color Perception and Measurement* [PowerPoint slides]. Retrieved from https://ucanr.edu/datastoreFiles/608-161.pdf

IMARC. (2018). Press Release: Parboiled and White Rice Market: Global Industry Trends, Share, Size, Growth, Opportunity and Forecast 2018-2023. Retrieved April 1, 2019, from https://www.imarcgroup.com/parboiled-white-rice-manufacturing-plant

IRRI. (2007). Lesson 6: Rice breeding methods. Retrieved from: http://www.knowledgebank.irri.org/ericeproduction/0.6_Rice_Breeding.htm

IRRI. (1979). Proceedings from the Workshop on Chemical Aspects of Grain Quality: *Gelatinization temperature of rice starch and its determination*. Los Baños, Laguna, Phillipines: Bhattacharya, K.R. Pages 231-249.

Islam, M.R., Shimizu, N., & Kimura, T. (2004). Energy requirement in parboiling and its relationship to some important quality indicators. *J Food Eng, 63*(4), 433-439.

Jaiswal, P.K. (1983). Specification of rice bran oil and extractions. In *Rice bran oil: status and prospects* (pp. 64-77). *Proceedings of a seminar*. Oil Technologists' Association of India.

Juliano, B.O. (1972). The rice caryopsis and its composition. In D.F. Houston (Ed.), *Rice Chemistry and Technology* (215-263) St Paul, MN: AACC.

Juliano, B.O. (1979). Proceedings from Workshop on Chemical Aspects of Rice Grain Quality: *The chemical basis of rice grain quality* (pp. 69-90). Los Baños, Laguna, Philippines: IRRI.

Juliano, B.O., Bautista, G.M., Lugay, J.C., & Reyes, A.C. (1964). Studies on Physiochemcial Properties of Rice. *J Agr Food Chem, 12*(2), 131-138.

Juliano, B.O. & Bechtel, D.B. (1985). The rice grain and its gross composition. In B.O. Juliano (Ed.), *Rice Chemistry and Technology* (2nd ed, pp. 17-57). St Paul, MN: AACC.

Juliano, B.O. (1993). Ch 3 GRAIN STRUCTURE, COMPOSITION AND CONSUMERS CRITERIA FOR QUALITY In B.O. Juliano (Ed.), *Rice in human nutrition* (pp. 39-47). Rome, Italy: FAO.

Kaddus Miah, M.A., Haque, A., & Paul, M. (2002). Parboiling of rice. Part 1: Effect of hot soaking time on quality of milled rice. *Int J of Food Sci Tech, 37*(5), 527-537.

Khullar, B. (2017). Indian scientists develop transgenic rice that can withstand drought. Retrieved from: https://www.downtoearth.org.in/news/agriculture/indian-scientists-develop-transgenic-rice-that-can-withstand-drought-57861

Lanning, S.B., Siebenmorgen, T.J., Counce, P.A., Ambardekar, A.A., & Mauromoustakos, A. (2011). Extreme nighttime air temperatures in 2010 impact rice chalkiness and milling quality. *Field Crop Res, 124*(1), 132-136.

Lanning, S.B., & Siebenmorgen, T.J. (2011). Comparison of Milling Characteristics of Hybrid and Pureline Cultivars. *Appl Eng Agric, 27*(5), 787-795.

Leethanapanich, K., Mauromoustakos, A., & Wang, Y.-J. (2016a). Effects of Soaking Temperature on Commingled Rice Properties. *Cereal Sci, 69*, 267-274.

Likitrattanaporn, C. & Noomhorm, A. (2011). Effects of simultaneous parboiling and drying by infrared radiation heating on parboiled rice quality. *Dry Technol, 29*(9), 1066-1075.

Luh, Bor S. & Robert R. Mickus. (1991). Chapter 4 Parboiled Rice. In B.S. Luh (Ed.), *Rice: Utilization Volume II* (pp. 51-81). New York, NY: Van Nostrand Reinhold Publishing

Maier, T.V., Lucio, M., Ho Lee, L., VerBerkmoes, N.C., Brislawn, C.J., Bernhardt, J., … Jansson, J.K. (2017). Impact of Dietary Resistant Starch on the Human Gut Microbiome, Metaproteome, and Metabolome. *mBio, 8*(5) e01343-17, 1-16.

Malt Products Corporation. (2019). Rice Syrups and Dry. Retrieved from https://maltproducts.com/rice-syrups/

Marcó, A., Rubio, R., Compaño, R., & Casals, I. (2002). Comparison of the Kjeldahl method and a combustion method for total nitrogen determination in animal feed. *Talanta, 57*(5), 1019-1026.

Matsler, A.L., & Siebenmorgen, T.J. (2005). Evaluation of operating conditions for surface lipid extraction from rice using a soxtec system. *Cereal Chem, 82*(3), 282-286.

Miller, JB., Pang, E., & Bramall, L. (1992). Rice: a high or low glycemic index food? *Am J of Clin Nutr, 56*(6), 1034-1036.

National Geographic Education Staff. (2014). Staple Food Crops of the World: Fast Facts. Retrieved from https://www.nationalgeographic.org/maps/wbt-staple-food-crops-world/

Newton, J., Wang, Y.-J., & Mauromoustakos, A. (2011). Effects of cultivar and processing condition on physicochemical properties and starch fractions in parboiled rice. *Cereal Chem, 88*, 414-420.

Normand, F.L., Ory, R.L. & Mod, R.R. (1981). Interactions of several bile acids with hemicelluloses from several varieties of rice *J Food Sci, 46*, 1159-1161.

Padua, A.B., & Juliano, B.O. (1974). Effect of Parboiling on Thiamin, Protein, and Fat of Rice. *J Sci Food Agr, 25*(6), 697-701.

Parnsakhorn, S. & Noomhorm, A. (2008). Changes in Physicochemical Properties of Parboiled Brown Rice During Heat Treatment. *Ag Eng Int*, *X* (Manuscript FP08 009), 1-20.

Prakash, J. (1996). Rice bran proteins: properties and food uses. *Crit Rev Food Sci Nutr, 36*(6), 537-52.

Raghavendra Rao, S.N., Ananthachar, T.K., & Desikachar, H.S.R. (1965). Oil content of bran from rice milled to different degrees of polishing. *J Food Sci Tech MYS, 2*, 115-116.

Raghavendra Rao, S.N. & Juliano, B.O. (1970). Effect of parboiling on some physiochemical properties of rice. *J Agr Food Chem, 18*, 289-294.

Resurrección, A.P., Juliano, B.O. & Tanaka, Y. (1979). Nutrient content and distribution in milling fractions of rice grain. *J Sci Food Agr, 30*, 475-481.

The Rice Association. (2018). “by-products.” Retrieved from http://www.riceassociation.org.uk /content/1/16/by-products.html.

Sadaka, S., & Bautista, R. (2014). Grain Drying Tools: Equilibrium Moisture Content Tables and Psychrometric Charts. Retrieved from https://www.uaex.edu/publications/pdf/FSA-1074.pdf

Schluterman, D.A. & Siebenmorgen, TJ. (2007). Relating Rough Rice Moisture Content Reduction and Tempering Duration to Head Rice Yield Reduction. *ASABE, 50*(1), 137-142.

Shaw, J.F., & Sheu, J.R. (1992). Production of high-maltose syrup and high-protein flour from rice by an enzymatic method. *Biosci Biotechnol Biochem, 56*(7), 1071-1073.

Siebenmorgen, T. (2018). Ch 14. Laboratory Measurement of Rice Milling Yield. In J. T. Hardke (Ed.), *Arkansas Rice Production Handbook – MP192* (pp. 173-180). Little Rock, AR: University of Arkansas Cooperative Extension Service Print Media Center.

Siebenmorgen, T. J., Bautista, R.C., & Counce, P.A. (2007). Optimal Harvest Moisture Contents for Maximizing Milling Quality of Long- and Medium-grain Rice Cultivars. *Appl Eng Agr, 23*(4), 517-527.

Siebenmorgen, T.J., Matsler, A.L., & Earp, C.F. (2006). Milling characteristics of cultivars and hybrids. *Cereal Chem, 83*, 169-172.

Siebenmorgen, T. J., Nehus, Z.T., & Archer, T.R. (1998). Milled Rice Breakage Due to Environmental Conditions. *Cereal Chem, 75*(1), 149-152.

Slavin, J. (2013). Carbohydrates, Dietary Fiber, and Resistant Starch in White Vegetables: Links to Health Outcomes. *Adv Nutr*, *4*(3), 351S–355S.

Sun, H. & Siebenmorgen, T.J. (1993). Milling Characteristics of Various Rough Rice Kernel Thickness Fractions. *Cereal Chem, 70*(6), 727-733.

Technavio. (2018). Global Packaged Rice Snacks Market 2018-2022. Retrieved from https://www.businesswire.com/news/home/20180718005365/en/Global-Packaged-Rice-Snacks-Market-2018-2022-New.

USDA. (2009). United States Standards for Rice. Retrieved from https://www.gipsa.usda.gov /fgis/standards/ricestandards.pdf

USDA. (2009a). United States Standards for Milled Rice. 7 CFR § 868 2019. Retrieved from https://www.ecfr.gov/cgi-bin/text-idx?SID=1fb891ea4cd23e305528c37c85cb2a3c&mc =true&node=sp7.7.868.e&rgn=div6#se7.7.868_1301

USDA Market News. (2019). National Weekly Rice Summary (Arkansas-Louisiana-Texas, California). Retrieved from https://www.ams.usda.gov/mnreports/lr_gr410.txt

Walton, M. (2003). Hybrid rice for mechanized agriculture. In *Hybrid rice for food security, poverty alleviation, and environmental protection.* S.S. Virmani, C.X. Mao, and B. Hardy (Eds.) Los Banos (Philippines): IRRI, pp. 407

Wang, Y.-J., White, P.J., & Pollack, L. (1992). Thermal and gelling properties of maize mutants from OH43 inbred line. *Cereal Chem, 69*(e), 328-334.

Webb, B. D., Bollich, C. N., Carnahan, H. L., Kuenzel, K. A., & McKenzie, K. S. (1985). Utilization characteristics and qualities of United States rices. In *Symposium on Rice Grain Quality and Marketing*, Los Banos, Philippines: IRRI, pp. 25–35.

Wimberly, J.E. (1983). Parboiling. In *Technical Hand Book for the Paddy Rice Post Harvest Industry in Developing Countries*, Manila, Philippines: IRRI, pp. 101-116.

Yogesh. (2018). Researchers develop transgenic rice with reduced arsenic accumulation. Retrieved from https://www.downtoearth.org.in/news/science-technology/researchers-develop-transgenic-rice-with-reduced-arsenic-accumulation-62173

Yuan, L.P. (1994). Increasing Yield Potential in Rice by Exploitation of Heterosis. In *Hybrid rice technology: new developments and future prospects*. S.S. Virmani (Ed.). Laguna, Philippines: IRRI, pp. 1-6.

Zion Market Research. (2018). Gluten-Free Product Market Will Reach USD 7.60 Billion By 2024, Globally: Zion Market Research. Retrieved from: https://www.globenewswire.com/news-release/2018/12/05/1662178/0/en/Gluten-Free-Product-Market-Will-Reach-USD-7-60-Billion-By-2024-Globally-Zion-Market-Research.html