Impacts of Feedstock and Parboiling Conditions on Quality Characteristics of Parboiled Rice

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Impacts of Feedstock and Parboiling Conditions on Quality Characteristics of Parboiled Rice

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Food Science

By

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ABSTRACT

Parboiling involves soaking, steaming, and drying, and is known to improve head rice yield (HRY), remove chalkiness, and retain nutrients. Because of an increasing number of rice cultivars developed, commingling of rice may happen during harvesting, distributing, or storage. Using commingled rice with a wide range of gelatinization temperatures \((T_o)\) as a feedstock may cause inconsistent parboiled rice products. Therefore, this study was aimed at investigating the effect of soaking temperature and steaming duration on the quality of parboiled, commingled rice. Rough rice samples of individual or commingled rice cultivars with different \(T_o\) ranges were soaked at different temperatures \((25, 60, 65, 70\) or \(75^\circ C)\) for 3 h alone or in combination with steaming at \(112^\circ C\) for 10, 15 or 20 min; the milling and physicochemical properties of the resultant rice samples were characterized. Soaking at \(25^\circ C\) caused no morphological change, however, soaking at temperatures above starch glass transition temperature but below \(T_o\) reduced chalkiness by facilitating a rearrangement of starch granules to form a more packed structure, thus increasing head rice yield. With increasing soaking temperature, head brown rice yield and \(T_o\) increased, whereas gelatinization temperature range and chalkiness reduced. During the soaking step, commingling or \(T_o\) difference had more influence on head brown rice yield than soaking temperature. However, when combined with the steaming step, soaking temperature was found to have more influence on the HRY of the resultant parboiled rice than commingling and steaming duration, whereas steaming duration had the greatest impact on yellowness, white core, deformed kernels and pasting viscosity. Commingled rice with a wide range of \(T_o\) tended to result in less desirable parboiled rice. It is recommended to select a soaking temperature close to \(T_o\) of commingled rice and a steaming duration to fully gelatinize starch without rendering
excessive starch swelling in order to optimize the desirable quality characteristics of parboiled rice.
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CHAPTER 1
INTRODUCTION

Parboiled rice consumption has been primarily of cultural preferences such as India, Pakistan, Bangladesh, Nigeria, and Brazil. Parboiled rice is believed to be more nutritious than milled rice. Recently, parboiled rice finds many applications in the food industry such as instant rice, frozen entrees, canned goods, ready-to-eat meals, and puffed cereals because of its ease of cooking and improved heat stability. Rice processors also favor parboiled rice because the parboiling process decreases breakage susceptibility of rice during dehulling and milling process, resulting in higher head rice yields. Parboiling process includes soaking, steaming, and drying, which all have impacts on the quality of parboiled rice. However, parboiled rice may possess unfavorable characteristics if it is not properly parboiled, such as discoloration, off odor and flavor, deformed grains, white core, and unsatisfactory sensory attributes (Bhattacharya, 2011). Therefore, it is important to understand how each factor affects the quality attributes in order to produce parboiled rice with desirable properties.

As the number of rice growers in the United States is increasing over the past few years in line with a dramatic increase in rice varieties, especially hybrid cultivars, rice processors are facing the problem of commingled rice upon receiving. Differences in inherent properties of individual cultivars, such as grain dimensions, chemical composition, and gelatinization temperature, reflect the differences in final properties of parboiled rice. Pureline and hybrid cultivars also show differences in milling characteristics, which could result in inconsistent quality of finished products if they are mixed and processed under the same condition (Lanning and Siebenmorgen, 2011). Owing to such differences, the optimal parboiling conditions may vary with cultivars. An intermingling between rice varieties both pureline and hybrid may occur
during harvesting, drying, storage, and distribution. This could result in inconsistent quality of finished parboiled rice if this commingled rice is parboiled together.

**LITERATURE CITED**


CHAPTER 2
LITERATURE REVIEW

2.1 Rice

Rice (Oryza sativa L.) is harvested as ‘paddy’ or ‘rough rice’ (Figure 2.1), which consists of an outer protective coating, the hull, and a caryopsis. Brown rice consists of pericarp, seed coat, nucellus, germ or embryo, and endosperm. The endosperm comprises the aleurone layer, subaleurone layer, and starchy endosperm. The starchy endosperm comprises the greatest proportion of the rice kernel and is where starch and storage protein are located (Champagne et al., 2004).

![Figure 2.1 Structure of rice spikelet (Haaland, 1980)](image)

2.2 Rice starch

The main component of the rice kernel is starch, accounting for about 90% of its dry weight; therefore, starch plays a critical role in rice quality (Juliano, 1979). Rice starch granules are polygonal and small, about 3 to 5 µm in diameter (Whistler and BeMiller 1997). Rice starch is present as tightly packed compound granules and composed of two polymers of glucose: amylose and amylopectin. Rice starches comprise about 70-80% amylopectin and 20 – 30%
amylose. Amylose molecules consist of essentially linear chains with 500-20,000 α-(1→4)-D-glucose units, and may have a small number of branches linked by α-(1→6) glycosidic linkages (Hoover, 2001). Amylopectin molecules are highly branched and serve as the skeleton of the starch granules with their branches formed by α-(1→6) glycosidic linkages that occur every 20-30 glucose units (Figure 2.2). Amylopectin is one of the largest molecules in nature, having a molecular size of 10,000 to 100,000 degree of polymerization (DP) (Manners, 1989).

Figure 2.2 The molecular structure of (A) amylopectin and (B) amylose

Figure 2.3 The cluster model structure of Amylopectin (Hizukuri, 1986)

Amylopectin chains are classified into three groups according to their lengths and arrangement: A, B, and C chains. A chains are connected to B chains and do not carry any other
chains; B chains carry A and/or B chains; each unit chain comprises only a single C chain that carries the sole reducing end group. A and B1 chains are located in one single cluster, whereas B2 and B3 chains extend into 2 and 3 clusters, respectively (Figure 2.3) (Hizukuri, 1986).

Hanashiro et al. (1996) separated amylopectin chains by employing high-performance anion-exchange chromatography equipped with pulse amperometric detection and assigned the average chain lengths of amylopectin chains as follows: A chains of DP 6-12; B1 chains of DP 13-24; B2 chains of DP 25-36, and B3+ chains of DP>37.

Amylopectin branched chains form a pattern of definite lengths and are arranged into alternating concentric crystalline and amorphous lamellae. Adjacent linear chains of longer than ~10 glucose units re-associate to form helical structures that constitute the crystalline lamellae, while the branching points constitute the amorphous lamellae (Fitzgerald, 2004). Individual amylose chains are believed to randomly intersperse among amylopectin, mostly in the amorphous lamellae. These alternate layers are radial oriented into growth rings from the hilum or nucleus of the granule to the periphery. Several growth rings are present in starch granules, which pack into grains (Figure 2.4) (Li et al., 2014).

![Starch structure and arrangement in cereal grain](https://example.com/starch_structure.png)  
**Figure 2.4** Starch structure and arrangement in cereal grain (AP=Amylopectin, AM = Amylose) (Li et al., 2014).
2.3 Rice protein

Protein is the second major component in milled rice, ranging from 5 to 14% at 12% moisture content. Protein content is affected by climate and agronomic conditions (Juliano, 1966), and is high in the bran (11.3-14.9%), and gradually decrease towards the center of the kernels. There are three types of protein bodies in rice grains: large spherical, crystalline, and small spherical (Hamaker, 1994). Some protein bodies are tightly bound to starch granules and remain intact during cooking, which affects rice cooking and textual properties (Hayakawa et al., 1980).

2.4 Rice lipid

A major proportion of rice lipids is concentrated in the pericarp, the aleurone layer, and the germ. Rice lipids are present in the form of lipid droplets with diameters of <1.5 µm in the aleurone layer, <1 µm in the subaleurone layer, and <0.7 µm in the grain embryo (Juliano, 1983). Lipids are classified into nonstarch lipids and starch lipids (Morrison, 1978). Nonstarch lipids are the main lipids in rice and located in the aleurone layer and embryo. The proportion of starch lipids in rice is relatively small but plays an important role in rice functionality. They can complex with amylose to form amylose-lipid complexes (Morrison, 1995). Ohashi et al. (1980) suggested that starch lipids restricted starch swelling via hydrophobic interactions between the hydrocarbon chains of lipids and amylose helices.

2.5 Starch gelatinization

Because of the presence of the amorphous regions, starch granules can slightly absorb water and reversibly swell at low temperatures. Upon heating in excess water and exceeding a certain temperature, i.e. gelatinization temperature (GT), the ordered structure of starch is disrupted. Some amylose becomes solubilized and leaches from granules, and the granules
increase in size until they can no longer maintain their integrity, and eventually collapse. Upon cooling, starch reassociates through hydrogen bonding and forms a three-dimensional gel network if amylose is present. This reorganization of gelatinized starch molecule is called retrogradation (Lund, 1984).

The ratio of amylose and amylopectin affects gelatinization and retrogradation of starch (Fredriksson et al., 1998). The crystalline regions of starch are primarily responsible for starch gelatinization temperature as measured by differential scanning calorimetry; therefore, high-amylopectin starch generally has high gelatinization temperatures (Tester and Morrison 1990).

2.6 Starch annealing

Annealing is the process of soaking starch in excess water at a temperature above the glass transition but below the gelatinization temperature of starch for a period of time, permitting molecular reorganization (Jacobs and Delcour, 1998; Tester and Debon, 2000).

Naturally, amylopectin molecules are orderly arranged into crystallites. However, due to differences in chain lengths and branching points, some chains may not form a crystalline structure but form a rigid glassy phase (Perry and Donald, 2000). When starch is subjected to excess water, the hydration of starch induces the vibrational movement of tangential and radial chains in both amorphous and crystalline areas. The rate of hydration and mobility of glucan chains drastically increases when temperature is elevated to above the glass transition temperature but below the gelatinization temperature of starch. This movement is in a side-by-side pattern, resulting in formation of a nematic structure. An increase in incubation time facilitates starch molecules to arrange into more ordered structure (Figure 2.5). Therefore, annealing is described as a crystal perfection process (Jayakody and Hoover, 2008).
Many studies have shown that annealing increases the onset gelatinization temperature and decreases the gelatinization temperature range (Jacobs et al., 1998; Qi et al., 2005; Shi, 2008). Annealing causes the twisting of uncoiled ends and lengthening of amylopectin double helices, leading to an increase in crystalline lamella thickness. This results in an increase in melting temperature of amylopectin double helices (Kiseleva et al., 2004). The decrease in the gelatinization temperature range shows the greater homogeneity and cooperative melting of crystallines after annealing (Jacobs and Delcour, 1998).

**Figure 2.5** Mechanism of annealing (Jayakody and Hoover, 2008)

### 2.7 Classification of rice grain

According to the Federal Grain Inspection Service (1994), U.S. rice is classified into three categories by the length-width ratio of kernel: long-, medium-, and short-grain (Table 2.1). It can also be grouped based on amylose content: waxy (1-2%), non-waxy (>2%), very low (2-9%), low (10-20%), intermediate (20-25%), and high (25-30%). Furthermore, GT is also used to
classify the rice as high (74.5-80°C), intermediate (70-74°C), and low (<70°C) (Coultate, 2002).

Long-grain rice usually has an intermediate GT, whereas medium- and short-grain varieties display relatively low GT (Webb, 1985). Most waxy and low-amylose starches show high GT (Juliano, 1985).

**Table 2.1** Length-width ratio of each class of rice

<table>
<thead>
<tr>
<th>Type</th>
<th>Length-width ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rough or Paddy Rice</strong></td>
<td></td>
</tr>
<tr>
<td>Long</td>
<td>≥ 3.4 to 1</td>
</tr>
<tr>
<td>Medium</td>
<td>2.3 - 3.3 to 1</td>
</tr>
<tr>
<td>Short</td>
<td>≤ 2.2 to 1</td>
</tr>
<tr>
<td><strong>Brown Rice</strong></td>
<td></td>
</tr>
<tr>
<td>Long</td>
<td>≥ 3.1 to 1</td>
</tr>
<tr>
<td>Medium</td>
<td>2.1 - 3.0 to 1</td>
</tr>
<tr>
<td>Short</td>
<td>≤ 2.0 to 1</td>
</tr>
<tr>
<td><strong>Milled Rice</strong></td>
<td></td>
</tr>
<tr>
<td>Long</td>
<td>≥ 3.0 to 1</td>
</tr>
<tr>
<td>Medium</td>
<td>2.0 - 2.9 to 1</td>
</tr>
<tr>
<td>Short</td>
<td>≤ 1.9 to 1</td>
</tr>
</tbody>
</table>

Source: Federal Grain Inspection Service (1994)

2.8 Rice quality

Grain chalkiness

Chalky grains are opaque, not translucent as the normal grains. Chalk mainly occurs at the center of the grain and can occupy more than 50% of the volume of the kernels. Chalkiness in rice is classified into four types: (a) white center or white core (chalky area located at the center), (b) white belly (chalkiness in the germ side), (c) milky white (chalkiness spreading entire grain except in the peripheral part), and (d) opaque. Chalky area in the first two types can range from tiny to very large (>70%) (Ikehashi and Khush, 1979). Chalkiness directly affects the appearance of rice and determines the rice grade and consumer acceptance. According to USDA
(2009), chalky kernels are defined as whole or broken kernels of rice which are one-half or more chalky. It is undesirable in all markets except the arborio market. The chalky grain allowance for commercial U.S. No.1 is 2% for brown rice and 1% for white milled rice.

Chalkiness has been reported to be influenced by many factors such as inherent genes and environmental conditions. Formation of chalky grains is enhanced by high temperature during the grain filling stages. Lisle et al. (2000) found an increase of chalky grains for three rice cultivars grown at elevated day/night temperature in a greenhouse study. They suggested that formation of chalky grains under high temperature stress was resulted from inefficient packing of starch, leading to inferior cooking quality. Field-scale research in multiple locations and multiple years (2007-2009) of six pureline and hybrid cultivars showed that nighttime air temperature during kernel development strongly impacted the level of chalkiness (Ambardekar et al., 2011). Lanning et al. (2011) reported that an increase in nighttime air temperatures interrupted the grain filling stages, thus causing chalk formation. Susceptibility and genetic responses to environmental changes, which are characteristic of cultivars, are also important.

The composition and structure of starch in chalky grains are different from those in translucent ones. It contains less amylose and an increased percentage of short branched-chain amylopectin. It is possible that starch synthase enzymes are interrupted either by environmental factors or gene damage in grain development, leading to an inferior activity to activate the elongation of glucan chains (Patindol and Wang, 2003). Singh et al. (2003) examined microstructure of chalky and translucent rice kernels using scanning electron microscopy and observed that in the chalky kernels of PR-101 and IR-8 cultivars, the cells and amyloplasts were loosely packed and air spaces and some disordered granular structures were present (Figure 2.6).
Kernel fissures or cracking are associated with breakage susceptibility of rice kernels during processing. Fissures are related to the hygroscopic nature of rice kernels that can adsorb or desorb moisture from or into the air until reaching an equilibrium state, which is the function of relative humidity (RH) and temperature of the surrounding air. The moisture gradients in the rice kernel during moisture migration cause hygroscopic stresses in the kernel. When these
stresses exceed the rice kernel mechanical strength, rice kernels release them as cracks or fissures. Fissures can develop in the field, during harvest, drying, and storage (Buggenhout et al., 2013b).

As rice kernels in the field mature, they begin to dry in the field. Moisture in the grain migrates out during the day and migrates in at night. This drying-reabsorption cycle continues during each successive drying day and may cause fissures if the tension at the grain center exceeds tensile strength of the grain (Kunze, 2008). Practically, rice is harvested when it matures, but not every rice grain in the same panicle reaches maturity at the same time. Therefore, when harvest is delayed and the rice grains are dried to a moisture content below a critical moisture content, which ranges from 12-15%, fissures can develop in the field (Buggenhout et al., 2013b).

After harvesting, rice kernels are dried in order to reduce the moisture content from the range of 16-26% to 12-13% to avoid microbial contamination and respiration processes (Ondier et al., 2010). Fissures can develop after drying because of the relaxation of stresses inside the grains initiating by the moisture gradient between grain surface and the core. During drying, the moisture in grain surface is removed faster than in the core, causing a gradient (Kunze, 2008). The moisture gradient is dependent on the drying rate determined by rice grain moisture content and drying air conditions, including air temperature, RH, and flow rate. Arora et al. (1973) found that a temperature difference greater than 43°C between the drying air and rice kernels caused fissuring, and recommended maintain the drying air temperature below 53°C in order to minimize kernel thermal stress. Nguyen and Kunze (1984) found that drying air temperature had a significant effect on kernel fissuring and a 10°C post-drying storage temperature produced more fissured kernels than did 45°C.
Milling and head rice yield

Milling and head rice yield are the most important quality parameters to both farmers and processors because rice is sold in form of milled rice. Milled rice yield refers to the weight of rice obtained after milling as a percentage of the total weight of the rough rice. Head rice yield is the weight of head rice, i.e. kernel with length greater or equal to three quarters of the average length of the whole kernel, remaining after milling as a percentage of the total weight of the rough rice.

Rice is milled to remove the germ and bran layers. The amount of bran layers remaining on the surface of rice kernels after milling indicates the degree of milling. The milled and head rice yields are related to the breakage susceptibility of rice kernels, which are influenced by a number of factors such as chalkiness, fissures, immaturity, and inherent characteristics of individual cultivars (e.g. kernel size, dimensions, and surface topography). Webb (1980) stated that cultivars with thicker kernel sizes had a thicker aleurone layer, thus requiring more milling pressure or longer milling durations to meet a desired degree of milling. An increase in degree of milling, i.e. greater amounts of bran or endosperm being removed, contribute to a reduction in head rice yield (Reid et al., 1998). Bautista et al. (2009) reported that chalkiness was negatively correlated with head rice yield because chalky kernels were weaker and more likely to break during milling than translucent kernels. Furthermore, unit operations in rice processing that cause mechanical stresses to rice kernels, such as harvesting, threshing, drying, dehulling, and milling, also greatly impact these yields (Buggenhout et al., 2013b).

Cooking quality

Cooking quality refers to the behavior of milled rice during cooking that involves rice grain volume expansion, water absorption, solids in cooking water, and sensory characteristics
including appearance, whiteness, hardness, stickiness, aroma, and taste (Juliano, 1982). In cooking process, there are sequences of changes in rice grains: glass transition, swelling, pasting, leaching, and retrogradation. Eating quality of cooked rice is mainly determined by hardness and stickiness (Bhattacharya, 2011).

Cooking quality of rice is mostly influenced by the predominant constituent of starch; therefore, amylose content and starch physicochemical properties (e.g. pasting and gelatinization characteristics) have been used as indicators for predicting rice cooking and processing properties (Bhattacharya, 2011). The volume expansion, water absorption, and tendency of disintegration of milled rice are influenced by starch amylose/amylopectin ratio. Rice with a high amylose content cooks dry and fluffy, whereas rice with an intermediate or low amylose content cooks moist, softer, and stickier (Luh and Mickus, 1991). Cooked waxy rice is very moist, sticky and glossy due to an absence of amylose, leading to the least volume expansion and water absorption (Juliano, 1972).

Amylopectin has been reported to strongly affect starch gelatinization properties. The amorphous lamellae of starch granule where the branched structures located are the area that starch readily absorbs water and swells. The long-chain amylopectin delays gelatinization and positively associates with starch gelatinization temperature, possibly by forming longer double helices within the crystalline lamellae, while short-chain amylopectin disrupts the packing order and facilitates gelatinization (Vandeputte et al., 2002). Radhika-Reddy et al. (1993) found that cooked rice hardness was positively correlated with the amount of long-B chains in the exterior region of amylopectin. Ong and Blanshard (1995) reported that the greater amount of long-B chains in the exterior region of amylopectin, the stronger and more resilient the starch granules were because long-B chains are involved in more than one cluster and less dispersed. Ramesh et
al. (1999) proposed that the texture of rice was mostly determined by the content of the long linear chains, including not only amylose but also the long-B chains in amylopectin. The amylopectin long chains could co-crystallize with amylose and form double helices through several adjacent clusters, thus reducing starch swelling and leaching, and leading to harder cooked rice.

Proteins also influence texture and pasting properties of rice. It was postulated that a high protein content in the outer layers of rice reduced stickiness of cooked rice (Onate et al., 1964) and prolonged cooking time (Juliano et al. 1965). The higher level of proteins may form a thicker barrier around the starch granules, delaying the water uptake process (Chakrabarthy et al., 1972). Additionally, the strong binding of starch granules and protein bodies in the endosperm restricts the swelling of starch granule during gelatinization, resulting in firmer cooked rice (Hayakawa, 1980). Martin and Fitzgerald (2002) reported that proteins affected cooked rice texture by competing with starch for water and the formation of disulfide bonds.

Lipids also have effects on restricting moisture uptake of rice during cooking through amylose-lipid complexes (Saleh and Meullenet, 2007). These complexes are thermally stable up to 100°C and contributed to stabilization of the rice grains during cooking (Billaderis et al., 1993). Such complexes are insoluble in water and could not be separated until above 94-98°C; thereby, lipids associated with the leached components could not be detected during cooking (Raphaelides and Karkalas 1988). Moreover, amylose-lipid complexes may also form from the naturally present starch lipids and the amylose molecules available during swelling, thus impeding the leaching of amylose (Morrison, 1988) and the swelling of starch (Tester and Morrison, 1990). Perdon et al. (2001) reported that lipid significantly affected milled rice flour paste viscosity and rice functional performance as well as sensory attributes. They hypothesized
that lipid formed a complex with amylose molecules, affecting water absorption and starch’s ability to swell. The amounts of rice bran, which is rich in proteins and lipids, remaining on rice kernels after milling also play a key role in cooked rice quality by being a barrier for water migration into the grains (Saleh and Meullenet, 2007).

2.9 Hybrid Rice

Hybrid rice technology was developed to overcome many weaknesses of pureline cultivars by crossbreeding between two genetically distinct parents (Deliberto and Salassi, 2011). Hybrid rice is gaining an increased amount of attention because of yield and disease resistance superiority over pureline cultivars (Bueno and Lafarge, 2009). Hybrid rice cultivars are superior in terms of yield, competitiveness with weeds, ability to withstand environmental stresses, and resistance to diseases and insects (Deliberto and Salassi, 2011).

Studies have shown differences in processing between hybrid and pureline cultivars. Siebenmorgen et al. (2006) found that for the same milling duration, hybrids (XL7 and XL8) were milled to lower surface lipid contents than pureline cultivars (Cocodrie, Cypress, and Lemont) because of lower bran levels of hybrid cultivars. Lanning and Siebenmorgen (2011) noted the difference in milling characteristics of two pureline cultivars (Wells and Francis) and four hybrid cultivars (XL723, CLXL729, CLXL730, and CLXL745). To obtain the same degree of milling, hybrid cultivars required shorter milling durations than pureline cultivars due to lesser brown rice total lipid contents and greater bran removal rates (Siebenmorgen et al., 2012).

2.10 Parboiling

Parboiling is a hydrothermal process of rice, which consists of soaking, steaming, and drying steps. Rough rice is the common feedstock for parboiling, but brown rice is also used because it hydrates faster and requires less energy and shorter time than rough rice.
Long-grain cultivars are generally used for parboiling. The caryopsis of long-grain rice is long, slender, and rather flat, thus helping facilitate water and heat penetration into the center of the endosperm. Therefore, soaking and heating are more effective for long-grain rice than for short- and medium-grain rice (Luh and Mickus, 1991).

**Soaking**

Soaking is the first step in which the rough rice is hydrated by soaking in water to a sufficient level for starch to gelatinize on the following heating step. Rough rice slowly absorbs water and reaches an equilibrium at approximately 30% MC when soaked at temperatures below gelatinization temperature. When rough rice is soaked at high temperatures above gelatinization temperature, the hydration rate increases exponentially after an initial lag period (Figure 2.7). Such an increase is caused by starch gelatinization, resulting in continuous hydration. After the grain moisture exceeds 30-32% wet basis, the hull splits open and no longer covers the endosperm. Rice grain continues to absorb more water, leading to leaching and deformation of the grain.

Soaking in hot water of 60 to 70°C and below gelatinization temperature is widely applied to parboiling because it reduces processing time. In addition to hydration of rough rice, soaking at such temperature also induces annealing effects (Jayakody and Hoover, 2008) and discoloration. Soaking at low temperatures needs more soaking time and could cause microbial fermentation; soaking at high temperatures could lead to husk splitting, gelatinization, and deformation of the grains (Bhattacharya, 2004). Kaddus Miah et al. (2002) described that hot soaking (80°C) increased the diffusion rate of water into the grains and drove water into the void spaces of endosperm to seal the internal fissures of the grains.
Ali and Bhattacharya (1980) reported that free amino acids and sugars considerably changed during soaking. A decrease in sucrose content was noted with progressive soaking temperature because of an enzymatic conversion of sucrose into reducing sugars. Free amino acids slightly increased with increasing soaking temperature. Lambert et al. (2008) proved that soaking at 50°C for 30 min caused enzymatic conversion of sucrose into reducing sugars (glucose and fructose) that leached out of the bran layer to soaking water. These products are precursors of Maillard reaction responsible for the discoloration of parboiled rice.

**Steaming**

Steaming is the process in which gelatinization takes place because the applied steam temperature is greater than the starch gelatinization temperature. Rough rice needs to be heated until fully gelatinized to avoid the presence of white belly kernels in parboiled rice products. Another cause of white bellies is the imbalance of final moisture equilibrium inside the grains after soaking. During soaking, if the moisture unevenly distributes throughout the grain, in
particular, moisture at the center is too low for the starch to gelatinize at steaming temperature, white bellies can be formed (Bhattacharya, 2004).

During steaming, the moisture content of the rough rice increases because of the additional water from condensation. Water-soluble substances such as B vitamins and minerals are dissolved and migrate into the inner part of the grains. Starch-lipid complexes also form. The protein bodies are disrupted and protein solubility is reduced. Moreover, enzymes and undesirable processes such as germination and proliferation of fungus spores, eggs and insects are inactivated (Luh and Mickus, 1991). The total amylose content remained unchanged (Raghavendra Rao and Juliano, 1970). However, Patindol et al. (2008) recently noticed a decrease in amylose content in rough rice and brown rice (Bolivar, Cheniere, Dixiebelle, Wells) after soaking at 65°C for 2 h following by steaming at 100°C or 120°C for 20 min as a result of leaching.

**Drying**

Following steaming, rough rice must be dried to 12-14% moisture for safe storage and high milled rice yield. During drying, the re-association of gelatinized starch occurs, i.e. retrogradation, which affects milling quality, volumetric expansion, water uptake, cooking time, as well as cooking and eating quality such as hardness and adhesiveness (Bhattacharya, 2004). Many methods have been applied to dry parboiled rice. Traditionally, it is dried in the sun, but a high percentage of broken kernels is obtained (Bhattacharya, 2004). Heated air, infrared, and microwave energy are some examples of present heating sources for drying.

Drying of parboiled rice is different from drying raw rough rice because the moisture content of the former is high at the beginning, and its starch granules are partially or completely gelatinized, therefore water mobility is low. As a consequence, moisture removal is easy at the
beginning and becomes more difficult afterwards. Buggenhout et al. (2013) suggested that a tempering step was needed to decrease the moisture gradients inside the kernels before moisture content drops below the critical moisture content (CMC; 15-20%) that induces fissuring. This process is employed by drying parboiled rice rapidly to the CMC, followed by subsequent slow drying to the final moisture content. Bhattacharya et al. (1971) applied two-stage drying with an intermediate tempering at 16-18% MC for 4 to 8 h before slow drying at the later step to reduce breakage of parboiled rice. In modern processes, rotary and fluidized bed dryers have been used in the first stage of drying.

Bualuang et al. (2013) compared drying efficiency between hot air and infrared to dry parboiled medium-grain rice and found that head rice yield of parboiled rice dried with heated air and a combination of hot air and infrared was slightly higher than that with infrared drying alone. This is possibly because at the beginning of drying the fast drying rate of infrared method causes high stress in grain kernels, causing more fissured rice kernels.

Production system

Traditionally, rough rice is soaked at ambient temperature until saturated, steamed in small kettles, and then dried by the sun. This practice can cause microbial fermentation and undesirable odor (Bhattacharya, 2004). Modern processes are developed to overcome this problem by soaking rough rice in hot water, approximately 70°C, for 3 to 4 h (Bhattacharya, 2013). Practically, there are many parboiling systems available among processors, as shown in Figure 2.8. Process a is called ‘single parboiling’. The rough rice is soaked in ambient water for approximately 3 days and steamed for a few min before drying in the yard. The ‘double-boiling’ method (Process b) is processed by steaming the rough rice prior to soaking for 24-36 h in order to reduce soaking time. Then, after soaking, rough rice is steamed and dried.
Modern processes were developed in Europe and the United States using a hot soaking technique (Process c). The rough rice is soaked with hot water for 3-4 h at ~70°C together with continuous recirculation of water. After that, rough rice is steamed and dried either by a rotary dryer of hot air dryer.

Process d is modified, based upon the work of Ali and Bhattacharya (1982) stating that soaking rice until reaching at 30% MC was not necessary. Twenty-four percent MC spreading evenly throughout the grain was sufficient for starch to gelatinize during normal atmospheric steaming. Lower moisture contents would be adequate if rough rice is steamed under high pressure. In this ‘short-soaking-tempering’ system, the rough rice is partially soaked to ~24% moisture content prior to tempering to equilibrate the moisture within the kernels.

There are many different versions of parboiling system such as ‘soak-only’, ‘pressure parboiling’, and ‘dry-heat parboiling’ system. In soak-only system, the rough rice is soaked in hot water for a sufficiently long time for full gelatinization. Pressure parboiling is done by briefly soaking rough rice before steaming under high pressure, and is applied for producing puffed rice and canned rice. Dry heating parboiling is the system that replaces the steaming process by high-temperature short time (HTST) treatment. Another modification is the use of brown rice as raw materials instead of rough rice to save production energy because brown rice rapidly hydrates. Brown rice is soaked in ambient or warm water until reaching moisture saturation. Then it is heated either by hot air or steam for 15-30 sec, tempered, and dried (Bhattacharya, 2004).
Figure 2.8 Different processes of parboiling. kpscg = kg/cm² gauge; m = moisture; HTST – high-temperature, short time.

All degrees are Celsius (Bhattacharya, 2004)
2.11 Changes of characteristics of rice after parboiling

Physical appearances

After parboiling, rice grain changes from opaque to translucent in appearance. Milled parboiled rice is shorter and broader than milled raw rice, possibly because of the irreversible swelling of starch granules (Bhattacharya and Ali, 1985). This change only occur in the parboiling processes under excess water, not in the limiting water processes such as dry heat and pressure parboiling (Bhattacharya, 2004).

In addition, the kernel becomes harder after parboiling (Raghavenda Rao and Juliano, 1970). The hardness of rice kernel decreased with an increase in soaking temperature (Pillaiyar and Mohandoss, 1981) and steaming time (Kar et al., 1999). Saif et al. (2004) reported that parboiling increased the ultimate tensile strength by 4-5 times and increased the modulus of elasticity of the rice kernel. The steaming duration and the degree of starch gelatinization were also correlated with these strength values. This strength reflected greater capacities of rice kernels to resist to any forces applied to them during milling of parboiled rice.

The color of rice changes from white to light yellow to amber depending on the severity of heat treatment. This discoloration is caused by the Maillard reaction and the bran components that migrate into the endosperm. Bhattacharya and Subba Rao (1966) found that hot soaking and steaming at high pressure were highly correlated with the color change because the husk cracked and husk pigment absorbed into the grain as a consequence. Soaking at higher temperatures and longer durations greatly contributed to the higher degree of changes in grain color. Steaming at high pressure also intensified the discoloration of the grains (Bhattacharya, 1996).

Moreover, chalkiness is eliminated after parboiling (Singh et al., 2013). Bhattacharya
(2004) postulated that gelatinized starch granules and disrupted protein bound to each other to form a compact mass that diminished light scattering at the boundaries of the granules. In addition, Bhattacharya (2011) proposed that the removal of chalkiness was due to starch gelatinization and water diffusion that filled air spaces within kernels.

**Milled rice yield and head rice yield**

Parboiling is an effective way to improve head rice yield; however, head rice yield of parboiled rice is affected by the parboiling conditions and the resulting changes in physico-chemical and mechanical properties. Head rice yield is greatly improved because of the removal of fissures and chalkiness. Nevertheless, improper parboiling may cause fissuring and white bellies, thus lowering head rice yield.

The severity of a parboiling treatment affects head rice yield. Patindol et al. (2008) compared head rice yield of brown rice steamed at 100°C for 20 min and that steamed at 120°C for 20 min. The severe one resulted in 89.6% head rice yield whereas the mild one had only 62.6%. The higher degree of starch swelling and gelatinization help strengthen the resistance to forces applied to rice kernels during milling. Kaddus Miah et al. (2002) suggested that in order to obtain a maximum head rice yield, the rice should be fully gelatinized or reach at least 40% degree of gelatinization as measured by differential scanning calorimetry.

**Pasting and thermal properties**

After parboiling, the swell ability and water-binding capacity of starch decreased, resulting in a decrease in pasting profile and peak viscosity (Raghavendra Rao and Juliano, 1970; Himmelsbach et al., 2008; Patindol et al., 2008). Gelatinization occurring in the parboiling
process disrupts starch granules, making gelatinized starch not be able to swell as much as native starch. Furthermore, the more compact structure of starch resulting from retro-gradation could inhibit swelling (Ali and Bhattacharya, 1980).

**Cooking quality**

Parboiling increased the required energy for cooking because the water uptake rate of parboiled rice was less than that of non-parboiled rice, resulting in longer cooking durations (Bhattacharya and Sowbhagya, 1971; Roy et al, 2004; Billiris et al., 2012). Cooked parboiled rice is less sticky, firmer and fluffier compared with non-parboiled rice (Ramesh et al., 2000). The hardness of cooked parboiled rice increased with the severity of parboiling conditions because of the reassociation of gelatinized starch (Ali and Bhattacharya, 1980). Formation of protein complexes linked by disulfide bonds during parboiling limited the leaching of solids during cooking, thus increasing hardness and reducing the stickiness of cooked rice (Derycke et al., 2005).

Water uptake ratio, volume expansion, and leached solids during cooking also reduced after parboiling (Islam et al., 2001; Patindol et al., 2008). Water uptake and volume expansion were strongly associated with leached amylose. Parboiling resulted in more organized and dense structures of amylose and amylopectin, thus minimizing the hydration that easily occurs at the amorphous area and impeding the leaching of amylose molecules. Moreover, during parboiling, lipids form complexes with amylose molecules, which retard the swelling and the solubilization of starch molecules during cooking (Gray and Schoch, 1962). Amylose-lipid complexes are heat stable; therefore, the higher the level of crystalline amylose-lipid complexes formed during parboiling, the firmer the texture of cooked parboiled rice (Ong and Blanshard, 1995).
Islam et al. (2001) found a strong positive relationship between maximum viscosity and volume expansion ratio of cooked rice (R = 0.94, 0.89, 0.99 for the steam temperature of 105, 110, and 120°C, respectively). In addition, total solid contents had a highly positive correlation with adhesion or stickiness of cooked rice (R = 0.94 and 0.96 for steaming temperature of 105°C and 120°C, respectively). Parboiling reduced the solid content in the cooking gruel because of the formation of more ordered structure of starch as well as complexes of starch granules and protein bodies.
2.12 LITERATURE CITED


CHAPTER 3

IMPACT OF SOAKING AND DRYING CONDITIONS ON RICE CHALKINESS AS REVEALED BY SCANNING ELECTRON MICROSCOPY

3.1 ABSTRACT

Chalkiness is one of the most influential factors on head rice yield. Parboiling is known to be an effective way to remove chalkiness and improve head rice yield. However, the steps involved in the removal of chalkiness are still not completely resolved. This study investigated the effects of soaking temperature, soaking duration as well as drying condition on the removal of rice chalkiness. Chalky brown rice kernels were selected and soaked at 25, 65, 70, or 75°C for 3 h. After 1, 2, or 3 h, the rice samples were frozen before drying or immediately dried. Soaking at 25°C did not remove chalkiness and caused no morphological change in starch granules. When the soaking temperature increased from 25 to 65,70, and 75°C, the chalkiness decreased from 100% to 34.1, 29.7, and 15.9%, respectively. Soaking rice at temperatures above starch glass transition temperature but below gelatinization temperature reduced chalkiness due to rearrangement of starch granules and protein denaturation to fill the void spaces in the chalky area. During soaking, the morphology of starch granules also changed from round to angular in shape. Drying at temperatures above starch glass transition temperature also facilitated rearrangement of starch granules to further reduce rice chalkiness.
3.2 INTRODUCTION

Chalkiness is one of the most important characteristics determining rice quality and consumer acceptance. Chalky portions of kernels appear opaque, and mainly occur at the center of kernels. Chalkiness is mainly influenced by cultivars and environmental conditions. Lisle et al. (2000) proposed that formation of chalky grains under high temperature stress resulted from inefficient packing of starch in a greenhouse study. Lanning and Siebenmorgen (2011) attributed chalk formation to an increase in nighttime air temperatures that interrupted the grain filling stages. Starch granules are loosely packed and round in shape in chalky kernels, but angular and tightly packed in translucent kernels (Singh et al., 2003). Chalkiness not only reflects an undesirable appearance but also contributes to a decrease in head rice yield because chalky kernels tend to be more susceptible to forces applied during milling (Webb, 1991).

Parboiling is a hydrothermal process involving soaking, steaming, and drying. The goal of traditional parboiling is to extend shelf life, improve resistance to insects, and prevent microbial contamination. Bhattacharya (1969) reported that parboiling also improved head rice yield and removed chalkiness. Raghavendra Rao and Juliano (1970) proposed that after parboiling, gelatinized starch granules and disrupted protein bodies bound to each other to form a compact mass that diminished light scattering at the boundaries of the granules, thus removing chalkiness.

Soaking is the first step of parboiling, in which rough rice or brown rice is soaked in excess water to reach ~30% moisture content (MC) to enable starch to gelatinize in the following steaming step. To date, there is little work regarding the impact of soaking on chalkiness. Therefore, the aim of this study was to investigate the impact of soaking and drying conditions on starch morphology as related to rice chalkiness.
3.3 MATERIALS AND METHODS

Materials

XL753, a long-grain hybrid rice cultivar, from the 2012 crop year was obtained from the University of Arkansas Rice Processing Program at 12.0% MC (Fayetteville, Arkansas) with an onset gelatinization temperature (T\text{o}) of 78.1°C as determined by differential scanning calorimetry using brown rice flour. This cultivar was selected due to a high percentage of chalkiness. Rough rice was dehulled using a Satake THU-35 dehusker (THU-35, Satake Corp., Hiroshima, Japan). Broken kernels were separated by a double-tray sizing device (Seedburo Equipment Co., Chicago, IL). Chalky kernels were sorted from whole kernels by visual observation, and the kernels with 100% chalkiness were used in this study.

Soaking conditions

Two grams of chalky brown rice kernels was soaked in 20 mL of water in a water bath at 25, 65, 70 or 75°C for 3 h and then dried at 26°C and 65% RH for 2 days to reach 12% MC. The soaking temperatures were selected to be above the glass transition temperature (T\text{g}), which was 60°C at 12% MC (Siebenmorgen et al., 2004), but 3-10°C below T\text{o} of XL753.

Drying conditions

Because the soaking temperature of 75°C provided the most significant decrease in chalkiness, it was chosen to study the impact of drying conditions on chalkiness. Two grams of chalky brown rice kernels with 100% chalkiness were soaked in 20 mL of water in a water bath at 75°C for 1, 2, or 3 h. Rice kernels were removed and dried at 26°C and 65% RH for 2 days or immediately frozen at -80°C for 72 h prior to drying either in an EMC chamber as before or under vacuum at 200 mTorr for 24 h to a final MC of ~12%. Freezing prior to drying was intended to retain the morphology of starch granules after soaking for observation.
Chalkiness

The percentage of chalkiness was measured using an image analysis system (Winseedle™ Pro 2005a Regent Instruments Inc., Sainte-Foy, Quebec, Canada). One hundred kernels were placed in a tray made of a 2-mm thick clear acrylic sheet (150×100 mm) with no kernel touching another, and then imaged with a scanner (Epson Perfection V700 Photo, Model# J221A, Seiko Epson Corp., Japan). The program differentiated the chalky areas in the rice kernels based on a background color, and calculated percent chalkiness as the chalky areas in the rice kernels over total projected area of 100 kernels.

Morphology

The morphology of translucent, chalky and treated rice kernels was observed using a scanning electron microscope (PHILIPS XL30, FEI-Phillips, Hillsboro, OR) at an accelerating voltage of 10 kV. The rice kernel was manually cracked crosswise, mounted on an aluminum stub with double-stick tape, and then coated with 20 nm of gold in a vacuum evaporator for 2 min. Representative micrographs of each sample were taken at 2000× magnification.

Statistical analysis

All experiments were conducted at least in replicate, and the differences between means were analyzed with JMP software version 12.0.0 (SAS Software Institute, Cary, NC) using analysis of variance (Tukey’s HSD test) with significant level at 0.05.

3.4 RESULTS AND DISCUSSION

The percentage of chalkiness remained unchanged at 100% when chalky brown rice kernels were soaked at 25°C for 3 h, but significantly decreased to 34.1, 29.7, and 15.9 when the soaking temperature was increased to 65, 70, and 75°C, respectively (Table 3.1). These results indicate that soaking at a temperature above $T_g$ but slightly below $T_o$ of starch reduced
chalkiness, presumably because starch transition from a glassy state to a rubbery state at that
temperature to rearrange into a more packed structure. The decrease in chalkiness was more
pronounced when the soaking temperature was closer to $T_o$. It is hypothesized that besides
starch, proteins also played an important role in the reduction of chalkiness during soaking.
Proteins are mobile at a temperature above -73°C (Ringe and Petsko, 2003), and albumin and
glutelin in rice proteins denature at ~46°C and 74°C, respectively (Adebiyi et al., 2009). Hence,
at the soaking temperatures of 65, 70 and 75°C, albumin was denatured, and glutelin became
denatured at 75°C. The unfolding of these proteins could fill the void spaces in the chalky area,
thus reducing chalkiness. Because glutelin is the predominant protein in rice (~75-90%) (Juliano,
1985), a more pronounced reduction of chalkiness was observed when glutelin was denatured by
soaking rice at 75°C.

Freezing was found to slow the reduction of chalkiness when comparing the frozen and
unfrozen rice dried in an EMC chamber, implying that freezing rendered starch molecules
immobile during drying, thus impeding the rearrangement of starch granules. On the other hand,
significant reduction of chalkiness in unfrozen rice dried in the EMC chamber indicates that
starch molecules were still capable of rearranging during drying, leading to further reduction of
chalkiness (Table 3.1). According to Zeleznak and Hoseney (1987), the $T_g$ of starch was below
room temperature when the MC was above 22%. Therefore, at the initial drying, the temperature
in the EMC chamber (26°C) was still above the $T_g$ of starch, thus starch molecules were still
mobile until the $T_g$ increased to above the drying temperature. Nevertheless, the impact of
soaking duration was more pronounced than that of drying method as evidenced by the larger
sum of squares, and their interaction was also significant (Table 3.2).
The morphological characteristics of the cross-section of translucent and chalky rice kernels, as revealed by SEM (Fig. 3.1), agree with the findings of Singh et al. (2003) that starch granules in translucent kernels were tightly packed and angular in shape, whereas those in chalky kernels were loosely packed and round in shape. The morphology of starch granules in a rice kernel soaked at 25°C for 1-3 h (Fig. 3.2A) remained similar to that of the chalky kernels (Fig. 3.1), indicating that a soaking temperature of 25°C was not sufficient to cause changes in starch morphology and supporting the chalkiness results (Table 3.1). Soaking at 75°C, regardless of the drying condition, caused the change of compound starch granules in chalky kernels from round to angular in shape and from loose to more packed (Fig. 3.2B-D), similar to those in translucent kernels (Fig. 3.1). These changes were attributed to starch swelling and rearrangement as well as protein denaturation, as previously explained. The change in morphology of starch granules was observed from the first hour and became more distinct after 2 h of soaking for all drying conditions.

The starch granules were smaller in size and more tightly packed after soaking for 2 or 3 h and followed by EMC drying without prior freezing (Fig. 3.2D). The results suggest that both soaking and drying at temperatures above the T_g of starch contributed to the reduction of rice chalkiness. Therefore, rice chalkiness may be removed not only by the gelatinization of starch and disruption of protein bodies by parboiling as previously proposed by Raghavendra Rao and Juliano (1970), but also by the swelling and rearrangement of starch granules and protein denaturation during soaking.
3.5 CONCLUSIONS

Soaking rice at temperatures above starch glass transition temperature but below gelatinization temperature reduced chalkiness due to rearrangement of starch granules and protein denaturation to fill the void spaces in the chalky area. In addition, drying at temperatures above starch glass transition temperature also facilitated rearrangement of starch granules to further reduce rice chalkiness.


Table 3.1 Percentage of chalkiness after soaking at varying temperatures for 1-3 h before drying under different conditions

<table>
<thead>
<tr>
<th>Soaking</th>
<th>Freezing</th>
<th>Drying</th>
<th>Soaking durations (h)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>25°C</td>
<td>No</td>
<td>EMC^1</td>
<td>NA^2</td>
<td>NA</td>
<td>100^a</td>
<td></td>
</tr>
<tr>
<td>65°C</td>
<td>No</td>
<td>EMC</td>
<td>NA</td>
<td>NA</td>
<td>34.1^b</td>
<td></td>
</tr>
<tr>
<td>70°C</td>
<td>No</td>
<td>EMC</td>
<td>NA</td>
<td>NA</td>
<td>29.7^c</td>
<td></td>
</tr>
<tr>
<td>75°C</td>
<td>No</td>
<td>EMC</td>
<td>NA</td>
<td>NA</td>
<td>15.9^e</td>
<td></td>
</tr>
<tr>
<td>75°C</td>
<td>Yes</td>
<td>Vacuum</td>
<td>24.8^a, AB</td>
<td>29.2^a, A</td>
<td>19.7^d, B</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>EMC</td>
<td>25.1^a, A</td>
<td>25.7^ab, A</td>
<td>19.8^d, B</td>
<td></td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>EMC</td>
<td>22.4^a, A</td>
<td>16.2^b, B</td>
<td>13.2^c, C</td>
<td></td>
</tr>
</tbody>
</table>

^1EMC drying was carried out at 26°C and 65% RH.
^2Not available.
^3Lower case letters represent statistical differences among different drying conditions under the same soaking durations.
^4Uppercase letters represent statistical difference among soaking durations under the same drying conditions.
Table 3.2 Analysis of variance (ANOVA) of percentage of chalkiness as affected by soaking duration, drying method and their interaction

<table>
<thead>
<tr>
<th>Factor</th>
<th>Prob &gt; F</th>
<th>Sum of Squares</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soaking duration</td>
<td>&lt;0.0001</td>
<td>41534</td>
</tr>
<tr>
<td>Drying method</td>
<td>&lt;0.0001</td>
<td>210</td>
</tr>
<tr>
<td>Interaction</td>
<td>&lt;0.0001</td>
<td>159</td>
</tr>
</tbody>
</table>

*Root mean square error = 1.1, $R^2 = 0.99$. 
Figure 3.1 Scanning electron micrographs of cross-section of (A) translucent and (B) chalky kernels at 2000× magnification.
Figure 3.2 Scanning electron micrographs of cross-section of rice kernels after soaking for 1, 2, or 3 h.

A: soaking at 25°C and drying in an Equilibrium Moisture Content (EMC) chamber.
B: soaking at 75°C, freezing, and drying by vacuum.
C: soaking at 75°C, freezing, and drying in an EMC chamber.
D: soaking at 75°C and drying in an EMC chamber.
CHAPTER 4

EFFECT OF SOAKING TEMPERATURE ON COMMINGLED RICE PROPERTIES

4.1 ABSTRACT

Parboiling involves soaking, steaming, and drying, which all have impacts on the quality of parboiled rice. Using commingled rice with a wide range of gelatinization temperature as a feedstock may lead to parboiled rice with inconsistent quality. This study investigated the effects of soaking temperature and commingling on rice properties prior to steaming in the parboiling process. Rough rice of four cultivars (Taggart, CL151, XL753, and CL XL745) were combined at 1:1 weight ratio, soaked at 65\(^\circ\), 70\(^\circ\) or 75\(^\circ\)C for 3 h, dried, and evaluated for milling and physicochemical properties. Both soaking temperature and difference in onset gelatinization temperature (T\(_o\)) of individual cultivars in commingled rice affected milling and physicochemical properties. The head brown rice yield (HBRY) increased with increasing soaking temperature and was greater when the soaking temperature was closer to the T\(_o\). The chalkiness decreased with increasing soaking temperature. The soaking temperature increased T\(_o\) and reduced gelatinization range of all single and commingled rice samples. Soaking at 65 and 70\(^\circ\)C increased the peak pasting viscosity of most samples, but soaking at 75\(^\circ\)C reduced peak pasting viscosity. Soaking rice at temperatures close to T\(_o\) increased HBRY, reduce chalkiness, but may also yield a darker, yellower rice due to the diffusion of pigments from hull and bran layer into endosperm. Soaking at 70\(^\circ\)C increased HBRY of most commingled rice samples and reduce the greatest percentage of chalkiness, thus possibly minimizing the varietal difference of commingled rice.
4.2 INTRODUCTION

Parboiled rice has been used in many applications such as canned rice, instant rice, ready-to-eat meals, and puffed cereals because of its ease of cooking and improved heat stability. Parboiling is a hydrothermal process involving soaking, steaming, and drying steps. Rough rice or brown rice is first soaked in excess water to become hydrated to allow starch gelatinization in the following steaming step. Drying is followed to dehydrate the rice kernels to approximately 12% moisture content (MC) for safe storage and good milling quality. The changes in rice properties after parboiling such as milling, physicochemical, cooking, and eating qualities are primarily attributed to the changes in starch as a result of gelatinization and retrogradation, although minor compositions like proteins and lipids also have influences on parboiled rice properties (Bhattacharya, 2004).

Soaking is an important step in the parboiling process. Rough rice is required to absorb water and reach equilibrium moisture content of approximately 30% for proper hydration (Gariboldi, 1974). The amount of absorbed water is dependent on soaking temperature and soaking duration. Bakshi and Singh (1980) reported that soaking at high temperatures increased diffusion coefficients, which leads to an increase in hydration as well as a reduction in soaking duration, thus preventing enzymatic reaction and microbial fermentation that could cause discoloration and off-flavor in parboiled rice. Bhattacharya and Subba Rao (1966) suggested that maximum milling yields and minimum breakages were obtained if rice kernels absorbed sufficient water during the soaking step. Chung et al. (1990) found an increase in head rice yield of parboiled rice with increasing soaking temperature of 50, 60, or 70°C for 5, 4, or 3.5 h, respectively. Sareepuangs et al. (2008) also observed the same trend when soaking rice at 40, 50, or 60°C for 3 h.
Recently, the development of rice breeding program causes a drastic increase in the number of rice cultivars in the U.S., particularly hybrid cultivars. Studies have shown differences in milling characteristics between hybrid and pureline cultivars. Siebenmorgen et al. (2006) found that for the same milling duration, hybrids (XL7 and XL8) were milled to lower surface lipid contents than pureline cultivars (Cocodrie, Cypress, and Lemont), which was proposed to be due to a thinner bran layer in hybrid cultivars. Lanning and Siebenmorgen (2011) noted differences in milling characteristics between two pureline cultivars (Wells and Francis) and four hybrid cultivars (XL723, CL XL729, CL XL730, and CL XL745). Siebenmorgan et al. (2012) showed that hybrid cultivars required shorter milling durations than pureline cultivars to obtain the same degree of milling.

Basutkar et al. (2014) studied the effects of commingling (pureline/pureline, pureline/hybrid, and hybrid/hybrid) on milling properties of long-grain rice cultivars by mixing the rice cultivars into varying ratios (0:100, 10:90, 25:75, 50:50, 75:25, 90:10, and 100:0). They found that the milling duration to reach the same degree of milling (0.4% surface lipid content) for each commingled sample varied with the ratio of individual cultivar in a commingled sample. The whiteness and yellowness of milled rice were not significantly affected by commingling. Commingling, however, had an influence on the milled rice yield, head rice yield, and chalkiness, which could be predicted by calculating the weight average of the individual cultivar for each property. Basutkar et al. (2015) suggested that commingling of rice may cause inconsistent quality of products especially when there was a great difference in onset gelatinization temperature ($T_o$) of the rice cultivars in commingles. The $T_o$ of commingled rice was governed by the rice cultivar with the lower $T_o$. The pasting viscosities of commingled rice changed proportionally according to the mass percentage of each cultivar in commingles.
It was hypothesized that using commingled rice with different $T_\circ$ as a feedstock for parboiling may cause inconsistent quality of parboiled rice. Because soaking is the first step of parboiling where rice is subjected to heat, this study aimed at investigating the impacts of varying soaking temperatures on the milling and physiochemical properties of commingled rice.

4.3 MATERIALS AND METHODS

Materials

Rough rice of long-grain pureline (Taggart and CL151) and hybrid (CL XL745 and XL753) cultivars from the 2012 crop year were used in this study and obtained from the University of Arkansas Rice Processing Program (Fayetteville, AR). These cultivars were selected because they had the least and the greatest $T_\circ$ among pureline and hybrid cultivars available from the 2012 crop year, as measured by a differential scanning calorimeter, of 72.1, 74.2, 73.3, and 78.1°C for Taggart (T), CL151 (CL), CLXL745 (CLXL), and XL753 (XL), respectively. Six possible combinations of commingled rice samples were prepared using a 1:1 ratio based on rough rice weight (approximately at 12.5% MC). The rough rice was accurately weighed and mixed 5 times, 2 min each time, using a rotary rice grader (TRG, Satake, Tokyo, Japan).

Soaking conditions

Soaking temperatures were chosen at 3-5°C below $T_\circ$ of individual and commingled rice samples. Rough rice (100 g) was soaked in 250 mL of deionized water in a water bath at 65°, 70°, or 75°C for 3 h in order to reach a minimum 30% MC. The soaked rice was then dried at room temperature overnight and afterwards at an equilibrium moisture content (EMC) chamber at 26°C and 65% RH for 2 days to reach ~12% MC.
Head brown rice yield

Dried rough rice was dehulled using a Satake THU-35 dehusker (THU-35, Satake Corp., Hiroshima, Japan). The broken brown rice kernels were separated by a double-tray sizing device (Seed bureo Equipment Co., Chicago, ILL). Head brown rice yield was expressed as a percentage of head brown rice mass to dried rough rice mass.

Physical properties

The color of brown rice was measured using a Hunter lab digital colorimeter (Colorflex EZ, Hunterlab, Reston, VA.) and chalkiness was measured by an image analysis system (Winseedle™ Pro 2005a Regent Instruments Inc., Sainte-Foy, Quebec, Canada). Several chalky and translucent kernels were scanned and used as references for the system to classify the chalk and translucent area based on number of pixels. To determine the chalkiness, one hundred random rice kernels were placed in a tray made from a 2-mm thick clear acrylic sheet (Plexiglass) with no grain touching each other, and then imaged with a scanner (Epson Perfection V700 Photo, Model# J221A, Seiko Epson Corp., Japan). The system measured the number of pixels and classify them according to the pre-set criteria. Chalkiness was expressed as percentage of the number of pixels in chalky area over the number of pixels in total kernel projected area.

Gelatinization properties

Brown rice was ground into flour using a UDY cyclone sample mill (UDY Corp., Ft. Collins, CO) fitted with a 0.50-mm sieve. The gelatinization properties of rice samples were determined using a differential scanning calorimeter (DSC, Diamond, Perkin-Elmer Co., Norwalk, CT). Approximately 4 mg of brown rice flour was measured into an aluminum sample pan and added with 8 µL of deionized water. The sample pans were then sealed and kept at room
temperature for one hour prior to scanning from 25°C to 120°C at 10.0°C/min. Onset (T₀), peak (Tₚ), and conclusion (T_c) temperature as well as gelatinization enthalpy (ΔH) were determined.

**Pasting properties**

The pasting properties of brown rice flour were characterized using a Rapid ViscoAnalyser (Newport Scientific Pty. Ltd, Warriewood, NSW, Australia). Rice slurry was prepared by mixing 3.0 g of rice flour (12% moisture basis) with 25.0 mL of water, and heated from 50°C to 95°C at 4°C/min, held at 95°C for 5 min, and then cooled to 50°C at 4°C/min and held at 50°C for 2 min. Data were collected using the RVA software – Thermocline for Windows.

**Statistical analysis**

Experiments were conducted in triplicate. Analysis of variance (ANOVA) was used to evaluate the effects of soaking temperatures, T₀ difference and their interaction, as well as the importance of these factors on head brown rice yield, chalkiness, color, as well as gelatinization and pasting properties. Mean differences were evaluated by Tukey HSD test. All statistical analyses were carried out at α = 0.05 using JMP software version 12.0.0 (SAS Software Institute, Cary, NC) using at α = 0.05.

**4.4 RESULTS AND DISCUSSION**

**4.4.1 Physical properties**

*Head brown rice yield*

The effects of soaking temperature on head brown rice yield (HBRY) varied with cultivars and commingles (Table 4.1). In the present study, HBRY was used to represent the milling yield of rice after soaking instead of head milled rice yield in order to avoid the influence of chalky kernels that tend to break during milling. The rough rice that was not subjected to
soaking was used as a control. The HBRY of all individual rice cultivars, except XL753 (XL), increased with increasing soaking temperature, and the highest HBRY was obtained when the soaking temperature was closer to but still below the $T_o$. The HBRY obtained after soaking at 75°C was slightly lower than those at 70°C.

The increase in HBRY is proposed to result from a reduction of fissured kernels that may break during milling (Cnossen et al., 2003). Recently, Buggenhout et al. (2014) proposed that fissures initially developed and thereafter gradually disappeared over the course of soaking. The fissures were visually inspected, and kernels with at least one visible fissure were considered as fissured. They observed that during the initial period of soaking (5 to 25 min), fissures increased up to more than 90% based on brown rice mass, remained steady, and then decreased when MC reached a certain level. This MC level varied with soaking temperature, for example, 28% and 31% MC for 55 and 40°C, respectively. A drastic reduction of fissures was observed when MC reached equilibrium at approximately 33%. They also suggested that higher soaking temperatures affected a greater extent of water absorption and starch swelling, leading to a greater fissure reduction, which is supported by the present results of increasing HBRY with increasing soaking temperature close to but not above $T_o$. The reduced HBRY obtained after soaking at above $T_o$ may be ascribed to excessive swelling of starch after gelatinization, leading to husk splitting (Bhattacharya and Subba Rao, 1966).

The HBRY of XL was significantly reduced at 65°C (13°C below $T_o$), but was close to that of its control when soaked at 75°C (3°C below $T_o$). Kunze and Hall (1965) reported that different rice cultivars had different equilibrium MC as well as different resistance to fissure, which can possibly explain the decrease in HBRY of XL when soaked at 65 and 70°C. XL may have a higher equilibrium MC than the others, and these two temperatures may not be sufficient
to affect MC to the level that can reduce a great number of fissures during soaking or to uniformly distribute moisture inside kernels, leading to moisture and/or temperature gradient that may cause fissures after drying.

Most commingled rice samples showed an increase in HBRY with increasing soaking temperatures, except that T/CL had a similar HBRY at 65, 70, and 75°C, and CL/CLXL had a slightly lower HBRY at 75°C than at 70°C. Moreover, the HBRY characteristic of individual rice cultivars can be observed in the commingles, for example, the decreased HBRY at soaking temperature of 65°C was also found in commingled rice containing XL.

The difference in $T_o$ between the two rice cultivars in commingled rice samples was 2.1, 1.2, 6.0, 0.9, 3.9, and 4.8°C for T/CL, T/CLXL, T/XL, CL/CLXL, CL/XL, and CLXL/XL, respectively. They can be divided into two groups according to $T_o$ difference: 1) T/CL, T/CLXL, and CL/CLXL with 1-2°C difference, and 2) T/XL, XLCL, and XL/CLXL with 4-6°C difference. When the differences in HBRY between the measured values and the calculated value based on weighted average were plotted against the different soaking temperatures (Fig. 4.1A), the group with a smaller $T_o$ difference better predicted HBRY. Therefore, using commingled rice with large $T_o$ difference would be more difficult to predict and manage to achieve the targeted properties.

**Chalkiness**

Chalkiness varied among cultivars with XL showing the highest chalkiness. Chalkiness decreased with an increase in soaking temperature, and was almost completely eliminated in individual rice cultivars when soaked at 75°C for 3 h (Table 4.2). The chalkiness of T, CL, and CLXL was reduced by 50-80% after soaking at 65°C for 3 h, but that of XL did not change until 70°C. These results show that soaking at temperatures close to or above $T_o$ helped remove
chalkiness. The change in chalkiness of commingled rice followed a similar trend as the individual cultivars. Commingled rice consisting of high \( T_o \) rice cultivars, such as CL and XL, required higher soaking temperatures to reduce chalkiness, and soaking at 75°C almost completely removed all chalkiness. The change in chalkiness of commingled rice samples was more accurately predicted by using weighted average chalkiness than HBRY (Fig. 4.1B).

Raghavendra Rao and Juliano (1970) proposed that the decrease in chalkiness after parboiling was caused by gelatinization of starch and disruption of protein bodies from the steaming step. However, the present results demonstrate that chalkiness was also removed by soaking alone. Recently, Leethanapanich and Wang (2015) observed that during soaking starch granules swelled and protein bodies rearranged to a more packed structure and filled void spaces, thus lowering chalkiness in rice. Adebiyi et al. (2009) reported that glutenin, the predominant protein in rice, had a denaturation temperature of 74°C. Therefore, the high soaking temperature of 75°C would have more influence on glutenin and consequently on chalkiness removal.

The reduction in chalkiness might be partially responsible for the increase in HBRY of most rice samples after soaking at 65 and 70°C because chalky kernels tend to break during milling (Bautista et al., 2009). However, it was noted that even though almost all chalkiness was removed after soaking at 75°C, the HBRY dropped for T, CL, CLXL, and CL/CLXL. As previously mentioned, soaking at temperatures above \( T_o \) resulted in husk splitting and deformed kernels, which could break and result in reduced HBRY during milling.
The color of brown rice samples became darker with lower \( L^* \) values and yellower with higher \( b^* \) values when soaking temperature increased (Table 4.1). Chung et al. (1990), Sareepuang et al. (2008), and Mir and Bosco (2013) observed a similar trend. The decrease in whiteness and increase in yellowness of parboiled rice have been ascribed to a result of migration of bran components into the endosperm and Maillard reaction between free amino acids and reducing sugars during soaking (Ali and Bhattacharya, 1980; Kimura et al., 1993; Lambert et al., 2008).

Nevertheless, the effect of soaking temperature on the extent of change in whiteness and yellowness varied among cultivars and commingles. In all commingled samples, the change in color was dominated by the cultivars that exhibited the most change. The whiteness of commingles with a large difference in color between the individual cultivars, such as CL/XL and CLXL/XL, tended to deviate from their weighted average (Fig. 4.1C). However, the predicted \( b^* \) of all samples appeared to be close to the actual values (Fig. 4.1D), possibly because of a small difference in \( b^* \) among individual rice cultivars. It is important to take the difference in color of individual rice cultivars into consideration when using commingled rice because a greater difference might result in inconsistent color in the finished products.

### 4.4.2 Gelatinization properties

Gelatinization temperatures \( (T_o, T_p, \text{ and } T_c) \) increased with increasing soaking temperature for all individual and commingled rice samples, and the increase became greater when the soaking temperature was close to \( T_o \) (Table 4.2). The increase in gelatinization temperature was attributed to an increase in starch crystallinity (Tester and Debon, 2000; Waduge et al., 2006), and the interactions of amylose-amylose and amylose-amylopectin during soaking from annealing (Adebowale et al., 2005).
For T/XL, the $T_p$ and $T_c$ were higher at 65°C than at 70°C, a trend that was different from the other samples and was attributed to inhomogeneous physical mixing of the two cultivars. Basutkar et al. (2015) proposed that the $T_o$ of commingled rice was determined by the rice cultivar with a lower $T_o$, and commingled rice with a great difference in $T_o$ may cause inconsistent quality of products. The present results support their findings and further demonstrate that this relationship remained after soaking at 65, 70, and 75°C for 3 h. For example, the $T_o$ of T/CL (72.5°C), T/CLXL (72.3°C), and T/XL (72.8°C) were close to the $T_o$ of T (72.1°C), and their increase in $T_o$ at increasing soaking temperature was similar to that of T.

Soaking temperature had little influence on gelatinization temperature range ($T_c-T_o$) of individual rice cultivars because $T_o$ and $T_c$ increased concurrently. The ($T_c-T_o$) was significantly larger in commingled rice than in individual rice because of the greater difference in $T_o$ and $T_c$ between the two individual rice cultivars. Nevertheless, the ($T_c-T_o$) decreased with increasing soaking temperature, and the impact of soaking temperature on ($T_c-T_o$) was affected by its range. Commingles with a large ($T_c-T_o$) required a higher soaking temperature to reduce ($T_c-T_o$) than those with a small ($T_c-T_o$). For example, the ($T_c-T_o$) of T/CL, T/CLXL, and CL/CLXL decreased after soaking at 65°C, whereas those of T/XL, CL/XL, and CLXL/XL did not change until soaking at 70°C. The present results imply that soaking reduced the difference in ($T_c-T_o$) in commingled rice, thus potentially minimize the varietal difference in commingled rice.

The $ΔH$ of all rice samples, except CL and T/CLXL, remained unchanged after soaking at different temperatures, although gelatinization temperatures increased during soaking from annealing. Lan et al. (2008) also found no change in $ΔH$ of wheat starches after annealing because no new double helices formation. It is also possible that some starch was gelatinized
after soaking at temperatures above $T_o$, thus lowering $\Delta H$, but the decreased $\Delta H$ was offset by the increased $\Delta H$ from annealing.

### 4.4.3 Pasting properties

The peak viscosity slightly increased at lower soaking temperatures, but decreased at 75°C for most rice samples (Fig. 4.2). The profiles of commingled rice samples were similar to those of individual rice cultivars, and strongly affected by the rice cultivars with high $T_o$, particularly XL753, as evidenced by the less significant decrease of peak viscosity at 75°C when XL753 was present in the commingled rice samples.

The reduced peak viscosity was proposed to mainly result from the interaction of denatured protein bodies with starch, which limited starch swelling, and to a less extent by the damage of starch granules (Derycke et al., 2005). The slight increase in peak viscosity at 65 or 70°C was proposed to be the result of annealing. Jacobs et al. (1996) observed an increase in peak and final viscosity of annealed rice starch. They proposed that annealing permitted amyllopectin molecules that were not perfectly ordered to rearrange into a more ordered structure. Therefore, annealed starch granules could swell to a larger volume than the native granules before disruption, thus increasing the peak viscosity. Dias et al. (2010) observed similar results from medium-amylose rice starch annealed at 45 and 50°C.

### 4.4.4 Relative importance of factors

The contributions of soaking temperature, $T_o$ difference, and their interactions on quality of commingled brown rice were analyzed by analysis of variance (Table 4.3). Rice properties including HBRY, chalkiness, whiteness, yellowness, gelatinization temperatures, and pasting viscosities, were strongly affected by both soaking temperature and $T_o$ difference of individual rice cultivars in commingled rice, and their interaction. Nevertheless, the relative impacts of
soaking temperature and $T_0$ difference on soaked rice properties were not the same as shown from different sum of square values that indicate the influence of each factor. Soaking temperature exerted more impacts on overall quality than did $T_0$ difference and their interaction. Chalkiness, $L^*$, $b^*$, $T_o$, $T_p$, and pasting viscosities were more influenced by soaking temperature, whereas HBRY, $T_c$, $(T_c-T_0)$, and $\Delta H$ were more influenced by $T_0$ difference. The influence of $T_0$ difference on HBRY was shown from the different effects of soaking temperature on different samples. In addition, breakage susceptibility was cultivar dependent and varied with the level of fissures, chalkiness, immaturity and kernel dimensions (Bhattacharya, 1969).

The prediction profile (Fig. 4.3) was created in order to illustrate the relationship of soaking temperature and $T_0$ difference with desirable properties. The highest desirability score was set for the condition that would give the highest HBRY, lowest percentage of chalkiness, lightest color, and least yellowness. Based on the present results, commingled rice with $T_0$ difference of 0.9°C had the highest desirability score at 0.69 when soaked at 70°C; commingled rice with $T_0$ difference of 6°C showed the highest desirability score at 0.49 when soaked at 75°C. This result indicates that using commingled rice with a greater $T_0$ difference was more likely to result in the parboiled rice with less desirable quality.

4.5 CONCLUSIONS

Soaking temperature and $T_0$ difference between individual rice cultivars in commingled rice significantly affected overall properties of commingled rice. Soaking rice at a temperature close to $T_0$ increased HRY and reduce chalkiness but also yielded a darker and more yellow rice. Using commingled rice with a great $T_0$ difference as a feedstock for parboiling can lead to undesirable quality characteristics. Increasing soaking temperature minimized the varietal
difference of commingled rice; however, potential gelatinization of low-\(T_o\) cultivars at high soaking temperatures changed the pasting profile when combined with high-\(T_o\) cultivars.
4.6 LITERATURE CITED


Table 4.1 Head brown rice yield, (HBRY) chalkiness, whiteness, and yellowness of Taggart, CL151, CL XL745, XL753, and their commingles after soaking at 65, 70, or 75°C for 3 h prior to drying to 12% MC, and their controls of no soaking.

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>Soaking Temperature</th>
<th>HBRY (%)</th>
<th>Chalkiness (%)</th>
<th>Whiteness (L*)</th>
<th>Yellowness (b*)</th>
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</thead>
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<tr>
<td>Taggart (T)</td>
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<td>22.1c</td>
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</tr>
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</tr>
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<td>0.0d</td>
<td>52.7d</td>
<td>23.3a</td>
</tr>
</tbody>
</table>

HSD
|       | 1.2 | 0.7 | 1.3 | 1.1 |

1Mean values followed by the same letter in the same column within the same sample are not significantly different based on Tukey’s HSD test.
2Onset gelatinization temperature measured by differential scanning calorimetry.
Table 4.1 Head brown rice yield, (HBRY) chalkiness, whiteness, and yellowness of Taggart, CL151, CL XL745, XL753, and their commingles after soaking at 65, 70, or 75°C for 3 h, and their controls of no soaking (Cont)

<table>
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<tr>
<th>Cultivar</th>
<th>Soaking Temperature (°C)</th>
<th>HBRY (%)</th>
<th>Chalkiness (%)</th>
<th>Whiteness (L*)</th>
<th>Yellowness (b*)</th>
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<tr>
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<td></td>
<td>89.9(^c)</td>
<td>4.4(^a)</td>
<td>61.2(^a)</td>
<td>21.9(^c)</td>
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<tr>
<td>70</td>
<td></td>
<td>91.3(^b)</td>
<td>2.0(^c)</td>
<td>60.4(^b)</td>
<td>23.3(^ab)</td>
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<tr>
<td>75</td>
<td></td>
<td>93.0(^a)</td>
<td>0.1(^d)</td>
<td>55.6(^c)</td>
<td>24.2(^a)</td>
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<tr>
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<td></td>
<td>97.2(^a)</td>
<td>1.4(^b)</td>
<td>56.9(^b)</td>
<td>22.3(^b)</td>
</tr>
<tr>
<td>70</td>
<td></td>
<td>97.0(^a)</td>
<td>0.7(^c)</td>
<td>55.4(^c)</td>
<td>22.2(^b)</td>
</tr>
<tr>
<td>75</td>
<td></td>
<td>96.5(^b)</td>
<td>0.0(^d)</td>
<td>53.5(^d)</td>
<td>23.1(^a)</td>
</tr>
<tr>
<td>CL/XL control</td>
<td>(74.9°C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>65</td>
<td></td>
<td>94.1(^a)</td>
<td>5.5(^a)</td>
<td>61.5(^a)</td>
<td>21.4(^b)</td>
</tr>
<tr>
<td>70</td>
<td></td>
<td>94.7(^a)</td>
<td>1.1(^c)</td>
<td>57.6(^c)</td>
<td>23.5(^a)</td>
</tr>
<tr>
<td>75</td>
<td></td>
<td>95.0(^a)</td>
<td>1.0(^c)</td>
<td>58.1(^c)</td>
<td>23.4(^a)</td>
</tr>
<tr>
<td>CLXL/XL control</td>
<td>(74.7°C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>65</td>
<td></td>
<td>92.3(^c)</td>
<td>3.4(^b)</td>
<td>61.0(^a)</td>
<td>22.1(^b)</td>
</tr>
<tr>
<td>70</td>
<td></td>
<td>94.5(^b)</td>
<td>1.9(^c)</td>
<td>59.0(^b)</td>
<td>23.1(^a)</td>
</tr>
<tr>
<td>75</td>
<td></td>
<td>95.8(^a)</td>
<td>0.0(^d)</td>
<td>54.4(^c)</td>
<td>23.8(^a)</td>
</tr>
<tr>
<td>HSD</td>
<td></td>
<td>1.2</td>
<td>0.7</td>
<td>1.3</td>
<td>1.1</td>
</tr>
</tbody>
</table>

\(^1\)Mean values followed by the same letter in the same column within the same sample are not significantly different based on Tukey HSD test.

\(^2\)Onset gelatinization temperature measured by differential scanning calorimetry.
Table 4.2 Gelatinization properties of Taggart, CL151, CL XL745, XL753, and their commingles after soaking at 65, 70, or 75°C for 3 h, and their controls of no soaking\(^1\)

<table>
<thead>
<tr>
<th>Cultivar/Commingle</th>
<th>Soaking Temperature (°C)</th>
<th>Gelatinization Temperature (°C)</th>
<th>ΔH (J/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T(_0)</td>
<td>T(_p)</td>
<td>T(_c)</td>
</tr>
<tr>
<td>Taggart control</td>
<td>72.1(^c)</td>
<td>78.0(^e)</td>
<td>84.0(^b)</td>
</tr>
<tr>
<td>(T) 65</td>
<td>73.3(^{bc})</td>
<td>78.8(^{bc})</td>
<td>84.5(^b)</td>
</tr>
<tr>
<td>70</td>
<td>75.2(^b)</td>
<td>80.6(^b)</td>
<td>87.1(^{ab})</td>
</tr>
<tr>
<td>75</td>
<td>79.9(^a)</td>
<td>84.8(^a)</td>
<td>90.3(^a)</td>
</tr>
<tr>
<td>CL151 control</td>
<td>74.2(^d)</td>
<td>80.1(^c)</td>
<td>84.9(^c)</td>
</tr>
<tr>
<td>(CL) 65</td>
<td>75.8(^e)</td>
<td>80.6(^c)</td>
<td>85.8(^e)</td>
</tr>
<tr>
<td>70</td>
<td>78.8(^{b})</td>
<td>83.0(^b)</td>
<td>88.5(^b)</td>
</tr>
<tr>
<td>75</td>
<td>81.3(^a)</td>
<td>85.7(^a)</td>
<td>91.8(^a)</td>
</tr>
<tr>
<td>CL XL745 control</td>
<td>73.3(^d)</td>
<td>78.7(^b)</td>
<td>85.0(^c)</td>
</tr>
<tr>
<td>(CLXL) 65</td>
<td>75.0(^{bc})</td>
<td>80.2(^b)</td>
<td>86.5(^{bc})</td>
</tr>
<tr>
<td>70</td>
<td>78.3(^b)</td>
<td>82.7(^a)</td>
<td>88.6(^{ab})</td>
</tr>
<tr>
<td>75</td>
<td>80.2(^a)</td>
<td>84.3(^a)</td>
<td>90.2(^a)</td>
</tr>
<tr>
<td>XL753 control</td>
<td>78.1(^c)</td>
<td>83.2(^b)</td>
<td>89.0(^b)</td>
</tr>
<tr>
<td>(XL) 65</td>
<td>78.0(^c)</td>
<td>83.0(^b)</td>
<td>88.5(^b)</td>
</tr>
<tr>
<td>70</td>
<td>79.8(^b)</td>
<td>84.6(^{ab})</td>
<td>90.1(^{ab})</td>
</tr>
<tr>
<td>75</td>
<td>81.5(^a)</td>
<td>86.4(^a)</td>
<td>92.2(^a)</td>
</tr>
<tr>
<td>T/CL control</td>
<td>72.5(^c)</td>
<td>79.1(^b)</td>
<td>85.4(^b)</td>
</tr>
<tr>
<td>(T) 65</td>
<td>74.3(^b)</td>
<td>80.0(^b)</td>
<td>86.3(^b)</td>
</tr>
<tr>
<td>70</td>
<td>74.1(^{bc})</td>
<td>79.7(^b)</td>
<td>86.2(^b)</td>
</tr>
<tr>
<td>75</td>
<td>79.0(^a)</td>
<td>83.9(^a)</td>
<td>89.6(^a)</td>
</tr>
<tr>
<td>T/CLXL control</td>
<td>72.3(^c)</td>
<td>78.5(^c)</td>
<td>84.9(^b)</td>
</tr>
<tr>
<td>(T) 65</td>
<td>74.4(^b)</td>
<td>79.5(^{bc})</td>
<td>85.6(^b)</td>
</tr>
<tr>
<td>70</td>
<td>75.8(^b)</td>
<td>81.0(^b)</td>
<td>87.1(^{ab})</td>
</tr>
<tr>
<td>75</td>
<td>79.4(^a)</td>
<td>83.8(^a)</td>
<td>89.4(^a)</td>
</tr>
<tr>
<td>HSD</td>
<td>2.1</td>
<td>2.5</td>
<td>3.1</td>
</tr>
</tbody>
</table>

\(^1\)Mean values followed by the same letter in the same column within the same sample are not significantly different based on Tukey’s HSD test.
Table 4.2 Gelatinization properties of Taggart, CL151, CL XL745, XL753, and their commingles after soaking at 65, 70, or 75°C for 3 h, and their controls of no soaking (Cont)\(^1\)

<table>
<thead>
<tr>
<th>Cultivar/Commingle</th>
<th>Soaking Temperature (°C)</th>
<th>Gelatinization Temperature (°C)</th>
<th>ΔH (J/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(T_o)</td>
<td>(T_p)</td>
</tr>
<tr>
<td>T/XL</td>
<td>control</td>
<td>72.8(^c)</td>
<td>82.5(^b)</td>
</tr>
<tr>
<td></td>
<td>65</td>
<td>75.3(^b)</td>
<td>84.2(^a)</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>74.8(^b)</td>
<td>81.2(^b)</td>
</tr>
<tr>
<td></td>
<td>75</td>
<td>78.6(^a)</td>
<td>85.7(^a)</td>
</tr>
<tr>
<td>CL/CLXL</td>
<td>control</td>
<td>73.3(^d)</td>
<td>79.9(^c)</td>
</tr>
<tr>
<td></td>
<td>65</td>
<td>76.2(^c)</td>
<td>81.0(^bc)</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>77.7(^b)</td>
<td>82.2(^b)</td>
</tr>
<tr>
<td></td>
<td>75</td>
<td>80.5(^a)</td>
<td>84.6(^a)</td>
</tr>
<tr>
<td>CL/XL</td>
<td>control</td>
<td>74.9(^c)</td>
<td>81.1(^c)</td>
</tr>
<tr>
<td></td>
<td>65</td>
<td>76.8(^b)</td>
<td>82.2(^bc)</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>78.0(^ab)</td>
<td>82.9(^ab)</td>
</tr>
<tr>
<td></td>
<td>75</td>
<td>79.0(^a)</td>
<td>84.0(^a)</td>
</tr>
<tr>
<td>CLXL/XL</td>
<td>control</td>
<td>74.7(^b)</td>
<td>80.1(^b)</td>
</tr>
<tr>
<td></td>
<td>65</td>
<td>75.6(^b)</td>
<td>81.7(^b)</td>
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<tr>
<td>HSD</td>
<td></td>
<td>2.1</td>
<td>2.5</td>
</tr>
</tbody>
</table>

\(^1\)Mean values followed by the same letter in the same column within the same sample are not significantly different based on Tukey’s HSD test.
Table 4.3 Analysis of variance (ANOVA) of soaked commingled rice properties as affected by onset gelatinization temperature ($T_o$) difference, soaking temperature and their interactions

<table>
<thead>
<tr>
<th>Quality characteristics</th>
<th>Soaking temperature</th>
<th>$T_o$ difference</th>
<th>Interaction</th>
<th>Root mean square error (RMSE)</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Prob &gt; F</td>
<td>Sum of Squares</td>
<td>Prob &gt; F</td>
<td>Sum of Squares</td>
<td></td>
</tr>
<tr>
<td>HBRY (%)</td>
<td>***</td>
<td>37</td>
<td>***</td>
<td>160</td>
<td>35</td>
</tr>
<tr>
<td>Chalkiness (%)</td>
<td>***</td>
<td>34</td>
<td>***</td>
<td>17</td>
<td>10</td>
</tr>
<tr>
<td>L*</td>
<td>***</td>
<td>184</td>
<td>***</td>
<td>106</td>
<td>43</td>
</tr>
<tr>
<td>b*</td>
<td>***</td>
<td>21</td>
<td>**</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>$T_o$ ($^\circ$C)</td>
<td>***</td>
<td>177</td>
<td>***</td>
<td>43</td>
<td>21</td>
</tr>
<tr>
<td>$T_p$ ($^\circ$C)</td>
<td>***</td>
<td>124</td>
<td>***</td>
<td>52</td>
<td>32</td>
</tr>
<tr>
<td>$T_c$ ($^\circ$C)</td>
<td>***</td>
<td>109</td>
<td>***</td>
<td>138</td>
<td>*</td>
</tr>
<tr>
<td>$T_c-T_o$ ($^\circ$C)</td>
<td>***</td>
<td>14</td>
<td>***</td>
<td>128</td>
<td>7</td>
</tr>
<tr>
<td>$\Delta H$ (J/g)</td>
<td>**</td>
<td>4</td>
<td>**</td>
<td>9</td>
<td>NS²</td>
</tr>
<tr>
<td>Peak viscosity (cP)</td>
<td>***</td>
<td>5166607</td>
<td>***</td>
<td>1450843</td>
<td>661154</td>
</tr>
<tr>
<td>Final viscosity (cP)</td>
<td>***</td>
<td>71613</td>
<td>***</td>
<td>91837</td>
<td>121037</td>
</tr>
<tr>
<td>Breakdown viscosity (cP)</td>
<td>***</td>
<td>4855536</td>
<td>***</td>
<td>964574</td>
<td>487148</td>
</tr>
<tr>
<td>Setback viscosity (cP)</td>
<td>***</td>
<td>4070041</td>
<td>***</td>
<td>912248</td>
<td>366037</td>
</tr>
</tbody>
</table>

1 * represents the level of statistical significance, *≤0.05, **≤0.01, ***≤0.001.
2 NS = not significant.
Figure 4.1 Differences between head brown rice yield (A), chalkiness (B), whiteness (C), and yellowness (D), and their weighted average for each commingled rice after soaking at 65, 70, or 75°C for 3 h. Weighted average for each commingle was calculated using the mass ratio of 1:1.
Figure 4.2 Pasting profiles of Taggart, CL151, CL XL745, XL753, and their commingles after soaking at 65, 70, or 75°C for 3 h and their controls of no soaking.
Figure 4.3 Prediction profile of optimum soaking temperature and $T_o$ difference for maximizing desirability score. Vertical dash line represents the soaking temperature and $T_o$ difference whereas horizontal dash line represents values obtained at condition that result in the highest desirability score.
CHAPTER 5
IMPACTS OF PARBOILING CONDITIONS ON QUALITY CHARACTERISTICS OF PARBOILED COMMINGLED RICE

5.1 ABSTRACT

Using commingled rice with a wide range of gelatinization temperatures may result in inconsistent quality of parboiled rice if it is parboiled together. This study investigated the effects of commingling, soaking temperature and steaming duration on qualities of parboiled commingled rice. Rough rice of purelines (Taggart and CL151) and hybrids (XL753 and CL XL745) cultivars were mixed at 1:1 weight ratio to obtain 3 commingled rice lots with difference in $T_o$ of 1.2, 3.9, and 6ºC. Rough rice was soaked at 65º, 70º, or 75ºC for 3 h, and then steamed at 112ºC for 10, 15, or 20 min prior to drying. The effect of soaking temperature and steaming duration varied with commingled rice. Soaking temperature greatly affected HRY and whiteness. Steaming duration was the most influential factor affecting yellowness, white core, deformed kernels and pasting viscosity. Increasing soaking temperature increased head rice yield and lowered the occurrence of white core. Steaming decreased white core but also potentially led to deformed kernels if steaming duration was excessive. Parboiled rice became darker and yellower with an increase in soaking temperature and steaming duration. Pasting viscosity decreased with increasing soaking temperature and steaming duration. Commingling with a wide range of gelatinization temperatures tended to produce parboiled rice with less desirable properties.
5.2 INTRODUCTION

Parboiled rice consumption has been primarily of cultural preferences in countries like India, Pakistan, Bangladesh, and Nigeria. Parboiled rice finds many applications in the food industry such as instant rice, frozen entrees, canned goods, and ready-to-eat meals because of its heat stability and retained nutrients. The parboiling process includes soaking, steaming, and drying, which all have impacts on the quality of parboiled rice. Parboiling decreases breakage susceptibility of rice during the dehulling and milling processes, resulting in greater head rice yield. However, unfavorable characteristics may develop if rice is not properly parboiled, for example discoloration, off-odor and flavor, deformation, white core, and unsatisfactory sensory attributes.

The effects of parboiling conditions on the qualities of parboiled rice have been extensively investigated. Bhattacharya and Subba Rao (1966a) found that the intensity of parboiled rice color was affected by the severity of the parboiling process, including soaking temperature, soaking duration, steaming pressure as well as steaming duration. Pillaiyar and Mohandoss (1981) reported a decrease in hardness of cooked rice kernels with increasing soaking temperature, whereas longer steaming durations increased the hardness of cooked rice (Kar et al., 1999; Saif et al., 2004). Patindol et al. (2008) reported head rice yield of brown rice was 89.6 and 62.6% when steamed at 100°C and 120°C for 20 min, respectively. Parboiling resulted in a decrease in overall pasting profile and peak viscosity of parboiled rice (Raghavendra Rao and Juliano, 1970; Ali and Bhattacharya, 1980; Islam et al., 2001; Manful et al., 2008; Patindol et al., 2008).
Because of a significant increase in rice cultivars, particularly the development of hybrid cultivars in the U.S., an intermingling between rice cultivars with pureline and hybrid and with a wide range of gelatinization temperatures could occur during harvesting, drying, storage, and distribution. Bhattacharya and Subba Rao (1966a) noted the differences in hydration rate of rough rice during soaking and milling yield of parboiled rice as affected by varietal differences, particularly in terms of starch gelatinization temperature. Basutkar et al. (2014) reported significant effects of commingled rice on milled rice yield, head rice yield, and chalkiness of milled rice. However, the effects of commingling on whiteness and yellowness was insignificant. Basutkar et al. (2015) proposed that a large variation in starch onset gelatinization temperature ($T_o$) of the rice cultivars in commingles may cause inconsistent quality of products because the $T_o$ of commingled rice was determined by cultivars with the lower $T_o$.

Besides gelatinization temperature, milling characteristics differ among cultivars, which could affect hydration rate and consequently rice quality after parboiling. The bran layer of hybrid rice cultivars was found to be thinner than that of pureline cultivars; therefore, hybrid rice required a shorter milling duration to reach the same degree of milling as pureline (Siebenmorgen et al., 2006; Lanning and Siebenmorgen, 2011; Siebenmorgan et al., 2012).

Varietal differences also had an influence on color and cooking quality of parboiled rice (Bhattacharya and Subba Rao, 1966b). Raghavendra Rao and Juliano (1970) attributed changes in pasting characteristics among different rice cultivars from parboiling to the differences in amylose content of individual rice cultivars. Patindol et al. (2008) found that milling, physicochemical, pasting, thermal, and cooking properties of parboiled rice were affected by cultivars in terms of chemical composition and gelatinization temperature.
Because of the aforementioned differences in rice properties among cultivars, the goal of this study was to investigate the impacts of parboiling conditions on the quality of parboiled rice when using commingled rough rice as a feedstock.

5.3 MATERIALS AND METHODS

Materials

Long-grain pureline (Taggart and CL151) and hybrid (CL XL745 and XL753) rice cultivars from the 2012 crop year were used in this study and obtained from the University of Arkansas Rice Processing Program (Fayetteville, Arkansas). These cultivars were selected because they had the lowest $T_o$ and the highest $T_o$ among pureline and hybrid cultivars available from the 2012 crop year, as determined by a differential scanning calorimeter, of 72.1, 74.2, 73.3, and 78.1°C for Taggart, CL151, CL XL745, and XL753, respectively. Three combinations of commingled rice samples were prepared using a 1:1 ratio based on rough rice weight (approximately at 12.5% moisture content, MC). Taggart/CL XL745, CL151/XL753, and Taggart/XL753 represented Low $T_o$/Low $T_o$ (L/L), High $T_o$/High $T_o$ (H/H), and Low $T_o$/High $T_o$ (L/H) commingles with $T_o$ differences of 1.2, 3.9, and 6.0°C, respectively. The rough rice was accurately weighed and mixed 5 times, 2 min each time, using a rotary rice grader (TRG, Satake, Tokyo, Japan).

Parboiling conditions

A partially-automated, pilot-scale parboiling unit fabricated by the University of Arkansas Rice Processing Program was used to parboil rice samples. Soaking temperatures, soaking durations, steaming pressure and steaming durations were set before starting the process. Rough rice was soaked at 65, 70, or 75°C for 3 h prior to steaming at 69 kPa (10 psi, 112°C) for 10, 15 or 20 min. The selected soaking temperatures were set approximately 3-7°C below $T_o$ of
rice samples. After steaming, rice was dried in an equilibrium moisture content (EMC) chamber at 26°C and 65% RH for 3 days to reach 12% MC.

**Milling properties**

Dried parboiled rice was dehulled using a Satake THU-35 dehusker (THU-35, Satake Corp., Hiroshima, Japan) and milled for 60 sec with a McGill No. 2 mill (PRAPSCO, Brookshire, TX) which had a 1.5 kg mass placed on the lever arm at 15 cm from the center of the milling chamber. The head rice kernels were separated from broken kernels by a double-tray sizing device (Seedburo Equipment Co., Chicago, IL). Head rice yield (HRY) was expressed as a percentage of head parboiled rice mass to dried parboiled rough rice mass.

**Color**

The whiteness (L*) and yellowness (b*) of parboiled rice was measured using a Hunter lab digital colorimeter (Colorflex EZ, Hunterlab, Reston, VA) and determined by CIE color scales. Approximately 30 g of head parboiled rice was filled in a clear, flat-bottom dish and placed at the center of the sample port. The cup was rotated 180° for the second reading.

**White core**

The percentage of white core was determined using an image analysis system (Winseedle™ Pro 2005a Regent Instruments Inc., Sainte-Foy, Quebec, Canada). Several white core and translucent parboiled kernels were scanned and used as references for the system to classify the white core and translucent area based on number of pixels. One hundred random rice kernels were placed in a tray made from a 2-mm thick clear acrylic sheet (Plexiglass) with no grain touching each other, and then imaged with a scanner (Epson Perfection V700 Photo, Model# J221A, Seiko Epson Corp., Japan). The system measured the number of pixels and
classified them according to the pre-set criteria. White core was expressed as the percentage of the number of pixels as white core area over the number of pixels in total kernel projected area.

**Deformed kernels**

Parboiled rice kernels were visually inspected from 50 g of head parboiled rice. Kernels with an abnormal shape were considered as deformed kernels, which were then collected and weighed. Deformed kernels was expressed as percentage of the mass of deformed kernels over the mass of parboiled rice sample.

**Pasting properties**

Parboiled head rice kernels were ground into flour using a UDY cyclone sample mill (UDY Corp., Ft. Collins, CO) fitted with a 0.50-mm sieve. The pasting properties of parboiled rice flour were characterized using a Rapid ViscoAnalyser (Newport Scientific Pty. Ltd, Warriewood, NSW, Australia). Rice slurry was prepared by mixing 3.0 g of parboiled rice flour (12% moisture basis) with 25.0 mL of water, heated from 50°C to 95°C at 4°C/min, held at 95°C for 5 min, cooled to 50°C at 4°C/min and then held at 50°C for 2 min. Data were collected using RVA software – Thermocline for Windows.

**Statistical analysis**

This experiment was performed using a full factorial design (3 × 3 × 3) with three main factors (T₀ difference, soaking temperature, and steaming duration) and three levels in each factor. Experimental data were conducted in triplicate and analyzed with JMP 12.0.0 (SAS Software Institute, Cary, NC). Analysis of variance (ANOVA) with a significant level at 0.05 were used to determine the effects of T₀ difference, soaking temperature, steaming duration, and their interactions on the quality characteristics of parboiled rice. Mean differences were evaluated by using Tukey’s HSD test.
5.4 RESULTS AND DISCUSSIONS

5.4.1 Head rice yield

HRY was comparable among most samples (Table 5.1). The effect of soaking temperature and steaming duration varied among commingled samples with L/L affected by both, L/H affected only by soaking temperature, and H/H not affected. The effect of steaming duration was only observed in L/L at soaking temperature of 75°C.

The preceding study that investigated the impact of soaking temperature alone on rice properties reported an increase in head brown rice yield of commingled rice with increasing soaking temperature (Leethanapanich et al., 2015). The maximum head brown rice yield of T/CLXL (i.e. L/L), CL/XL (i.e. H/H), and T/XL (i.e. L/H) was obtained when soaking temperature was 75°C. Similar results, particularly among L/L and L/H samples, were observed in the present study. It is hypothesized that higher soaking temperatures accelerated hydration rate as well as reduced chalkiness and fissures as a result of the swelling and rearrangement of starch granules and protein denaturation at the same time. The decrease in chalkiness and fissures may increase kernel resistance to breakage during milling. It is worth noting that soaking temperature of 75°C, which was above the T₀ of low T₀ cultivars, resulted in the greatest HRY for both T/CLXL and T/XL, which was different from the findings obtained from single rice cultivars, in which soaking temperatures below, but close to T₀, yielded the greatest head brown rice yield (Leethanapanich et al., 2015). It is hypothesized that annealing from soaking, which caused a reduction in gelatinization temperature range and an increase in T₀, may allow for soaking temperature for commingled rice to be slightly above their T₀.

There was little difference in terms of steaming duration on HRY in all commingled rice, except that the HRY of L/L declined with increasing steaming duration at the soaking
temperature of 75°C, which presumably was too severe for L/L. The high soaking temperature of 75°C was above T_o of L/L and thus some starch may already gelatinize and swell during the soaking step. Therefore, when soaking at 75°C was combined with a steaming duration of 20 min for L/L, starchy endosperm may be disrupted, causing hull splitting and reduced HRY. In addition, the leached starch from excessive swelling may adhere to the hull, causing the separation of hull from the endosperm difficult and more likely to break during dehulling. Steaming was reported to increase the hardness of the rice kernels after parboiling as a result of starch gelatinization, thus increasing the HRY (Soponronnarit et al., 2005). This study shows that soaking temperature may play a more dominant role in affecting HRY than did steaming duration, and therefore attention should be paid to selecting an appropriate soaking temperature according to the T_o of the rice sample.

5.4.2 Color

In general, L* values decreased and b* values increased with increasing soaking temperature and steaming duration; however, the response to soaking temperature and steaming duration varied among commingled rice (Table 5.1). For L/L, yellowness (b*) increased at 70°C of soaking or steaming duration increased from 10 to 15 min; whiteness (L*) was not affected by soaking temperature but it decreased after steaming for 15 min at 65 and 70°C, and for 20 min at 75°C. For L/H, the changes in yellowness as affected by soaking temperature were only observed when soaking temperature increased from 65 to 70°C at steaming duration of 10 min; whiteness decreased with increasing soaking temperature and increasing steaming duration from 10 to 20 min, but no effect of steaming duration was observed at soaking temperature of 75°C. For H/H, whiteness decreased after soaking at 75°C and yellowness increased after soaking at 70°C.
The change in color after parboiling was due to Maillard reaction and diffusion of hull and bran pigment into the endosperm during soaking and steaming (Ali and Bhattacharya, 1980; Lambert et al., 2008). It is possible that higher soaking temperatures increased the amount of dissolved pigments, rate of pigment migration, water diffusion, and Maillard reaction. Longer steaming duration facilitated higher rate of pigment migration and Maillard reaction. The difference in color of parboiled commingled rice and how it change during parboiling may be primarily related to variation in kernel and chemical compositions of individual rice cultivars, but not associated with difference in $T_o$, as observed from the greater increase in yellowness with increasing soaking temperature in H/H compared with L/L.

5.4.3 White core

The occurrence of white core indicates incomplete starch gelatinization during parboiling, which can be either from insufficient soaking that leads to uneven moisture distribution inside the kernels or from inadequate steaming duration. For all commingled samples, white core diminished with higher soaking temperatures and longer steaming durations, but steaming duration clearly played a major role in reducing white core. White core was lower in L/L and L/H than in H/H at 65°C of soaking and 15 min of steaming, presumably because the lower $T_o$ cultivars would require a shorter steaming duration to fully gelatinize starch (Table 5.1).

5.4.4 Deformed kernels

Deformed kernels were formed as a result of husk splitting during soaking and/or steaming. Soaking temperature and steaming duration had different impacts on deformed kernels in commingled rice (Table 5.1). H/H showed significantly lower percentages of deformed kernels when soaked at 70 or 75°C and steamed for 20 min compared with L/H and L/L because of their higher $T_o$. There was no significant difference in deformed kernels in H/H among all
soaking temperatures for the same steaming duration, whereas a significant increase in deformed kernels was observed in L/L and L/H, particularly after soaking at 75°C, because of their lower To cultivars.

Deformed kernels increased with longer steaming duration. For H/H, at lower soaking temperatures like 65 and 70°C, the effect of steaming duration was pronounced at 15 and 20 min but at 75°C, the effect was observed for 20 min steaming. This might be due to the effect of annealing during soaking at higher temperature like 75°C, which caused an increase in To, therefore, longer steaming duration would be required to cause deformed kernels. The deformed kernels increased in L/H when rice was soaked at 65 or 70°C and steamed for 20 min as well as when rice was soaked at 75°C and steamed for 15 min and 20 min. This implies that steaming duration had more impacts on deformed kernels when soaking temperature was below To; whereas deformed kernels were affected by both soaking temperature and steaming duration when soaking temperature was higher than To. As the soaking temperature and steaming duration increased, the white core decreased but the deformed kernels increased. This inverse relationship highlights the importance of identifying parboiling conditions to simultaneously achieve minimum deformed kernels and white core.

5.4.5 Pasting properties

A decrease in peak, final, and setback viscosity was observed after parboiling for all commingled rice (Table 5.2). The effect of soaking temperature on the peak viscosity differed from the results in the preceding study (Leethanapanich et al., 2015). The preceding study investigated the soaking temperature effect alone and reported lowered peak viscosities when commingled rice samples containing low To cultivars were soaked at 75°C. However, the present study showed that L/H soaked at 75°C and steamed for 10 min had lower peak viscosity than L/L
under the same condition, indicating that steaming exerted more significant impacts on pasting viscosities, particularly on peak viscosity likely through starch-protein interaction. At 20 min of steaming, peak viscosity of all commingled samples decreased with increasing soaking temperature. However, at 10 and 15 min of steaming, the change in peak viscosity with increasing soaking temperature varied. For example, at 15 min of steaming, the peak viscosity of L/L and H/H decreased when soaked at 70°C, whereas that of L/H decreased when soaked at 75°C. These results show that the trend of soaking was not followed when steaming was combined, and more reactions were involved in the steaming step of parboiling.

The peak viscosity of L/L was slightly higher than those of H/H and L/H at the same parboiling condition, possibly because of their lower lipid and protein contents after milling. The decreased peak viscosity of parboiled rice was reported to be the interaction of protein and starch that restricts the starch swelling (Derycke et al., 2005). Lipid that is concentrated in the bran layer also restricted starch swelling through inclusion complexation (Gray and Schoch, 1962). The bran layer of individual cultivar in L/L may be thinner than others; therefore, at the same milling duration, the greater amount of lipid and protein may be removed.

The reduction in setback and final viscosities after parboiling for all samples indicates less disruption of starch granules and a small amount of leached amylose during cooking of parboiled rice because of restricted swelling from interaction between starch and protein or lipid (Gray and Schoch, 1962; Derycke et al., 2005). The extent of reduction in final and setback viscosities varied among commingled rice. H/H exhibited a smaller reduction in final and setback viscosities from 10 to 20 min for all soaking temperatures, whereas L/L and L/H showed a greater reduction, suggesting that under the same parboiling condition, starch in H/H was less disrupted than those in L/L and L/H because H/H had higher T₀.
5.4.6 Relative importance of factors

Commingling, soaking temperature, steaming duration, and their interactions all had impacts on the parboiled commingled rice properties, but their impacts varied with properties. In Table 5.3, sum of square indicates how much each factor affected the quality characteristics of parboiled rice. HRY was strongly affected by soaking temperature, followed by commingling and steaming duration, but not affected by their interactions. Steaming duration was the most influential factor affecting white core, deformed kernels and pasting viscosities. Leethanapanich et al. (2015) reported that $T_o$ difference from commingling had more impact on head brown rice yield than soaking temperature when rice was soaked only without the steaming step. However, in the present study, soaking temperature had more influence on HRY than commingling. It is possible that soaking alone increased the resistance to breakage of individual cultivars, but the extent of the soaking temperature effect were varied with cultivars. Nevertheless, the commingling effect on HRY diminished when soaking was combined with steaming because starch gelatinization occurring in the steaming step hardened the rice kernels and might reduce the difference in breakage susceptibility among cultivars. This implies that soaking at high temperatures followed by steaming could reduce the difference in breakage susceptibility in commingled rice.

Besides HRY, the presence of white core and deformed kernels are also important to the quality of parboiled rice because they are removed after parboiling, thus lowering the final HRY. Therefore, prediction profiler was prepared by considering HRY, white core, and deformed kernel, and the desirability scores from 0 to 1 were set for each quality characteristics. The best parboiling conditions would result in maximum HRY and minimum white core and deformed kernels, and an example is depicted in Fig. 5.1. The condition that would render the highest
desirability score of 0.84 was from H/H when soaked at 75°C for 3 h and steamed at 112°C for 15 min, which resulted in 71.3% HRY, 0.8% white core, and 2.5% deformed kernels based on the present results. This result agrees with our previous study (Leethanapanich et al., 2015) that soaking temperatures close to but below $T_o$ would give the highest HRY. The parboiling condition that would produce the highest score for L/L (0.81) was soaking at 75°C for 3 h and steaming at 112°C for 15 min to give 71.5% HRY, 0% white core and 6.7% deformed kernels. For L/H, soaking at 75°C for 3 h and steaming at 112°C for 10 min gave the highest desirability score (0.78) with 71.4% HRY, 1.8% white core, and 3.8% deformed kernels. At the given highest desirability score, the percentage of deformed kernels in L/L and the percentages of white core and deformed kernels in L/H were higher than those in H/H. Furthermore, it can be seen that the highest desirability score was obtained from H/H ($T_o$ difference of 3.9°C), followed by L/L ($T_o$ difference of 1.2°C) and then L/H ($T_o$ difference of 6.0°C), suggesting that although $T_o$ difference is important in parboiling when using commingled rice, the $T_o$ of commingles relative to the soaking temperature is also important. Therefore, the soaking temperature for commingled rice can be close to or even slightly above it $T_o$ without affecting the resultant parboiled rice quality.

5.4 CONCLUSIONS

Both soaking temperature and steaming duration are key factors determining parboiled rice quality; however, their impacts to each quality characteristics were different. HRY was strongly affected by soaking temperature, whereas white core, deformed kernels, and pasting viscosities were mainly influenced by steaming duration. It is recommended to choose soaking temperature close to $T_o$ and steaming duration not too long to cause excessive starch swelling. Commingled rice with a great $T_o$ difference from individual cultivars tended to yield undesirable
properties. In addition, the $T_0$ of commingles relative to the soaking temperature is also important in optimizing the parboiling process.
5.6 LITERATURE CITED


Table 5.1 Milling and physical qualities of parboiled commingled rice as affected by commingling, soaking temperature, and steaming duration

<table>
<thead>
<tr>
<th>Sample</th>
<th>Soaking Temperature (°C)</th>
<th>Steaming duration (min)</th>
<th>HRY (%)</th>
<th>Whiteness (L*)</th>
<th>Yellowness (b*)</th>
<th>White core (%)</th>
<th>Deformed kernels (%)</th>
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HSD\(^2\) 2.9 2.6 1.2 1.5 5.5

\(^1\) Mean values in a column followed by the same letter in each sample are not significantly different based on Tukey’s HSD test; small and capital letters compared values at different soaking temperatures and different steaming durations, respectively.

\(^2\) Mean differences greater than the HSD suggest significant differences among those two means.
Table 5.2 Pasting viscosity of parboiled commingled rice as affected by commingling, soaking temperature, and steaming duration

<table>
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<th>Sample</th>
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<th>Steaming duration (min)</th>
<th>Peak Viscosity (cP)</th>
<th>Final Viscosity (cP)</th>
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<td>84</td>
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<sup>1</sup> Mean values in a column followed by the same letter in each sample are not significantly different based on Tukey’s HSD test; small and capital letters compared values at different soaking temperatures and different steaming durations, respectively.

<sup>2</sup> Mean differences greater than the HSD suggest significant differences among those two means.
Table 5.3 Analysis of variance (ANOVA) of parboiled commingled rice quality as affected by commingling, soaking temperature, steaming duration, and their interactions.

<table>
<thead>
<tr>
<th>Quality characteristics</th>
<th>Sum of squares</th>
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<tr>
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<td>Commingling (C)</td>
</tr>
<tr>
<td>HRY</td>
<td>12 (*)&lt;sup&gt;1&lt;/sup&gt;</td>
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<tr>
<td>Whiteness (L&lt;sup&gt;a&lt;/sup&gt;)</td>
<td>40 (***)</td>
</tr>
<tr>
<td>Yellowness (b&lt;sup&gt;a&lt;/sup&gt;)</td>
<td>30 (***)</td>
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<tr>
<td>White core</td>
<td>5 (***)</td>
</tr>
<tr>
<td>Deformed kernels</td>
<td>459 (***)</td>
</tr>
<tr>
<td>Peak viscosity</td>
<td>119869 (*** *)</td>
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<tr>
<td>Final viscosity</td>
<td>740791 (*** *)</td>
</tr>
<tr>
<td>Setback viscosity</td>
<td>266506 (*** *)</td>
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</table>

<sup>1</sup>Sum of squares (P-value), the levels of statistical significance of the mean values are ≤0.05, ≤0.01, ≤0.001, and NS = not significant.
**Figure 5.1** Prediction profiler represents obtained values from each sample at different condition. This figure only show the results based on the condition that gave maximum desirability score (dash line) when the highest desirability score was set at maximum head rice yield and minimum white core and deformed kernels.
CHAPTER 6
OVERALL CONCLUSIONS

This study demonstrates that commingling, soaking temperature, and steaming duration all affected HRY, color, white core, deformed kernels and pasting viscosities. Chalkiness decreased after soaking rice at high soaking temperatures by swelling and rearrangement of starch and denaturation of protein to form a more packed structure. Soaking temperature exerted more influence on HRY of parboiled rice than did commingling and steaming duration. Soaking commingled rice at temperatures below but close to $T_o$ increased HRY, reduced chalkiness, and decreased gelatinization temperature range. However, the soaking temperature varied with commingled rice and could be above $T_o$ of low $T_o$ rice cultivars. Steaming duration played a dominant role on the presence of white core and deformed kernels as well as the decrease in overall pasting profile. To achieve a high HRY with low percentages of white core and deformed kernels, the soaking temperature is recommended be close to $T_o$ and steam duration not too long to ensure complete starch gelatinization but not excessive starch swelling. Using commingled rice with similar $T_o$ tends to produce more desirable properties. Closer attention should be paid when selecting parboiling conditions for commingled rice with a great $T_o$ difference in order to minimize white core and deformed kernels while achieving high HRY.