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Review

The U.S. Parboiled Rice Production: Processing Innovations, Market Trends, and Circular Economy Pathways

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Abstract

Parboiling enhances the nutritional, structural, and economic value of rice, yet its adoption in the United States remains limited despite rising domestic and export demand. This review summarizes key stages of the parboiling process and their effects on milling yield, grain integrity, nutrient retention, and glycemic response. It outlines major industry challenges, including high energy and water use, uneven heating and drying, handling of defective kernels, limited automation in smaller mills, labor shortages, and emerging climate-related risks. Advances such as vacuum soaking, infrared and microwave-assisted drying, smart sensors, and AI-driven control systems show strong potential to improve efficiency and product quality. Circular-economy strategies, including biomass energy recovery, water reuse, and by-product valorization, offer additional sustainability gains. Continued research, modernization, and policy support are critical to strengthen competitiveness and positioning of the U.S. parboiled rice sector for a more resilient and sustainable future.

Keywords: parboiled rice; nutritional characteristics; rice variety; head rice yield; processing techniques

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1. Introduction

Parboiled rice, derived from the partial boiling of paddy before milling, is an ancient hydrothermal process believed to have originated in South and West Asia. The process typically involves three key stages of soaking, steaming, and drying, which gelatinize starch within the grain and cause nutrients from the bran and germ to diffuse into the endosperm [1]. The result is rice with enhanced milling yield, reduced breakage during polishing, improved nutritional retention, and longer shelf life compared to raw milled rice. Historically, parboiling was practiced at household and village levels as a preservation method, but over the last century, it has evolved into a large-scale industrial process central to many rice-based economies.

In the United States, commercial parboiling emerged in the early 1940s, driven by wartime demand for stable, nutrient-rich rice products. Converted Rice, Inc. (now Mars Food and Nutrition) pioneered large-scale parboiling with the launch of "converted rice," later branded as Uncle Ben's Rice, introducing parboiled rice to American consumers in 1943 [2]. The postwar expansion of rice production in Arkansas, Louisiana, and Texas established the foundation for a modern rice-processing industry. Research from universities

such as the University of Arkansas and Louisiana State University catalyzed innovations in continuous-flow parboiling and automated drying systems that enhanced efficiency, energy utilization, and head rice yield [3]. By the 1970s, the United States had become a key exporter of parboiled rice, primarily serving West African and Caribbean markets.

Globally, parboiling accounts for nearly 50–60% of rice consumed, especially in South Asia, Southeast Asia, and sub-Saharan Africa, where both artisanal and semi-mechanized operations predominate [4]. These regions rely largely on traditional batch processes that, although labor-intensive, provide flexibility to meet local preferences for texture, color, and aroma. In contrast, the U.S. parboiling industry is characterized by large-scale, capital-intensive systems equipped with automation and control [5]. These facilities, located primarily in Arkansas, Louisiana, and Texas, produce roughly 15–20% of the U.S. rice supply [6] and are primarily export-oriented, supplying consistent-quality parboiled rice to international markets.

While parboiled rice has traditionally been viewed in the U.S. as a product for food service and ready-to-eat applications, market trends are shifting. Rising consumer awareness of nutritional quality, lower glycemic index [7], and improved functional properties has renewed interest in parboiled rice among health-conscious consumers and food manufacturers. Moreover, growing demand for fortified, quick-cooking, and shelf-stable products is creating new domestic opportunities for value-added parboiled rice.

Recent innovations—such as vacuum soaking, infrared heating, and fluidized-bed drying have shown promise in enhancing product quality while reducing resource use [5]. The U.S. industries are also trying to align with sustainability and decarbonization goals, adopting circular-economy strategies such as waste-heat recovery, biomass energy from rice husk, and water reuse systems [8]. These potential advancements can position the U.S. rice sector to become a global leader in sustainable and precision-controlled parboiling operations.

Despite the historical and economic significance of U.S. parboiled rice, comprehensive studies integrating technological, economic, and sustainability perspectives are limited. Existing research often focuses on specific processing techniques or quality attributes, with little attention to holistic modernization strategies. This review aims to fill this gap by consolidating scientific, industrial, and economic insights to guide the advancement of U.S. parboiled rice production, emphasizing sustainability, energy efficiency, and competitive innovation.

For this review paper, an initial pool of approximately 150–200 publications published primarily between 2000 and 2024 was screened based on title and abstract relevance. Articles were excluded if they focused exclusively on non-parboiled rice, were unrelated to processing, quality, sustainability, or policy aspects, or lacked relevance to industrial-scale practices. After screening, 106 key articles were retained and synthesized to provide a structured overview of processing technologies, challenges, innovations, and future directions relevant to the U.S. parboiled rice sector. The objectives are to (1) trace the evolution and current structure of U.S. parboiled rice production; (2) examine the technological and quality outcomes of different processing methods; (3) highlight sustainability and energy efficiency innovations; and (4) propose strategies for competitiveness, resilience, and decarbonization.

As the global rice trade becomes increasingly quality- and sustainability-driven, advancing U.S. parboiling capabilities represents both an opportunity and a necessity for maintaining leadership in rice processing and export.

2. U.S. Production and Market Trends

The United States ranks among the top ten rice producers globally, contributing approximately 9–10 million metric tons of paddy rice annually, around 2% of global

production [6]. Rice cultivation is concentrated in the southern states, where favorable climate, fertile alluvial soils, and modern irrigation systems enable high productivity. Arkansas leads national rice production, accounting for nearly half of U.S. output, followed by California, Louisiana, Mississippi, and Texas. The Mississippi Alluvial Plain, which includes eastern Arkansas and northern Mississippi, forms the largest contiguous rice-producing region in the country, characterized by large, mechanized farms and widespread adoption of high-yield hybrid cultivars.

Parboiled rice represents about 15–20% of total U.S. rice production and has grown steadily since 2015, driven by rising export demand and technological innovation [6]. Nearly 90% of the nation's parboiled rice is produced in the Mid-South region—Arkansas, Louisiana, and Mississippi where state-of-the-art facilities employ continuous or semi-continuous systems with automated soaking tanks, pressure-steam autoclaves, and hybrid fluidized-bed dryers [5]. These systems achieve consistent head rice yields above 68% and maintain moisture levels below 14%, reducing grain breakage during milling. Industrial modernization, paired with growing consumer interest in fortified and quick-cooking rice, continues to expand the role of parboiled products in both domestic and export markets. The parboiled rice segment accounts for roughly $800–900 million of the $3.5 billion U.S. rice industry value, with 70–75% of output exported primarily to West Africa, Central America, and the Caribbean [2].

Consumer preferences in the U.S. are evolving toward convenience, nutrition, and sustainability, creating new opportunities for parboiled rice [9]. Leading processors such as Riviana and Mars are expanding product lines with fortified, organic, and quick-cooking parboiled rice, reflecting the broader shift toward functional and sustainable food products.

The United States has continued to invest in modern rice mills with efficient and effective equipment needed for parboiling, which helps support local farmers and increases production efficiency. Parboiled rice is not just important in the U.S. market. It plays a major role in exports too. The U.S. exported more than 1 million metric tons of parboiled rice in 2022, mainly to Nigeria, Ghana, Haiti, and other countries in West Africa and the Caribbean [6]. Parboiled rice is also a staple in many ethnic communities in the U.S., including African, Caribbean, and South Asian households, helping drive domestic demand. Parboiled rice contains about 80% more thiamine and 30% more niacin than white rice, two essential vitamins that support energy and brain function [1].

In the United States, the quality standards for parboiled rice are highly regulated and based on scientific criteria, focusing on precise grading, food safety, and consistent physical and chemical characteristics. In contrast, markets in Africa and the Caribbean place greater importance on how the rice performs during cooking, the strength of the grains, and how well the rice suits traditional local dishes [10]. Data presented in Table 1, from 2013 to 2023 indicate a gradual increase in the share of parboiled rice allocated to export markets, reflecting sustained demand from West Africa and the Caribbean, while the proportion of domestic consumption has remained relatively stable or slightly declined. These trends highlight the continued export-oriented nature of the U.S. parboiled rice sector and underscore the importance of maintaining consistent quality, supply reliability, and competitiveness in international markets when projecting future industry growth.

Technological advancements in parboiled rice production are likely to continue to meet diverse consumer preferences and its demand in a growing population. The advancement of parboiled rice in the US is not limited to improving the overall quality, but also contributes to a more sustainable and environmentally friendly process. Manufacturers and researchers are working on techniques to enhance the texture of parboiled rice, making it more desirable to consumers. These include techniques to optimize the parboiling process to achieve

desirable texture and conducting research on different rice varieties that naturally tend to have desirable texture [11,12].

Table 1. US rice production from 2013 to 2023 with different shares of consumption and export (Derived from USDA Economic Research Service, Rice Yearbook and Rice Outlook reports 2013–2023, and authors' calculations).

Year	Total Rice Production (Million Metric Tons)	Parboiled Rice (Million Metric Tons)	Share of Parboiled (%)	Domestic Consumption of Parboiled (%)	Export Share of Parboiled (%)
2013	9.6	1.6	16.7	30	70
2014	10.1	1.7	16.8	31	69
2015	9.1	1.5	16.5	32	68
2016	8.9	1.4	15.7	33	67
2017	9.8	1.6	16.3	32	68
2018	10.3	1.8	17.5	31	69
2019	8.2	1.3	15.9	30	70
2020	9.4	1.6	17.0	29	71
2021	9.3	1.6	17.2	30	70
2022	10.0	1.8	18.0	28	72
2023	9.5	1.7	17.9	28	72

USDA does not separately report national parboiled rice production or its domestic and export utilization. Parboiled rice quantities and shares shown here are estimated from milled rice production and trade data and reflect industry-level patterns rather than direct USDA tabulations.

3. Parboiling Process: Principles and Practices

Despite several variations in traditional methods of parboiling, the main production steps remained: hydration, heat step for gelatinization, moisture removal from the kernels by dehydration followed by milling process. Figure 1 illustrates the parboiling process and stages in the production of milled parboiled rice from rough (paddy) rice. In general, there are four main stages, including soaking, steaming, drying, and milling.

Parboiling is traditionally done using paddy rice, meaning the grains are processed with their husks still on. Treating rice in this form helps protect the kernels and contributes to the nutritional and milling qualities associated with parboiled products. Although parboiling can also be carried out on brown rice, this method is used far less often in modern commercial practice in the United States. Working with brown rice may allow the grains to hydrate more quickly and reduces bulk because the husk has been removed, but these advantages have not made it the standard approach. Parboiling paddy rice is also known to influence the grain's sensory properties, often giving the cooked rice a slightly stronger aroma and a more yellowish color [13].

In parboiling process, rough rice is hydrated in a soaking process using excess water. The soaking conditions such as temperature and time should be carefully controlled. The temperature of soaking stage is lower than the gelatinization temperature of rice starch. The gelatinization temperature can vary depending on rice varieties [14]. An average moisture content of 30–32% wet basis is achieved when rough rice is soaked under the gelatinization temperature [15–17]. However, excessive or uncontrolled soaking conditions can cause the moisture content to exceed this optimal range. While soaking at or below the gelatinization temperature, the hydration rate of rice grains increases due to increase in water absorption. When soaking temperature exceeds the gelatinization point, the hydration rate becomes

rapid, causing the starch granules to break apart, resulting in the loss of solids and reduced grain quality [11].

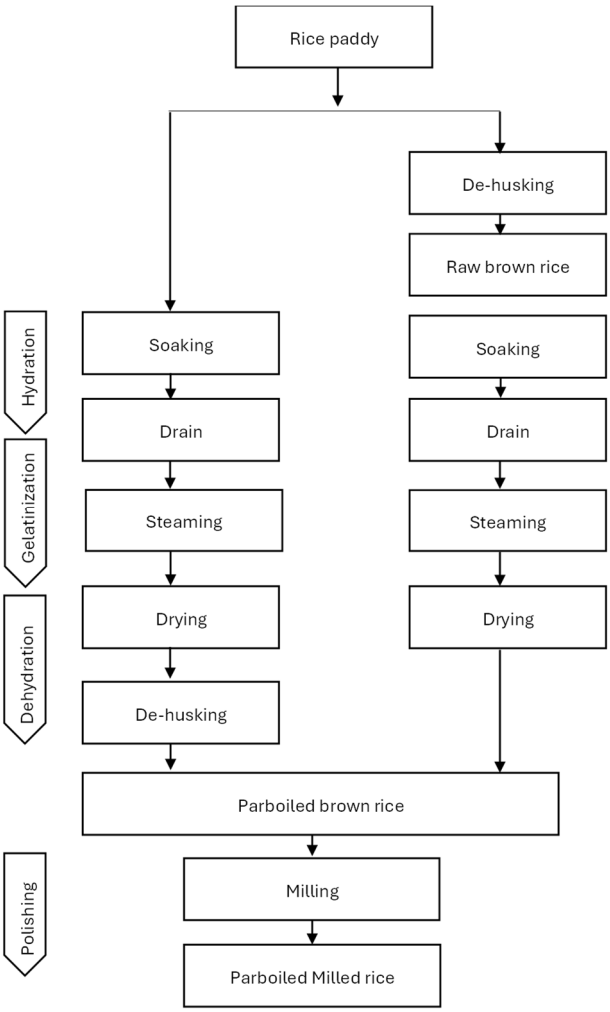


Figure 1. Parboiling process pattern and stages of converting paddy rice to milled rice.

After soaking process, the excess water is drained followed by steaming stage of hydrated rough rice. The starch is either partially or fully gelatinized, depending on the heating load. This is done by using steam with conditions varying from 100 °C to 120 °C for 5–20 min. The degree of gelatinization in rice kernels determines the changes in rice properties [18,19]. After the steaming stage, the moisture content of the rice kernels increases to about 35% wet basis. Thereafter, the process transitions to a drying stage that lowers the moisture level to approximately 12% wet basis [5,20].

Drying is an essential step in parboiling rice. It has direct impact on the milling yield of rice [21,22]. Multistage drying with intermediate tempering is usually necessary to achieve moisture removal from 35% to 12% wet basis [11,21]. Tempering is an essential step in the parboiling process of rice that involves intermittent drying and moisture equilibration within the rice kernel. This step has been shown to significantly enhance both the nutritional and physical qualities of parboiled rice, making it more desirable for consumption. Tempering facilitates the diffusion of water-soluble nutrients like thiamine, niacin, and minerals from the bran into the endosperm during hydrothermal treatment. This nutrient migration reduces nutrient loss during polishing. Studies have shown that parboiled rice subjected to tempering has higher retention of B vitamins and essential minerals [23]. Also, tempering minimizes leaching losses of soluble components during drying, thus improving the overall retention of micronutrients [3]. It reduces kernel breakage by

promoting gradual moisture redistribution and stress relaxation within the grain. During rapid drying, moisture gradients between the surface and core can induce internal fissures, leading to broken grains during milling. Tempering mitigates this by allowing moisture to equilibrate, resulting in better head rice yield [24]. Moreover, properly tempered rice exhibits improved kernel hardness, reduced chalkiness, and enhanced cooking quality. Table 2 below summarizes the benefits of tempering on parboiled rice.

Table 2. Benefits of tempering on parboiled rice quality and nutrition.

Attribute	Without Tempering	With Tempering
Nutrient retention	Low (due to leaching)	High (due to inward diffusion)
Head rice yield	Lower (more breakage)	Higher (fewer fissures)
Kernel hardness	Moderately soft	Harder and more uniform
Chalkiness	Higher	Lower
Cooking quality	Inconsistent	Improved texture and aroma

The most common approach is the two-stage drying, which involves the parboiled rice drying first to a moisture content of 18–20% wet basis, following tempering for around 4–8 h, and second stage drying to a moisture content of 12% [11,21]. In industrial-scale parboiling production, the heated air is generally used in the drying operation. The rotary-drum type, hot-air rotary driers, vertical column dryers, and fluidized bed dryers are generally used in combinations [15,25].

Post drying, the parboiled rice is milled to remove the husk and bran layer to the desired degree of milling. In the US, milling is of two kinds, abrasive and frictional [21]. In the abrasive milling process, rice grains are rubbed or ground against a rough surface like an abrasive stone. This allows gradual and uniform bran removal for better control of the degree of milling. The abrasive milling devices are either Vertical cone mills or Horizontal abrasive milling devices. The frictional rice milling operation removes the outer bran layers by gently rubbing the rice grains against a smooth surface or against each other. Friction milling uses a softer approach, polishing the rice with less damage or breakage. Modern parboiled rice mills use multiple abrasive mills in series, each removing a small fraction of the bran, whereas friction milling devices are usually not used for primary milling but largely appear as final polishers.

In the parboiling industry, methods that reduce broken rice and improve quality are preferred [26]. The process is adjusted for each rice variety to get good quality and yield. Table 3 provides an overview of the parboiling conditions from various studies.

Parboiling performance is governed by trade-offs among process intensity, product quality, and energy efficiency, as evidenced by the wide range of processing conditions and outcomes summarized in Tables 2 and 3. The soaking temperature–time combinations and steaming severities reported in Table 3 represent the primary control parameters. As shown in Table 2, process modifications such as tempering can mitigate some adverse effects of process intensity by improving head rice yield and nutrient retention.

Parboiling systems have improved over the years, moving from basic manual processes to more advanced and automated processes. There are basically three main systems commonly practiced in the parboiled rice industry: batch, semi-continuous, and continuous systems. Each system has its own design, level of automation, and impact on quality. The efficiency of these systems is evaluated based on their quality, such as head rice yield and energy consumption [5].

Table 3. Summary of parboiling conditions from past research.

Rice Type (Variety)	Soaking Parameters	Steaming Parameters	Parameter Trends	References
Brown rice (Puntal, Jacint)	Soaking temperature: 65.8 °C Soaking duration: 150 min	Steaming temperature of 112.8 °C for 90 s	Higher soaking temperatures reduce hydration time but increase over-hydration risk.	[27]
Brown rice (Puntal, Cocodrie, Jacinto, XL8, Koshihikari, Basmati, SisR215)	Soaking temperature: 50 °C Soaking duration: 30 min	Steaming temperature of 80 °C for 10 min, 100 °C for 2 min, 105 °C for 10 min and 125 °C for 17 min	Moderate soaking with controlled steaming improves efficiency and kernel integrity.	[28]
Paddy rice (SCSBRS Tio Taka, Epagri 109, SCS 114 Andosam)	Soaking temperature: 65 °C Soaking duration: 360 min	Steaming temperature of 110 °C, for 7 min	Longer soaking enhances hydration uniformity but increases drying energy demand.	[29]
Paddy rice (Supanburi 1)	Soaking temperature: 80 °C Soaking duration: 300 min	Steaming temperature of 102 °C for 70 s	High soaking temperature with short steaming enables rapid processing with controlled heat exposure.	[30]

Batch parboiling is the oldest and remains the most widely used method in domestic small-scale operations. In this system, soaking, steaming, and drying are performed in separate units, and a fixed amount of paddy is processed per cycle. The process is manually controlled; it requires an operator to monitor and adjust processing time, temperature, and other parameters at each step. While batch systems are flexible, they often result in inconsistent quality, grain distortion, and lower throughput [1].

Semi-continuous systems improve batch systems by adding a degree of automation and integrating features of both batch and continuous processes. These systems combine staged soaking, steaming, and drying in a more streamlined flow, allowing better throughput than traditional batch methods while keeping capital and complexity lower than fully continuous installations [8]. Semi-continuous approaches are increasingly adopted in mid-sized mills aiming to scale production without full continuous investment.

Continuous systems represent a modern evolution in parboiling technology, where paddy moves through soaking, steaming, and drying in a synchronized automated flow with precise control of temperature, time, and other parameters [31]. Compared to batch processes, continuous systems achieve higher energy efficiency, improved milling yields, and reduced labor and product variability [7].

Several continuous parboiling systems have been developed, such as the CFTRI, Schule, Infrared heating system, CRGA, and LSU continuous-flow dryer [5]. Batch processing still predominates in many U.S. rice mills due to its operational simplicity and initial low capital cost; however, the continuous system is gaining more awareness for its efficiency, consistency, and scalability.

4. Grain Quality and Processing Characteristics

The parboiling process makes certain changes to the rice's physicochemical, milling, functional, and nutritional quality (Figure 2). This section discusses these changes, along with the potential health benefits of consuming parboiled rice compared to regular rice. The impact of using different rice quality and different drying methods on these quality parameters will be discussed as well.

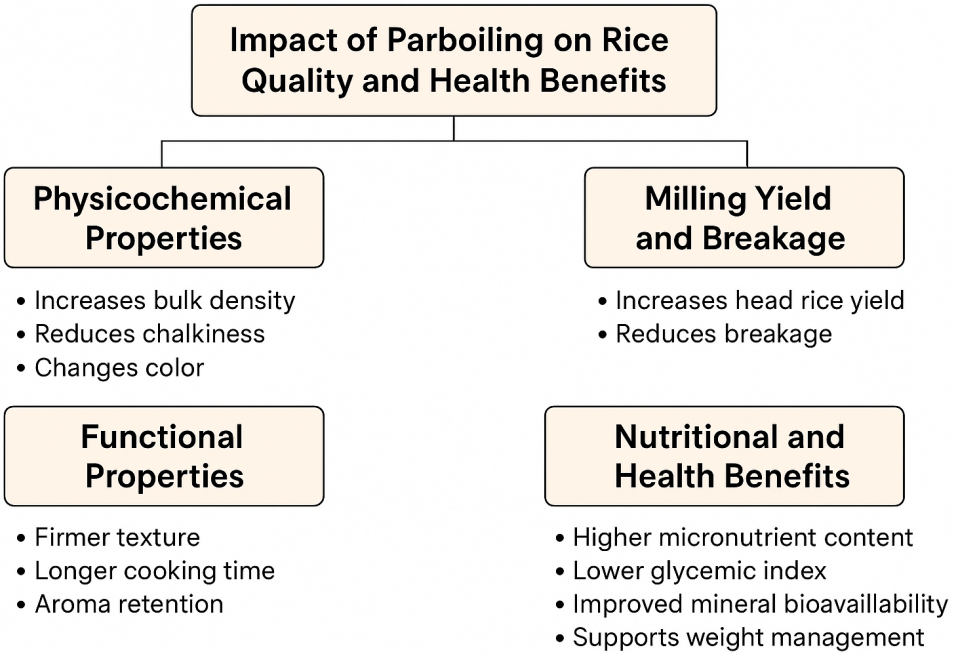


Figure 2. Showcase the changes in the properties and quality of rice during parboiling.

4.1. Impact of Parboiling on Physicochemical Properties of Rice

The impact of parboiling on the rough rice depends on specific processing conditions used, such as soaking time, steaming pressure, temperature, and rice variety [32]. Parboiling increases the bulk density and true density of the grain. Bhattacharya [1] showed that during parboiling, starch granules gelatinize and bind with broken proteins to form a compact structure, which reduces light scattering between granules. Therefore, parboiled rice, in general, has lower chalkiness than non-parboiled rice. However, one of the main disadvantages of parboiled rice is the color change. Parboiling reduces L* (lightness) and a* (redness) values while increasing the b* (yellowness) value, resulting in a pale-yellow or amber color. According to Pal et al. [33], the L* value for white rice typically ranges from 49.75 to 58.28 but decreases to 48.08–53.34 in parboiled rice. Similarly, the a* value reduces from 3.79 to 6.58 in white rice to 2.30–4.94 in parboiled rice, while the b* value increases from 12.27 to 15.59 to 14.23–17.89. These changes may be due to the transformation of rice from opaque to translucent due to the gelatinization process and may be attributed to the Maillard reaction and the diffusion of pigments from the bran layer into the endosperm during steaming. The color difference increases with increasing moisture content after soaking, the intensity of steaming conditions, and the degree of starch gelatinization [28].

The main trade-off in parboiling is that while it strengthens grain structure and reduces chalkiness, the resulting pale-yellow to amber color may be less appealing to consumers. Optimizing soaking and steaming conditions is essential to balance quality improvement with visual acceptability.

4.2. Milling Yield, Head Rice Recovery, and Breakage Reduction

One of the primary advantages of parboiling is its potential to increase head rice yield (HRY) and reduce breakage compared to non-parboiled rice. Head rice is kernels that consist of whole grains, which are typically at least three-fourths (75%) of the original kernel length after removal of husk and bran layers. Broken rice is valued as low as 60% of whole grains, showing significant economic value of the HRY [34].

HRY is an essential factor for both farmers and processors as it significantly affects the economic value of rice in the market. HRY is used to assess the grain quality and efficiency of the milling process. After parboiling, the rough rice undergoes the milling

process, which is essential to remove husk, germ, and bran layers from the surface layers of the rice kernel. The breakage of rice kernels during milling occurs when rice kernels are exposed to mechanical stress higher than the strength of the kernel [18]. The extent to which bran is removed during milling is referred to as the degree of milling (DOM), and the quality of milled rice is primarily determined by its DOM. Ali et al. [35] reported that increasing the degree of milling, which removes greater amounts of bran and endosperm, reduces head rice yield. Over-milling reduces the nutritional value of rice, such as minerals, proteins, iron, and vitamins, and removes all of the bran along with part of the endosperm, which increases grain breakage. One of the most preferred methods for determining DOM is the extraction of surface lipid content (SLC) of milled rice, as bran contains about 20% oil. Therefore, the surface lipid content serves as an effective measure of the extent of bran removal from the rice kernel [36,37].

In parboiled rice, increasing the degree of milling enhances kernel smoothness but decreases head rice yield and nutrient retention, while minimal milling preserves bran-derived nutrients yet results in firmer texture and longer cooking time. Optimizing milling parameters is therefore critical to balance structural integrity, nutritional quality, and processing efficiency.

4.3. Influence of Rice Variety on the Quality of Parboiled Rice

Rice varieties are primarily classified as pureline or hybrid cultivars based on their breeding strategy. These genetic differences directly influence grain morphology, chemical composition, and endosperm structure, which collectively determine milling behavior and parboiling performance.

Parboiling induces irreversible physicochemical changes in rice grains, all of which are strongly variety dependent. Rice varieties are commonly classified based on amylose concentration as low (12–20%), intermediate (20–25%), or high (25–33%) amylose [38].

High-amylose rice forms rigid and thermally stable starch granules, leading to the formation of firm, non-sticky grains after cooking. Low-amylose rice contains structurally weaker granules that gelatinize more readily, producing softer and more adhesive textures. Varieties with intermediate amylose content generally provide optimal textural balance and consumer acceptability in parboiled rice products. In addition to starch composition, protein and lipid contents in rice varieties further affect water diffusion and swelling behavior [39]. Rice varieties with higher protein or lipid content exhibit reduced hydration rates during soaking, resulting in delayed or incomplete gelatinization and potential color variation in parboiled grains.

Endosperm density and microstructural characteristics further affect parboiling efficiency. Varieties with compact endosperms require longer soaking durations and higher steaming pressures to achieve complete starch gelatinization, whereas chalky or porous grains are prone to rapid water uptake, excessive swelling, and fissure formation during thermal treatment [40]. Therefore, varietal selection is crucial for optimizing parboiling conditions to maximize head rice yield and quality while minimizing structural damage.

4.4. Functional Properties: Texture, Cooking Time, Aroma Retention

Textural attributes such as cohesiveness, hardness, and chewiness play a pivotal role in consumer preference and acceptance. Hardness of rice is influenced by its amylose and amylopectin content, while the cohesiveness of rice is attributed to the formation of a stronger structure that holds the cells tightly together during cooking.

Parboiled rice tends to remain firm, separate, and less sticky compared to non-parboiled rice, mainly due to the process minimizing kernel solubility and leaching of solids into the cooking water. Li et al. [41] suggested that the reduction in the stickiness

of parboiled rice is associated with limited starch leaching behavior during cooking. The formation of amylose-lipid complexes during parboiling contributes to the firmness of cooked rice, with greater amounts of these complexes resulting in a firmer texture [42,43]. The limited leakage of amylopectin to the surface of the rice following starch gelatinization results in the less sticky texture of parboiled rice. This observation is supported by Bello et al. [44], who found that parboiled rice exhibits a firmer texture and less stickiness compared to non-parboiled rice.

Water absorption is directly proportional to the degree of parboiling; a high degree of parboiling causes high starch gelatinization, which creates a denser rice structure that absorbs less water during cooking. Studies have shown that water absorption in parboiled rice occurs more slowly than in white milled rice, mainly due to the husk, embryo, pericarp, and seed coat acting as physical barriers that reduce water penetration [45,46]. However, pre-cooking treatments such as soaking can reduce this effect. For example, soaking rice at temperatures between 60 °C and 62 °C for about 4 h can significantly reduce cooking time by increasing water absorption and causing partial starch gelatinization during soaking. Graham-Acquaah et al. [47] noted that both the temperature and duration of soaking influence the rate of water absorption and the cooking behavior of rice. The authors established in the literature that parboiled rice generally requires a longer cooking time than white rice, typically ranging from 20 to 25 min in excess water cooking, while white rice usually cooks in about 15–20 min, depending on variety and processing parameters. Parboiling also increases cooking volume while reducing the amount of solids content in the cooking gruel. These make parboiled rice more suitable for large-scale cooking as well.

The aroma of rice is a key quality attribute that influences consumer preference. During parboiling, heat and moisture change several chemical reactions such as starch gelatinization, lipid oxidation, and the Maillard reaction, which lead to the formation of aroma compounds [48]. These compounds, known as volatile organic compounds (VOC), include aldehydes, ketones, alcohols, and pyrazines, which contribute to the nutty or roasted aroma of parboiled rice [49]. For example, compounds like limonene produce a citrus smell, nonanal contributes a waxy citrus scent, benzaldehyde gives an almond note, while pentanal is known for its green, nutty odor [50]. However, the concentration of volatile compounds can change during cooking or storage, and poor storage conditions may lead to oxidation or loss of aroma. Proper storage conditions in a low-temperature and relative humidity environment (i.e., cool and dry place) help preserve the aroma quality [15]. Additionally, the degree of milling affects the aroma strength; for instance, excessive milling removes surface layers rich in aroma compounds [49].

4.5. Nutritional and Health Benefits of Parboiled Rice as Compared to Non-Parboiled Rice

The milling process removes superficial layers of the rice caryopsis, including the bran and germ, which results in a higher concentration of carbohydrates but a significant reduction in essential vitamins and minerals. Rice bran is a rich source of dietary fiber, protein, minerals, and a wide range of phytochemicals. These include γ-oryzanol, tocols (tocopherols and tocotrienols), and polyphenols, all of which contribute to the antioxidant, anti-inflammatory, and cholesterol-lowering properties associated with whole grain rice consumption [33]. Parboiling enhances the nutrients of the endosperm by facilitating the migration of water-soluble nutrients from the bran into the endosperm during soaking and steaming [2]. The nutrient redistribution helps retain valuable micronutrients that would otherwise be lost during milling. There is a rise in parboiled rice production at a commercial scale because of its high concentration of nutrients, phytochemical composition, and digestibility. This section gives an overview of the nutritional properties of parboiled rice.

The loss and diffusion of protein in parboiled rice depend on the intensity of the thermal treatment applied during parboiling [8]. Additionally, the drying stage induces structural changes in rice proteins, which can also influence the overall texture of parboiled rice [51]. The amino acid composition and protein level in parboiled rice remain stable. The protein content in parboiled rice in Asian countries is about 8.38% to 11.34%, which is relatively higher than 7% found in non-parboiled rice [8]. For the US long-grain rice, a 6–7.5% protein range is common [52], with parboiling causing modest increases relative to milled white rice due to protein redistribution rather than true protein enrichment [53]. Although the protein bodies in the kernel may rupture during steaming, the total protein and amino acid content of parboiled rice are not significantly reduced. However, thermal treatment can help hydrolyze the protein, increasing the disulfide bond, which elevates the viscosity and hardness of the rice during cooking. In addition, parboiling also creates or strengthens a protein barrier within the rice endosperm. The protein barrier influences the texture properties of cooked rice by increasing hardness, reducing stickiness, and limiting the leaching of solids during the cooking of parboiled rice [54]. Also, maintaining stable protein levels ensures that parboiled rice retains important nutritional benefits, supporting its value as a staple food.

In rice, there are mainly two types of lipids present, which are starch and non-starch lipids. Brown rice contains 0.66–0.76% of starch lipids and 2.9–3.4% of non-starch lipids [21,55]. The starch lipids are concentrated inside the endosperm part of the rice kernel, while the non-starch lipids are mainly located in the bran and embryo parts. Lipids play important roles in the preservation, processing, and cooking quality of rice. The bran, which is the outermost layer of the kernel, contains 15–25% lipids along with other beneficial compounds. The bran and embryo account for approximately 60% of the total non-starch lipid content, most of which is removed during milling [55]. Starch lipids are found in relatively low amounts and are mainly amylose. After parboiling, the overall quantity of fat (lipids) in rice does not change because the process does not remove or add fats [9]. However, a slight increase in lipid concentration within the endosperm may occur due to the migration of lipids from the bran into the inner layers of the grain. The study by Oli et al. [51] reported that during parboiling, lipid bodies and spherosomes in the rice kernel are broken down, leading to the release of fats. These fats migrate to the grain surface, which causes the bran to become greasy and potentially contributes to off-flavor development due to lipid oxidation. Thus, optimizing parboiling conditions is essential to preserve flavor and minimize undesirable sensory effects.

Parboiled rice contains higher levels of minerals than white rice. These compounds are predominantly present in the germ and aleurone layer at higher concentrations; however, grinding significantly decreases the level of minerals [56,57]. Mineral concentration increases up to 18% in parboiled milled rice when compared to non-parboiled milled rice [9]. Previous studies found that the calcium, potassium, sodium, and iron levels in parboiled rice are higher than in raw rice [9,58]. Parboiled rice contains a higher amount of minerals due to the diffusion of nutrients from the outer layer of the grain and from the husk into the endosperm during the parboiling process [57]. The diffusion and retention of minerals within the grain are influenced by several factors, including mineral distribution, soaking solubility, and migration rates [59]. The ash content indicates the amount of minerals present in the rice grain. The ash content of parboiled brown rice (1.18%) and non-parboiled brown rice (1.21%) exhibited no significant difference, indicating that parboiling does not affect the mineral content of rice [9,27].

Starch is the primary component of rice and serves as one of the most important sources of dietary energy for humans. During the parboiling process, the application of heat and water causes starch gelatinization, which breaks down the crystalline structure

inside starch granules. This leads to changes in the grain structure and composition. Several studies have reported a reduction in starch content after parboiling, which may be due to changes in structure and leaching [59]. According to Muchlisyiyah et al. [8], the starch content in parboiled rice typically ranges from 83.19% to 86.51%. Parboiling promotes a more compact and organized molecular structure of amylose and amylopectin, which helps reduce water absorption in loose areas and prevents amylose from leaking out during cooking [59,60].

Also, lipids bind to amylose during parboiling to form amylose-lipid complexes, which slow down starch swelling and dissolving during cooking [28,54]. These complexes are more heat-resistant and contribute to the firmer texture of parboiled rice [43,61]. Derycke et al. [54] reported that starch amylose content ranges from 17% to 23%. Rice with high amylose content exhibits high volume expansion and a high degree of flakiness. The firmer texture of parboiled rice is due to high lipid-amylose complexes, which do not melt at normal cooking temperatures. It makes the grain less tender and harder after cooling. The starch fills small cracks in the rice kernel during parboiling, which helps reduce breakage during milling and improves the overall milling quality of the rice [18,38].

The parboiling process enhances the nutritional value of rice by promoting the migration of micronutrients from the bran into the endosperm [14,28]. As a result, parboiled rice retains higher levels of essential B vitamins, such as thiamine and nicotinic acid, compared to raw milled rice [62]. Several studies have shown that soaking temperature plays a significant role in nutrient migration, especially for thiamine. Soaking rice at temperatures between 30 °C and 70 °C has been reported to gradually increase thiamine content, as higher temperatures enhance the diffusion of thiamine from the outer bran layers into the inner endosperm [20,63]. The behavior of riboflavin during parboiling follows a non-linear pattern in relation to soaking temperature. As the soaking temperature increases, riboflavin content rises, reaching its peak at approximately 70 °C. However, further increase in soaking temperature beyond this point leads to a decline in riboflavin content, which is due to thermal degradation. Manful et al. [64] observed that riboflavin content peaked at 0.278 mg/g when rice was soaked at 70 °C and steamed for 12 min, but decreased significantly when the soaking temperature increased to 90 °C.

4.6. Health Benefits of Parboiled Rice

Incorporating parboiled rice into a balanced diet is a strategic choice for pursuing a healthy lifestyle. The parboiling process retains essential vitamins and minerals that are typically lost during the milling of regular white rice [8]. One notable health benefit is its effect on blood sugar levels. Research has shown that parboiled rice has significantly lower blood glucose levels, making it suitable for both healthy individuals and those with Type 2 Diabetes Mellitus (T2DM) [65]. This effect is primarily attributed to its higher resistant starch and protein content, as well as changes in its grain structure during processing.

During parboiling, amylose-lipid complexes form harder for enzymes to break down. These complexes remain insoluble and slow down digestion, which lowers the glycemic index (GI) of rice [65,66]. GI measures the relative change in blood glucose level after eating. The intensity of the parboiling process directly impacts GI, such as the more intense the parboiling process, the lower the GI. For instance, Larsen et al. [65] reported that pressure-parboiled rice has a GI of 39, compared to 46 for traditional parboiled rice and 55 for non-parboiled rice. This shows that parboiling significantly reduces the glycemic index of rice [65].

According to Bhar et al. [67], parboiled rice increases vitamin B6, which supports heart health by reducing the risk of coronary heart disease (CHD), hypertension, and nonfatal heart attacks (myocardial infarction). Moreover, soaking and steaming allow

phytase enzymes to break down phytic acid. Phytic acid inhibits the absorption of essential minerals due to its strong binding affinity with nutrients such as calcium, iron, and zinc. As a result, parboiled rice enhances mineral bioavailability, including iron and zinc, which are essential in preventing anemia and supporting immune function [68]. Zinc deficiency, for instance, has been linked to growth retardation and immune functions. Additionally, lower phytic acid levels improve the absorption of magnesium, manganese, and potassium, which contributes to preventing asthma, diabetes, and cardiovascular diseases [69].

Parboiled rice also supports weight management due to its starch digestibility. Compared to raw white rice, parboiled rice digests more slowly [70,71]. Starch is classified into three types based on digestion rate: Rapidly Digestible Starch (RDS), Slowly Digestible Starch (SDS), and Resistant Starch (RS) [48]. RDS raises blood sugar quickly and can lead to higher insulin levels, whereas SDS digests more slowly, resulting in a gradual release of glucose that promotes satiety. RS is not digested in the small intestine and contributes to gut health. Therefore, parboiling improves metabolic responses by increasing the RS content up to 8% and reducing RDS levels [70].

Studies across various rice cultivars show that parboiled rice has higher RS and SDS, and lower RDS [32]. Uncooked parboiled rice with high amylose content showed the highest RS compared to medium-amylose or waxy rice varieties [32].

Parboiled rice can also help fight micronutrient deficiencies through fortification [72]. Fortified rice can have 15 to 80 times more folate than regular rice. Even after washing and cooking, about 90% of the added folic acid is retained. Fortification does not affect rice sensory attributes, including texture, taste, aroma, or color [73]. Parboiled rice can also be fortified with iron and zinc. The process involves soaking rice in water that contains minerals. As the rice absorbs the water, the nutrients enrich the endosperm and whole kernel [74]. Studies show that iron content in fortified parboiled rice can increase by more than double, and zinc levels can be five times higher than in unfortified rice [75,76].

5. Challenges in the U.S. Parboiled Rice Industry

While the challenges facing the U.S. parboiled rice industry are discussed individually in the subsections below and shown in Figure 3, they are highly interconnected and systemic in nature. Resource-intensive operations exacerbate energy and cost pressures, while limitations in process control and automation amplify risks of non-uniform heating, grain damage, and quality losses. These technical constraints are further reinforced by infrastructure gaps and external drivers such as labor shortages, climate variability, and regulatory compliance costs. Recognizing these linkages is essential for identifying integrated solutions rather than addressing challenges in isolation.

5.1. Resource Intensity: Energy and Water Use

Parboiling is inherently more resource-intensive than conventional rice milling, with soaking, steaming, and drying accounting for the majority of energy and water consumption. Parboiled rice is gaining more awareness in the U.S, but it still accounts for only about 10% of the total rice consumed. Hence, many rice mills still rely on conventional methods with limited innovation in parboiling technology. Countries in Asia where parboiled rice is a major part of the diet have invested more in improving parboiling processes to increase efficiency and reduce costs. The gradual adoption of parboiled rice consumption in the U.S. has hindered the allocation of resources and attention toward advancing its research and development. Conventional parboiling is resource-intensive, requiring up to 2000–2500 kWh of energy and around 20 to 25 m^3 of water per ton of rough rice [77]. The commercial milling industry uses steam for starch gelatinization, which requires boilers that increase processing costs and fuel consumption, resulting in higher greenhouse gas

emissions. Additionally, moisture content after steaming can rise to 45–50%, adding extra drying costs [77,78]. generates wastewater, air emissions, and solid wastes, resulting in adverse environmental impacts [79]. Studies have shown that the energy required for parboiling can be three to five times higher than that used for milling white rice [78]. The energy demand in parboiling operations depends on several factors, including the method of parboiling, state of rice, rice variety, quantity, and key process parameters such as soaking and steaming temperature and time, and applied pressure [8]. The high energy requirements for parboiled rice processing pose a challenge to the economic viability of small-scale processors and compromise the sustainability of the rice industry, especially amid rising energy prices. Kwofie and Ngadi [5] explain that energy consumption is typically estimated based on the amount and calorific value of fuel used. For instance, pressure parboiling systems require more energy than traditional hot soaking methods due to high thermal and pressure inputs. Bello et al. [15] emphasizes that integrating multiple drying methods can significantly lower the energy required for parboiling. For example, Ertekin et al. [80] reported that combining infrared drying with hot air fluidized bed drying reduced energy consumption by a factor of 4.6, compared to using hot air drying only. Additionally, tempering during the drying stage has been identified as an effective strategy to further reduce energy consumption. Golmohammadi et al. [81] observed that intermittent tempering decreases rice breakage and significantly reduces energy use up to 64% when three tempering phases are applied, compared to continuous drying. Islam et al. [82] estimated energy consumed for an optimized industrialized system of processing rice to range from 4.0 to 5.5 kJ/kg, with total energy required for one ton of rice ranging between 350 and 920 kWh. Notably, parboiling and drying account for more than 90% of the total energy used in rice milling operations.

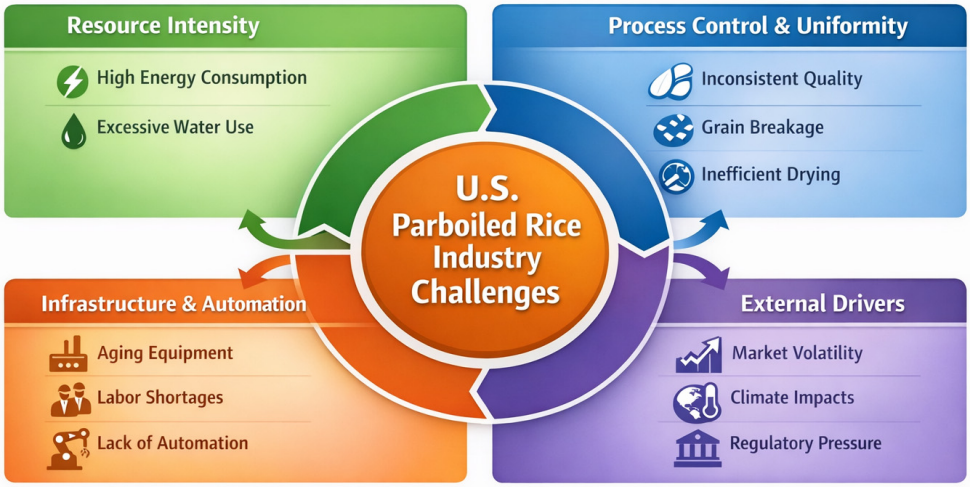


Figure 3. Key challenges in the U.S. parboiled rice industry, grouped into four interrelated categories: resource intensity (energy and water use), process control and uniformity, infrastructure and automation constraints, and external drivers including market, climate, and regulatory pressures.

Parboiling consumes high volumes of water, especially during the soaking phase. Each kilogram of rough rice parboiled generates approximately 1 to 1.2 liters of wastewater [58]. The effluent from rice mills is often yellowish, features an offensive, pungent odor, and contains organic debris and other pollutants. If not properly managed, it can cause groundwater contamination and pose a public health hazard. Managing and valorizing wastewater streams is a crucial challenge, especially in regions like Arkansas, which produces more than half of the nation's rice. The soak water includes a high concentration of suspended and dissolved organic compounds that decompose over time, which reduces dissolved oxygen (DO), chemical oxygen demand (COD), and increases turbidity, acidity, biochemical

oxygen demand (BOD), iron, hardness, chloride, and sulphate in local water bodies. The rice cultivation areas in the U.S. rely on irrigation; for example, Arkansas alone uses over 1.4 million acre-feet of water annually, and increasing water demand for both cultivation and parboiling processing may increase water scarcity, particularly under climate change scenarios [5].

More research should focus on reducing soaking and steaming times, improving energy efficiency and sustainability, and enhancing the grain quality of parboiled rice. Evaluating emerging technologies such as ohmic heating, radiofrequency, ultrasound, and fluidized bed drying on a pilot scale could help identify practical, cost-effective solutions for U.S. rice processors. Strengthening collaboration between universities, industry stakeholders, and government agencies could help develop more efficient, cost-effective, and sustainable parboiling systems tailored to U.S. conditions.

5.2. Process Control and Uniformity Challenges

Achieving uniform heat and moisture distribution across large grain volumes remains a central technical challenge in U.S. parboiled rice processing. Maintaining uniform heating is a critical challenge in the U.S parboiled rice industry. Each parboiling stage, including soaking, steaming, and drying, must be carefully monitored and controlled to prevent heat damage and ensure consistency. Uneven heat distribution can cause parts of the rice kernel to be overexposed to heat, which can lead to grain defects such as darkening, hardening, or brittleness [22]. These defects affect the grain appearance, texture, and milling quality. Inconsistent heating results in non-uniformity in the parboiled rice produced, with some grains becoming softer or harder than others [2]. Studies have shown that upward temperature is significantly higher than in other directions, with a significant increase observed above 90 °C [34]. This suggests that the perforation at the bottom of the sample holder may cause uneven steam flow through the rough rice mass. The use of an advanced vessel with a wire mesh 150 mm above the base reduces energy consumed compared to the conventional vessel method designs by preventing direct contact between grains and hot water. Achieving even heat transfer across all grains is especially difficult in large-scale operations. To minimize heat damage and enhance grain quality, the industry must adopt advanced control systems to ensure uniform heat and maintain optimal temperature and moisture levels through all stages of parboiling.

The two-stage drying technique combining high and low temperature drying with tempering intervals has proven effective for improving drying efficiency and final product quality. In the U.S., the rotary drum dryer is mostly used as the initial high-temperature drying system, which rapidly reduces the moisture content of parboiled rice from approximately 38–34% to 18–14% [3,83]. The rotary drum dryer consists of an inclined or horizontal rotating cylinder into which parboiled rice is fed from one end. As the drum rotates, grains are exposed to hot air and heated walls, which facilitate rapid moisture removal. However, its drying mechanism operates at high thermal energy and causes continuous tumbling of the grain, which often compromises grain quality and safety. During operation, parboiled rice is exposed to hot air, typically above 120 °C, as the drum rotates to mix and drops repeatedly. This results in rapid surface moisture removal and the development of steep internal moisture gradients, which generate stress and cracks within the kernels. Additionally, the non-uniform distribution of heat and airflow inside the rotating drum leads to uneven drying. As the drum rotates, grains move along its length, exposing them intermittently to hot air streams. However, the distribution is not consistent; for instance, grain near the drum shell receives more exposure to heat, while those deeper in the grain bed experience limited contact with the hot air stream and dry more slowly. The spatial variation in heat and airflow to moisture content creates significant

differences in drying rates across the grain batch, resulting in moisture stratification, which leads to non-uniform milling, where softer grains break more easily, thereby reducing overall head rice yield [84]. Moisture stratification often occurs in rotary drum drying systems, where uneven heat exposure and airflow distribution create varying moisture content across the grain mass. Moisture stratification also promotes microbial growth and spoilage, leading to color changes and reduced shelf life of grain. Although rotary drum dryers have been proven to be effective from a throughput perspective, the thermal and mechanical environment generates structural damage, which negatively affects the milling quality, cooking properties, and overall appearance of parboiled rice.

One of the major challenges facing the U.S. parboiled rice industry is managing broken and heat-damaged kernels. These defects significantly reduce market value and affect consumer satisfaction. Broken kernels are mainly caused by internal stress during parboiling, especially when the rice grain structure is weak. When the force applied during handling or drying is more than kernel strength, breakage occurs [84]. Factors such as internal fissures, chalkiness, kernel shape, and moisture content play a key role in determining the kernel's resistance to breakage [22]. Also, chemical changes during heating, such as protein polymerization, amylose lipid complex formation, and amylopectin retrogradation, can make the kernels more brittle and prone to breakage. Immature kernels are small and chalky compared to mature rice. As a result, they respond poorly to thermal processing and are more susceptible to breaking or cooking unevenly during parboiling. Immature grains also tend to be softer and less resistant to pressure, making them more prone to cracking and damage during mechanical handling [28]. Heat-damaged kernels are caused by overheating or uneven steaming and drying [85]. These kernels may appear darker and become very hard or brittle. Too much heat can lead to overcooked or partially burnt rice, which negatively affects the visual appeal, texture, and cooking quality of the rice. These defects often result from improper control of temperature and moisture during the parboiling and drying stages. Overheating causes uneven gelatinization and drying stress, further weakening the grain structure. Based on current trends, many U.S. rice processors use advanced sorting machines, such as optical sorters and grading systems, to remove defective kernels. While these technologies help improve quality, these machines increase operational costs and are not always accessible to smaller processors.

5.3. Infrastructure and Automation Gaps

Infrastructure and automation limitations constrain the ability of many U.S. rice mills, particularly small and mid-scale facilities, to adopt advanced parboiling technologies. While the demand for parboiled rice is on the rise with a compound annual growth rate of 4.1%, the infrastructure to support local processors is limited. Most U.S. rice mills are designed primarily for milling white rice, and fitting these mills for parboiling involves substantial capital investments in new equipment, training, and facility upgrades. This lack of modern infrastructure limits the capacity of U.S. rice processors to meet increasing demand for parboiled rice, both for domestic usage and international export.

5.4. External Drivers and System-Level Constraints

In addition to technical and infrastructure challenges, external drivers such as market dynamics, regulatory compliance, and climate variability exert increasing pressure on the U.S. parboiled rice sector. Climate change is increasingly affecting agricultural systems. In the last ten years, the United States has experienced more frequent droughts, higher temperatures, and extreme weather events. These changes directly influence the types of rice that can be grown and their quality, making it harder for parboiling operations to consistently produce rice that meets quality standards [86].

Labor shortage is a barrier to the full adoption and efficient operation of parboiling systems in the U.S. rice industry. Rice parboiling is a complex process involving controlled soaking, steaming, drying, and milling. It requires skilled personnel to manage equipment, monitor critical parameters, and ensure grain quality. However, many rice mills, especially in rural regions in the southern part, lack access to trained labor and technical expertise, which limits the adoption of parboiling altogether in some facilities. The aging workforce, low interest in agriculture, and high turnover rates make it difficult to retain qualified staff. Lack of technical skills in parboiling can lead to poor process control during critical stages like drying and milling, and then compromise grain quality and milling yield. Inconsistent handling of equipment also increases downtime and safety risks. Hired laborers unfamiliar with food safety protocols or automation systems may further contribute to these issues.

Rice is particularly sensitive to heat and water stress, especially during critical growth stages such as flowering and grain filling. High day and night temperatures can reduce grain weight, increase chalkiness, weaken the grain, and thereby lower the milling yield [87]. Water stress shortens the grain-filling period, resulting in smaller, lighter grains with higher chalkiness and lower strength. Managing these stresses is essential for parboiling operations that require uniform raw materials for consistent processing performance.

Beyond the field level, extreme climate events disrupt rice supply chains by delaying planting and harvesting, damaging transportation infrastructure, and affecting post-harvest storage. These disruptions increase operational uncertainty, contribute to price fluctuations, and raise financial risks for parboiling industries that rely on predictable rice supplies.

Adaptive strategies are needed to address these challenges. Biotechnology advances, such as developing heat- and drought-tolerant rice cultivars, offer potential solutions to maintain grain quality under changing climate conditions. The use of improved climate forecasting, precision agriculture tools, and decision-support systems can also improve planning of planting, irrigation, and harvest timing, and help parboiling operations manage risks more effectively. Overall, the U.S. parboiled rice industry faces interconnected challenges where high energy and water use make processing costly and environmentally intensive. Uneven heating, drying issues, and grain defects worsen these costs and highlight the need for better technology and infrastructure. Labor shortages, limited research, and climate impacts further strain production and supply chain stability. Focusing first on energy efficiency, modern equipment, and workforce training can improve grain quality, reduce waste, and strengthen the industry's competitiveness.

6. Innovations in Parboiled Rice Processing

Technological innovations in parboiling will help reshape the U.S. rice industry, shifting from empirical, batch-based approaches toward precision-engineered, data-driven systems. Past research discussed and listed in Table 4, such as vacuum soaking, infrared (IR) steaming, and microwave-assisted drying, has demonstrated remarkable improvements in process efficiency, energy savings, and product quality. Vacuum soaking has been reported to accelerate rice hydration by enhancing pressure-driven mass transfer and reducing soaking duration compared with conventional atmospheric soaking methods [15,47]. IR steaming uses electromagnetic radiation for volumetric heating, reducing thermal stress and fissuring while improving control over starch retrogradation [45]. Superheated steam, along with fluidized bed drying, seemed to improve parboiled rice processing efficiency and attain better quality rice [88]. Microwave drying integrates dielectric heating to achieve rapid, uniform moisture reduction; it has been shown to reduce drying time by up to 40% and increase energy efficiency by 25% compared to convection-based systems, all while preserving kernel translucency and nutrient density [89]. The combined use of IR and microwave hybrid systems represents a major frontier in industrial parboiling optimization.

Table 4. Emerging processes and digital innovations in parboiled rice processing and their key outcomes.

Innovation/Tool	Main Role	Key Outcome	Commercial Statues and Cost Implication	References
Accelerated tempering	Efficient drying	Shorter drying time, less energy consumption	Commercial, Low to moderate cost	[24]
Vacuum soaking	Enhanced hydration kinetics	Accelerated water absorption	Pilot-Commercial, High cost	[15,47]
Superheated steam and fluidization	Efficient processing and drying	Shorter drying, higher energy efficiency	Commercial, High cost	[88]
IR steaming	Volumetric radiant heating	Less fissuring, improved starch control	Early commercial, Moderate-High cost	[45]
Microwave-assisted drying	Fast dielectric drying	Shorter drying, higher energy efficiency	Pilot-Early commercial, Very high cost	[89]
PLCs, AI models	Automated process control	Reduced human error, predicted HRY/quality	Fully commercial, Moderate cost	[5]
HSI/NIR	In-line quality sensing	Detect chalkiness, fissures, and protein	Commercial, Low-moderate cost	[90]
IoT, blockchain, digital twins	Smart, traceable, optimized plants	Energy-efficient, traceable, sustainable systems	Experimental, High	[8]

Simultaneously, digital tools such as real-time sensors, artificial intelligence (AI), and Internet of Things (IoT) platforms are transforming automation and quality control in rice processing. Programmable Logic Controllers (PLCs), fed by sensor data on temperature, humidity, and airflow, dynamically adjust process parameters to reduce human error and energy waste [5]. AI models trained on historical drying curves accurately predict end-points to avoid over-drying, while adaptive neural networks forecast HRY and nutritional quality under variable steaming conditions. Advanced imaging tools such as hyperspectral imaging (HSI) and near-infrared (NIR) spectroscopy now provide real-time detection of chalkiness, fissures, and protein content with micron-level accuracy [90]. IoT-enabled smart dryers autonomously regulate airflow and heat input, while enabling remote monitoring and predictive maintenance. Integration with blockchain platforms offers traceability for batch-level energy use and product quality. Finally, digital twins and computational modeling tools such as CFD and LCA allow researchers to simulate and optimize entire parboiling operations, setting the stage for intelligent, energy-efficient, and sustainable rice engineering systems [91,92]. Overall, the innovations discussed span a wide range of technology readiness levels, from early-stage and pilot-scale developments to commercially implemented solutions, with adoption in the U.S. varying by mill size, capital availability, and regulatory context.

7. Circular Economy and Sustainability Opportunities

Circular economy principles are transforming the U.S. parboiled rice sector by converting agricultural waste streams into energy, functional materials, and value-added nutrients. The shift from a linear "take–make–dispose" model to a circular "reuse–recycle–recover" approach enhances both environmental sustainability and operational profitability [8]. The performance indicators reported in this section are drawn from a combination of pilot-scale

demonstrations, best-case literature values, and commercially implemented systems, and are presented to illustrate the potential range of achievable sustainability gains rather than uniform industry-wide performance. Table 5 reflects circular economy-driven resource reuse for the parboiled rice industry. By-products such as rice bran, husk, and broken kernels are now integral to secondary industries. Rice bran is used for extracting high-value oils rich in antioxidants, while broken kernels are milled into starches and flours for instant foods. Rice husks, with high silica content, serve as feedstock for bioenergy and even building materials. Advances in recovery technologies have enabled the extraction of 90–95% pure amorphous silica from rice husk ash (RHA), which finds application in ceramics, batteries, and nanocomposites. Meanwhile, cellulose fibers from straw are repurposed into bioplastics and paper substitutes, aiding decarbonization of the packaging industry. Milling facilities in Arkansas and Louisiana now incorporate these recovery processes, demonstrating the feasibility of agro-industrial circularity [8].

Table 5. Circular economy-driven resource reuse for the parboiled rice industry.

Circular Economy Innovation	Description	Benefits and Applications	Implementation Status	References
Rice bran valorization	Oil extraction	Antioxidant-rich oils for nutraceuticals	Commercially implemented	[93]
Broken kernel reuse	Starch and flour production	Instant foods	Commercially implemented	[94]
Rice husk utilization	Bioenergy, building materials	Biochar, syngas, purified silica	Commercial to pilot-scale	[58]
Straw fiber reuse	Bioplastics, paper substitutes	Packaging decarbonization	Pilot-scale to emerging commercial	[95]
Water recycling	Closed-loop soaking water reuse	Reduced freshwater use	Pilot-scale/limited industrial adoption	[96]
Heat recovery	Exhaust heat capture	Up to 30% energy saving	Commercially implemented (site-specific)	[5,97]
Renewable energy integration	Pyrolysis/gasification of husks	Net-zero emissions, powering operations	Pilot-scale to early commercial	[92]
Sustainability assessment	Life Cycle Assessment (LCA)	Benchmarking GHG, driving cleaner tech adoption	Commercially implemented (decision-support tool)	[91,92]

Resource efficiency is further enhanced through water recycling and heat recovery systems. Closed-loop designs recirculate condensate water from steaming for reuse in soaking, significantly lowering freshwater demand. Waste heat recovery units capture thermal energy from exhaust air to preheat incoming streams, cutting thermal energy usage by up to 30% [2]. Life Cycle Assessment (LCA) tools now guide sustainability benchmarking, showing that drying and steaming stages dominate GHG emissions. However, integrating renewable energy can cut emissions by 40%, making parboiled rice production more competitive. Although parboiled rice has a 20–30% higher embodied energy than milled rice, its longer shelf life and nutritional superiority justify investment in cleaner technologies. Innovations in pyrolysis and gasification are enabling rice husks to be transformed into biochar, syngas, and pyro-oils, some of which now power steam boilers in closed-loop systems [2,58,92]. These green energy loops offer a clear path toward achieving net-zero parboiling operations in the near future.

8. Policy, Trade, and Regulatory Landscape

The U.S. parboiled rice industry operates within a strict regulatory landscape shaped by federal safety standards, international trade agreements, and sustainability mandates. Domestically, the USDA and FDA regulate parboiled rice under the Grade Standards for Rice (7 CFR §868) and Fortification Standards (21 CFR §137.350), which require enrichment with iron, niacin, and thiamine. Compliance with Hazard Analysis and Critical Control Points (HACCP) protocols and Good Manufacturing Practices (GMPs) ensures food safety, traceability, and alignment with export market demands. These regulatory frameworks are foundational to maintaining public health, enabling market differentiation, and promoting the credibility of U.S. rice in global supply chains. Export activities are governed under WTO and USMCA agreements, providing tariff stability and market access—especially in West Africa and the Caribbean, where parboiled rice consumption is dominant. However, exporters must also navigate labeling, residue limits, and phytosanitary guidelines under Codex Alimentarius and region-specific rules, such as those from ECOWAS [6].

Government initiatives increasingly support modernization efforts and the transition toward a circular economy. Programs like the USDA BioPreferred Program, EPA AgSTAR, and DOE Industrial Efficiency Grants provide technical and financial support for mills installing biomass boilers, water recycling units, and IoT-based energy monitoring platforms. These incentives align with national sustainability goals while improving cost-efficiency. Concurrently, labeling regulations are evolving to include environmental disclosures alongside nutrition. QR-based traceability systems allow consumers to view product origin, water footprint, and carbon emissions. Major companies are adopting blockchain-secured traceability to authenticate product claims and support compliance with international sustainability standards.

While regulatory frameworks play a critical role in ensuring food safety, product quality, and environmental protection, they can also influence the pace of technological adoption in the parboiled rice sector. For large processors, standardized compliance pathways and economies of scale often facilitate investment in advanced automation, energy-efficient drying systems, and waste-recovery technologies. In contrast, small and mid-scale processors may face proportionally higher compliance and permitting costs, which can slow adoption despite potential efficiency gains. At the same time, federal and state-level incentive programs, sustainability mandates, and export-driven quality standards can enable innovation by encouraging modernization and supporting the uptake of cleaner and more efficient technologies.

9. Strategic Roadmap, Recommendations, and Conclusions

The U.S. parboiled rice sector reflects a mature, yet evolving agro-industrial system positioned between traditional processing practices and emerging precision-driven technologies. This review has highlighted how parboiling fundamentally alters grain structure, enhances milling yield, improves nutrient retention, and lowers glycemic response, attributes that reinforce its nutritional and functional advantages over conventional milled rice. At the same time, the industry faces structural constraints, including high energy and water intensity, process variability, infrastructure gaps, and increasing climate-related risks.

A central theme emerging from this synthesis is that the competitiveness of U.S. parboiled rice will depend less on incremental process optimization and more on system-level integration. Future progress requires alignment across rice breeding, post-harvest handling, parboiling parameters, and downstream market positioning. Grain variety selection, thermal processing intensity, and milling practices must be considered as an interconnected value chain rather than isolated operational stages. Establishing clearer

quantitative linkages among raw material characteristics, process conditions, nutritional outcomes, and economic returns remains an important research priority.

Sustainability considerations further redefine the strategic direction of the industry. While parboiling inherently demands greater energy inputs than conventional milling, advances in heat recovery, renewable energy integration, and water reuse demonstrate that environmental performance can be substantially improved. The transition toward circular resource utilization, particularly biomass valorization and waste stream recovery, offers a pathway to decouple production growth from environmental burden.

Equally important is the human and institutional dimension. Workforce development, digital literacy, and collaborative research networks will determine how effectively emerging technologies are translated into commercial practice. Strengthening partnerships among land-grant universities, technology providers, and processing facilities can accelerate innovation diffusion, particularly for small and mid-scale mills.

In the global context, U.S. parboiled rice holds a distinct advantage in quality consistency, regulatory compliance, and technological sophistication. As international markets increasingly prioritize traceability, nutritional functionality, and environmental accountability, these strengths position the United States to move beyond volume-based competition toward value-based differentiation.

In conclusion, the long-term resilience of the U.S. parboiled rice industry will depend on integrated modernization, climate adaptability, and sustainable resource management. By bridging scientific advancement with industrial implementation, the sector can reinforce its export leadership while aligning with broader goals of food security, environmental stewardship, and public health.

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