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Review

Parboiled Rice Processing Method, Rice Quality, Health Benefits, Environment, and Future Perspectives: A Review

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Abstract: Parboiled rice is recognized for its greater milling yield and reduced rice breakage compared to raw rice during processing. Additionally, parboiled rice has better glycemic control and numerous health benefits. However, the production of parboiled rice requires energy-intensive processing as well as wastewater production. This study reviews parboiled rice, including its processing condition, nutritional properties, potential use, emerging green technologies, and health benefits. It also discussed the outlook and challenges regarding parboiled rice. In addition, a novel overview of emerging green solutions applied to the process to minimize wastewater creation during parboiling and reduce excessive energy usage is provided. The limitation of parboiled rice for a new market preference is the color. An intense process would cause an unwanted physical appearance. A thorough study should balance the multiple advantages of parboiled rice with the reasonable intensity of the process. Due to its multiple advantages, parboiled rice is demonstrated to be a possible breakthrough in the agriculture and food industries. This review aims to provide a thorough understanding that can be used for academic and industrial purposes.

Keywords: parboiled rice; processing; properties; benefits; emerging technology

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1. Introduction

Rice (*Oryza sativa* L.) is a staple food for approximately half of the world's population. In 2021/22, the world's rice production was 509.87 million metric tonnes [1]. Asia contributes to more than 90% of global production and 88% of consumption [2]. Rice is consumed as a whole grain (brown, milled, or parboiled) as well as in flour and fermented forms. Around 60% of India's marketed paddy rice grains are parboiled [3]. Before milling, parboiled rice is made by soaking, steaming, and drying the rice. As a result of its low glycemic index, parboiled rice is being increasingly consumed worldwide [4–7].

Asia and several African nations are the most significant industrial producers and consumers of parboiled rice [3]. It is preferred over milled white rice due to regional culinary preferences and the improved sensory quality that emphasizes a softer texture and milder flavor [8]. In addition, it has higher calcium, selenium, and vitamin B6 contents, as well as lower phytic acid concentration [9]. Agronomic conditions during harvest also contribute to the necessity of parboiling rice, since nearly all rice grown during the rainy season and rice that has been flooded during harvest are prone to excessive breakage during milling [10]. Parboiling the rice increases its economic value by increasing the head rice yield (HRY) [11]. Head rice yield is a proportion of whole milled rice kernels (or at least 75% of the original kernel length).

As mentioned above, parboiling is a common paddy processing procedure that involves soaking paddy in water and then steaming and drying it. The grain hydrates during soaking; the starch gelatinizes during steaming to cover up the cracks inherently present in the kernels; and drying restores its hardness [12]. The net result of this processing is a significantly greater head rice yield than in the case of raw rice [10]. Retrogradation is the opposite of gelatinization and occurs during drying and storage. Gelatinization breaks down starch crystallites and traps excess water with glycosidic chains. Retrogradation reforms starch crystallites and releases water. Due to the energy-changing condition of starch in the grain, parboiling profoundly affects the grain's physicochemical, functional, and nutritional qualities [7,13]. In traditional parboiling, however, the soaking procedure uses up to 1 to 1.2 L water per kg of the parboiled rice, which produces significant volumes of wastewater; moreover, the soaking, steaming, and drying stages are highly energy-intensive (0.8–13 4 MJ/kg) [14–17]. It is therefore necessary to find ways and means of reducing the resources needed to produce parboiled rice. Several studies have been published which are concerned with reducing the amount of soaking wastewater and energy consumption by modifying the three steps [14–17]. Modeling of the soaking step with limited water has also been performed [18]. Reusing or recycling water to reduce net freshwater consumption has also been investigated [19].

As awareness of the health benefits of food products increases, efforts must also be made to improve product quality, production efficiency, and overall sustainability. Several studies have aimed to achieve this [14,16,20–24]. However, the information is highly fragmented and not adequately critical. This review aims to synthesize our current understanding of the parboiling process, the physicochemical and functional transformations that occur in parboiled rice, the emerging approaches to reduce excessive energy consumption, the health benefits of parboiled rice, and other aspects of parboiling including future perspectives and challenges in this area.

2. Techniques for Parboiling

Traditional parboiling techniques differ based on region and operating scale, but the core process consists of three steps, as mentioned earlier: hydration, thermal treatment, and drying. Paddy is hydrated by soaking to a moisture content of 24–30% wet basis. This is followed by thermal treatment (mainly steaming) to cause gelatinization. The gelatinized mass is then dehydrated to a 12–14% milling-appropriate moisture content. Large-scale commercial parboiling procedures are modified to make them more efficient and cost-effective and to enhance product quality [25].

Variations in parboiling conditions yield rice with differing physical qualities, which may affect consumer preference. The summary of the parboiled rice processing condition variation can be seen in Figure 1. Table 1 provides a brief comparison of the parboiling processes reported earlier. A comparison of rice parboiling methods with respect the soaking and steaming steps is set out below.

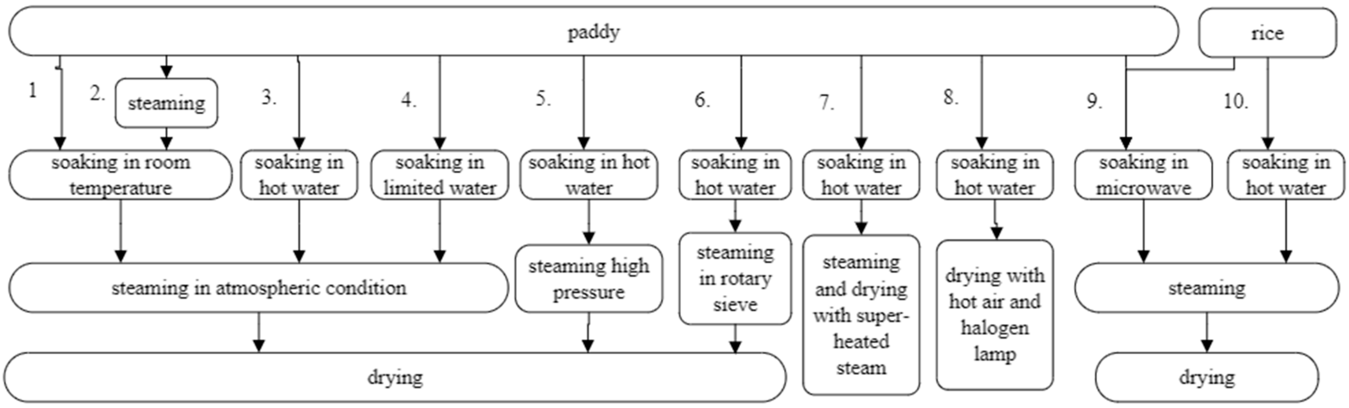

Figure 1. Summary of parboiled rice production.

Table 1. A comparison of several parboiling methods.

Process	Benefits	Disadvantages	Reference
1. The single-batch boiling process Soaking at ambient temperature for 2 h, steaming at 100 °C, and drying using sun drying/shade drying until moisture is 12–14%	Simple, easy, and low-cost technology	Off-flavor development	[3,26]
2. Double boiling process Steaming at 100 °C, then soaking for 36 h at ambient temperature and drying using sun/shade drying until 13% moisture content	Faster soaking process	Off-flavor development and grain bursting	[3,26]
3. Hot water soaking process Soaking in hot water at 60–75 °C until 24% moisture, steaming at atmospheric pressure, and sun drying or hot air drying until 12–14% MC	Reduce soaking time and reduce odor generation	Off-flavor generation High wastewater generation	[6,27]
4. Limited hot water soaking process Minimum water or recycling water during soaking at 70 °C, steaming at 100 °C, and drying at room temperature	Reduce wastewater generation	Risk of uneven quality	[18,28]
5. Pressure parboiling process Soaking until the moisture content reaches 24% (40–70 °C), steaming above atmospheric pressure at 115 °C (69.98 kPa) for 10 min, and drying in a convection oven for 48 h at 25 °C	Shorter processing time	Darker color and more rigid texture	[29,30]
6. Pressure parboiling process Soaking at 70 °C for 5 h, steaming at 103° C for 5–10 min, and sieving for 5–15 rpm; drying is only tempered at ambient temperature until moisture was 12–14%	Decrease parboiling time and even the quality of parboiled rice.	Complex operation	[21]
7. Superheated steam process Paddy is steamed and dried using a superheated steam in a fluidized drier; the steam pressure of 1.2 bar and at three temperatures (120, 140, 160°C) for 6 h were investigated	Combining steaming and drying using superheated steam; less chalky kernel, higher head rice yield, lessen dark color	High process installation cost, complex operation	[23]
8. Dry heat process with halogen lamp drying Dried using a halogen lamp in a hot air-fluidized bed drier at 130, 150, and 170 °C with the halogen power set at 1500, 3000, and 4000 W	No steam needed	Possible complete gelatinization, darker than superheated fluidized bed drier	[14]

Table 1. *Cont.*

Process	Benefits	Disadvantages	Reference
9. Brown rice process Soaking brown rice until the moisture content reaches 24% (40–70 °C), steaming 100–120 °C for 10–15 min, and hot air drying at 30–50 °C until 12–14% MC	Faster hydration	Risk of caking during the process and higher solid loss	[11,31]
10. Microwave-assisted soaking process Soaking in 0.4–0.7 kW for 10–20 min; dried in a hot air oven at 40 °C until 12–14% MC	Faster hydration, more uniform microstructure	Higher energy consumption and expensive	[17]

2.1. The Single-Batch Boiling Process

The most traditional method of parboiling, normally undertaken on a domestic scale, is a batch process [2]. Since there is no access to steam, the rice is parboiled using hot water. Paddy is soaked at a relatively ambient temperature for several hours, drained, and then cooked with a small amount of water at the bottom to generate steam in situ. Alternatively, paddy is soaked for a few hours and briefly boiled. Such treatments often resulted in grain distortion, known as "white belly", and some off-flavor generation [32]. This small-scale process eliminates inherent microbial fermentation that hinders parboiling on a large scale. Sometimes, the method used is separate soaking and steaming without boiling. It is conducted using a false-bottomed iron tank or drum to soak rice in water heated by a fire beneath. Rice is steamed by draining and reheating water from underneath the false bottom. Paddy is steamed in the upper tank and soaked in pot water. Some areas surrounding South Asia also employ this strategy [3,26].

Because heating such a large volume of water is costly and produces temperature gradients (hotter on top, cooler on bottom) and differential hydration, entrepreneurs performed industrial-scale parboiling by soaking paddy in ambient water. "Single boiling" is when parboiling rice with only one steaming process. Soaking 5–30 tons requires three days in water at ambient temperature. After the water was drained, the soaked grain was moved by hand in baskets to cylindrical steaming tanks with conical bottoms, hatches, and steam pipes. Each tank can hold 200–500 kg of paddy. Rice is steamed for a few mins and dried in the yard while the condensate drains [32]. This method of parboiling is the simplest, easy to install, and with low technological cost, but the disadvantage is the inevitably generated off-flavor.

After starch gelatinization, paddy must be further dried to reduce the moisture content from 30–55% to 12% dry basis (db) [2]. At the earlier stage of parboiling, the most commonly used methods of paddy drying were sun drying or shade drying. After paddy parboiling and starch gelatinization, drying is important since it affects the rice's storage life and milling quality. During the harvesting season, a vast drying space is required on drying floors, which are often made of concrete or brick [32].

2.2. Double Boiling Process

Factories develop a double boiling method after a single boiling process. Two batches of boiling water are required. The soaking time might be lowered from 24 to 36 h since paddy is steamed before being soaked in water. After soaking, the wet paddy is once again steamed. This process also generates off-flavor during the soaking process due to fermentation. Compared to the single batch boiling process, the soaking process is faster, whereas the double boiling process will also promote grain bursting. The techniques have a relatively high capacity of 50–100 tons of paddy per day [32].

2.3. Hot Water Soaking Process

After a few decades of soaking cold or warm water via the single and double boiling processes, an effort was made in the literature to remove the off-flavor during the parboiling process. The process was called CFTRI hot-soaking. The previously available equipment (in the single and double boiling process) needed only minor adjustments to conduct the new methods. Steam or piped water-heated soaking tanks were heated to around 90 °C. Paddy is washed and lifted to an overhead bin, placed into water, and the rice is soaked for 3–4 h at ~70 °C with circulated water to equalize top and bottom temperatures. A previously owned double boiling miller also adopts this method by circulating hot steam and then pumping cold water, resulting in a 60–65 °C average temperature during circulation which needed 6 h of soaking time [32]. Currently, this method is conducted by soaking at 60–85 °C for 12–22 h then steaming at 85–90 °C for 3–8 min [15]. The hot water soaking process may reduce the soaking duration, thus lessening the odor generation. Meanwhile, the color of the wastewater of the hot soaking process is yellower than the room temperature soaking process, which means that the organic substance in the wastewater is higher.

In Thailand, Vietnam, and Cambodia, paddy drying cost is around 4–5% of the production process (IRRI, n.d). In other countries, the cost of paddy drying can be more than 5%. Many techniques have been used to dry parboiled paddy, with sun or shade drying and mechanical drying being the most prevalent. Other nations also utilize the fluidized bed of superheated steam, hoover, and rotary drying technologies [33]. Most rice mills utilize the conventional process of hot air drying. It is achieved by maintaining a thin layer of paddy grains. However, it has numerous drawbacks, including high energy consumption, poor drying efficiency, and reduced dried product quality. A previous researcher studied the drying characteristics of parboiled thin-layer rice. At 7–10 cm bed depth and 112–116 °C air temperature, they discovered a head rice yield of 65 to 68% with an energy expenditure of 8.5–10.7 MJ kg^{-1} [34]. The drying rate increased as the heat and mass transfer coefficient increased with increasing air velocity.

2.4. Limited Hot Water Soaking Process

Raw paddy is washed and soaked in large amounts of water during the paddy parboiling process. Several researchers have made an effort to reduce the amount of water. Gunasekera (2016) recycled the same water along the production line instead of using new water input during recirculation in the soaking process [28]. They found that the quality of rice generated by parboiling the paddy with re-used soaking water was identical to that of paddy treated without the process adjustment. In this process, freshwater usage is significantly reduced. In the modern parboiled factory, this circulating water of hot soaking process in the ratio of paddy and water around is limited to 1:1. The potential for the fortification of minerals by using limited water was conducted previously [18,35]. The limited water-soaking approach can lower the cost of rice fortification and reduce effluent treatment without compromising rice quality. The minimum use of water may be linked to uneven hydration of the paddy, this could be avoided by circulating water during the soaking process. The drying process was conducted at room temperature to minimize the nutrient loss of the fortified rice.

2.5. Pressure Parboiling Process

The pressure parboiling process involves steaming above atmospheric pressure. In this method, the paddy is briefly soaked until the moisture content reaches 24% before being steamed or cooked using pressurized steam [29,30]. Washing and steaming the paddy under 98–196 kPa pressure is conducted for 10–20 min. However, severe product defects and consumer resistance emerged from this process; the parboiled rice was discolored, and gritty grains made cooking challenging. After cooking, the product was soft yet retained intense grain discoloration [32]. Even so, the pressure will accelerate the gelatinization process and shorten the overall parboiling process. The grain parboiled using the pressure parboiling process has a low final moisture content (less than 25%). The process of parboiling was undertaken in a faster and more efficient timeframe. Hot air drying also has drawbacks in the uniformity of the drying process. In addition, fluidized and spouted bed dryers are utilized to avoid the problems associated with hot air dryers. The primary purpose of designing these dryers was to reduce heat damage by drying parboiled rice at a greater temperature and in less time. Bootkote et al. (2016) dried the parboiled paddy in a hot air-fluidized bed drier at 110–180 °C, 3.5 m s^{-1} air velocity, and 1 cm bed depth [36]. Nevertheless, fluidized bed dryers are efficient when the moisture content of the grain surpasses 18%. The combination of the pressure parboiling process and the fluidized bed drier is expected to speed up the drying process.

2.6. Rotating Sieve Pressure Parboiling Process

The rotating sieve parboiling system is still under development in Thailand [21]. This parboiling process involves a rotating sieve system. Most of the time, the paddy was placed on a fixed sieve, and saturated steam was poured into the stack. In the traditional method, steaming the paddy bed evenly was difficult and caused uneven contact between the steam and the paddy. The quality of parboiled rice was affected by these contacts. The time or temperature of the parboiling process can be changed to fix this. These methods are more expensive and use more energy to produce parboiled rice and take less time than a fixed sieve system (5 min at 10 and 15 rpm and 10 min at 5 rpm) to bring the sample into full contact with the steam (15 min). A rotating sieve was used to parboil rice, resulting in a better taste. Parboiling rice with a rotating sieve for longer periods caused an increase in starch gelatinization and HRY but decreased the number of cracks and whiteness. The pressure process was changed into a rotating sieve process, which reduced the time required for the sample to come into full contact with the steam compared to the fixed sieve system and led to a more uniform product. Moreover, the end product of the parboiling process only requires ambient temperature drying until it reaches a moisture content of 12–13%. However, the disadvantages of the rotational sieving process are the need for an additional installation and the complex operation.

2.7. Superheated Steam Parboiling Process

A group of researchers from Thailand tried to develop the parboiling process by combining the steaming and drying processes [23]. The parboiling used a superheated steam process. This revolutionary technology has the potential to replace the conventional parboiling process and minimize the chalkiness of rice. Superheated steam was applied at 120, 140, and 160 °C. The results indicated that superheated steam drying could tackle the chalkiness and low yield issues related to rice whose quality falls below the national standard. Superheated steam drying incorporated the steaming and drying processes of the conventional parboiling process into a single, more efficient operation for the rice processing plant. The head rice yield is greater for the superheated-steam-dried samples of nearly all varieties than the conventionally parboiled samples. The superheated steam-dried samples are significantly darker than the parboiled samples. This strategy might reduce the number of necessary steps and increase the efficiency of the process. However, the color issue must be resolved to avoid consumer displeasure in South East Asian countries which have a preference for white rice [23,37]. In addition, the superheated steam procedure and equipment are costly and labor-intensive.

Superheated steam is created by heating vapor above its saturation temperature at a specific pressure. The pressure for water in this condition is one atmosphere, whereas the temperature is 100 °C; the water vapor behaves similarly to any other hot gas. When it encounters other surfaces, it releases its latent and sensible heat, which can be used to dry paddy with high moisture content. Combining hot air and infrared drying was utilized by another study [38]. The authors reported an increase in head rice production, a decrease in drying time due to a higher heat and mass transfer coefficient, and an increase in diffusion rate due to an increase in infrared intensity. Paddy can also be dried using high-power ultrasound in conjunction with fluidized bed drying while spending 22% less specific energy than fluidized bed drying alone. Using a vibrating infrared dryer, a group of researchers—Das et al. (2009)—evaluated the drying quality of paddy with a high moisture content [38]. Increased effective moisture diffusivity and lower drying periods resulted in increased drying rates. As radiation intensity increased, the drying rate constant increased from 0.028 to 0.030 kg [H_2O] kg^{-1} [dry matter] s^{-1}. Nevertheless, infrared heating is a surface-heating event with a shorter penetration than microwave heating. The parboiled paddy's microwave- and infrared-assisted drying is more efficient and less energy-intensive. However, if these current techniques are not applied properly, they have disadvantages. Instead of drying rice, uncontrolled microwave energy might cause the paddy to break. The yield decreases when a head rice paddy is dried at high microwave power levels.

2.8. Brown Rice Process

Another alternative for parboiling involves parboiling dehusked brown rice as a starting point. Brown rice weighs three-fourths as much as paddy and has two-thirds of its volume. Therefore, the procedure will be quicker, easier, and less expensive. The brown rice is soaked in ambient or warm water for 15–30 s before being exposed to hot air or steamed under pressure. It is then tempered before drying. Previous studies researched brown rice soaked at 45 °C for 2 h to reach 32% moisture, steamed for 60 min at 100 °C, and then dried for 1 h [31]. The challenge for this technique was the high risk of caking and breaking the parboiled brown rice. This process effectively reduced the energy and time required to produce parboiled rice. However, the large-scale process needed to be highly maintained to avoid caking and cracking problems.

3. Energy Consumption

Generally, parboiling is an energy-intensive procedure. The quantity of rice being processed, the parboiling method employed, the variety of rice, the state of rice (rough or dehusked), and parboiling variables such as soaking temperature, steaming time, and pressure determine the intensity of energy consumption. The primary difference between the various parboiling techniques is the time–temperature combinations for soaking and steaming. Reportedly, the rice condition substantially impacts the energy used [15]. Table 2 illustrates the parboiling energy usage based on the employed technique. These energies were derived from a theoretical framework of heat soaking and steaming. The energy necessary for soaking was evaluated as the heat required to bring the soaking water to the desired temperature from its ambient temperature. The steaming energy was also measured as the heat gained by the paddy's dry mass and the moisture gained by the paddy grains. Selecting a pressure parboiling system instead of a traditional hot soaking approach will increase energy consumption [39].

Table 2. Several parboiling systems and energy consumption.

Parboiling System	Country	Sample	Parboiling Process	Energy Consumption	Reference
Hot air fluidized drying (no steaming)	Thailand	Dried paddy MC 13% (d.b.)	Soaking at 70 °C for 5 h, hot air fluidized bed drying at 130–170 °C	1.31−1.45 MJ/kg (electric)	[14]
Hot air fluidized bed drying combined with halogen lamp drying (no steaming)	Thailand	Dried paddy MC 13% (d.b.)	Soaking at 70 °C for 5 h, hot air fluidized bed drying at 130–170 °C with halogen lamp 1500–4000 W	0.82−1.34 MJ/kg (electric)	[14]
Hot water soaking, steaming	Ghana	Raw paddy MC data not available	Soaking at 60–85 °C for 12–22 h; steaming at 85–90 °C for 3–8 min	08.7–13.48 MJ/kg (wood)	[16]
Microwave, steaming	India	Raw paddy MC 23% (d.b.)	Soaking in microwave (420 W) for 7 min, steaming at 120 °C	4567.08 kJ/kg (electric)	[17]
Soaking, steaming, drying (traditional)	India	Raw paddy MC data not available	Soaking overnight, steaming, and sun drying	1659–2758 MJ/t	[40]
Hot soaking and steaming	India	Dried paddy MC 14.9% (d.b.)	Soaking at 70 °C, steaming at 100 °C 10 min	276 MJ/t	[39]
Pressurized soaking and steaming	India	Dried paddy MC 14.9% (d.b.)	Soaking at 60 °C pressurize steaming	251 MJ/t	[39]

Meanwhile, P. Roy et al. (2006) evaluated energy consumption utilizing rice husk as fuel in direct combustion systems for total parboiling (pre-steaming and steaming) [40]. They reported 2583, 2758, and 1659 MJ/t for the vessel, small-boiler, and medium-boiler processes, respectively. Combining processing techniques has been suggested as an approach to reduce energy use. They studied the cost and energy consumption of a regional parboiler for rice. The rice produced by the local boiler had a high market value, but its energy consumption was extremely high. Work on reducing parboiled rice processing energy was also conducted by Bualuang et al. (2013), who compared hot air and infrared drying of parboiled rice and discovered that drying energy consumption could be reduced by 4.6 times when infrared drying is combined with hot air [41]. However, this technique decreased the quality of the final product due to the yellowing of the rice. Apart from that, tempering rice during drying also reduced energy during rice processing. Golmohammadi et al. (2015), who studied the effect of intermittent tempering on rice, discovered that tempering reduces breakage and drastically cuts energy consumption [42]. The authors discovered that utilizing three tempering phases can save up to 64% of energy consumption compared to a continuous dying procedure.

Furthermore, another study was also intended to evaluate the energy requirements and quality indicators of parboiling [43]. The authors reported that the duration and temperature of paddy parboiling steaming are the determining factors in its energy usage. According to the literature, the energy requirement for paddy ranged from 4.0 to 5.5 kJ/kg. The energy required to process one ton of rice varied between 350 and 920 kWh. The parboiling and drying processes account for more than 90% of the overall energy consumption in a rice milling system. Among other things, rice quality could be affected by energy consumption.

A comprehensive comparison was conducted between traditional parboiling (CP) and microwave-assisted parboiling (MWP) based on actual and theoretical energy consumption, and the viability of the MWP was determined, taking process economy and parboiled rice quality into consideration. Compared to hot water soaking, MWS (microwave-assisted soaking) resulted in overall energy savings of 20.48% [17]. Srisang et al. (2021) researched parboiled rice production using hot-air-fluidized bed drying and halogen lamp drying (HAFH) [14]. The combined drying system reduced the number of manufacturing steps (the steaming process) and the drying time by approximately 1.75–1.9 min compared to the traditional parboiling method. Meanwhile, the reduction in the drying time is around 0.55–1.2 min compared to HAF (hot-air-fluidized bed drier without halogen lamp). The shorter drying process of HAFH is due to the lower moisture content within the rice grains and the higher grain temperature during the process. Compared to the traditional parboiling method, the savings in process steps and time in HAFH resulted in a 22% reduction in specific energy consumption (SEC) in the manufacturing process.

4. Head Rice Yield Improvement

Rice grains are mechanically strained throughout harvesting, threshing, drying, dehulling, and milling. Rice grains crack under tension. Processing intensity determines the quantity of fractured kernels. Broken kernels cause market losses, price decreases, decreased product output from milling procedures, and storage issues. Breakage is determined by fissures, chalkiness, immaturity, and rice kernel size [10]. Dehulling and milling produce kernel breakage. Head rice yield (HRY) is the proportion of rough-milled rice that remains as head rice [44]. HRY is essential for continuous, multi-break, sequential commercial operations that mill tons of rice per hour. Rice kernel breakage is affected by both cultivar and grain cultivation and processing history [45]. Blending kernels with high and low moisture during harvest may cause low-MC grains to absorb moisture, but high-MC grains to release it into the air. Rice grains absorb or desorb moisture from the surrounding air until equilibrium is reached. This equilibrium condition depends on the air's relative humidity and temperature [46–48]. In rice kernels, moisture-sorption-induced moisture content gradients generate hygroscopic strains. When MC gradients exceed the mechanical strength of rice kernels, cracks occur [49]. These cracks are perpendicular to the longitudinal axis of the rice grain [50,51]. These fissures then weaken the rice kernels during dehulling and milling [52,53]. The illustration of MC gradients in paddy can be seen in Figure 2.

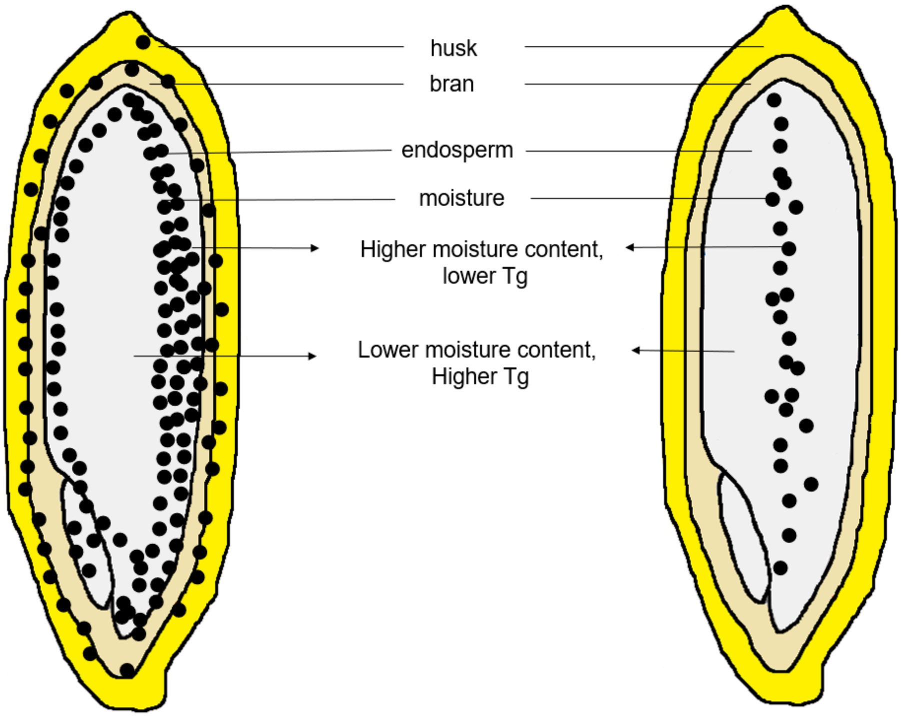

Figure 2. Illustration of gradient moisture content in paddy that leads to different glass transition temperatures (Tg).

Rice grains absorb water when it rains, dews, or when its MC is below the equilibrium state of the air. This moisture sorption may result in cracking when rice grains are dried to an MC of less than 12 to 15%. Furthermore, harvesting affects grain fissures because fields are drained to facilitate grain drying and mechanized harvesting. Early field drainage reduces milling rice concentrations during harvest. The drying MC gradients determine the ability of rice grains to fracture. The greater the MC gradients within the kernels and the more fissured the rice grains become after drying, the more surface moisture is removed. Rice kernel glass transitions reveal the effect of MC gradients on fissuring during water desorption. In response to a given melting temperature (MC), the glass transition temperature (Tg) is the temperature at which the kernel becomes brittle or elastic. Moisture content (MC) determines rice's Tg. Below Tg, amorphous rice kernel material is vitreous, and above Tg, it is rubbery. The expansion coefficients, specific volumes, and diffusivities of vitreous rice kernels are decreased [54–57].

Chalkiness is another factor that affected the head rice yield of rice. According to many research studies, chalky rice kernels are more susceptible to breakage during dehulling and milling than transparent rice kernels, which reduces HRY [58]. The poor hardness of chalky rice kernels, which makes them less resistant to mechanical pressures, contributes to their lower resistance to grain breaking [59]. Using nitrogen fertilizer has a favourable effect on the HRY of chalky rice varieties. Fertilization with nitrogen increases the number of protein bodies within the endosperm. As a result, the spaces between the irregularly shaped, loosely packed starch granules in chalky rice are filled. Consequently, the fragility of the chalky kernels decreases. This reduces rice fragmentation during dehulling and milling [60]. Immature rice kernels lack tensile strength and, as a result, shatter very easily during dehulling and milling [61,62].

Parboiling is one method for preventing rice from breaking. According to Bhattacharya (2004), one of the primary benefits of parboiling is the reduction in breakage during dehulling and milling [32]. The HRY of rice after parboiling will normally increase if the process is carried out correctly. The HRY of parboiled rice depends on the parboiling circumstances and the resultant physicochemical and mechanical modifications, specifically, starch gelatinization and kernel fissuring influence the rigidity of parboiled rice. Starch gelatinization caused homogenous and compact ultrastructure that increases the grain hardness of rice. Soaking and heating conditions affect the level of starch granule swelling and the degree of starch gelatinization. Gelatinization modifies the characteristics of rice starch, notably Tg and crystallinity. The gelatinization temperature increases in a smaller amount of moisture content [63]. Soaking is essential for achieving equilibrium of moisture content across the entire kernel. Using differential scanning calorimetry, a gelatinization degree of approximately 40% is required for maximum HRY to reduce milling breakage [64,65]. Tempering before drying is crucial before reaching the critical moisture content necessary to increase HRY (15–20%) [66]. Tempering rice shortly after drying can help prevent it from fissuring when cooled. The glass transition concept may help explain moisture desorption-induced fissuring during the drying and subsequent cooling of hydrothermally treated rice. Visualization techniques such as magnetic resonance imaging and X-ray microtomography may be helpful to monitor breakages and fissures during the various steps of the parboiling process. The data from the visualization are helpful in understanding the breakage susceptibility of the grain [10,29].

5. Nutritional and Functional Characteristics

Due to the parboiled rice's high concentration of phytochemical composition, nutritional potential, and digestibility qualities, parboiled rice production has been on the rise in the commercial sector. This situation has led to progress in investigating parboiled rice's nutritional value, physicochemical composition, and digestibility properties. Remarkable characteristics such as the high nutrient content and the chemical nature of parboiled rice are of significance to the industry of food processing. This section provides pertinent information concerning parboiled rice's physicochemical composition, nutritional value, and digestibility properties.

5.1. Moisture Content

Moisture content (MC) quantifies the water present in a sample. Rice has a relatively high MC during harvest, which is reduced to storage-appropriate levels through drying. Numerous metrics, such as density, bulk density, porosity, and frictional value, change systematically with increasing or decreasing moisture content throughout the investigated range of 10–29% (wet basis, wb). The effect of moisture content on the density and bulk density of paddy and brown rice was contrary to its effect on the density and bulk density of white rice [67–69]. After drying, the moisture percentage of parboiled rice is approximately 10 to 14% [70]. The moisture content is crucial to define the cooking properties, milling properties, and shelf life of the parboiled rice [26,71].

5.2. Protein

Proteins are large macromolecular structures composed of many long chains of amino acid residues. Especially in comparison to other cereal grains, rice's protein content of approximately 7% is rather low. Due to the enormous volume of rice produced per year (about 741 million tonnes), a substantial amount of rice protein per human capita consumption is potentially available [72]. Table 3 represents the protein content of some varieties of parboiled rice and raw rice. The amount of protein content of rice before and after parboiling was relatively stable; parboiled rice protein content was around 8.38% to 11.34%. However, the structural change of the parboiled rice is also linked to the change of the protein during heat–moisture treatment and the drying process. Although the protein bodies in the kernel are ruptured during the steaming process, the total protein and amino acid content of parboiled rice does not change [32]. However, heat treatment helps hydrolyze the protein, increasing the disulfide bond, which elevates the rice's viscosity and hardness. [26]. The protein in parboiled rice will define the rice flour's functionalities and cooking properties. Both protein and lipid content in rice will define the hydrophobicity of rice [73].

Table 3. Proximate composition of raw and parboiled rice from various research studies.

Variety	Protein		Lipid		Ash		Starch		References
	Raw	Parboiled	Raw	Parboiled	Raw	Parboiled	Raw	Parboiled	
KDML105	10.33–10.41	10.08–11.34	2.81–2.92	2.42–2.81	0.52–0.83	0.45–0.57	84.3–85.68	84.81–86.51	[74]
Athikaraya	10.11	11.21	1.96	2.73	1.89	1.96	NA	NA	[75]
Meter	9.09	9.28	2.26	2.46	2.26	2.46	NA	NA	[75]
Jyothi	8.28	8.65	1.93	2.16	2.85	2.23	NA	NA	[75]
Chai Nat1	NA	8.94	NA	3.52	NA	NA	NA	83.29	[76]
Riceberry	NA	9.76	NA	3.80	NA	NA	NA	83.19	[76]
San-Pah-Twang	NA	8.38	NA	3.50	NA	NA	NA	83.55	[76]

NA = the data are not available in the reference.

5.3. Lipid

One of the most sensitive food ingredients is fats (or lipids). Consumers are susceptible to flavor differences, and lipid breakdown is directly linked to food flavor variations. Brown rice contains crude fat (phospholipids, proteolipids, and other lipids)of around 2%. Since crude fat resides predominantly in the germ and aleurone layer, the over-milling of rice may result in a reduction in fat content to 0.1% [72]. Endosperm and other tissues almost entirely lack fat. Rice lipids affect preservation, processing, and preparation. Rice bran, the outermost layer of the rice kernel, contains 15–25% lipids and beneficial compounds [77]. The overall lipid quantity of brown rice does not change after parboiling. The parboiling process slightly increases the lipid quantity of endosperm due to the penetration of lipids from the bran to the internal part of the grain. The lipid quantity of milled parboiled rice was higher than that of milled raw rice (Table 3). Excessive parboiling of rice at every stage of the process would lead to an off-flavor due to lipid oxidation [78]. This is validated by another study by Oli et al. (2014), which explains that the lipid bodies and spherosomes of non-starch lipids are broken down and fat is liberated from the kernel's surface [26]. As the fat diffuses to the surface, the bran of parboiled rice becomes greasy. Brown rice kernels after milling contain fewer lipids than parboiled rice kernels.

5.4. Ash

Inorganic chemicals, primarily phosphate, potassium, and magnesium, make up around 1% of brown rice. Ash content in the proximate analysis represents the mineral content of rice grains. Table 3 shows that ash content in several varieties of parboiled rice ranged between 0.45 and 2.46%. Because these compounds are present in large concentrations in the germ and aleurone layers, grinding significantly reduces their levels [72]. Beneficial micronutrients contained in rice grains include iron, zinc, copper, and selenium [79,80]. The presence of heavy metals such as arsenic during cultivation can accumulate in food crops and be ingested by humans in rice grains [81]. Comparing the mineral content of brown rice and white rice reveals that white rice contains a lesser amount of each element than brown rice [82]. Previous studies found that the Ca, K, Na, and Fe of parboiled rice samples are higher than those of raw rice because the rice grain absorbs minerals from the outer part of the grain [70]. The water-soluble nutrients diffuse from the outer layer of the grain and the husk into the endosperm, this explaining the high content of water-soluble minerals in parboiled compared to non-parboiled samples.

5.5. Starch

Most of the starch is composed of amylose and amylopectin, which are made up of the same fundamental glucan polymers but have varying lengths and degrees of branching. Starch is the major constituent in rice grains, becoming the most important energy source for human consumption; it accounts for 72–82% of brown rice grain's dry weight and 90% of milled rice grain's dry weight [83]. According to a previous study by S. Kumar and Prasad, (2018), parboiling decreases starch content [70]. Attributed to gelatinization during the heating/cooking process, parboiled rice's starch is irreversibly swollen. Depending on the conditions of the procedure, it may also be thermally broken down into substances of low molecular weight. The low molecular weight of starch may leach moisture during soaking and steaming. Table 3 displays the starch content of different varieties of parboiled rice ranging between 83.19% and 86.51%. Rice's amylose content is the most significant factor in determining its eating and processing properties. It is largely composed of α-1,4 glucose molecules with lengthy straight chains. It may also contain a few a-1,6 branching sites, however. The linear structure of amylose confers unique features to the starch, such as the ability to form compounds with iodine. The apparent amylose content (AAC) of a starch sample can be assessed via the iodine–amylose complex. AAC is distinguished from amylose by the presence of long branch chains of amylopectin, which can likewise create color when treated with iodine. The AAC of waxy rice is below 2%, whereas the AAC of common rice varies from deficient (5–12%) to low (12–20%) to moderate (20–25%) to high (25–33%). [72,84].

5.6. Functional Compound

There are limited studies regarding the bioactive compound in parboiled white rice. Most of the bioactive compounds were only found in parboiled colored rice. There is a slight decrease in the total phenolic content of parboiled white rice after the treatment [64,65]. The decrease in phenolic content of the pigment during parboiling may be due to leaching, thermal decomposition, and interaction with other molecules, mainly proteins [75]. Rice protein content comprises amino acids (AAs). Parboiled rice is a good source of seven out of nine essential amino acids, namely, Threonine, Histidine, Valine, Methionine, Phenylalanine, Isoleucine, and Lysine. The amounts of AA in parboiled rice are shown in Table 4. The majority of the AAs in cooked rice are essential AAs. Essential AAs cannot be produced in the human body; therefore, we must obtain it from our daily consumption. The greater Lysine level of parboiled rice versus milled rice may be due to the release of free AAs by proteolytic activity during steeping and prior to steaming [73]. Other studies have found that AA content in rice was affected by the development stage of the rice grain [85]. Rice bran contained a higher AAs concentration than rice endosperm because AAs was largely localized in the outer bran layers and moved to the endosperm. This factor may have contributed to a higher level of Lysine during extraction.

Most of the bioactive compounds decreased after hydrothermal parboiling treatment. Previous studies examined several phenolic compounds in parboiled rice. Phenolic acids are hydroxylated derivatives of hydro benzoic and hydrocinnamic acids found in plants as esters, glycosides, and complexes [73]. Parboiled rice has 10 out of 11 phenolic acids tested. During parboiling, phenolic acids migrate from the bran layers, changing the distribution of phenolic acids in milled rice. Tian et al. (2004) found numerous arabinoxylans in aleurone layer walls, which may have kept ferulic acid in the bound form [86]. Ferulic acid predominates in wheat, rice, and barley. Ferulic acid has antioxidant activity, anti-inflammatory, and anti-cancer properties. Higher phenolic acids caused a greater color difference. Bran fatty acid esterified to the cell wall provided most cereal grains' phenolic acid. Polishing milled rice reduces its nutritional content, reducing phenolic compounds. Heat treatment also destabilizes cell wall structure and binding, making bound phenolics such as p-coumaric acid and ferulic acid more extractable and releasable [73,87,88].

Table 4. Amino acid and Phenolic compound of parboiled milled (adapted from [73]).

Name of Compound	Relative Amount (%)	Name of Compound	Relative Amount (µg/g)
Aspartic acid	0.58–2.22	Gallic acid	5.63–12.15
Glutamic acid	1.32–3.53	Protocatechuic acid	3.63–11.85
Serine	2.89–4.48	Catechin	0.02–11.34
Glycine	0.21–2.05	Chlorogenic acid	Nd
Threonine	10.74–13.33	Caffeic acid	Nd–0.81
Citrulline	0.09–6.45	Vanillic acid	Nd–0.88
Arginine	6.60–9.14	p-coumaric acid	4.74–15.11
Histidine	9.49–13.78	Ferulic acid	7.86–21.6
Amino butyric acid	0.11–1.87	Sinapic acid	0.73–3.51
Tyrosine	6.56–8.01	Luteolin	Nd–1.96
Alanine	0.89–7.47	Quercetin	2.01–5.39
Cystine	1.34–6.24		
Valine	8.41–11.99		
Methionine	7.65–12.48		
Phenylalanine	4.57–11.20		
Isoleucine	3.87–6.67		
Lysine	3.10–4.18		
Proline	0.02–3.90		

Nd = not detected.

5.7. Digestibility

Parboiled rice is noted for its superior digestibility properties compared to raw white rice [6,7]. The digestibility features of a starch products are described via their impact on human blood glucose levels after human consumption. Starch's digestive qualities may have a significant impact on human health. Starch is classified into three types: resistant starch, slowly digested starch, and rapidly digestible starch [89]. Table 5 shows the digestibility of parboiled rice from various studies. The first thing to bed measured for digestibility properties was rapidly digestible starch. Rapidly digestible starch (RDS) relates to increased blood glucose and insulin levels. The fastest rate at which glucose is released into the system after consuming a starchy diet is known as RDS. The slowly digestible starch (SDS) is starch digested at a slower rate than RDS. The SDS is the preferred starch digestibility rate because it induces a slower rise in postprandial blood glucose levels and sustained blood glucose levels over time compared to RDS. SDS is linked with a diminished feeling of hunger after eating because of the slower speed of carbohydrate hydrolysis. Regardless of variety, parboiled rice revealed lower RDS and elevated SDS and RS [90].

Table 5. Starch digestibility (RDS—rapidly digestible starch; RDS—slowly digestible starch; RS—resistant starch) and glycemic index (GI) of raw and parboiled rice from various research studies.

Variety	RDS		SDS		RS		GI		References
	Raw	Parboiled	Raw	Parboiled	Raw	Parboiled	Raw	Parboiled	
BPT5204	69.80	69.64	18.37	16.07	11.83	14.29	80.59	80.37	[90]
ASD 16	74.68	66.81	20.35	21.69	4.97	11.49	83.37	79.12	[90]
IR 50	71.27	64.81	14.82	20.91	13.91	14.29	80.57	77.82	[90]
Ponni	67.88	64.80	16.78	11.76	15.34	23.44	78.37	77.02	[90]
Basmati	66.40	64.86	13.70	16.60	19.90	18.54	76.88	77.20	[90]
Chokuwa	NA	NA	NA	NA	NA	NA	78.71–84.64	58.80–62.53	[91]
Tainan11	60.97	43.76	37.08	45.83	1.95	10.42	102.39	92.43	[7]
Xuenuomi	NA	57.84	NA	30.43	NA	11.72	NA	NA	[92]
Heizhenzhu	NA	51.77	NA	40.01	NA	8.22	NA	NA	[92]
Haishuidao	NA	25.83	NA	45.84	NA	28.32	NA	NA	[92]
Riceteck	NA	NA	NA	NA	1.31	1.84	NA	NA	[93]
San-Pah-Twang	NA	NA	NA	NA	0.20	2.03–2.54	40.22	34.45–39.11	[94]

NA = the data are not available in the reference.

Resistant starch (RS) is known as undigested starch. The effect of parboiling increased RS and decreased RDS [7]. The RS and RDS concentrations of uncooked parboiled rice with a high level of amylose were significantly greater than those of waxy and medium-amylose varieties [92]. Unprocessed, uncooked rice has low starch resistance towards digestibility, whereas cooking rice increases starch digestibility. Slight parboiling increased RS, which is resistant to small intestinal digestion. However, gut microbes can ferment it, releasing butyric acids that are beneficial to colon health, including via inhibiting prevention of colon health [95]. The cooked grain amylolysis method is explained as a proxy for glycemic index (GI) measurements. In vitro techniques aid in defining rice varieties and estimating amylolysis in cooked grains.

The GI measures the proportional increase in blood glucose two hours after consuming food [89]. The estimated GI of samples of fortified parboiled rice ranged from 50.97 to 59.79, which was lower than that of unfortified parboiled rice (58.80 to 62.53) and raw rice (78.71 to 84.4) [91]. A range of low-to-moderate GI values was also reported for the fortified rice [96]. It has been discovered that heat treatment during parboiling debranches amylopectin and creates linear amylose molecules, hence decreasing the GI of rice [79]. The amylose–lipid complex forms more efficiently during parboiling and remains insoluble in water, making it more resistant to enzyme hydrolysis [94]. In addition, the amylose–lipid complex produced during parboiling enhances grain toughness by altering the rice's structure, resulting in a low GI. Thus, parboiling under pressure could be extremely beneficial, especially for producing cooked rice with a lower GI [90].

The reduced digestibility of rice was attributable to the higher gel network formation during gelatinization and retrogradation of amylopectin, particularly in parboiled rice, which inhibited enzymatic activity during the oral to gastrointestinal phases [7,26,97]. The results demonstrated that the hydrolysis extent of parboiled rice was less than that of the control rice, indicating the establishment of a harder structure in the rice after parboiling and drying treatment, as corroborated by a previously published study [5]. A lower percentage of starch hydrolysis was reported in rice that had been pressure-cooked compared to non-parboiled rice [90]. Additionally, parboiling may have damaged the protein structure, resulting in a weakened barrier between the starch and the enzymes [7].

6. Potential Use

Rice Fortification

Fortification is the process of adding nutrients to foods to improve their nutritional value. Rice is widely consumed as a staple food and can be used as a vehicle for food fortification. Rice fortification is an efficient and cost-effective technique for increasing micronutrient intake in rice-consuming countries. Diets in underdeveloped nations are predominantly composed of cereal-based products. They lack micronutrients and only meet the daily minimum for many vital elements [98]. A successful fortification method should have a high micronutrient content, excellent bioavailability, excellent storage stability, and the retention of sensory attributes. There are several methods of rice fortification, including pre- and post-harvest fortification, where post-harvest fortification includes germination, soaking and parboiling, sonication, dusting, spraying/coating, and extrusion [99]. Parboiling is one of the typical non-destructive methods used to improve the nutritional value of rice. Nutrient-rich water may be used to soak paddy during the soaking steps. The parboiling procedure permits micronutrients in the bran to permeate the endosperm, which is often removed during milling and polishing. Increasing the external availability of micronutrients in soaking water can improve endosperm quality. Thus, rice is steeped in micronutrient-rich water. With the introduction of water, dissolved micronutrients infiltrate the kernel and become densely packed [99].

Table 6 represents the fortification of parboiled rice. The head rice yield was unaffected by the soaking method or fortifier [18]. Due to their negative effect on total concentration in the parboiled rice grains, increasing milling time and washing the parboiled rice reduced mineral bioavailability. However, consumption of the mineral in fortified parboiled rice is still much greater than that of unfortified raw or parboiled rice grains [100]. In most cases, parboiling begins with paddy, while in other cases, parboiling is performed on dehulled rice (brown rice). In these processes, the fortified rice is soaked, steamed, and finally dried. This procedure reduces the number of additives lost during dehulling [101,102]. Sonication and minimal water soaking can be used to intensify the soaking procedure. Rice nutrient absorption was promoted by limited water soaking, as opposed to to excessive water soaking [35]. Rice grain sonication encourages the development of surface micropores. Rice surface modification increased vitamin absorption by up to 140%. Sonicated rice absorbs 94% more vitamins than non-sonicated rice [103].

Table 6. Fortification of parboiled rice.

Parboiled Rice Variety	Micronutrient (Concentration Used)	Method of Fortification	References
Langi, long grain variety	Folic acid (160 mg/100 g)	Soaking	[102]
BRRI dhan58 and dhan74	Zinc (24.2 mg/kg)	Genetically and spraying	[104]
Long grain, Roy J	Ca (50 g/L calcium lactate) and Fe (995 mg/L ferrous sulfate)	Limited water soaking	[18]
SPR 1 and CNT 1	Zinc (50–400 mg Zn/kg)	Genetically and soaking	[100]
White rice	Fe (862.93 g/100 g)	Cold plasma	[105]
Long grain, Roy J	Folic acid (35 mg folic acid/L) and β-carotene (50 mg pure β-carotene/L)	Limited water soaking	[35]
Hai7, XS110 and Biyuzaonuo (Glutinous and non-glutinous japonica)	Fe (0.05–2 g/L)	Germination and soaking	[106]
Non-waxy rice variety (TH82)	Vitamin B (25–1000 ppm)	Soaking sonicated and non-sonicated	[103]
Brown rice (Suijing No.3)	Zinc (25 mg/L)	Germination and soaking	[107]
Waxy, low, and high amylose	Phenolic content (1 g/10 L butterfly pea extract)	Soaking with butterfly pea extract	[108]

Soaking and germination for mineral fortification of parboiled rice indicate that the mineral content and germination time will affect the bioavailability of the fortified rice. For instance, iron enrichment during germination with 0.05–2 g/L ferrous sulphate increased the iron concentration in germinated brown rice by 1.1–15.6% relative to that in ungerminated brown rice [106]. Ramli also confirmed this and suggested that zinc levels in the range of 25–75 mg/L might meet the recommended daily intake. The maximal zinc bioavailability (26.31%) was attained when GBR25 was germinated for 28 hrs. In addition, germination would boost parboiled rice's total phenolic content and antioxidant activity [107]. The enhancement of phenolic content can be accomplished by soaking in a floral extract rich in phenolics. Based on the total phenolics fortification of various rice varieties with butterfly pea (*Clitoria ternatea*) flower extract by parboiling, it was determined that the composition of rice influences the absorption and fixation of phenolic compounds. The parboiling procedure identifies milled rice with low amylose for maximum phenolic enrichment [108].

7. Health Benefits

Parboiling consists of soaking rice kernels in warm water to increase the solubility of nutrients in the rice bran, followed by steaming to transport these nutrients from the bran to the endosperm [109]. Given the difference in nutritional content as described in Section 3, it has been suggested that brown rice (BR) should be preferred in meals due to its numerous health benefits. One of the essential health benefits of parboiled rice is the alteration of the starch during processing. Parboiled rice is known for lowering blood glucose levels for both healthy people and people with diabetes type 2 [110]. The process of parboiling rice improved the smooth morphology of its carbohydrates, which may be responsible for its resistance to digestion. This was supported by other studies that mentioned that parboiling might increase RS levels in rice [111]. Other investigations demonstrated that parboiling increased RS and decreased RDS. After 10 min of pressure cooking, the RS content dramatically increased to 7.95%, with a minor increase in SDS [7]. The high proportion of resistant starch (RS) or dietary fibers and proteins might alter intestinal incretin hormones (such as GLP1 and GIP) and control insulin release [110,112].

Phytic acid (PA), which accounts for 80% of the phosphorus in seeds, functions as an antinutrient and inhibits the proper absorption of nutrients from the diet [9,113,114]. Parboiled brown rice (PBR) PA content is approximately half that of BR [115,116]. Thus, a high PA content can reduce the bioavailability of minerals and other nutrients. In addition, after the absorption of nutrients during processing, the amount of Se in 100 g of parboiled rice is 9.3 g, which is approximately 1.6 times more than that in brown rice. Selenium (Se), upon incorporation into selenoproteins, contributes to the activation and proliferation of cells engaged in immune response and anticancer mechanisms by mitigating inflammation generated by reactive oxygen species [117,118]. Therefore, it aids immunoregulation, avoiding autoimmunity and chronic inflammation [118]. Moreover, it increases thyroid hormone metabolism, cardiovascular, and neural health [118–120]. While dietary Se is often found in cereals, vegetables, fish, meat, dairy products, etc., and is vital to our health, excessive Se could be hazardous [118].

Calcium levels in parboiled rice are six times higher than in brown rice [9]. According to [121], calcium-rich diets are an effective treatment for osteoporosis because they minimize the incidence of osteoporotic fractures. In addition, calcium supplements have been shown to reduce the prevalence of gestational hypertension, which is frequent in women with gestational diabetes [122,123]. This reduces smooth muscle contractility, lowering preterm birth, which is associated with mother and infant mortality [122]. In addition, since parboiled rice is 25% higher in vitamin B6 than brown rice, it is an excellent source [9]. Several primary benefits of having a vitamin B5-rich diet were its antioxidant capacity and antitumor actions via reduced cell proliferation and angiogenesis [124]. It is required to manufacture neurotransmitters such as serotonin, dopamine, and γ-aminobutyric acid (GABA). Vitamin B6 is related to a lower risk of coronary heart disease (CHD) and nonfatal myocardial infarction (MI), in addition to its other advantages [124]. Vitamin B6 is effective in reducing hypertension/high blood pressure.

Furthermore, brown rice is already known to be consumed due to its perceived health benefits. A study comparing the digestibility of both parboiled and brown rice was conducted. After consuming parboiled brown rice, the blood glucose response area under the curve was lowered by 35% and 38% in diabetic and healthy participants, respectively. In both groups, blood glucose reactions to white rice and brown rice were not statistically different from one another [110]. Brown rice processed via parboiling and microwave drying may be beneficial for patients with obesity and diabetes, as well as for individuals seeking healthier choices [118].

Parboiled germinated brown rice of KDML 105 has beneficial bioactive components such as ferulic acid, p-coumaric acid, GABA, γ-oryzanol, and γ-tocotrienol, when compared to white rice and brown rice. These findings imply that frequent eating of parboiled rice may prevent liver cirrhosis and cancer by reducing inflammation and liver fibrosis [125]. This was also supported by other studies which demonstrated that parboiled germinated brown rice is high in anti-inflammatory effects and could improve the cardiac structure in hypertension rats [126,127].

Moreover, serving parboiled rice powder with buttermilk every half an hour can prevent diarrhea in youngsters [128]. This apparent benefit of parboiled rice consumption, which is not well publicized in the literature, must be acknowledged by consumers and food technologists in order for parboiled rice to be appropriately exploited in the improvement of human nutritional industries.

8. Wastewater Treatment

Due to paddy's need for soaking, the manufacture of parboiled rice typically consumes a considerable amount of water. The effluent from rice mills is generally yellowish, features an offensive, pungent odor, and is composed of organic debris and other pollutants. A total of 1–1.2 L of wastewater are produced per kilogram of paddy [129]. The effluents from rice parboiling plants do not include hazardous substances, but untreated wastewater is a rich source of organics and nutrients; thus, this wastewater's regular disposal is an environmental hazard. The soak water includes a high concentration of suspended and dissolved organic compounds that decompose over time, resulting in water and groundwater contamination. Dischargeable wastewater from processing industries has contaminated the groundwater. Several water quality indices, including turbidity, acidity, biochemical oxygen demand (BOD), dissolved oxygen (DO), chemical oxygen demand (COD), iron, hardness, chloride, and sulphate, were identified [130].

Rice parboiling effluent contains a high concentration of organic and inorganic elements, constituting a substantial source of pollution [131]. Several studies are contradictory regarding the toxicity of rice parboiling wastewater effluent to living organisms. Gerber et al. (2016) employed zebrafish exposed to raw effluent; they revealed negative correlations with indicators of sperm quality, acute toxicity, and chemical metrics for iron, phosphate, and total suspended solids concentrations [132]. Gerber et al. (2018) found that the effluents were also phytotoxic to lettuce and cucumber seeds [133].

Several researchers investigated the electrocoagulation removal of pollutants from rice mill effluent. BOD, COD, and TDS removal efficiencies of Fe–Fe electrodes were 76.27%, 70.20%, and 59.11%, respectively [131]. Additionally, the effluent of parboiled rice was treated by phytoremediation, utilizing an aquatic plant system containing water lettuce (*Pistia stratiotes*). The results of the system indicate that soluble COD (SCOD), ammoniacal nitrogen (NH_4-N), nitrate nitrogen (NO_3-N), and soluble phosphorus (sol. P) are removed at up to 65%, 98%, 70%, and 65%, respectively [134].

There are novel approaches to transforming waste items into energy and products with added value. A previous study employed parboiling wastewater as a form of carotenoid production from natural *Phaffia rhodozyme* sources. It showed increased carotenoid synthesis based on their potential use as dyes and their potent biological antioxidant ability [135]. Mukherjee et al. (2016) developed a remediation method by utilizing wastewater to cultivate a consortium of six algae with the highest fresh weight productivity, best comprehensive bioremediation, most significant P accumulation, and highest P release in soil [136].

A group of researchers have developed a new approach to minimizing water consumption and energy in water recycling by employing cost-effective techniques for removing impurities [129]. Current methods for reducing pollution and reusing and recycling waste items are outlined in the study. Gunasekera (2016) also found that the amount of fresh water utilized in a process can be reduced by reusing or recycling water in the same or another operation along the process line [28]. Results indicated freshwater savings in the parboiling process for all three kinds of paddy when the water was recycled or reused; freshwater savings of around 50% were found in the next batch's soaking operation.

9. Future Perspectives

The increasing demand for highly nutritive rice is boosting the global market for parboiled rice. Numerous characteristics of parboiled rice, such as its non-sticky nature, rapid water absorption, good digestibility properties, and high mineral content, drive the global parboiled rice market. The increasing demand for long rice grains drives the global parboiled rice industry. Unfortunately, compared to other types of rice, parboiled rice is more expensive and necessitates more processing steps. New technologies have been developed for the parboiling process to reduce costs and optimize operations, with most of these technologies focusing on the hydration and drying processes. Further investigation into the economic feasibility of the technology developed in terms of the extent of the changes in the quality of the parboiled rice during processing should be conducted.

A significant factor affecting the physicochemical changes of parboiled rice is its diffusion during the hydration process. Rice diffusion is affected by grain composition, structure, post-harvest processing, temperature, and humidity. Rice starch suffers substantial gelatinization and re-crystallization after parboiling. Starch polymorphisms impact the texture of cooked parboiled rice following re-crystallization. Changes in starch crystalline properties amount to one of the prominent factors affecting thardness and digestibility properties. Parboiled rice has a distinct flavor because it is less sticky and fluffier. Parboiled rice kernels are thicker and shorter. During parboiling, the white belly of milled rice is removed. Due to husk color diffusion into the endosperm during non-enzymatic Maillard browning, parboiled rice turns amber [26]. The primary disadvantages of parboiled rice are the texture and color, which vary according to consumer preference. The process's intensity would lead to impaired coloring and digestibility to some extent. There should be a study conducted to balance the digestibility and the unwanted darker color of the parboiled rice. Nevertheless, the current technology of parboiled rice requires high investment. A particular focus on modern and simple parboiling processes is also required to obtain more feasible processing steps in parboiled rice processing. Hence, parboiled rice should be recognized as one of the low-GI dietary sources in the effort to supply new alternatives for staple foods and health-related purposes.

Emerging green technologies emphasize essential goals, including installing cleaner technologies to reduce waste creation, effluent pollution load, and toxic chemical use, and to promote solid waste conversion into valuable resources. Resource recovery rice mill wastewater remediation and solid waste management could produce monetary value. Switching from waste disposal as a source of valuable products, future initiatives should identify value-added product recovery and quantification sources. The following steps should promote sustainable growth and greener economies: conventional treatments produce difficult-to-manage sludge and need energy; and reusing waste yields value-added products and zero discharge. Processes that generate secondary energy and valuable goods need intensification and industrial application to succeed. Nutrient recovery plants are rarely used in wastewater remediation. Nutrient recovery and wastewater treatment should be sustainable and cost-effective. Few studies have addressed this subject, and most do not document their methods. Thus, experimental methods in commercial rice mills require significant attention. Treatment plants use integrated processes, and optimization should enhance the combination of treatment methods. Proper disposal is needed, even for small amounts of secondary by-products. More study into methods of disposing of rice mill effluent while benefiting the environment, such as nutrient recovery, secondary energy production, and solid waste reuse, is needed. [129].

10. Conclusions

This article describes parboiled rice's production techniques, physicochemical qualities, functional properties, health benefits, and waste-processing products. The extensive amount of energy used during parboiling can be addressed via the use of various kinds of parboiling (soaking, steaming, and drying) with the available resources. Parboiled rice has a stable amount of starch, lipids, and protein. The heat-labile phytochemical is reduced during the parboiling process, but the water-soluble nutrient is diffused inwards in the grain. The starch structure and crystal properties are altered during the soaking, steaming, and drying processes. Parboiled rice's distinctive qualities and properties are attributable to starch digestibility properties, which have a low glycemic index for human consumption compared to those of raw rice. Since parboiled rice is rich in nutrients and dietary fiber, it can also be utilized in dietary consumption and biomedical goods for various purposes. The soaking step of the parboiling process can also be utilized in the fortification process. Meanwhile, the significant amount of post-production wastewater is minimized via the use of limited water and recycling during the process. The effluent can be treated with electrocoagulation and bioremediation processes.

However, there are drawbacks of parboiled rice due to its darker color—a consequence of the operation's intensity. The relevant interlinked organizations and agencies should emphasize the health benefits of parboiled rice in its marketing strategy. Additionally, research and development should be conducted on parboiled rice in multiple disciplines, including engineering, food production, technoeconomics, medicine, and postharvest handling and management. Methods of expanding the niche market for parboiled rice must be identified. Scientific research is required to replace staple meals produced with raw rice with those produced with parboiled rice while maintaining the calorie intake and health benefits. For this reason, future research should focus on obtaining parboiled rice with high resistant starch while maintaining a physical appearance similar to that of raw rice. In addition, these investigations may bring new perspectives on the development of parboiled rice with a better physical appearance, good health benefits, and lower production costs. Consequently, it is advantageous to determine the fundamental issues associated with parboiled rice in other places outside South Asia to increase consumption.

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