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Rice Production, Quality, and Nutrition: A Comprehensive Review on Challenges, Opportunities, and Global Perspectives

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Improving rice's quality can significantly raise its worth for growers and consumers alike. This comprehensive review addresses the multifaceted aspects of rice, the staple food for over half the global population, and delves into the challenges and opportunities associated with its production, quality, and nutritional enhancement. It highlights the pervasive issue of micronutrient malnutrition affecting billions and the pressing need for sustainable solutions. The intricate connection between rice production and environmental changes, coupled with the looming challenges of climate change, is thoroughly explored. The paper emphasizes the role of quality control throughout the rice value chain, shedding light on the diverse factors influencing rice preferences and the economic implications of premium varieties. Micronutrient deficiencies, including iron, zinc, and selenium, pose significant health risks, particularly in underdeveloped regions. The review underscores the potential of rice bio-fortification as a promising strategy for long-term nutritional security. It draws attention to the disparities in approaches between developed and economically challenged nations, advocating for cost-effective methods to enhance the nutritional content of widely consumed cereals. The analysis of the global rice production landscape, with a focus on Thailand's premium varieties and India's Basmati rice, unveils the intricate interplay of market dynamics, policies, and consumer preferences. The paper provides insights into the challenges faced by the Basmati rice industry in Pakistan, attributing stagnation to inadequate research and development investments and a lack of policy commitment. The historical evolution of rice varieties and the impact of ecological and socioeconomic factors on rice types and grades are discussed. The distinctions between Indica and Japonica rice varieties, along with the varying amylose content, highlight the complexity of rice diversity on a global scale. Furthermore, the review examines contemporary challenges in Asian rice farming, emphasizing the importance of management techniques and selective breeding in improving overall quality. It delves into the complexities of rice grain quality, including the influence of environmental factors, post-harvest treatments, and economic considerations in the rice trade. In conclusion, this comprehensive review provides a nuanced understanding of the intricate world of rice production, addressing issues ranging from nutritional security to market dynamics. It serves as a valuable resource for policymakers, researchers, and stakeholders seeking to navigate the complexities of rice cultivation in a changing global landscape.

Keywords: Nutritional Enhancement, Rice Biofortification, Basmati Rice, Micronutrient Deficiencies.

Introduction:

Rice, as the most widely consumed cereal and a fundamental food staple, serves as a primary source of carbohydrates for over half of the global population. Unfortunately, a significant portion of the world's inhabitants, around half, grapples with deficiencies in essential vitamins and minerals. Micronutrient malnutrition affects over three billion people, contributing to 3.1 million child deaths annually due to malnutrition, with these numbers on an upward trend [1].

More than half of the world's population relies on rice as its primary food source, with Asia accounting for nearly ninety percent of global rice production and consumption. Rice production is intricately linked to environmental changes. Various factors impact food security, and future challenges are anticipated. Although the effects of environmental changes on rice cultivation are already visible, significant gaps persist in understanding how both short-term and long-term environmental shifts will hinder rice farming and their corresponding impact on nutritional security [2]. This review explores the effects of climate change on rice production, conducting a detailed comparison of current and future climate change situations, as well as examining the roles of rice in food and nutrition sustainability. It also provides a general overview of various biotic and abiotic environmental stresses associated with rice cultivation, along with mitigation strategies for these stresses to ensure sustainable rice production in the face of future climatic changes [3].

Malnutrition, including protein deficiency and micronutrient inadequacies such as iron, zinc, and selenium, poses a significant issue in underdeveloped areas, leading to various diseases. In both cereal and legume crops, the nutritional value is lower when crops are grown under higher temperatures and CO_2 levels, another effect of climate change. Rice bio-fortification emerges as a promising technique for addressing long-term and sustainable nutritional security. This review attempts to provide an impression of the bio-fortification of rice with micronutrients, vitamins, and other bioactive compounds in addressing nutritional security [4].

Developed nations tackle deficiencies through fortification programs, a luxury often unaffordable for economically challenged countries. Consequently, an alternative and cost-effective approach involves enhancing the nutritional profile of major cereals, particularly those widely consumed. To elevate the nutritional content of rice, research initiatives should shift focus towards developing high-yielding cultivars with enriched nutrients, achieved through selective breeding or genetic modification. As literacy rates rise and dietary awareness increases, individuals exhibit a growing inclination towards health-conscious choices and a preference for nutritionally fortified foods. The quality of rice emerges as a crucial factor determining economic value in both export markets and consumer acceptance [5]. The FAOSTAT database reveals a consistent rise in global rice production from 1961 to 2017, with an average of 51 kg per hectare. This represents a notable progression in rice technology and research. However, the complexity of enhancing rice quality is amplified by diverse perspectives among consumer groups. While farmers prioritize seed quality for planting and dry grain for consumption, millers and dealers focus on factors such as moisture content, variety integrity, and milling recovery.

This simplistic view overlooks the intricate quality control feedback loops within the entire value chain. With the commercialization of rice farming, a farmer's evaluation of quality may be influenced by customer preferences in different regions of the country or the world [6]. The elevated expenses associated with premium rice varieties like Thailand's Hom and India's Basmati, coupled with noteworthy price variations across different rice types and grades, have generated interest and prompted initiatives aimed at enhancing overall rice quality [7]. Broadening the market reach to attract a more extensive customer base has the potential to elevate the economic value of a specific rice grain variety, even at higher prices. Efforts to delineate rice quality in different nations and regions, utilizing input from local experts and an analysis of the physicochemical attributes of the grain, have underscored the recognized diversity in rice quality. Interviews unveil the perspectives of consumers and other participants in the value chain regarding the factors influencing rice quality. In Southeast Asia, superior rice is characterized by its softness, fragrance, and nutritional value [8].

These attributes are linked to the physical traits of the grains, such as their uniformity, whiteness, and slender shape, particularly in South Asia. Additionally, fragrance and satiety are crucial factors. However, there are notable variations in quality among the prevalent grain varieties cultivated, traded, and consumed in each country and region. While jasmine rice is renowned for its softness and aroma, the majority of rice grown and consumed in Southeast Asia lacks a distinctive scent; jasmine rice is relatively scarce in Thailand and even more so in other parts of the region [9]. The predominant rice variety consumed in the region is parboiled rice, mainly cultivated in South Asia. It is characterized by its neutral taste and white appearance. Parboiled rice undergoes a distinctive process where it is cooked in its husk before milling, imparting a unique flavor and color. However, it lacks the aromatic qualities of basmati or jasmine rice. Despite advancements in parboiling technology that produce rice with less color, parboiled rice is still marketed in shades such as gold, apple, or rose to cater to varied cultural preferences [9] [10]. The expectation is that the demand for premium rice will increase alongside rising income levels. However, it is noteworthy that Basmati rice constitutes a mere 3 percent of India's annual rice production, despite its higher price compared to lower-quality milled rice [11]. In contrast, less than one-third of Thailand's rice production is accounted for by Hom Mali, and Japan produces 25% of China's rice. While the issue of quality unquestionably poses challenges in commercial rice cultivation, its impact could be substantial [12].

Rice growers cultivating for personal consumption primarily evaluate rice varieties based on their performance in terms of yield and resistance to diseases. This paper explores the ecological and socioeconomic factors influencing the diversity of rice types and various grades. These distinctions are characterized by genetic, environmental, and management requirements [13]. These factors also play a crucial role in shaping the quality and pricing of rice. This text delves into the process of classifying rice according to various grain types and quality grades, sourced from numerous small-scale farms. It underscores advancements in rice breeding and management spanning both the farm and post-harvest phases, with a primary emphasis on maintaining quality control across the entire value chain. The essay explores the potential for augmenting the nutritional value of rice grains, considering both agricultural practices and their impact on human well-being [14].

The endosperm of Oryza sativa L., a type of grass, is under consideration, specifically referring to rice. Rice, a highly consumed grain, has become prevalent even in Africa, largely replacing indigenous African rice. This review focuses on the agroecological niche of each rice variety, specifically exploring the ecological and socioeconomic factors that influence the quality of rice grains [15]. The eco-geographic classification designating rice cultivars suitable for tropical temperatures is termed Indica, while the classification for those adapted to temperate climates is known as Japonica. Due to genetic incompatibility, the cross-fertilization of these two main groups results in sterile hybrids, leading to their occasional classification as subspecies. Japonica, recognized for its short and medium-grain rice, has traditionally been associated with rice varieties from Japan, Korea, and northern China [16]. The reduced amylose percentage in this rice contributes to a tender and moist texture upon cooking, whereas indica varieties with higher amylose content yield rice that is firm and dry. The distribution of rice varieties from tropical and temperate regions, with a few notable exceptions, reflects the dominance of either indica or japonica-type grains [17]. While the majority of rice varieties worldwide contain more than 10% amylose, the predominant types in Laos, where glutinous rice is prevalent, typically have 10% or less amylose.

China's indica rice varieties, constituting 75% of the country's rice cultivation, exhibit amylose concentrations closely resembling those of rice types found in South and Southeast Asia. As previously mentioned, Thailand is renowned for its abundance of long and slender rice grains, and rice varieties with an amylose content of 20% or less are relatively uncommon [18][19]. The global majority of rice varieties generally have more than 10% amylose, but in Laos, where glutinous rice is widespread, the prevalent types typically feature 10% or less amylose. China's indica rice varieties, representing 75% of the country's rice cultivation, showcase amylose concentrations that closely mirror those found in rice types in South and Southeast Asia. As mentioned earlier, Thailand is recognized for its plentiful long and slender rice grains, and rice varieties with an amylose content of 20% or less are relatively scarce [20]. The Indica variety, extensively cultivated across tropical South and Southeast Asia, as well as China's subtropical zone, stands as the predominant type of rice grown globally. Indica rice witnesses significantly larger export volumes compared to Japanese rice. Its international market value is shaped by various factors, including price support, subsidies, tax regulations, and distinctions in grain quality. This becomes particularly relevant in the context of rice exports from China, where a food security policy is in place. This policy imposes restrictions on the export of indica rice while permitting the export of more expensive varieties [21][22].

In India, over 90% of the cultivated rice belongs to the indica variety. The remaining portion is primarily composed of Basmati, an aromatic and expensive rice variety that DNA analysis has identified as being more closely related to the japonica group of rice types. Thailand exhibits a diverse array of rice grain variations and grades, with specific quality standards set for both jasmine and non-aromatic rice. This highlights how each rice variety is distinctly characterized by its unique agroecological niche [23]. In Thailand, the classification of rice varieties, encompassing both traditional landraces and modern high-yielding cultivars, is primarily as indicated. This designation is attributed to the fact that 98% of the country's rice-growing regions are situated between latitudes 12° and 20° N. However, there are exceptions to this pattern, as seen in tropical Japanese cabbage cultivars. While these cultivars make up around 0.5% of the total cabbage production in the country, they are specifically cultivated for subsistence in the highlands [24].

In Thailand, rice cultivation involves two plant species, yet the market and consumers recognize five main types. Each variety exhibits additional variation based on grade or supplier, influencing the corresponding price range. The adoption of modern high-yielding cultivars began gaining traction in the 1970s. The spatial distribution of rice, with its diverse plant and grain types, is influenced by local demand for specific varieties and environmental conditions that impact crop growth, yield, and grain quality [25]. The primary rice crop in Thailand is largely comprised of traditional photoperiod-sensitive tall plant varieties, cultivated during the wet season with water from the monsoon rains. Twenty percent of the country's rice fields are irrigated using modern, high-yielding, photoperiod-insensitive varieties [26]. These varieties are grown as an additional crop during the dry season. In addition to cultivating crops during the wet season, there is occasional year-round cultivation with two to three crops. Forty percent of the agricultural area in the country is responsible for producing 50% more rice per crop compared to traditional rain-fed varieties, contributing to half of the nation's annual rice production.

Although the difference is less noticeable for lower grades, there may be instances where grain derived from photoperiod-sensitive old varieties is more expensive than grain from modern types. The quality of rice is influenced by social and economic variables, which are reflected in consumer preferences and choices regarding specific varieties and price ranges of grain [27]. This is illustrated by the persistent traditional preferences for sticky rice in the northeast and north, and for non-aromatic, non-sticky rice with a robust, dry consistency when cooked, in the central plain and other regions of the country. For individuals with limited financial resources, the primary consideration in choosing rice is their budget. Grains with a higher amylose content have a greater capacity to absorb water, leading to an increased volume expansion ratio [28]. This ratio is determined by dividing the volume of cooked rice by the volume of raw rice. For those aiming to cut down on their rice expenses, the idea that specific grain varieties can produce a greater quantity of cooked rice from the same amount of raw grain helps balance the lower cost. However, it's important to note that the majority of the 3 million tonnes of exported parboiled rice is sourced from the grain of modern high-yielding cultivars with enhanced characteristics [29].

Rice Cultivation:

Thailand's share of the global rice trade has increased from 18% to 24%, attributed to the presence of amylose. Parboiled rice in Thailand remains relatively unfamiliar to the general public, with limited information available on its production and export. In contrast, South Asian nations have a well-established tradition of parboiling rice. Regulations mandate that Hom Mali, a premium and fragrant type of jasmine rice, must be produced using the traditional photoperiod-sensitive cultivars, KDML105 and RD15, cultivated exclusively during the rainy season. Less than 10% of Hom Mali rice is grown using RD15, a variety developed through mutation breeding. RD15 has the advantage of maturing 10-15 days faster than KDML105 and is cultivated in areas with a shortened monsoon period. Approximately 33% of Hom Mali's annual rice production is exported [16]. The registration of Hom Mali, and in specific instances Thai Hom Mali, as trademarks in importing countries provides legal protection against competition from other producers. Individuals seeking cost savings do not typically choose Hom Mali rice in the domestic market, where high-quality varieties are priced at three times or more than plain, unflavored rice. While KDML105 can be cultivated nationwide, the majority of its cultivation is concentrated in a specific region in the lower Northeast, where the grain is predominantly produced [30].

Recognized as the highest quality Hom Mali rice by the market and priced accordingly, Cambodia is experiencing economic benefits from its distinct traditional plant species, namely Phka Rumduol and Phka Malis. The quality of the jasmine rice variety is approaching and occasionally surpassing that of the Hom Mali variety. The inverse relationship between quality and quantity limits output, even though the application of irrigation and fertilizer can enhance the yield of Hom Mali. The badh 2.1 gene plays a crucial role in regulating the unique aroma, primarily stemming from the chemical compound 2-acetyl-1-pyrroline [31]. However, the processing and management of the grain significantly impact the intensity of the fragrance. Premium-quality Hom Mali rice is distinguished by its strong aroma, along with physical attributes such as luster, whiteness, and resilience against breakage during the milling process. The mutation of KDML105 induced by gamma irradiation gave rise to the RD15 variety. Furthermore, this mutation also resulted in the development of the superior glutinous variety RD6. These three closely related varieties KDML105, RD15, and RD6 jointly occupy five percent of the total rice area during the main season [32].

Pakistan's Basmati Rice Industry:

Insufficient investment in agricultural Research and Development (R&D) in Pakistan has led to suboptimal yields and a productivity growth curve below its potential, particularly for basmati rice varieties. Despite being the world's fourth-largest rice exporter in terms of quantity, rice is Pakistan's second-largest export earner, following cotton. This achievement resulted from the liberalization of the rice trade in the early 1990s, allowing the private sector to operate freely. While this initially boosted rice exports, subsequent stagnation occurred in the productivity, export, and value-added aspects of Pakistani rice varieties, especially basmati [33]. Over the last decade, the overall growth in Pakistan's rice exports has remained unchanged, and basmati's growth has significantly declined. External factors and the emergence of competing varieties have impacted the current rice production scenario in Pakistan, including basmati. The lack of investment in R&D for basmati is a critical factor hindering the country's ability to adapt to changing environmental and market conditions. This R&D deficit places the rice sector in a reactive position, lacking proactive preparation for shifting dynamics. Market changes have diminished Basmati's exclusive status as the premium variety for international buyers. Newer long-grain, non-aromatic varieties have encroached on basmati's share of the premium rice market. While low-value, non-basmati varieties can cater to low-priced, lower-quality markets, premium varieties require greater R&D investment to maintain their competitive edge [4][34].

This challenge may also indicate a lack of policy commitment. Policymakers, considering rice a success story, may view further investment as unnecessary, especially after the liberalization of trade relieved the state of responsibility for serious R&D in Basmati. In the last decade, the government has focused significantly on developing horticulture, livestock, fisheries, and forestry, diverting attention from grain crops. Successful examples from around the world highlight the importance of significant investment in chosen "champion" products. Given basmati's high market value and potential for export expansion, it should be a major strategic commodity for the government. However, policymakers seem not to fully appreciate the importance of promoting basmati [35]. Underinvestment in R&D is not solely reflected in funding levels but also in the misalignment of resource utilization. Pakistan's R&D in rice follows a supply-driven rather than demand-driven system, excluding farmers, industry, businesses, and service providers from influencing the research agenda. This results in a lack of incentives for innovative research and a reluctance among stakeholders to actively participate in R&D efforts and other necessary reforms [36].

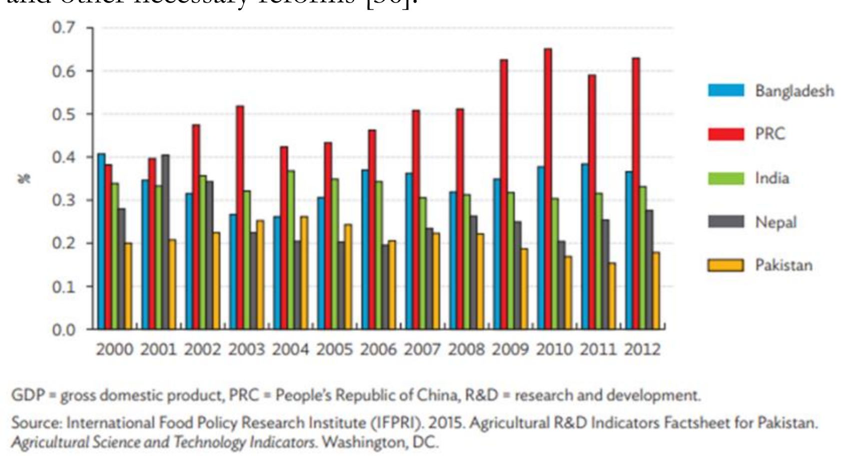

Figure 1: The percentage of Agricultural Gross Domestic Product (GDP) allocated to Research and Development (R&D) in Agriculture, spanning from 2000 to 2012 [36].

Cultivating Basmati rice in both Pakistan and India faces similar challenges arising from market dynamics, regulatory frameworks, and ecological factors. The geographical scope for growing this crop is limited to the Punjab regions of both countries and certain Indian states Jammu, Haryana, Uttaranchal, and Western Uttar Pradesh all situated above latitude 27° N. Consumer preferences for grains often adhere to longstanding traditional practices. For instance, glutinous rice serves as the primary staple in Laos, northern and northeastern Thailand, and among specific ethnic Dai or Tai communities in northern Myanmar and southwestern China. South Asia has a deep-rooted tradition of consuming parboiled rice for generations, although individual tastes and preferences can evolve over time.

The historical evolution of rice varieties in Thailand is evident in the use of rice husk reinforcement in ancient temple bricks. Prior to the eleventh century, round and large grain variations were present, disappearing from the lowlands subsequently. Slender grain types gained prominence from the eighteenth century onward and are now considered the standard. Urbanization in China has led to a notable increase in rice consumption among individuals previously reliant on wheat. The migration of African rice variety Oryza glaberrima may contribute to the growing demand for rice. However, the specific impact of migrant workers and immigrants from Asia on this overall increase remains uncertain. Likewise, the extent to which changes in dietary habits among non-rice eaters contribute to this shift is not determined [37].

Table 1: Government Institutes' Investment in Rice Research [36].

Institute	PRs (million)	Approximate $ Equivalent (million)	Number of Years
NIAB	74.9	0.6	20
NIBGE	33.5	0.3	12
PARB	110.6	0.9	5
PARC	50.8	0.4	17
RRI	533.9	4.3	20
Total	**803.7**	**6.4**	

NIAB = Nuclear Institute for Agriculture and Biology, NIBGE = National Institute for Biotechnology and Genetic Engineering, PARB = Punjab Agricultural Research Board, PARC = Pakistan Agricultural Research Council, RRI = Rice Research Institute.

Source: Data obtained by the author from the NIAB, NIBGE, PARB, PARC, and RRI.

Historical Perspective and Contemporary Challenges in Asian Rice Farming:

Improving the overall quality through management techniques and selective breeding is a common practice. Despite eco-geographical limitations affecting the production of specific rice varieties like Hom Mali and Basmati, advancements in breeding, management practices, on-farm operations, and postharvest treatments have elevated the quality characteristics of each variety. The selection of specific rice grain attributes, including size, shape, endosperm appearance, aroma, and cooked texture, has historically been driven by sensory qualities long before precise measurements and a comprehensive understanding of the genetic or physicochemical foundations were available [38]. In the early 20th century, the distinctive physical characteristics of milled rice from Siam, now Thailand, such as its long and slender grain, facilitated its classification into various types, setting it apart from rice produced in neighboring countries. Superior Siam rice types featured elongated, slender grains with near-transparent qualities, while inferior types exhibited nearly opaque white areas on the underside of the grain. Burma's rice, dense and white, contrasted with the somewhat transparent Cochinchina rice, which was not as dense and pale.

Local rice variations were often named based on desired qualities, such as fragrances or sweet-smelling flowers, and the distinction between non-glutinous and glutinous grains was made using specific terms for the type of endosperm starch they contained. Despite ongoing national and international rice breeding initiatives introducing new variations, the ultimate judgment of their quality remains in the hands of customers and the market, with older rice varieties continuing to maintain their appeal. In Japan, the enduring popularity of Koshihikari, a premium short-grain Japanese rice introduced in 1953, exemplifies this trend. In Thailand, the majority of Hom Mali rice production is attributed to the cultivar KDML105, developed in the 1950s. While contemporary varieties like PTT1 have gained popularity due to their lower cost, KDML105's enduring appeal is evident even though it yields only half as much. Introduced in 2003, the Indian Pusa Basmati 1121 cultivar has been successful, combining the photoperiod insensitivity and increased output of modern rice cultivars with the distinctive qualities of Basmati rice. The economic value of India's rice production has significantly increased with the cultivation of Basmati rice, contributing to 60% of the country's rice export earnings. The success of specific contemporary high-yielding aromatic rice strains can be attributed to their excellent grain quality [39].

While more than 50 high-yielding modern rice varieties have been released since 1969, meeting the quality requirements of various consumer groups, it is anticipated that the identification of relevant genes and quantitative trait loci will advance rice breeding. However, environmental factors and management techniques are expected to have a substantial impact on rice grain quality, especially for premium and expensive varieties. The method of harvesting crops has a significant influence on rice quality. Hand-harvesting involves cutting the crop and allowing it to dry until reaching the ideal moisture level for milling and storing. Combined harvesting, increasingly common in contemporary rice farming, improves efficiency but requires appropriate post-harvest treatment to avoid negative impacts on grain quality. Sun-drying rice during the tropical summer may expose it to impurities, and combined harvesting without proper maintenance can result in decreased grain quality, as seen in Thailand in 1992-1993 due to insufficient post-harvest care. The commercialization of regional rice varieties with restricted production levels has been made possible by the development of extremely efficient small- to medium-sized contemporary rice mills. With the capacity to process 0.5–20 tonnes of paddy per day, these mills enable the direct delivery of rice with unique properties, including colored pericarp, organic rice, or "sushi" rice, to eateries, merchants, and customers in the city or beyond. For milled or white rice, the most widely sold and consumed type of rice in the retail market, unbroken grain is usually desired, but it is more expensive [40].

The broken grain is made up of little fragments. In Africa, this generalization is not always accurate. However, there is a growing demand for broken rice in some metropolitan areas of Senegal, the Gambia, and Mauritania. It is also priced differently in these places. Fragmented jasmine rice is relatively more expensive than standard fragmented rice but less expensive than intact jasmine rice; Senegal, Côte d'Ivoire, and Ghana are major importers of this rice variety. "Head rice" is the benchmark for unbroken grains, i.e., a rice kernel that is at least 75–80% longer than it was originally. In certain rice genotypes, environmental factors have a substantial impact on the resistance to grain breakage, which is the primary determinant of head rice production. However, in other genotypes, this resistance is more consistent. For example, the yield of head rice in some rice types is low in low-nitrogen conditions and increases in high-nitrogen environments. IR22 Star bonnet produced a significant amount of rice per head despite having a limited nitrogen source. In Thailand, the cultivar RD21 showed a good production of undamaged rice grains all through the growing season. When compared to the dry season crop, the rainy season crop in this area often yields more rice per grain. Since they are paid less for head rice yields that are about 40% below the standard, farmers who are compensated based on the head rice production of their paddy may be the ones who suffer the most from milling breakage expenses [41].

When compared to food rice, feed-grade rice is offered for a substantially lower price and is defined as paddy with a head rice yield of 20% or less. Higher yields of rice up to 60% have a major impact on rice mills' profit margins. Nevertheless, farmers do not receive better prices as a result of these larger yields. Even though farms can now produce rice of good quality thanks to technology, efforts to increase rice production, particularly in Africa face fierce competition from imports. This is mostly because post-harvest management is not given enough consideration in the transmission of rice technology, and there is a mismatch between the concept of rice quality and the tastes of urban customers [42]. Asia produces most of the world's rice, which is grown on a large number of small farms with a wide range of ecological and socioeconomic characteristics. Effectively classifying and handling rice after harvesting are essential components in guaranteeing superior quality. Several paddy kinds are combined into a single batch in the lack of a sorting device to separate rice according to different grain types and grades. This batch is then processed into lower-quality milled rice. One of the contributing factors to the issue is the absence of motivation for mills or farmers to control grain quality. Interviews with mill operators, farmers, and paddy purchasers in Thailand indicate that the paddy market functions as a sorting and pricing location for rice from diverse fields. This makes segmented marketing, storing, and processing possible. Furthermore, farmers receive input from the market to help them decide which type of rice to grow and to guide their farming management decisions for the upcoming season. Following distinct phases of processing, storage, transportation, and trading, the sorting process starts with figuring out the price that is given to farmers according to the type and caliber of rice crop they have harvested [42].

The rice buyers, who work as employees of mills and paddy assembly facilities or as independent traveling dealers, are the main arbiters in this sorting procedure. They act as a go-between for the bigger purchasers and the smaller farming operations. In the Hom Mali region, for example, a half-millimeter difference in grain length, a slight variation in husk color, or the ability to smell differences in scent strength can all be used by paddy purchasers to quickly distinguish between various mega-varieties. The vast majority of the country's annual rice harvest is made up of mega-varieties, which are widely recognized. However, because of the significant interaction effects of genotype and environment, grain grown from the same variety may show significant variations in both quality and price Simple instruments for quickly determining the amount of amylose in combinations of non-glutinous and glutinous grains include moisture meters, sample mills, and tinctured iodine from the first aid kit. These instruments are especially helpful in areas where nearby fields or the same field are planted with both varieties of grains at various times of the growing season. These tools also help to ensure precision and lucidity in the evaluation of quality and setting of prices [43].

The pricing of paddy is primarily determined by its moisture content, with distinctions between fresh or green (moisture content 20% or higher) and dry (moisture content 15% or less) paddy. Farmers' remuneration depends on the prospective mill's quality assessment, often involving grinding a small paddy sample to examine husk contents and grain breakage resistance. Modern sample mills enhance this process's precision. The transition from brown rice to white rice involves separating the endosperm from the embryo, pericarp, and aleurone layer through polishing and vacuum-forming in various mills. Mechanical drying or parboiling improves recently harvested paddy quality. Accelerating the drying process with mechanical methods ensures an optimal moisture level for maximum undamaged rice grain yield during milling. Parboiling, involving heating paddy before milling, increases head rice yield by fusing starch grains, enhancing rice value. Parboiled rice often produces 58% head rice and 7% broken grains, outperforming raw paddy rice with 26% broken grains and 39% head rice. Rice husk, once considered waste, is now a lucrative biofuel for various rice processing businesses. In Sri Lanka, parboiled bran commands a higher price due to a 26% increase in fat content resulting from parboiling. While the Thai government supports dryer construction for farmers, rice mills prefer mechanical drying using rice husks as fuel. However, this approach is not widely adopted by Thai farmers, partly due to the convergence of fresh paddy prices, driven by water content, and the need for immediate sales post-harvest [43].

Milled rice is categorized based on its origin and resistance to milling breakage. Grades such as 100% for Thai rice, 25% for Indian rice, 5% for Vietnamese rice, and 4% for US Long grain #2 rice emphasize the significance of milling breakage resistance in determining rice quality and value. These grades are qualitative, with the highest score being 100%, followed by subsequent increments of 5%, 10%, 15%, and 25%. Grain acceptability is determined by factors such as length, permissible breakage, and legal limits for defects, flaws, and contaminants. Unfavorable growing conditions or early harvesting can lead to improperly sized rice kernels. Inadequate milling may hinder grain development, resulting in green or discolored grains, and diminishing milled rice quality. Rat's teeth rice or yellow grain, characterized by finely milled rice with a yellowish tint, is often linked to fungal infection, thriving in warmer climates and high moisture storage conditions.

Various contaminants further reduce rice quality, including unhusked grain, chalky grain, weedy rice with a crimson pericarp, and a mix of glutinous and non-glutinous kernels. Translucency, a prized characteristic in milled rice like jasmine rice, is desirable, while grain chalkiness, an opaque patch in translucent non-glutinous grain, is undesirable. Basmati rice, despite having a moderately opaque endosperm, is nicknamed "chalky," and even premium Basmati rice cannot have uneven chalkiness. Increasing the value of rice for a specific variety involves sorting and quality control throughout the manufacturing and distribution process, particularly at the intermediate stage of the value chain, including paddy trading, milling, and parboiling. Financial incentives drive these efforts, with rice from small-scale farms sorted at the paddy market, processed, stored, and ultimately consumed by the end customer [44].

Crop Yield and Human Health:

Limited data supports a clear connection between the perceived value of rice by growers, consumers, or the market and its nutritional content. Contrary to popular belief backed by health benefit studies, there isn't a distinct property in rice with the highest vitamin and mineral concentrations. Evaluating the nutritional value involves quantifying elements or molecules that impact health, often requiring technological methods for measurement. Golden rice, known for its bright yellow color and high beta-carotene concentration, is an exception. Despite being anticipated to begin production in Bangladesh by the end of 2019, there is uncertainty around its nutritional superiority. Rice, among major staple crops, contains the least iron and zinc. Some mega-varieties in Thailand have lower Fe and Zn than less widely grown varieties, contributing to micronutrient deficiencies in rice consumers globally.

Other factors affecting rice quality include low levels of protein (nitrogen, N), dietary fiber, selenium, and amylose concentration, influencing starch absorption. Additionally, dangerous elements like mercury, cadmium, lead, and arsenic can impact the health of rice consumers. Environmental conditions, especially soil nitrogen levels, affect rice grain protein content, often inversely correlated with grain yield. Despite the creation of high-protein rice breeding lines, low heredity of protein content remains a challenge. Unlike wheat, where protein content is crucial for market distinction, rice protein content is often overlooked by consumers. Bio-fortification efforts for zinc in rice have shown promise, but the relationship between yield and grain zinc density poses challenges [34]. The application of foliar zinc and genetic engineering techniques aims to increase zinc and iron content in rice, though public and policymaker resistance to genetically modified crops hampers progress. Parboiling doesn't significantly affect iron and zinc concentrations but can be enhanced by incorporating salts like $FeSO_4$ and $ZnSO_4$ during soaking. Selenium levels in rice are lower compared to other crops, affecting approximately one billion people globally. Soil treatment of selenium shows a more favorable response in rice compared to foliar selenium, unlike zinc. Overall, the nutritional value of rice involves complex factors influenced by environmental conditions, genetic modifications, and processing methods.

Consumers, especially those who consume rice consistently throughout their lives, are raising concerns about the elevated levels of arsenic, cadmium, lead, and mercury in rice compared to other food sources. Arsenic pollution is aggravated when rice is grown in wetlands, where groundwater used for irrigation evaporates, concentrating arsenic in the soil. Rain and floodwater further leach arsenic back into the soil, affecting the groundwater levels. In regions like Bangladesh, the concentration of arsenic in rice grains is not influenced by soil arsenic levels but is found to exceed safe limits. Rice cultivated in areas affected by industrial pollution in China showed dangerously high levels of heavy metals, although rice sold in Zhejiang province met permissible limits. Local consumption of rice near contamination sources, as seen near a zinc mine in Thailand, led to health concerns due to mercury contamination.

Insufficient levels of phosphorus in rice seeds adversely affect initial growth. Phosphorus application in low-phosphorus soil enhanced shoot growth, but direct seed application showed varied outcomes. Zinc application improved seedling vigor when administered to mother plants or applied to seeds before sowing. Rice genotypes with higher seed zinc content, particularly in native varieties grown in northern Thailand's highlands, respond better to slash-and-burn farming practices that exacerbate zinc deficiencies in the soil. The impact of nutrient-enriched or contaminated rice is noticeable, with potential benefits for both agricultural households and rice-dependent communities. While there may be economic incentives for producing nutrient-enriched rice, the challenge lies in differentiating it in the market and creating a distinct channel for low-income rice consumers. Golden rice, with its high beta-carotene content and attractive color, has market potential and could attract a premium price, especially if it addresses vitamin A deficiency in low-income consumers. However, establishing effective mechanisms for distribution and market differentiation remains crucial [45].

Improving rice quality is crucial for increasing income and yields for farmers. However, achieving premium pricing as a quality improvement goal may not be practical due to eco-geographical constraints, especially in the production of premium rice varieties. Nevertheless, breeding and effective management practices within various rice varieties globally have led to price increases based on improved quality. For instance, the resistance to milling breakage is a quality feature that enhances rice quality and contributes to higher prices, given the widespread preference for intact rice kernels. Practical examples of quality improvement can be observed in processes such as combined harvesting, mechanical paddy drying, and parboiling. The effective control of rice quality involves sorting paddy from diverse small farms across Asia and implementing postharvest management to categorize rice into different grain types and quality levels. Quality management is essential, as higher prices are typically offered to those who produce higher-quality rice, including farmers, dealers, and mills. Conversely, a lack of sorting or quality control when milling heterogeneous paddy samples together can result in lower-quality rice and a waste of resources intended for quality improvement.

Breeding and agronomic management on the farm are additional approaches to enhance rice quality. However, for low-income rice consumers to benefit from nutrient-enriched grain, there needs to be a system to recognize and preserve the distinction between enriched and unenriched grains. It's unlikely that consumers with limited incomes would willingly pay for the addition of nutrients like iron and zinc to parboiled rice. Ambitious development strategies aiming to enhance grain quality and increase rice value should consider the following: geography and ecology limit rice production at the highest price points; post-harvest management is crucial for maintaining and improving farm-acquired quality; and mechanisms for differentiating rice based on grades and prices are essential, especially for nutrient-enriched rice targeted at low-income consumers.

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