



ISSN Print: 2664-6064
 ISSN Online: 2664-6072
 NAAS Rating (2026): 4.69
 IJAN 2026; 8(10): 24-31
www.agriculturejournal.net
 Received: 26-08-2026
 Accepted: 29-09-2026
 Published: 09-10-2026

Hima bindu Chetlapalli
 Ph.D. Scholar in Food and
 Nutrition, College of
 Agriculture, Vellayani,
 Thiruvananthapuram, Kerala,
 India

Reshmi R
 Assistant Professor
 (Community Science), Krishi
 Vigyan Kendra, Kerala
 Agricultural University,
 Kottarakkara, Kollam, Kerala,
 India

PR Geeta lekshmi
 Associate Professor and Head,
 Department of Postharvest
 Management, College of
 Agriculture, Vellayani,
 Thiruvananthapuram, Kerala,
 India

Chithra N
 Assistant professor and Head,
 Department of Agriculture
 Microbiology, College of
 Agriculture, Vellayani,
 Thiruvananthapuram, Kerala,
 India

Dr. Pratheesh Gopinath
 Assistant professor and Head,
 Department of Agriculture
 Statistics, College of
 Agriculture, Vellayani,
 Thiruvananthapuram, Kerala,
 India

Beela GK
 Professor and Head, Krishi
 Vigyan Kendra, Ambalvayal,
 Wayand, Kerala, India

Corresponding Author:
Hima bindu Chetlapalli
 Ph.D. Scholar in Food and
 Nutrition, College of
 Agriculture, Vellayani,
 Thiruvananthapuram,
 Kerala, India

Fortifying the staple: A review of rice fortification technologies, nutrient retention and implementation challenges

Hima bindu Chetlapalli¹, Reshmi R², PR Geeta lekshmi³, Chithra N⁴, Pratheesh Gopinath⁵, Beela GK⁶

DOI: <https://www.doi.org/10.33545/26646064.2026.v8.i10a.765>

ABSTRACT

Rice is a key staple meal and a significant source of nutritional energy, especially in Asia, where it accounts for a large portion of daily food consumption. However, milling and polishing remove nutrient-rich bran and germ layers, causing significant vitamin and mineral losses and boosting the risk of micronutrient deficiencies in populations with poor dietary diversity. Rice fortification is a feasible technique for improving the nutritional value of this widely consumed staple without requiring significant modifications to existing dietary practices. This review addresses the major approaches of food fortification, including mass, targeted, and market-driven fortification, as well as conventional and innovative strategies for rice. Particular attention is placed on parboiling, dusting/coating, and extrusion technologies, with nutrient stability taken into account during processing, storage, and cooking. The review also discusses elements that influence enriched rice's technological performance, such as sensory quality, micronutrient stability, processing conditions, cost, infrastructure, and quality control requirements. Nano-encapsulation and digital fortification quality evaluation tools are emerging techniques that have the potential to improve nutritional bioavailability, accuracy, and monitoring. Despite its potential for widespread population coverage and multiple micronutrient delivery, rice fortification continues to encounter hurdles in terms of nutrient losses, sensory acceptability, fortification consistency, cost, and implementation capability. A technology-specific and context-sensitive approach that incorporates appropriate fortification methods, quality assurance, consumer acceptance, and effective monitoring is thus required for long-term rice fortification and better vitamin delivery.

Keywords: Rice fortification, micronutrient deficiencies, fortification technologies, nutrient retention, extrusion, dusting, parboiling, nutrient stability, bioavailability, food fortification

1. Introduction

Agriculture plays a pivotal role in ensuring food security, sustaining livelihoods, and delivering the food which is necessary to fulfil the dietary demands of a booming global population. However, as establishing healthy diets depends equally on the nutritional quality and variety of foods, increasing food production alone does not ensure sufficient nutrition (Yilmaz *et al.*, 2022) [56]. As a result, modern food systems place a greater emphasis on both the production of nutrient-rich foods that can solve persistent nutritional issues as well as the availability of sufficient food (Khouri *et al.*, 2014) [33].

Globally, cereals account for a major proportion of diets, and supply a significant amount of energy to population. In terms of production, consumption, and dietary significance, the three main cereals are wheat, rice, and maize (Abeywardena *et al.*, 2010) [3]. Whole grains offer energy as well as different levels of dietary fiber, vitamins, minerals, and other bioactive chemicals. Regular consumption of whole grains has been linked to positive effects on the risk of a number of chronic diseases (Ackland *et al.*, 2016) [4]. Due to their extensive use, cereals are now crucial tools for enhancing the nutritional value of diets through strategies like food fortification and dietary variety.

Among these cereals, Rice (*Oryza sativa* L.) is one of these grains that plays a significant role in global food systems, particularly in Asia. Roughly 90% of the world's rice is produced and consumed in Asia, where it plays an integral part in daily diets and is directly linked to food security (Allgrove *et al.*, 2015) [6]. Rice contributes significantly to dietary energy in Asian nations due to its high per-capita consumption, especially among people that rely substantially on this staple meal (Amankwah *et al.*, 2018) [8]. Its dietary relevance is further increased by the fact that this grain is further processed into a variety of traditional and commercial products, including as breads, cakes, noodles, and other food items (Andango *et al.*, 2007) [9]. Although rice is an important source of dietary energy and contains moderate levels of protein and minerals, processing has

a major effect on its nutritional content. Polishing and milling remove the bran and germ, which contain significant amounts of vitamins and minerals that diminishes the concentrations of several micronutrients in the ultimate polished rice. Additionally, rice contains nutrients such as thiamine, niacin, and riboflavin, but their preservation is dependent on the degree and technique of processing (Barclay, 1998) [14]. As a result, populations that consume excessive quantities of polished rice, particularly those with minimal dietary diversity, may be at risk of not obtaining enough essential micronutrients. Nutrient losses during rice processing have thus become a significant factor in determining rice nutritional quality (Bonto et al., 2018) [17].

This concern is part of the broader global burden of micronutrient malnutrition, or "hidden hunger," which refers to insufficient intake or status of key vitamins and minerals despite adequate or even excessive energy consumption. Iron, zinc, vitamin A, folate, vitamin D, and other micronutrient deficiencies continue to be major public health concerns, affecting growth, cognitive development, immunological function, metabolism, and overall health (Stevens et al., 2022; Fernández-Gaxiola et al., 2024; Han et al., 2022) [26, 30]. Because of their higher dietary needs, pregnant women, women of reproductive age, children, and adolescents bear a disproportionately significant burden. Iron deficiency is one of the common micronutrient deficits globally along with poor consumption of calcium, vitamin D, and B-group vitamins, particularly folate. (Han et al., 2022) [30]

The persistence of micronutrient deficiencies despite the availability of staple foods emphasizes the significance of increasing the nutritional quality of regularly consumed diets. Dietary diversity is an important strategy for ensuring sufficient micronutrient intake; however, economic, geographical, cultural, and food-access barriers may limit the regular consumption of diverse nutrient-rich foods in vulnerable communities. As a result, complementary measures that improve the nutritional content of commonly consumed basic foods can help alleviate micronutrient deficiencies. In this perspective, rice's nutritional value and widespread consumption make it an appropriate vehicle for delivering essential vitamins and minerals to vulnerable populations. (Angeles et al., 2008) [11].

2. Food fortification

Food fortification is defined as the process of adding vital vitamins and minerals to regularly consumed foods such as corn flour, edible oil, salt, rice, and wheat flour to prevent nutritional deficiencies. These foods are known as fortified food carriers because they deliver essential nutrients. Over the last century, fortification initiatives have been extremely efficient in alleviating the prevalence of nutritional diseases such as vitamin deficiencies, goitre, pellagra, and rickets. Although the world has changed drastically since the commencement of fortification programs in the 1920s, the goal has shifted from addressing specific deficiencies to improving the overall dietary intake (Dwyer et al., 2015) [24].

In 1999, the WHO Regional Office for the Eastern Mediterranean launched a program supported by UNICEF and the Micronutrient Initiative, which resulted in the widespread adoption of micronutrient-fortified foods by 2009. According to the WHO and FAO, fortification was defined as the addition of key micronutrients such as vitamins, minerals, and amino acids to commonly consumed food. This method is effective and cost effective to alleviate micronutrient deficiencies, improving nutritional status, and offering public health benefits with minimal health risks. (Olson et al., 2021; Naik et al., 2024) [39, 41].

Fortification with commercial foods like milk, margarine, flour, fruits, vegetables, grains, and oils has decreased the incidence of deficiencies in multiple studies, demonstrating the effectiveness of fortification programs in nations like India, Switzerland, the United States, and Canada (Nagar et al., 2018) [38]. Ensuring that every individual obtains the energy, macronutrients, and micronutrients they require from their diet to sustain a healthy and productive life is the ultimate

purpose of food fortification. Each country's fortification policies are determined by a variety of criteria, including nutrients, food vehicles, income level, and geographic location.

3. Methods of food fortification

Food fortification implementation varies depending on the population's nutritional needs, the desired coverage, the food vehicle, and the regulatory and delivery environment. As a result, many fortification systems have been developed to address micronutrient deficiencies at the population or subgroup levels while also providing flexibility in program implementation and food production. These approaches are broadly categorized as mass, targeted, and market-driven fortification, as outlined in the following sections (WHO, 2022; Ashraf, 2025) [12].

3.1. Mass fortification

The most popular and economical form of fortification is mass fortification, which involves adding vital micronutrients to staple foods that the majority of people consume.

This tactic works especially well in low- and middle-income nations where micronutrient shortages are common. Wheat flour, rice, maize flour, salt, sugar, and cooking oil are examples of foods that have been fortified. USI has greatly decreased iodine deficient illnesses worldwide, making it one of the most effective examples of mass fortification (Andersson et al., 2012) [10].

Similarly, reducing anaemia and neural tube abnormalities has been made possible by adding iron and folic acid to wheat flour (Keats et al., 2019) [32]. In order to ensure wide coverage and impact, mass fortification is usually required by government regulations and carried out through the food processing industry. To obtain maximum effectiveness, challenges such as nutrient deterioration during storage and cooking, regulatory compliance, and consumer acceptance must be addressed.

3.2. Targeted fortification

Targeted fortification aims to improve nutritional status for high-risk groups, including pregnant women, infants, and those with certain medical disorders. This strategy is effective for treating inadequacies in vulnerable groups who may not benefit from mass fortification. Targeted fortification involves creating specific food products like ready-to-use therapeutic foods (RUTF) and complementary foods for newborns. These products are commonly fortified with minerals including iron, zinc, vitamin A, and folic acid to promote growth and immunological function (Gombart et al., 2020) [28]. Bio-fortification, a type of targeted fortification, involves developing crops with increased micronutrient content to improve their nutritional value. Bio-fortified rice with added iron and zinc, as well as vitamin A-rich golden rice, have been created to address inadequacies in populations that rely primarily on rice-based diets (Majumder et al., 2019) [36]. Targeted fortification is effective in lowering inadequacies in specific groups, but requires adequate distribution systems and consumer education for optimum use.

3. Market driven fortification

Private sector-led fortification is frequently voluntary and not mandated by governments. Micronutrients are added to processed meals to meet consumer demand for healthier options. Market-driven fortification includes iron and B vitamin fortified cereals, vitamin D-enriched dairy products, and calcium-fortified beverages. In high-income nations, customers are more health-conscious and prepared to pay a premium for fortified foods (Martins et al., 2024) [37]. Market-driven fortification offers a variety of nutrient-rich products, but its success relies on consumer purchasing power, awareness, and regulatory control to prevent misleading health claims. The concentration on premium-priced items may exclude low-income groups who require fortified foods.

4. Techniques of food fortification

Since food fortification is a popular tactic to improve food quality, prevent vitamin deficiencies, and promote public health. Numerous techniques are used, each specifically designed to address various target groups, food carriers, and nutrient stability. The food matrix, nutrient stability, affordability, and consumer acceptance all play a role in the method selection.

4.1. Direct addition

It is also termed as industrial fortification. In this technique micronutrients are added to food products during the production stage. This is the most commonly utilized approach for staple foods like flour, rice, and dairy. Fortification ensures steady nutrient levels during storage, transportation, and cooking. Fortification premixes, a mixture of vitamins and minerals, are often employed to ensure equitable distribution of nutrients in the finished product. A few instances of direct additions include the adding of iron to wheat and maize flour to treat anaemia and the addition of iodine to salt to prevent goitre and iodine deficiency conditions (Zimmermann *et al.*, 2008) [57]. Rickets can be prevented by fortifying milk with vitamin D (Alvi *et al.*, 2016) [7]. One benefit of direct addition is that it can cover a wide portion of society without changing eating patterns and is considered to be cost-effective for big populations. Industrial fortification is successful, but it needs robust regulatory frameworks to keep an eye on compliance and avoid over- or under-fortification.

4.2. Bio-fortification

Bio-fortification is a sustainable and cost-effective method for increasing crop nutrient content by conventional breeding or genetic alteration. This strategy is especially useful for rural populations with limited access to industrially fortified foods. To address vitamin A insufficiency, rice has been genetically engineered with beta-carotene (Beyer *et al.*, 2002) [15]. Zinc-fortified wheat has been shown to enhance immunological function and growth (Bouis *et al.*, 2017) [18]. Bio-fortified crops, like iron-rich beans and vitamin A-rich orange-fleshed sweet potatoes, have been found to reduce micronutrient deficits. Because nutrients remain ingrained in the plant itself, bio-fortification is sustainable and may be advantageous for rural communities that have limited access to fortified foods. Although biofortification has long-term advantages, there are obstacles to overcome, such as consumer acceptability, regulatory approval, and the requirement for widespread farmer adoption (Jha *et al.*, 2022) [30].

4.3. Home fortification

Home fortification is the addition of micronutrient powders or lipid-based supplements to cooked foods. This approach is particularly effective for treating deficits in young children and pregnant women. Micronutrient powders (MNP) include vital elements like iron, vitamin A, and zinc and can be combined with meals without affecting flavour or texture. Research indicates that home fortification can enhance iron status and prevent anaemia in children (Zlotkin *et al.*, 2003) [58].

MNP sachets containing iron, zinc, and vitamins were added to infant and young children's meals (Suchdev *et al.*, 2012) [47]. Lipid-based nutrient supplements (LNS), including high-energy pastes supplemented with vitamins and minerals, can aid from preventing malnutrition in children. Home fortification offers specific benefits, particularly for young and pregnant women, which is simple to incorporate into everyday meals. Affordability, adherence, and distribution logistics are important factors to consider when scaling up implementation.

4.4. Nanotechnology in food fortification

Nanotechnology is transforming food fortification by improving micronutrient bioavailability, stability, and controlled release. Nano-encapsulation encases vitamins and minerals in nanoscale carriers such liposomes, polymers, or lipid nanoparticles to prevent degradation

and increase absorption in the body (Chaudhry *et al.*, 2008, Ashraf *et al.*, 2021) [19]. Nano-iron can fortify staple foods like flour and rice without producing colour or flavour changes, surpassing the limits of traditional iron fortification [108]. Nano-emulsions have improved the solubility of fat-soluble vitamins (A, D, E, and K) in water-based meals, leading to increased bioavailability. Nano-liposomes effectively transport sensitive nutrients such as omega-3 fatty acids and probiotics. Silica-based nanocarriers have been studied for targeted nutrient delivery in the digestive tract (Bondu *et al.*, 2022) [16]. Nanotechnology in food still poses safety and regulatory concerns, despite its potential benefits. Ensuring consumer safety requires extensive study and governmental clearances. Nanotechnology holds promise for addressing global micronutrient inadequacies, leading to more effective and sustainable food fortification solutions.

5. Advanced tools for fortification

Advanced tools for food fortification enhance precision, monitoring, and scalability in addressing micronutrient deficiencies. The Digital Fortification Quality Traceability Plus (DFQT+) system provides real-time quality monitoring, while Bio Analyte I Check devices are portable and user-friendly tools for quickly assessing micronutrient levels (e.g., vitamins and minerals) in fortified meals.

These devices have been utilized in over 60 low- and middle-income nations to improve fortification quality. GAIN developed the Fortification Assessment Coverage Toolkit (FACT), a standardized survey method to evaluate fortified food coverage, consumption, and quality in population-based and targeted initiatives. Food fortification formulator is an spreadsheet-based application determines fortification amounts based on eating habits, prices, and nutrient stability. USAID's AFFORD program developed qualitative spot tests, such as Xylenol Orange for wheat flour and white rice and Dithizone for maize flour and rice, to detect the presence of zinc in fortified foods. (GAIN, 2025, AFFORD, 2025) [2]

6. Why rice fortification?

When unmilled, rice is an excellent source of both macro and micronutrients. To produce the widely consumed starch-rich white rice, the fat and micronutrient-rich bran layers are removed during rice milling. In the rice-producing nations of southeast and northeast Asia, which are among the world's most densely inhabited regions, white rice is the most important staple food. 90% of the world's rice is produced and consumed in Asia. Rice accounts for 30% of calories on average, and in certain low-income nations, this number can rise to almost 70%. (FAO, 2010) [27]

Rice is thus a potentially good product for supplying micronutrients to a large number of people, with the potential to significantly reduce micronutrient deficits. However, this will only achieve the desired result provided the sensory properties of the end product are not significantly altered and consumers are not opposed to adopting fortified rice into their daily diet. Furthermore, using rice to supply micronutrients will only be effective if fortified rice is economically available to low-income people. Unpolished rice contains high levels of vitamins B₁, B₆, E, and Niacin. During polishing, the majority (75-90%) of these vitamins are eliminated. (USDA, 2012) [49].

7. Vitamin and mineral loss during rice milling

Brown rice is produced by milling paddy rice, which removes its outer hull, germ, and bran layers. Brown rice can be further milled to remove the bran layer, yielding white rice (Dexter, 1998) [23]. Paddy rice yields around 25% hulls, 10% bran, and 65% white rice (Chen *et al.*, 1998) [20]. Rice milling depletes B vitamins and minerals including iron and zinc from the outer germ and bran layers (fig. 1). Washing or rinsing rice, as well as some cooking procedures, can lead to nutritional loss (WHO *et al.*, 2006) [53]. To minimize nutritional loss and VMD, rice grains can be fortified with bioavailable vitamins and minerals.

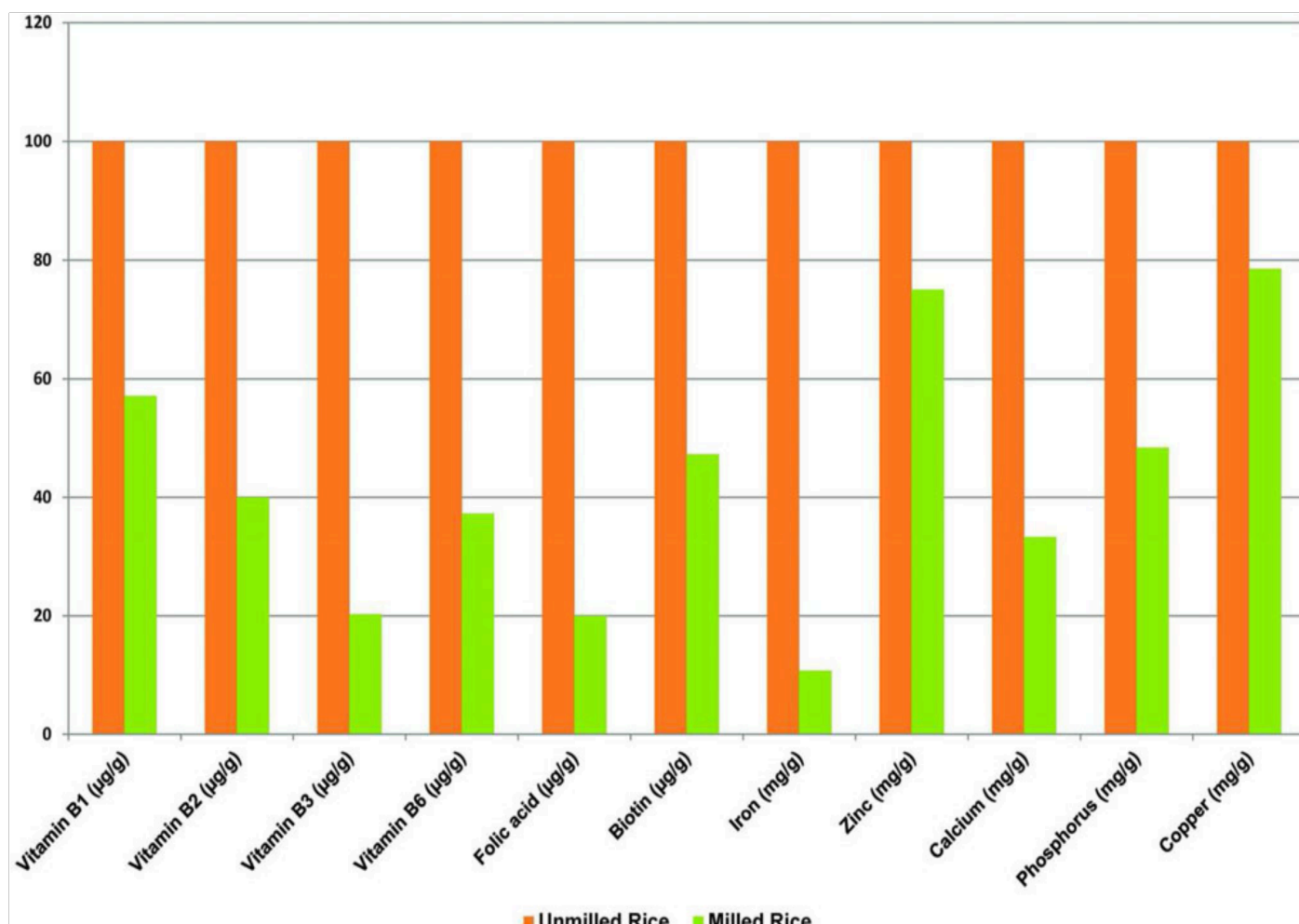


Figure 1. Per cent rice milling losses of vitamins and minerals.

Source: Adapted from Chen et al., 1998 20

8. Cooking and textural properties of rice

Consumer preferences for rice are primarily influenced by its kernel form, colour, flavour, aroma, amylose content, taste, and other rice qualities. Rice's starch features, including gelatinization, gelling ability, and amylose content, have a significant impact on its dietary habits and cooking characteristics (Farooq et al., 2025) [25]. Rice cooking quality can be assessed by measuring the gelatinization temperature of its starch. The gelatinization temperature of rice starch typically ranges from 55-79° C which varies by starch granule size, shape, structure, and rice type additionally starch's amylose concentration is strongly linked to its cooking properties. Lastly, environmental factors can also significantly impact the cooking quality and starch behaviour of rice. (Nie et al., 2025)

Cooking time and gelatinization temperature show a positive association. However, there is no data to support or describe the relationship between gelatinization temperature and cooked rice texture. Gelatinization temperature and amylose content have a negative association. As amylose content increases, gelatinization temperature decreases and vice versa. Certain varieties of rice require minimal cooking time but high gelatinization temperatures. There is limited data to suggest a single variety having high gelatinization temperature and cooking time simultaneously (Xie et al., 2025) [55].

In rice the ratio and concentration of amylose in starch have a major impact on its consuming and cooking capabilities. Amylose content is a key determinant in determining rice quality. However, rice cooking quality depends on parameters such as water absorption, volume expansion, and elongation ratio. Rice's physiological qualities vary significantly depending on its amylose level. Scientists divide rice cultivars into three categories based on their amylose content (Xianting et al., 2023) [54]. The primary protein found in stored grain is Oryzenin,

along with prolamins, globulins, and albumins. Oryzenin consists of inter- and intra-molecular subunits which are connected by disulfide bridges. Rice stickiness decreases as oryzenin content increases after storage.

9. Innovations in rice fortification

Rice is fortified using a variety of processes. The addition of micronutrients to rice is dependent upon the type of fortification and the techniques employed. These technologies include extrusion, dusting, and parboiling. These methods, which are covered below, have been shown to be successful in raising the mineral content of rice.

9.1. Parboiling

Soaking, steaming, and drying are the three primary stages of the hydrothermal parboiling process. Worldwide, parboiling accounts for about 15% of milled rice. The top producers of parboiled rice are West Asia, Bangladesh, Sri Lanka, India, and Thailand. These nations produce and consume almost 90% of the world's parboiled rice. The limited consumption of a variety of foods is the primary source of micronutrient deficiencies, which is a major problem for many people in poor nations. The most significant postharvest procedure for rice is parboiling, which is typically employed to preserve quality. The quality-related characteristics of parboiled rice are determined by a number of variables. One of the main reasons paddy rice loses vital components is prolonged parboiling. The physiochemical features of rice are positively impacted by parboiling since it reduces breakage during handling but significantly increases water absorption, cooking duration, and thiamine concentration. Since parboiled rice has better aroma, texture, and cooking capabilities than brown and white rice, it was developed in order to improve quality attributes for consumers. Several methods are introduced to address micronutrient. Parboiling is a well-known fortification technique that has long been employed

at both the residential and industrial levels as a primitive method. It has been discovered that fortifying rice during the parboiling process can significantly boost its iron content up to 140 mg/kg of dry weight. The milling, nutritional, organoleptic and quality aspects of rice are enhanced by parboiling. Additionally, it lowers nutrient losses during the polishing process and increases head rice production (Junaid *et al.*, 2022) [31]. And also contaminants related to rice kernels are eliminated during the soaking procedure. During processing and storage, parboiling stops the formation of an unpleasant flavour and yellow hue (Liu *et al.*, 2025) [34]. Water is used to soften the rice kernel's endosperm in parboiling process while steaming causes the starch to gelatinize, which is the final and primary factor in the production of rice texture. In addition of making milling easier, parboiling rice improves its flavour and aroma thereby rendering it more appealing to consume.

9.2. Dusting technology

Dusting technology, often known as coating, is the next technological advancement. It is one of the most crucial methods to preserve vitamins and minerals that are lost during the milling and washing operations. This method involves spraying rice with a nutritious suspension that adheres to the outer layer of the bran.

On the other hand, micronutrient loss results from extensive washing before cooking. The powdered rice off colour and flavour are also a drawback. Commercial premixes, however, promise to be resistant while washing and cooking. Dusting technique has the advantage of investing less capital than extrusion technology. Rice is tempered at room temperature (20 to 25 °C) for 30 to 40 minutes using dusting technology. Following this, the sample is dried for 30 to 60 minutes at 50 °C. and sprayed with a fortificant solution. In several nations, this procedure has been implemented. One drawback of this method is that, prior to cooking, powdered rice needs to be given a minimal amount of washing. (Junaid *et al.*, 2022) [31]

9.3. Extrusion technology

Extrusion is a flexible, practical, and highly effective food processing technology, where Raw flour undergoes numerous structural and chemical changes throughout the extrusion process, including protein denaturation, complex formation between lipids and amylose, starch gelatinization, and degradation processes. Extrusion cooking technology is widely being used in manufacturing food products, including modified starches, breakfast cereals, flat breads, infant meals, and meat snacks. The impact on final product quality depends on minor modifications in processing circumstances which includes Extruder type, feed moisture, screw configuration, temperature profile, screw feed rate, and screw speed. Because of its unique characteristics, including its appealing white colour, bland flavour, hypo allergenicity, and ease of digestion, rice flour is used as a desirable ingredient in the extrusion process (Sule *et al.*, 2024) [48]. Extrusion technology uses an extruder with a hammer mill, single or double screw, mixer and dryer at a temperature between 70–100 °C, which is then progressively raised to 100–140 °C. As the dough passes through the extruder's screw, high pressure is applied. Compared to parboiling and dusting, extrusion technology is more expensive, since it has a few drawbacks like preparatory steps including milling, dough preparation, and the extrusion process. However, broken rice kernels that are damaged during threshing and other processing operations might be used to partially make up for this loss because they are sold for a significantly lower price. To put it briefly, extrusion technology has certain drawbacks, such as the expensive cost of extruders, which raises the price of extruded rice by 15–20%. (Steiger *et al.*, 2014) [45]

10. Comparison of rice fortification technologies

The ability to incorporate micronutrients into rice kernels is essential, but so is the stability of the added nutrients during processing, storage, washing, and cooking. Differences in processing conditions, nutrition retention, sensory attributes, raw material requirements, and manufacturing costs can all have a significant impact on a

technology's applicability for large-scale uses. As a result, the performance of dusting, coating, and extrusion technologies must be evaluated using critical factors such as process stability, storage stability, washing and cooking stability, and cost (Steiger *et al.*, 2014) [45].

10.1. Process stability

The first challenge for micronutrients in rice fortification is the production of fortified kernels. Stability is influenced by the amount of heat used, the humidity during heating, the drying steps, and the presence of air. Coating or extrusion processes typically have process losses ranging from 0% to 20%, depending on the procedure, nutrient, and matrix. Dusting's process loss is regarded the least of all losses because no high pressure is applied; yet, segregation is a hurdle. (Alavi *et al.*, 2008) [5]

10.2. Storage stability

Storage stability is determined by a variety of factors, the most important of which is vitamin A, which, unlike other nutrients, is susceptible to oxidation, particularly in the presence of moisture and high temperatures. The presence of iron ions increases storage losses, even when non-water-soluble iron phosphates or pyrophosphates are used. Rice has a water content of approximately 12.5–14%, and at a storage temperature of 30 °C, monthly vitamin A losses in extruded kernels may be between 4 and 10%. To stabilize this vitamin, it is recommended that you utilize an antioxidant (ideally BHT). The packing material, light exposure, and method (e.g., cold, warm, and hot extrusion) are all important aspects (Pinkaw *et al.*, 2012) [43]. In addition to vitamin A, vitamin B1 is heat sensitive and endures some losses. To ensure a reported vitamin level, overages must be applied, and the required amounts must be determined by studies. Other vitamins remain stable for several months on the shelf.

10.3. Washing stability

Dusting is not recommended when rice is rinsed or soaked and rinsed prior to cooking. Furthermore, most coated rice variants exhibit significant washing losses, with a few outliers, such as when ethyl cellulose is employed in the coating. Washing losses are very minimal in warm- and hot-extruded kernels; in cold extrusion, loss is mostly determined by washing intensity and the binder matrix.

10.4. Cooking stability

Dusting and coating prevent cooking with an excessive amount of cooking water, which is wasted after cooking. When multiple cooking procedures are tested, the lowest losses are discovered when rice absorbs all of the cooking water (10–20%); only vitamin B12 losses are significantly higher (about 40%). Cooking with an excess of water that is then removed leads in increased losses, primarily in highly water-soluble vitamins (e.g., vitamin B12; 50–60%), but losses of poorly water-soluble vitamins, such as thiamine mononitrate, are extremely minimal (about 10%). Soaking rice overnight and heating it for 2 hours results in very large losses, even for vitamin A (up to 50%) and vitamin B12. (Peil *et al.*, 1982) [42]

10.5. Costs

It is difficult to objectively compare the costs of various rice fortification technologies because a number of factors are incorporated into the calculation, such as location, prices for intact rice kernels or broken rice, electricity, steam, and water costs, plant configuration (e.g., which extruder is combined with which dryer), and depreciation and interest costs.

The cost of raw materials, particularly rice, dominates final costs. If the technology allows for the use of inexpensive broken rice as a starting material, there is a cost benefit. This is one of the primary benefits of extruded FRK.

Rice flour, derived from broken rice, is the starting material. The resulting kernels are similar to whole, unbroken rice kernels. If the market price differential between broken and intact kernels equals the production cost of extruded kernels, extrusion will be even less expensive than dusting. Coating technologies necessitate entire rice ker

nels, which are more expensive. Broken rice can be coated in some circumstances, but it is not as appealing.

Energy costs are another expense factor to consider. Water and/or steam are used during extrusion, whether it is cold, warm, or hot, and must be removed at the end of the process. The drying stage is significantly more expensive than the preconditioning step (in warm and hot extrusion) and the actual extrusion operation. Drying is typically accomplished using a fluid bed or pasta dryers and is energy intensive. Thus, the additional expenses of fortification for rice millers could range from 3-6% of the cost of bulk rice.

11. Advantages of rice fortification

• Wide population reach

Rice is regularly consumed in many countries, particularly in populations where it is a major staple, allowing fortified rice to potentially deliver micronutrients to large population groups through an established dietary vehicle (De-Regil *et al.*, 2014) [22].

• Improvement of micronutrient intake

Fortification can increase the intake of selected micronutrients such as iron, vitamin A and folic acid. WHO recommends iron fortification of rice as a public-health strategy in settings where rice is a staple food (WHO, 2022).

• Minimal change in established dietary practices

Because fortified rice can be incorporated into existing rice-consuming diets, it can provide additional micronutrients without requiring major changes in food consumption patterns (WHO, 2022).

• Potential for multiple micronutrient delivery

Rice can be fortified with combinations of vitamins and minerals according to the nutritional needs of the target population. This provides flexibility when several micronutrient inadequacies coexist (Dary *et al.*, 2006) [21].

• Good sensory acceptability is achievable

Appropriately formulated fortified rice can achieve organoleptic properties and consumer acceptance comparable with conventional milled rice. Ferric pyrophosphate-fortified rice, in particular, show

12. Disadvantages of rice fortification

• Nutrient losses during washing and cooking

Micronutrients may be lost during household preparation, particularly when rice is washed, soaked or cooked in excess water. Pyo *et al.* (2022) [44] reported increased micronutrient losses when fortified rice was cooked using excess water.

• Possible changes in sensory characteristics

The fortification process can influence the colour, flavour, aroma and other organoleptic properties of rice. Some coated kernels have been reported to develop distinctive colours and flavours that may reduce consumer acceptance (Liu *et al.*, 2025) [34].

• Variable stability of micronutrients

The stability of added nutrients differs according to the micronutrient, chemical form, fortification technology and storage conditions. Vitamin A, for example, may show greater variability in retention than some mineral fortificants (Pyo *et al.*, 2022) [44].

• Difficulty in achieving uniform fortification

Maintaining consistent nutrient concentration among fortified kernels and ensuring an appropriate blending ratio with non-fortified rice are important quality-control challenges. Variations in processing and kernel characteristics can influence the final nutrient concentration (Steiger *et al.*, 2014) [45].

• Infrastructure and quality-control requirements

Large-scale rice fortification requires suitable processing facilities, quality-control systems, trained personnel and monitoring mechanisms. These requirements can be challenging in settings where rice production and milling are highly decentralized.

• Cost of implementation

Although fortification can be a cost-effective nutrition intervention, expenses associated with fortificants, processing equipment, quality assurance, packaging and monitoring can affect feasibility, particularly in resource-constrained settings (WHO, 2018) [29].

Conclusion

Rice fortification is a promising food-based technique for increasing micronutrient consumption via a commonly consumed staple. According to the review, the success of rice fortification is determined not only by the quantity of nutrients given, but also by how well they are retained during processing, storage, washing and cooking. Parboiling, dusting/coating, and extrusion all have unique technological advantages and limits, while future technologies such as nano-encapsulation and digital quality-monitoring systems have the potential to improve precision and nutrient delivery even further. However, sensory acceptance, fortification homogeneity, nutrient stability, production cost, infrastructure, and quality assurance are still key implementation obstacles. To achieve long-term nutritional benefits at the population level, future rice fortification programs should combine proper technology selection with rigorous quality control, regulatory monitoring, consumer acceptance, and affordability.

Future perspectives

Future rice fortification research should focus on precision fortification, increased nutrient stability, bioavailability, and the development of fortifiers that are washable and cooking stable. Emerging technologies, including as micro- and nanoencapsulation, digital quality monitoring, and AI-assisted formulation, provide prospects to improve nutrient delivery, process control, and fortification efficiency. To encourage greater acceptance of fortified rice, more focus should be placed on customer acceptability, affordability, sustainable processing, and effective quality-assurance procedures. Integrating technological innovation with population-specific nutritional needs, as well as effective regulatory monitoring, could increase rice fortification prominence as a long-term strategy for treating micronutrient deficiencies.

References

1. USAID Advancing Food Fortification Opportunities to Reinforce Diets (AFFORD). Qualitative Spot Tests for Zinc Detection. 2025.
2. Global Alliance for Improved Nutrition (GAIN). Fortification Tools and Resources. 2025.
3. Abeywardena S, Bower C, Halliday J, Chan A, Sullivan EA. Prevalence of neural tube defects in Australia prior to mandatory fortification of bread-making flour with folic acid. *Aust N Z J.* 2010;34:351–5.
4. Ackland ML, Michalczyk AA. Zinc and infant nutrition. *Archives of biochemistry and biophysics.* 2016;611:51-57.
5. Alavi S, Bugusu B, Cramer G, Dary O, Lee TC, Martin L, McEntire J, Wailes E. Rice fortification in developing countries: a critical review of the technical and economic feasibility. 2008.
6. Allgrove J, Shaw NJ. A Practical Approach to Vitamin D Deficiency and Rickets. Calcium and bone disorders in children and adolescents. 2015;28:119-133.
7. Alvi SN, El Tabache C, Al-Ashwall A, Hammami MM. Vitamin D content in fortified low fat milk in Saudi Arabia. *Annals of Saudi Medicine.* 2016;36(5):325-327.
8. Amankwah N, Han Z. Cardiomyopathy secondary to selenium deficiency: A review of clinical cases. *Open Nutr J.* 2018;12(1):74-88.

9. Andango PE, Osendarp SJ, Ayah R, West CE, Mwaniki DL, De Wolf CA, Kraaijenhagen R, Kok FJ, Verhoef H. Efficacy of iron-fortified whole maize flour on iron status of schoolchildren in Kenya: a randomised controlled trial. *The Lancet*. 2007;369(9575):1799-1806.
10. Andersson M, Karumbunathan V, Zimmermann MB. Global iodine status in 2011 and trends over the past decade. *The Journal of nutrition*. 2012;142(4):744-750.
11. Angeles-Agdeppa, Capanzana, Barba, Florentino, Takanashi. Efficacy of iron-fortified rice in reducing anemia among schoolchildren in the Philippines. *International journal for vitamin and nutrition research*. 2008;78(2):74-86.
12. Ashraf SA. Food fortification as a sustainable global strategy to mitigate micronutrient deficiencies and improve public health. *Discover Food*. 2025;5(1):201.
13. Ashraf SA, Siddiqui AJ, Abd Elmoneim OE, Khan MI, Patel M, Alreshidi M, Moin A, Singh R, Snoussi M, Adnan M. Innovations in nanoscience for the sustainable development of food and agriculture with implications on health and environment. *Science of the Total Environment*. 2021;768:144990.
14. Barclay D. Multiple fortification of beverages. *Food and Nutrition Bulletin*. 1998;19(2):168-171.
15. Beyer P, Al-Babili S, Ye X, Lucca P, Schaub P, Welsch R, Potrykus I. Golden rice: introducing the β -carotene biosynthesis pathway into rice endosperm by genetic engineering to defeat vitamin A deficiency. *The Journal of nutrition*. 2002;132(3):506S-510S.
16. Bondu C, Yen FT. Nanoliposomes, from food industry to nutraceuticals: Interests and uses. *Innovative Food Science & Emerging Technologies*. 2022;81:103140.
17. Bonto AP, Camacho KSI, Camacho DH. Increased vitamin B5 uptake capacity of ultrasonic treated milled rice: A new method for rice fortification. *Lwt*. 2018;95:32-39.
18. Bouis HE, Saltzman A. Improving nutrition through biofortification: a review of evidence from HarvestPlus, 2003 through 2016. *Global food security*. 2017;12:49-58.
19. Chaudhry Q, Scotter M, Blackburn J, Ross B, Boxall A, Castle L, Aitken R, Watkins R. Applications and implications of nanotechnologies for the food sector. *Food additives and contaminants*. 2008;25(3):241-258.
20. Chen H, Siebenmorgen TJ, Griffin K. Quality characteristics of long-grain rice milled in two commercial systems. *Cereal chemistry*. 1998;75(4):560-565.
21. Dary O, Hurrell R. Guidelines on food fortification with micronutrients. World Health Organization, Food and Agricultural Organization of the United Nations: Geneva, Switzerland; 2006:1-376.
22. De-Regil LM, Peña-Rosas JP, Laillou A, Moench-Pfanner R. Considerations for rice fortification in public health: conclusions of a technical consultation. *Annals of the New York Academy of Sciences*. 2014;1324(1):1-6.
23. Dexter PB. Rice fortification for developing countries. Fayetteville, Ark, USA: OMNI/USAID; 1998.
24. Dwyer JT, Wiemer KL, Dary O, Keen CL, King JC, Miller KB, Philbert MA, Tarasuk V, Taylor CL, Gaine PC, Jarvis AB. Fortification and health: challenges and opportunities. *Advances in nutrition*. 2015;6(1):124-131.
25. Farooq MA, Yu J. *Starches* in rice: Effects of rice variety and processing/cooking methods on their glycemic index. *Foods*. 2025;14(12):2022.
26. Fernández-Gaxiola AC, García-Guerra A, Neufeld LM. Persistent challenges of micronutrient deficiencies in Latin America need action. *Food and Nutrition Bulletin*. 2024;45(2_suppl):S7-S10.
27. Food and Agriculture Organization. The state of food insecurity in the world. Rome: FAO; 2010.
28. Gombart AF, Pierre A, Maggini S. A review of micronutrients and the immune system—working in harmony to reduce the risk of infection. *Nutrients*. 2020;12(1):236.
29. Guideline WHO. Fortification of rice with vitamins and minerals as a public health strategy. Geneva, Switzerland; 2018.
30. Han X, Ding S, Lu J, Li Y. Global, regional, and national burdens of common micronutrient deficiencies from 1990 to 2019: A secondary trend analysis based on the Global Burden of Disease 2019 study. *EClinicalMedicine*. 2022;44.
31. Junaid-ur-Rahman S, Chughtai MFJ, Khaliq A, Liaqat A, Pasha I, Ahsan S, Tanweer S, Saeed K, Siddiqi A, Mehmood T, Ali A, Aziz S, Sameed N. Rice: a potential vehicle for micronutrient fortification. *Clinical Phytoscience*. 2022;8:14.
32. Keats EC, Neufeld LM, Garrett GS, Mbuya MN, Bhutta ZA. Improved micronutrient status and health outcomes in low-and middle-income countries following large-scale fortification: evidence from a systematic review and meta-analysis. *The American journal of clinical nutrition*. 2019;109(6):1696-1708.
33. Khoury CK, Bjorkman AD, Dempewolf H, *et al*. Increasing Homogeneity in Global Food Supplies and the Implications for Food Security. *Proceedings of the National Academy of Sciences*. 2014;111(11):4001-4006.
34. Liu J, Zheng X, Khattak S, Qv Y, Wang Y, Uyanga VA, Huo Y, Liu Z, Cui Y, Chen Y, Liu Y. A systematic review of post-harvest rice fortification: Technologies, sensory characteristics, consumer acceptance, and bioavailability. *Food Chemistry*. 2025;485:144491.
35. Liu J, Zheng X, Khattak S, Qv Y, Wang Y, Uyanga VA, Huo Y, *et al*. A systematic review of post-harvest rice fortification: Technologies, sensory characteristics, consumer acceptance, and bioavailability. *Food Chemistry*. 2025;485:144491.
36. Majumder S, Datta K, Datta SK. Rice biofortification: high iron, zinc, and vitamin-A to fight against “hidden hunger”. *Agronomy*. 2019;9(12):803.
37. Martins AC, Kraemer MVDS, Rodrigues VM, Hinnig PDF, Fernandes AC, Bernardo GL, Proença RPDC, Uggioni PL. Market-driven fortification of vitamins and minerals in packaged foods targeted at children in Brazil. *Nutrition Bulletin*. 2024;49(2):209-219.
38. Nagar L, Popli H, Gupta A, Ruhela M. Food fortification to combat micronutrient deficiencies and its impact on sustainable development goals. *International Journal of Health Sciences and Research*. 2018;8(7):307.
39. Naik B, Kumar V, Rizwanuddin S, Mishra S, Kumar V, Saris PEJ, Khanduri N, Kumar A, Pandey P, Gupta AK, Khan JM. Biofortification as a solution for addressing nutrient deficiencies and malnutrition. *Heliyon*. 2024;10(9).
40. Nie M, Zhang Y, Li J, Wang A, Shan Y, Li Y, Wang L, Jeevarathinam G, Rustagi S, Blecker C, Wang F. An Overview of the Retrogradation Properties of Starch in Rice-Based Foods: Influencing Factors, Regulating Approaches and Mechanisms. *Comprehensive Reviews in Food Science and Food Safety*. 2026;25(1):e70347.
41. Olson R, Gavin-Smith B, Ferraboschi C, Kraemer K. Food fortification: the advantages, disadvantages and lessons from sight and life programs. *Nutrients*. 2021;13(4):1118.
42. Peil A, Barrett F, Rha C, Langer R. Retention of micronutrients by polymer coatings used to fortify rice. *Journal of Food Science*. 1982;47(1):260-262.
43. Pinkaew S, Wegmuller R, Hurrell R. Vitamin A stability in triple fortified extruded, artificial rice grains containing iron, zinc and vitamin A. *International Journal of Food Science and Technology*. 2012;47(10):2212-2220.

44. Pyo E, Tsang BL, Parker ME. Rice as a vehicle for micronutrient fortification: A systematic review of micronutrient retention, organoleptic properties, and consumer acceptability. *Nutrition reviews*. 2022;80(5):1062-1085.
45. Steiger G, Müller-Fischer N, Cori H, Conde-Petit B. Fortification of rice: technologies and nutrients. *Annals of the New York Academy of Sciences*. 2014;1324(1):29-39.
46. Stevens GA, Bennett JE, Hennocq Q, *et al.* Trends and Mortality Effects of Vitamin A Deficiency in Children in 138 Low-Income and Middle-Income Countries Between 1991 and 2013: A Pooled Analysis of Population-Based Surveys. *Lancet Global Health*. 2015;3(9):e528–e536.
47. Suchdev PS, Ruth LJ, Woodruff BA, Mbakaya C, Mandava U, Flores-Ayala R, Jefferds MED, Quick R. Selling Sprinkles micronutrient powder reduces anemia, iron deficiency, and vitamin A deficiency in young children in Western Kenya: a cluster-randomized controlled trial. *The American journal of clinical nutrition*. 2012;95(5):1223-1230.
48. Sule S, Okafor GI, Momoh OC, Gbaa ST, Amoyeze AO. Applications of food extrusion technology. *MOJ Food Processing & Technology*. 2024;12(1):74-84.
49. U.S. Department of Agriculture (USDA). Food Composition Tables. National Nutrient Database for Standard Reference Release 26. 2012.
50. USAID advancing food fortification opportunities to reinforce diets (AFFORD). Qualitative Spot Tests for Zinc Detection. 2025.
51. World Health Organization. Guideline: Fortification of wheat flour with vitamins and minerals as a public health strategy. World Health Organization. 2022.
52. World Health Organization. Guideline: Fortification of wheat flour with vitamins and minerals as a public health strategy. World Health Organization. 2022.
53. World Health Organization/Food and Agriculture Organization. Guidelines on food fortification with micronutrients. Geneva: WHO; 2006.
54. Yin X, Chen X, Hu J, Zhu L, Zhang H, Hong Y. Effects of distribution, structure and interactions of starch, protein and cell walls on textural formation of cooked rice: A review. *International Journal of Biological Macromolecules*. 2023;253(6):127403.
55. Xie H, Hong Y, Li L, Cheng L, Du J, Li Z, Li C, Ban X, Gu Z. Influence of structural changes of starch in starchy foods during storage on their edible quality: A review. *Carbohydrate Polymers*. 2025:124684.
56. Yılmaz A, Yılmaz H, Soydemir HE, Ciftci V. The Effect of PGPR and AMF Applications on Yield Properties and Protein Content in Soybean (*Glycine max* L.). *International Journal of Agriculture and Wildlife Science (IJAWS)*. 2022;8:108–118.
57. Zimmermann MB, Jooste PL, Pandav CS. Iodine-deficiency disorders. *The Lancet*. 2008;372(9645):1251-1262.
58. Zlotkin S, Arthur P, Schauer C, Antwi KY, Yeung G, Piekarz A. Home-fortification with iron and zinc sprinkles or iron sprinkles alone successfully treats anemia in infants and young children. *The Journal of nutrition*. 2003;133(4):1075-1080.

How to cite this article: Chetlapalli HB, R R, lekshmi PG, N C, Gopinath DP, GK B. Fortifying the staple: A review of rice fortification technologies, nutrient retention and implementation challenges. *International Journal of Agriculture and Nutrition*. 2026;8(10):24-31. doi: <https://www.doi.org/10.33545/26646064.2026.v8.i10a.765>