



Review Article

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From Polishing to Fortification: Nutrient Trade-Offs, Health Implications, and Food-System Choices in Rice-Based Diets—A Review

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To Cite This article: Loso Judijanto*, From Polishing to Fortification: Nutrient Trade-Offs, Health Implications, and Food-System Choices in Rice-Based Diets—A Review. *Am J Biomed Sci & Res.* 2026 32(4) AJBSR.MS.ID.004182, DOI: [10.34297/AJBSR.2026.32.004182](https://doi.org/10.34297/AJBSR.2026.32.004182)

Received: 📅 September 07, 2026 **Published:** 📅 October 21, 2026

Abstract

Rice milling creates an important but insufficiently integrated food-system trade-off. Removing the bran and germ improves whiteness, texture, cooking characteristics, and consumer acceptance, but simultaneously reduces dietary fibre, lipids, micronutrients, and diverse bioactive compounds concentrated in the outer grain layers. Fortification can subsequently increase selected micronutrients in polished rice, yet it does not recreate the complete nutritional and structural properties of the intact grain. This qualitative literature review synthesises evidence published primarily between 2020 and 2026 concerning rice milling, nutrient retention, brown-rice consumption, fortified rice, consumer acceptance, rice-bran utilisation, and public-health implications. The analysis develops a Nutrient Retention–Restoration–Accessibility framework that distinguishes nutrients preserved through reduced milling from nutrients restored through fortification and from nutritional benefits that depend on affordability, acceptability, and effective delivery. Evidence indicates that greater milling intensity generally reduces fibre, minerals, lipids, vitamin E, B vitamins, and phytochemicals while increasing relative starch content and often improving palatability. Brown and less-polished rice may offer metabolic advantages, although clinical evidence is heterogeneous. Conversely, fortified rice can improve delivery of iron, folate, zinc, thiamine, and vitamin B12 when formulation, blending, cooking, quality assurance, and programme implementation are adequate. The review concludes that brown rice, moderate milling, targeted fortification, biofortification, and rice-bran valorisation should be viewed as complementary options rather than mutually exclusive interventions.

Keywords: Rice milling, Brown rice, White rice, Rice bran, Nutrient retention, Fortified rice, Micronutrient fortification, Dietary fibre, Food-system nutrition, Public health

JEL Classification: I12, I18, D12, L66, Q18

Introduction

Rice occupies an exceptional position in the global food system. For billions of people, particularly in Asia, it is not simply another cereal but a daily dietary foundation. Consequently, apparently small changes in its nutrient composition, processing, availability, price, or consumption pattern can acquire population-level nutritional

significance. Modern rice markets, however, usually reward characteristics that are visible and immediately perceptible—whiteness, uniformity, gloss, softness, aroma, and cooking convenience—while many nutritionally valuable components are located in grain structures removed during the production of highly

polished white rice. This creates a basic processing dilemma: the attributes that enhance market acceptance may not be identical to those that maximise nutrient retention. The rice kernel is structurally heterogeneous. The starchy endosperm provides most of the grain's available carbohydrate, whereas the bran, aleurone, sub-aleurone tissues, and germ contain disproportionately high concentrations of dietary fibre, lipids, minerals, vitamins, phenolic compounds, phytosterols, tocopherols, tocotrienols, and γ -oryzanol. Research on rice milling therefore consistently demonstrates that degree of milling is not a purely cosmetic characteristic. As the outer tissue layers are progressively removed, the composition of the edible kernel changes substantially [18,20,24,42]. Experimental work has shown decreasing protein, lipid, fibre, minerals, vitamin E, thiamine and other nutraceutical components with increasing degree of milling, although the magnitude and sequence of change depend on variety, milling equipment, tissue structure, and measurement method.

This process should not be interpreted simplistically. White rice is not nutritionally meaningless: it remains a major source of energy, starch, and some protein. Furthermore, polishing improves storage characteristics, visual appearance, softness, cooking performance and, in many consumer groups, sensory acceptance. Gondal, *et al.*, (2021) [13], for example, found that participants generally preferred white over brown forms of comparable rice varieties, with texture, hardness, chewiness and color strongly influencing liking. More recent evidence from urban consumers in the Philippines likewise indicates that healthier rice types can be acceptable yet still be valued below premium white rice, with willingness to pay shaped by income, attitudes toward healthy eating and overall diet quality [8]. Thus, the nutritional debate cannot be separated from consumer behaviour. A product with theoretically superior nutrient composition has limited public-health value if consumers reject it, preparation is inconvenient, or deterioration during storage undermines quality. The second part of the dilemma is fortification. Once polished rice has become the dominant consumption form, staple-food fortification offers a mechanism for increasing intake of specific nutrients without requiring substantial changes in eating behaviour. Extruded or coated fortified kernels can deliver iron, folic acid, zinc, thiamine, vitamin B12 and other nutrients through a food already consumed daily. Studies demonstrate that appropriately manufactured fortified rice can retain much of its added micronutrient content through normal washing and absorption cooking, although excess-water cooking followed by decanting can produce considerable losses [17,30]. Fortified-rice programmes have also reported improvements in haemoglobin and anaemia outcomes in some populations [25].

Nevertheless, preservation of the natural grain matrix and post-processing fortification are not biologically identical strategies. Conventional fortification adds a defined set of nutrients at specified concentrations. It does not normally reconstruct dietary fibre, native lipid fractions, the physical architecture of the bran layer, the complete mineral spectrum, or the diversity of phytochemicals originally present in the intact kernel. This distinction is particularly

important when health outcomes depend not only on micronutrient concentration but also on starch accessibility, food structure, fibre fermentation, lipid composition, phytochemical interactions and satiety. The contrast becomes especially relevant because rice bran itself is increasingly understood as a nutrient-rich food resource rather than merely a milling residue. Reviews published during the present decade describe bran as a source of protein, fibre, oil, γ -oryzanol, phenolic acids, tocopherols, tocotrienols, phytosterols, polysaccharides and other functional compounds [10,36,38,41]. The major constraint is rapid hydrolytic rancidity following milling, which makes stabilisation technologies central to food-grade utilisation [21,45]. These developments suggest that the conventional binary debate—brown rice versus white rice, or natural nutrition versus fortification—is inadequate. The real food-system problem involves at least four simultaneous objectives: preserving nutrients when technologically and socially feasible, restoring micronutrients when population deficiencies warrant intervention, maintaining affordability and consumer acceptance, and recovering useful nutritional components from milling streams rather than treating them as low-value waste.

This review therefore addresses eight questions: how milling alters nutrient distribution, which compounds are most sensitive to removal of bran and germ, whether compositional differences correspond to meaningful health effects, what fortified rice can realistically restore, what it cannot restore, why consumers continue to prefer polished products, how rice bran can be valorised, and how these dimensions can be integrated into a more coherent rice-policy framework. Together, these questions shift the analysis from isolated nutrient accounting toward a food-system evaluation of processing, health, consumer acceptance, circularity and policy. The article advances a Nutrient Retention–Restoration–Accessibility (NRRRA) framework. Retention refers to keeping nutritionally valuable components within the edible grain through reduced or optimised milling. Restoration refers to adding selected nutrients after processing or increasing them through biofortification. Accessibility refers to whether nutritionally improved rice can actually be purchased, prepared, accepted, and consumed at scale. These dimensions provide a more balanced analytical foundation than treating either whole-grain preservation or fortification as universally sufficient.

Literature Review

Rice Grain Anatomy and Nutrient Topography

The nutritional effects of milling originate in the non-uniform distribution of components within the rice grain. Dehusking removes the largely inedible husk and produces brown rice, whereas subsequent milling removes varying proportions of pericarp, seed coat, nucellus, aleurone, sub-aleurone tissue and germ. The residual product increasingly consists of the starchy endosperm. Contemporary compositional research confirms that nutrients and bioactive compounds are concentrated differently across these anatomical zones [18,24,48]. Stepwise milling of pigmented rice illustrates this gradient particularly clearly. Zhang, *et al.*, (2022)

[49] separated black-rice bran into sequential fractions and found progressively declining concentrations of phenolics, flavonoids and anthocyanins from the outermost toward the innermost bran layers. Antioxidant and carbohydrate-hydrolysing-enzyme inhibitory activities followed a similar pattern. This indicates that milling does not merely reduce the quantity of “bran” as a homogeneous material, it removes biochemical compartments sequentially.

Lipids and lipid-soluble components are likewise concentrated in the bran and germ. Rice-bran oil contains unsaturated fatty acids as well as γ -oryzanol, ferulic-acid-related compounds, tocopherols, tocotrienols and phytosterols [29,39]. γ -Oryzanol has attracted interest for antioxidant, lipid-modulating and anti-inflammatory properties, although much mechanistic evidence remains experimental rather than definitive clinical proof [32]. Rice bran also contains structurally complex carbohydrates and polysaccharides. *Chen, et al.*, (2023) [7] reviewed the extraction and biological functions of rice-bran polysaccharides, while Sapwarbol, Saphyakhajorn and Astina (2021) [36] emphasised fibre, protein and γ -oryzanol among its major functional components. These compounds broaden the nutritional relevance of bran beyond vitamins and minerals. Conventional micronutrient fortification cannot be expected to recreate such a multicomponent food matrix.

Degree of Milling as a Nutritional Determinant

Degree of Milling (DOM) provides one of the clearest bridges between food engineering and nutrition. Kim, Yang and Chung (2020) [18] demonstrated that increasing DOM reduced fatty acids, vitamin E homologues, phenolics and antioxidant activity. Longvah and Prasad (2020) [24] similarly documented substantial milling-

associated nutrient losses across traditional rice landraces but also showed that absolute losses varied among genotypes. Therefore, claims of a single universal percentage loss for iron, zinc, vitamins or fibre are scientifically inappropriate. *Wang, et al.*, (2021) [42] reported that increasing milling from brown rice toward more heavily milled Simiao rice progressively reduced protein, lipid, dietary fibre, thiamine, vitamin E and niacin while increasing relative total starch and modifying pasting characteristics. Estimated glycaemic index also increased in the milled products. *Li, et al.*, (2025) [20] extended this structural interpretation by demonstrating that progressive milling removed specific outer tissue layers at different DOM thresholds, protein, lipid, dietary fibre and minerals declined while palatability improved. Importantly, the authors concluded that excessive milling produced additional nutritional loss with comparatively limited further improvement in palatability, suggesting a technological rationale for moderate milling.

A more recent commercial-milling analysis similarly found that dietary fibre and minerals decline as milling proceeds, while starch digestibility and visual appeal increase [46]. This trade-off is central to the present review because it suggests that the relevant decision is not restricted to brown rice versus fully polished rice. Intermediate products may retain portions of the aleurone and other tissues while still improving texture and cooking characteristics.

Figure 1 illustrates why milling intensity should be considered a nutritional control variable rather than simply a quality-grading operation. It also separates nutrient retention achieved by limiting outer-tissue removal from nutrient restoration achieved through downstream fortification (Figure 1).

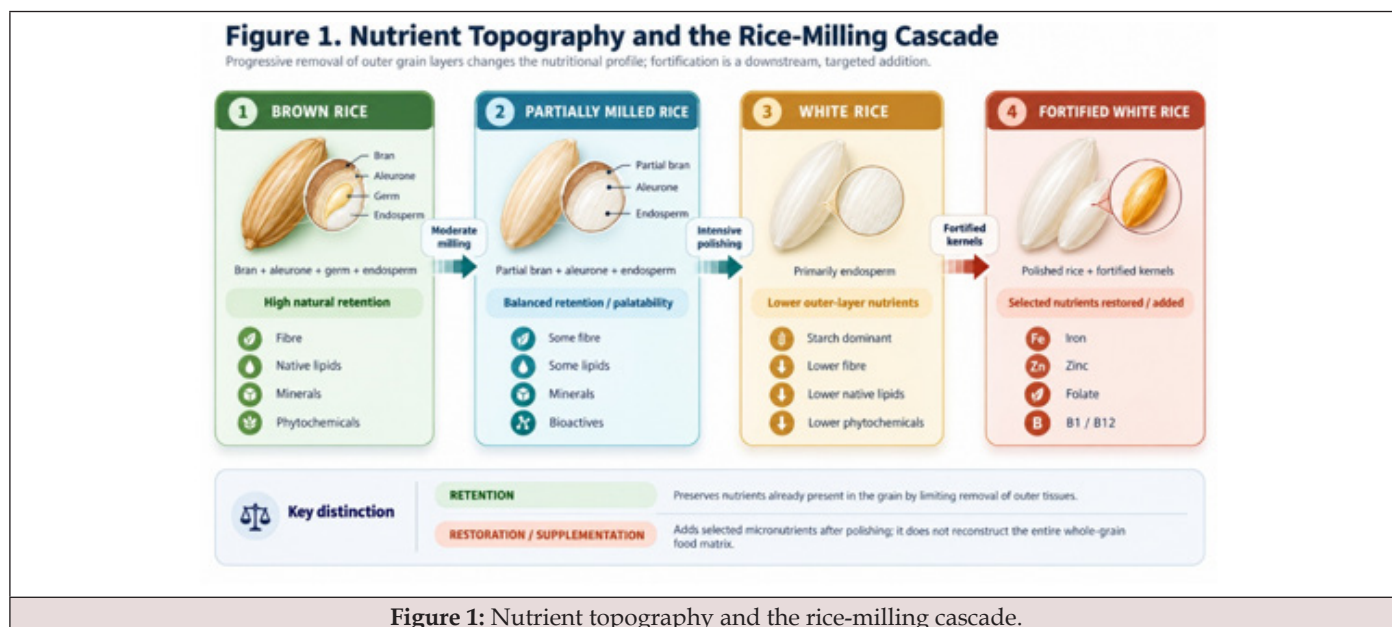


Figure 1: Nutrient topography and the rice-milling cascade.

The diagram distinguishes *removal* from *addition*. Milling progressively removes anatomical structures that contain multiple nutrients and bioactive substances simultaneously. Fortification

occurs downstream and selectively adds specified micronutrients. Consequently, fortified white rice can contain more iron, zinc or folate than the original grain while still containing less fibre, native

lipids or phytochemical diversity. This is why nutrient concentration alone cannot describe whether fortification has “restored” the intact food matrix.

Brown Rice, Digestibility and Metabolic Health

The biological consequences of consuming brown rather than white rice are plausible because fibre, lipids, phenolics and the intact physical structure can affect gastric emptying, starch accessibility, glucose absorption and microbial fermentation. However, human evidence is not uniformly conclusive. *Golzarand, et al.*, (2022) [12] synthesised randomised controlled trials comparing brown and white rice and reported reductions in body weight, body mass index and waist circumference with brown rice, but no consistent significant effects across all glycaemic and lipid outcomes. Abdul Rahim, Norhayati and Zainudin (2021) [1] similarly concluded that brown-rice interventions did not uniformly improve all markers of glycaemic control in individuals with prediabetes or type 2 diabetes. These findings caution against assuming that compositional superiority automatically translates into large clinical effects.

Yu, et al., (2022) [47], combining prospective cohorts and randomised trials, found that higher white-rice intake was associated with higher type-2-diabetes risk and brown-rice intake with lower risk in observational cohorts, however, intervention findings for cardiometabolic risk factors were inconsistent. The distinction is crucial. Cohort associations can be influenced by broader dietary patterns, socioeconomic factors, physical activity, cultural serving sizes and accompanying foods. The evidence therefore supports a prudent conclusion: replacing highly refined rice with less-refined alternatives may improve dietary quality, but white rice should not be treated as a single independent cause of diabetes. Mai, Trang and Hai (2020) [26] reported improvements in selected metabolic-syndrome outcomes after pre-germinated brown-rice consumption in a Vietnamese trial. Germination itself can modify the grain, increasing or redistributing compounds such as γ -aminobutyric acid and altering sensory characteristics [15,50]. Experimental evidence also suggests potential microbiome-related pathways, although animal studies such as *Han, et al.*, (2024) [14] should not be directly extrapolated to human clinical outcomes.

Rice Bran as a Functional Food Resource

The nutritional significance of milling cannot be evaluated without considering the fate of bran. Bran is not destroyed when polished rice is produced, it is displaced into a separate processing stream. Whether that constitutes “nutrient loss” at food-system level depends on what subsequently happens to the bran. *Spaggiari, et al.*, (2021), Eng and Mohd Rozalli (2022), Tan, Norhaizan and Chan (2023), and *Ronie, et al.*, (2024) [10,33,38,41] describe extensive opportunities to convert bran into food ingredients, dietary-fibre preparations, protein concentrates, bran oil, nutraceutical ingredients and other products. Rice-bran proteins are also being investigated as carriers for bioactive compounds [51]. Such utilisation changes the question from “are nutrients removed?” to

“are removed nutrients retained within the human food chain?”

The principal technological obstacle is rapid rancidity. Disruption of the grain during milling brings lipase and lipid substrates into contact, promoting hydrolytic deterioration. *Liao, et al.*, (2020) [21] demonstrated that hot-air-assisted radio-frequency treatment substantially suppressed enzyme activity while retaining important lipid components. Yilmaz Tuncel (2023) [45] reviewed extrusion, microwave, infrared and other approaches for rice-bran stabilisation. Green extraction technologies can then be used for recovery of oil and bioactives [11]. Recent synthesis further emphasises that stabilisation and extraction must be considered jointly because shelf-life extension, recovery of bioactive compounds and final product functionality are interdependent in food-grade rice-bran utilisation [9,32]. Fermentation provides another avenue. *Ardiansyah* (2021) [4] reviewed evidence that solid-state fermentation can enhance the value and bioactivity of rice bran, while *Sutthanut, et al.*, (2022) [40] documented prebiotic and antimicrobial properties in fermented bran extracts. *Andriani, et al.*, (2022) [3] similarly reviewed processing and extraction methods capable of increasing antioxidant availability. These findings support viewing rice bran as a secondary nutritious raw material rather than an unavoidable waste fraction.

Fortification: Restoration, Supplementation and Delivery

Rice fortification must be distinguished from both reduced milling and crop biofortification. Post-harvest fortification generally introduces micronutrients through coated or extruded fortified kernels that are blended with conventional rice. Biofortification, by contrast, raises nutrient concentration in the crop through plant breeding or agronomic strategies. *Jongstra, et al.*, (2022) [16], for example, evaluated zinc-biofortified rice among Bangladeshi preschool children, illustrating that the nutritional intervention occurs upstream of industrial post-harvest fortification. Fortification technologies have advanced considerably. *Jyrwa, et al.*, (2020) [17] showed that extruded kernels containing iron, folic acid and vitamin B12 retained substantial nutrient content under common cooking methods, however, cooking in excess water and discarding the water caused much greater nutrient losses. *Akasapu, et al.*, (2020) [2] investigated cold-plasma-assisted iron fortification, demonstrating that novel surface-modification technologies may improve iron loading and in-vitro availability. Pyo, Tsang and Parker (2022) [30] concluded from a broad systematic review that extrusion and coating can provide acceptable micronutrient retention and consumer acceptance when appropriately formulated. A 2025 systematic review similarly concluded that fortification technology strongly influences nutrient retention, sensory properties, consumer acceptance and bioavailability, reinforcing the need to evaluate process design rather than treating all fortified rice as technically equivalent (*Liu, et al.*, 2025) [23]. The distinction between *efficacy* and *food-matrix reconstruction* is therefore essential. Fortification can be highly effective at increasing selected

micronutrient concentrations without recreating fibre, intact bran structure, tocotrienol-rich oils or the spectrum of phenolics that were removed. These should not be interpreted as contradictory observations.

Method

Review Design

This study employed a Qualitative Literature Review (QLR) design. It was deliberately structured as an interpretive and thematic synthesis rather than a systematic literature review or meta-analysis. The purpose was not to generate a pooled effect size or claim exhaustive identification of every publication, but to integrate several bodies of evidence that are commonly treated separately: rice-processing science, nutritional composition, metabolic-health evidence, micronutrient fortification, consumer sensory research, rice-bran utilisation, and food-policy considerations. A qualitative approach was appropriate because the central research problem is multidisciplinary and includes outcomes that cannot be meaningfully reduced to one quantitative endpoint. For example, the percentage retention of vitamin E during milling, haemoglobin response to fortified rice, consumer liking scores, cost of fortified kernels, and stability of rice-bran oil are different forms of evidence. The analytical objective was therefore explanatory integration rather than statistical pooling.

Literature Identification

The review prioritised peer-reviewed journal literature published from 2020 through 2026. Relevant publications were identified through combinations of Scopus-, Web of Science-, PubMed-, ScienceDirect- and Google-Scholar-oriented search strategies using terms including rice milling, degree of milling, brown rice, white rice, rice bran, nutrient retention, vitamin E, dietary fibre, rice fortification, fortified rice kernel, iron-fortified rice, zinc-fortified rice, consumer acceptance, glycaemic response, rice bran stabilisation, rice bran valorisation, gamma-oryzanol, tocotrienol, and combinations of these terms. The search process was purposive and iterative. Highly relevant contemporary reviews were used to identify additional original studies. Priority was given to peer-reviewed studies that directly examined milling-induced compositional change, rice-bran composition or processing, human health outcomes, fortification technology, micronutrient retention, or consumer response.

Evidence Inclusion and Interpretation

Four principles governed interpretation. First, compositional evidence was distinguished from clinical evidence. A higher concentration of a bioactive compound does not automatically establish a disease-prevention effect. Second, animal and in-vitro studies were used to clarify plausible mechanisms but not to make direct human-health claims. For example, *Saji, et al., (2020) [35]* demonstrated effects of rice-bran phenolic extracts on pancreatic β -cell-related gene expression in experimental systems, whereas

Zou, et al., (2020) [54] investigated obesity-related mechanisms in mice. These findings inform biological plausibility but are not substitutes for human trials. Third, association was distinguished from causality. Observational associations between white-rice consumption and type 2 diabetes were interpreted alongside randomised intervention evidence rather than treated as definitive causal proof [47]. Fourth, technological efficacy was distinguished from programme effectiveness. A fortified kernel may retain nutrients under controlled conditions but still fail to produce population benefit if blending, storage, distribution, labelling, cooking practices or compliance are inadequate.

Thematic Coding

Evidence was synthesised across eight themes: nutrient gradients within the rice kernel, milling intensity and nutrient retention, metabolic implications of whole versus polished rice, effectiveness and limitations of fortification, consumer acceptance and sensory constraints, bran stabilisation and valorisation, affordability, quality assurance and public-health equity, and integrated rice-system strategies. These themes were subsequently organised within the Nutrient Retention–Restoration–Accessibility framework so that potentially competing interventions could be interpreted as complementary options serving different nutritional purposes.

Results: Thematic Findings

Theme 1: Milling Produces a Nutrient-Retention Gradient

The strongest and most consistent finding across the literature is that increasing rice-milling intensity alters nutritional composition directionally. Removal of outer grain layers reduces lipid, dietary fibre, minerals and several vitamins while increasing the relative dominance of starch. The exact percentage change varies considerably among studies, demonstrating why universal loss percentages should be avoided. *Kim, Yang and Chung (2020) [18]* found significant declines in vitamin E homologues, fatty acids, phenolics and antioxidant activity with increasing DOM. *Longvah and Prasad (2020) [24]* showed substantial but genotype-dependent nutrient losses among landraces. *Wang, et al., (2021) [42]* recorded declines in protein, lipid, fibre, vitamin B1, vitamin E and niacin, while *Li, et al., (2025) [20]* linked specific structural removal of pericarp, seed-coat/nucellus and aleurone tissues to compositional change. These observations establish milling as a controllable nutritional variable rather than an all-or-nothing transformation. This gradient also has implications for digestibility. Removing structural barriers and fibre generally increases starch accessibility, potentially raising the rate of digestion. However, the impact on actual postprandial glucose response depends on rice variety, amylose content, cooking, cooling, serving size and meal composition. Therefore, degree of milling should be treated as one determinant within a larger glycaemic system rather than as an independent metabolic switch.

Theme 2: Nutritional Value Is Concentrated Disproportionately in the Bran Fraction

Rice bran contains an unusually dense combination of fibre, oil, protein and phytochemicals relative to its contribution to total grain weight. Contemporary reviews consistently identify γ -oryzanol, tocopherols, tocotrienols, phytosterols, phenolic acids, rice-bran polysaccharides and unsaturated fatty acids as nutritionally relevant components [7,10,29,31]. Lipidomic research reinforces the complexity of this fraction. Santos, *et al.*, (2023) identified phospholipids, glycolipids and oxylipins in rice bran and investigated changes associated with consumption among hypercholesterolaemic children. Liu, *et al.*, (2024) [22] further showed dynamic changes in functional lipid molecular species during storage, emphasising that nutritional potential depends on post-milling handling. Rice-bran benefits should nevertheless be interpreted cautiously. Many claims regarding anticancer, neuroprotective, antidiabetic or immunomodulatory effects originate from mechanistic, cell or animal studies. Reviews such as Sapwarabol, Saphyakhajorn and Astina (2021), Sivamaruthi, *et al.*, (2023), and Kodape, Kodape and Desai (2025) [19,36,37] demonstrate broad biological interest, but the strength of human evidence varies substantially across endpoints. The nutritionally defensible conclusion is therefore that bran supplies compounds with plausible functional significance, not that consuming bran inevitably prevents particular diseases.

Theme 3: Brown Rice and White Rice Differ Metabolically, but Evidence Is Heterogeneous

Brown rice preserves outer-grain structures that alter nutrient density and potentially slow carbohydrate digestion. Meta-analyses nevertheless produce more nuanced findings than common public-health messaging. Golzarand, *et al.*, (2022) [12] reported favourable effects on selected adiposity measures but inconsistent lipid and glycaemic effects. Abdul Rahim, Norhayati and Zainudin (2021) [1] found no universal improvement across metabolic markers. Yu, *et al.*, (2022) [47] observed a higher risk of type 2 diabetes associated with higher white-rice intake and an inverse association for brown rice in cohort evidence, but randomised substitution trials provided less consistent cardiometabolic results. This inconsistency has at least four explanations. First, “brown rice” encompasses cultivars with different starch structures and phenolic profiles. Second, participants may differ in baseline metabolic status. Third, intervention duration is often relatively short. Fourth, replacement of white rice with brown rice may alter not

only fibre and micronutrients but also total energy intake, satiety and accompanying foods. Consequently, the evidence supports greater dietary diversification and whole-grain inclusion but does not justify portraying white rice itself as metabolically toxic. The more defensible public-health interpretation is comparative: highly polished rice generally provides less fibre and fewer micronutrients and phytochemicals than less-polished rice, and high habitual intake may be problematic when embedded within diets already characterised by low fibre and high glycaemic load.

Theme 4: Fortification Can Effectively Restore Selected Micronutrients

Fortification is most defensible when evaluated against the problem it is designed to solve: inadequacy of selected micronutrients in populations that consume large amounts of rice. Contemporary evidence also shows that technological choices alter retention, sensory performance and bioavailability, making formulation and process control central to programme effectiveness [17,23,30] demonstrated substantial retention of iron in extruded fortified rice during rinsing and absorption cooking, while folate and vitamin B12 retention was lower but still meaningful. Decanting excess cooking water substantially increased losses. Pyo, Tsang and Parker (2022) [30] concluded that both extrusion and coating can yield acceptable retention and organoleptic characteristics, with formulation strongly influencing performance. Human programme evidence also demonstrates potential benefit. Mahapatra, *et al.*, (2021) [25] reported that a multi-micronutrient fortified-rice intervention among schoolchildren increased mean haemoglobin, reduced anaemia prevalence and improved cognitive scores relative to comparison conditions. This does not imply that fortified rice always produces such effects, but it demonstrates why fortification cannot reasonably be dismissed as nutritionally meaningless. Akasapu, *et al.*, (2020) [2] showed that innovative cold-plasma treatment could facilitate iron fortification and improve in-vitro iron availability. Emerging technological pathways therefore extend beyond conventional coating and extrusion. At the same time, technological sophistication creates greater requirements for quality assurance, dosage control, blending uniformity and regulatory enforcement.

Figure 2 compares the nutritional domains addressed by nutrient preservation and conventional rice fortification. The matrix clarifies which components are retained by less intensive milling, which are reduced during polishing, and which can be selectively restored or added through fortification (Figure 2).

Figure 2. Nutrient Retention–Restoration Matrix

Different rice strategies preserve, reduce, or add different nutritional components.

Nutritional component	 Brown / less-polished rice	 Polished white rice	 Fortified polished rice
Dietary fibre	✓ High relative retention	↓ Reduced	– Usually not restored
Native lipids	✓ Retained	↓ Strongly reduced	– Usually not restored
Vitamin E / tocotrienols	✓ Better retained	↓ Reduced	– Rarely targeted
Phenolic compounds	✓ Better retained	↓ Reduced	– Not normally restored
γ-Oryzanol	✓ Bran-associated	↓ Strongly reduced	– Not normally restored
Iron	✓ Native level retained	↓ Often reduced	+ Can be substantially increased
Zinc	✓ Native level retained	↓ Often reduced	+ Can be substantially increased
Folic acid	– Native level	↓ Reduced	+ Can be added
Thiamine (B1)	✓ Better retained	↓ Reduced	+ Can be added
Vitamin B12	↓ Naturally negligible	↓ Negligible	+ Can be intentionally added
Starch	– Present	⬆ Dominant fraction	⬆ Dominant fraction remains
Palatability	🕒 Variable	✓ Generally high	🕒 Similar to white rice if well formulated

How to read the matrix
 Retained / better retained
 Reduced by polishing
 Added / increased by fortification
 Not normally restored / targeted
 Variable / context dependent

Figure 2: Nutrient Retention–Restoration Matrix.

The figure demonstrates why “fortification versus brown rice” is a false dichotomy. Less-polished rice is primarily a retention strategy, whereas fortified rice is primarily a targeted restoration or supplementation strategy. Both can be rational simultaneously. For instance, fortification can introduce vitamin B12, which rice does not naturally provide in nutritionally meaningful amounts, while moderate milling can preserve fibre and bran-associated bioactives that conventional fortification does not replace.

Theme 5: Consumer Acceptance Is a Binding Constraint

Nutritional recommendations that ignore sensory preference are unlikely to achieve population-scale impact. Gondal, *et al.*, (2021) [13] found white rice more highly liked than corresponding brown varieties, with hardness and chewiness particularly important determinants. Brown rice also has longer cooked requirements and can develop off-flavours through lipid oxidation. In addition, a 2025 willingness-to-pay study found that consumers could accept brown, coloured and low-glycaemic-index rice while still discounting these products relative to premium white rice, showing that nutritional messaging alone may be insufficient to change purchasing behaviour [5,6,8] showed that germination and wet-milling technologies can modify brown-rice processing characteristics and provide value-added product opportunities, while Zhou, *et al.*, (2021) [51] demonstrated that germination changes both metabolite and volatile profiles. Such research illustrates that acceptance barriers are technological problems that can potentially be engineered rather than fixed cultural constraints.

Moderate milling may be particularly important. Li, *et al.*, (2025) [20] observed that palatability improves with milling, but nutritional deterioration continues beyond the point at which large sensory gains are obtained. This creates a potential optimisation zone in which parts of the aleurone layer remain while cooking quality approaches that of more heavily polished rice.

Theme 6: Rice-Bran Valorisation Can Recover Displaced Nutritional Value

The environmental and nutritional implications of polishing depend substantially on the downstream use of bran. If nutritionally dense bran is diverted entirely to low-value applications, the human food system loses a potentially useful source of fibre, oil, protein and bioactives. If it is rapidly stabilised and incorporated into safe foods, oils or functional ingredients, much of that value can remain within the food economy. Yadav, *et al.*, (2024) [44] reviewed the use of extrusion to incorporate rice bran into products including noodles, bread, pasta, biscuits and meat analogues. Nidhishree, *et al.*, (2024) [28] examined broader value-added applications, and Zolqadri, *et al.*, (2023) [52] described rice-bran protein as an emerging material for delivery systems. Ronie, *et al.*, (2024) [33] similarly emphasised the food and non-food applications of bran while identifying rancidity, antinutrients and potential contaminant exposure as limitations requiring management. Recent reviews extend this perspective by highlighting integrated stabilisation, extraction and rice-bran-oil valorisation pathways that can improve recovery of nutrients and minor bioactive compounds while

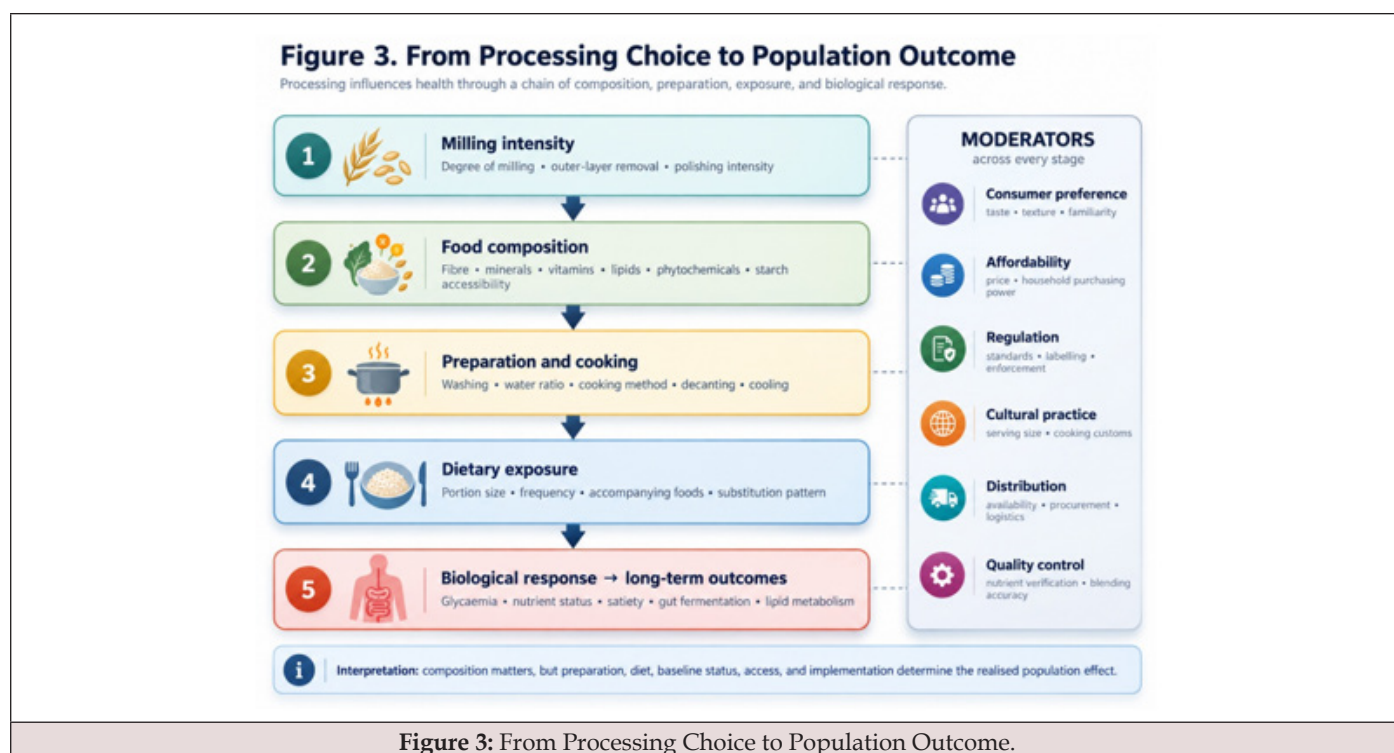
supporting higher-value applications [9,32]. The circular-economy interpretation should not be romanticised. Stabilisation requires energy and infrastructure, extraction can require solvents or other inputs, and bran quality varies. However, these challenges favour technological optimisation rather than treating bran as inherently unsuitable for food use.

Theme 7: Food Policy Must Distinguish Product Standards from Health Claims

The Indonesian context illustrates the importance of quality assurance. SNI 9372:2025 establishes fortified-rice requirements, and contemporary Indonesian oversight specifies fortification targets including vitamin B1, folic acid, vitamin B12, iron and zinc. In 2026, Bapanas reported substantial inconsistencies among some products marketed with fortification-related claims and intensified laboratory and market oversight. Official information also indicates that price premiums observed in parts of the market were much greater than the estimated incremental production cost of fortification. This development requires analytical care. Evidence

of non-compliant products is not evidence that the nutritional principle of fortification is invalid. It is evidence that standards, truthful labelling, laboratory verification and enforcement matter. A scientifically defensible policy critique should therefore distinguish between (1) fortification as a nutritional technology and (2) potentially misleading marketing or non-compliant implementation. Similar ethical questions have been discussed internationally. *Muralidharan, et al., (2024) [27]*, analysing mandatory fortified-rice policy in India, questioned the balance of benefits, risks, evidence and resource requirements. Their argument demonstrates that large-scale mandatory fortification requires surveillance of actual deficiency patterns, cumulative exposure from multiple interventions, potential excess intake, programme cost and transparency.

Figure 3 integrates the pathways through which rice processing may ultimately influence health outcomes. It explicitly shows that composition is only the first step in a chain moderated by preparation, dietary exposure, affordability, regulation, distribution, cultural practice and quality control (Figure 3).



The model explains why simple causal statements such as “white rice causes diabetes” or “fortified rice prevents anaemia” are inadequate without contextual qualification. Processing changes composition, but downstream cooking, dietary pattern, baseline nutritional status and implementation determine the realised biological outcome.

Theme 8: No Single Rice Product Solves Every Nutritional Problem

The evidence ultimately undermines the search for a single universally optimal rice product. Brown rice maximises preservation of the intact grain but may be less acceptable to some consumers and presents storage challenges, whereas moderately

milled rice offers a potential compromise between nutrient retention and palatability. Fortified white rice can deliver selected micronutrients to populations already consuming polished rice, but it does not reconstruct the whole-grain matrix. Biofortified rice increases intrinsic concentrations of selected nutrients but may require long breeding, seed-system and adoption pathways. Rice-bran valorisation, by contrast, recovers nutritional value after milling but requires stabilisation, manufacturing capacity and market development. These approaches are therefore better understood as components of a portfolio strategy than as mutually exclusive solutions.

Discussion and Analysis

Reframing the “Remove and Add Back” Argument

The intuitive criticism of polished-and-fortified rice is compelling: why remove nutrient-rich tissues and then pay to add nutrients back? The argument correctly identifies a processing inefficiency when nutritionally valuable components are removed unnecessarily. It also draws attention to the cultural construction of whiteness as a quality attribute and to the possibility that processing decisions favour visual and sensory characteristics over nutrient density. However, the argument becomes scientifically incomplete when it assumes that fortification merely replaces nutrients that were originally present. Vitamin B12 provides the clearest counterexample: rice is not naturally an important source, yet fortification can introduce it deliberately. Iron and zinc may also be added at levels exceeding those of the original grain when public-health objectives justify such concentrations. Fortification can therefore perform a supplementation function, not merely restoration. Conversely, the pro-fortification argument becomes incomplete if an increase in five micronutrients is treated as nutritionally equivalent to the whole grain. Fibre, native oils, food structure and phytochemical diversity are not interchangeable with iron, folate, zinc, thiamine and vitamin B12. These sets of nutritional attributes solve different problems. Accordingly, the key analytical distinction is that retention prevents avoidable nutritional displacement, whereas fortification targets specific nutritional inadequacies. These functions overlap only partially because preservation retains the original food matrix while fortification selectively changes nutrient composition. Public policy therefore does not have to choose exclusively between them.

Nutritional Efficiency versus Processing Efficiency

Industrial milling is often evaluated in terms of head-rice yield, throughput, breakage, whiteness, market grade and storage performance. Nutritional efficiency adds another criterion: how much useful nutritional value remains in forms consumed by humans after processing. A milling system can therefore be technologically efficient but nutritionally inefficient if it produces highly attractive rice while diverting nutrient-rich fractions away from human consumption. Conversely, a system that retains excessive bran without solving rancidity or acceptance problems

may preserve nutrients in theory but fail commercially.

The optimal outcome is likely context dependent. In markets where consumers readily accept brown rice, retaining the full bran layer may be practical. In markets strongly oriented toward soft white rice, moderate milling may achieve greater population benefit than an idealised whole-grain campaign with low uptake.

This interpretation is supported by contemporary DOM research. Nutritional losses are frequently greatest during early outer-layer removal, but sensory improvements do not necessarily increase proportionally throughout the entire milling range. *Li, et al.*, (2025) [20] specifically suggested that retaining portions of aleurone can preserve nutritional value while maintaining favourable cooking quality.

Fortification Should Be Judged by Appropriate Outcomes

Fortification should be assessed against clear endpoints: micronutrient concentration, stability, retention after cooking, bioavailability, population intake, biomarkers of status, deficiency prevalence and programme cost-effectiveness. These outcomes are technology-sensitive, and recent synthesis confirms that extrusion, coating, dusting, soaking, parboiling and emerging methods differ materially in sensory characteristics, nutrient stability and bioavailability [17,23] demonstrate why preparation practices matter. High iron retention under absorption cooking did not guarantee similar retention when water was discarded. Pyo, Tsang and Parker (2022) [30] similarly identified cooking method and fortificant chemistry as important determinants. Thus, fortification policy must include consumer preparation behaviour rather than assuming the nutrient concentration measured in uncooked grain equals the dose consumed. *Mahapatra, et al.*, (2021) [25] provides evidence that programme delivery can produce measurable outcomes, but *Muralidharan, et al.*, (2024) [27] reminds policymakers that mandatory interventions should also consider baseline exposure, simultaneous supplementation, uncertainty and risk. These positions are not mutually exclusive. They reflect the distinction between demonstrating potential efficacy and deciding whether, where and how a programme should be implemented.

The Missing Middle: Moderately Milled Rice

Public discourse tends to divide rice into brown and white forms, but contemporary milling research suggests that intermediate products deserve much more attention. Treating degree of milling as a continuum instead of a binary classification makes it possible to search for technically and nutritionally efficient intermediate products. Moderate milling can retain parts of bran or aleurone while removing outer tissues responsible for some of the hardness, pigmentation and storage instability associated with brown rice. This creates a continuum rather than a binary choice. The appropriate degree could potentially be optimised for specific cultivars through simultaneous measurement of nutrient retention, cooking time, sensory acceptance, glycaemic response,

storage stability and milling economics. A policy promoting only brown rice could therefore miss a potentially larger behavioural opportunity. If a moderately milled product preserves a meaningful proportion of fibre, minerals and bioactives while receiving consumer acceptance close to white rice, its population-level nutritional contribution may exceed that of a nutritionally superior product consumed by only a small minority. Research by Wang, *et al.*, (2021), Kim, Yang and Chung (2020), Longvah and Prasad (2020) and Li, *et al.*, (2025) [18,20,25,43] collectively provides a basis for cultivar-specific optimisation rather than one universal milling threshold. This evidence supports optimisation approaches that integrate anatomical layer retention, cooking quality and sensory performance rather than relying on whiteness alone as the principal milling target.

Consumer Preference Is Part of Nutrition Science

The common separation between sensory science and public-health nutrition is artificial. Food that is nutritionally optimal but rarely eaten cannot deliver its theoretical benefits. Gondal, *et al.*, (2021) [13] showed the importance of texture and colour in rice acceptance. This implies several intervention possibilities: breeding brown or intermediate rice with softer textures, improved hydration and cooking technologies, germination, parboiling, consumer education, and gradual rather than abrupt transitions in degree of milling. Consumer communication should also be designed carefully. Presenting white rice as “empty” or unhealthy may be counterproductive, culturally insensitive and scientifically inaccurate. A better communication strategy explains the trade-off: less-polished rice retains more fibre and several nutrients, whereas fortified products provide specific added micronutrients.

Rice Bran Changes the Food-System Accounting

If bran removed during milling becomes nutritious food, bran oil, fibre concentrate or therapeutic food ingredient, the meaning of “nutrient loss” changes. Nutrients have moved rather than disappeared. The relevant indicator should therefore be human-food nutrient recovery: what proportion of nutrient-rich milling fractions ultimately returns to human diets in safe, acceptable and affordable products? Such a metric would distinguish true nutritional losses from transfers into side streams that are subsequently stabilised and returned to human diets. Rice-bran research is increasingly compatible with such a metric. Spaggiari, *et al.*, (2021), Tan, Norhaizan and Chan (2023), Yilmaz Tuncel (2023), Zolqadri, *et al.*, (2023), Yadav, *et al.*, (2024), Nidhishree, *et al.*, (2024), Ronie, *et al.*, (2024) and Kodape, Kodape and Desai (2025) [19,29,34,39,42,45,46,53] collectively document growing technical opportunities for extraction, stabilisation, fermentation, extrusion and functional-food development. Bran use may also have targeted nutrition applications. Weber, *et al.*, (2023) [44] described a trial protocol in Indonesia investigating rice bran in ready-to-use therapeutic foods for severe acute malnutrition, demonstrating that the ingredient is already moving beyond conventional cereal

by-product applications into clinical-nutrition research.

Food Equity: Who Can Access Which Rice?

Nutrition policy cannot assume that every household has equal choice. Brown rice, speciality fortified rice and premium functional products may have different retail prices and distribution channels. Public programmes, by contrast, can deliver fortified staples at scale but depend heavily on procurement standards and quality control. Recent Indonesian experience demonstrates both sides of this equation. Fortification has a legitimate nutritional rationale, but official 2026 investigations reported products with claims, prices or measured nutrient contents that did not always correspond to applicable standards. Bapanas reported that the estimated additional production cost attributable to proper fortification was around Rp1,000/kg, while some observed products carried substantially greater retail premiums. This means the consumer-protection issue should not be framed as evidence against fortification itself. The policy response is stronger verification of product claims, transparent pricing, laboratory testing, traceability, enforcement and public reporting. A fair rice-nutrition strategy should also avoid creating a two-tier system in which nutrient-dense or correctly fortified products are available primarily to affluent consumers while vulnerable households continue to rely on lower-quality alternatives. Public procurement can help prevent this by specifying measurable nutritional standards rather than marketing categories.

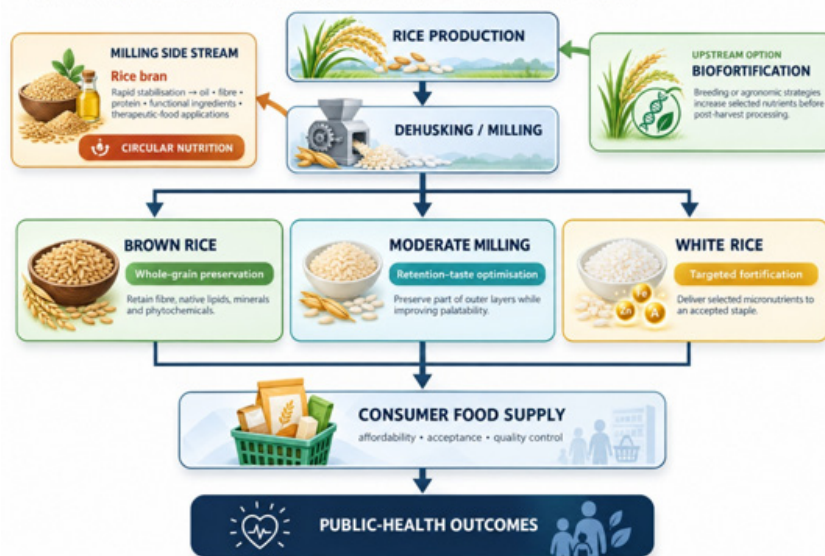
Towards an Integrated Rice Strategy

The findings support a portfolio model consisting of six mutually reinforcing interventions. First, nutritionally unnecessary over-milling should be avoided where consumer acceptance can be maintained at lower degrees of milling, and moderately milled rice should be developed as a mainstream rather than a niche category. Second, targeted fortification should be retained where population micronutrient deficiencies, dietary patterns and programme evaluation justify its use, while biofortified cultivars should be considered when crop-based nutrient enhancement is agronomically and economically suitable. Third, a rice-bran food-value chain should be strengthened through rapid stabilisation, safe storage, oil extraction, protein and fibre ingredients, fermentation and functional-food applications. Fourth, consumer information and quality assurance should be strengthened so that claims such as “fortified,” “whole grain,” “high fibre,” or “premium” correspond to measurable product characteristics. Together, these interventions connect processing decisions to both nutritional outcomes and market credibility.

Figure 4 summarises the proposed integrated policy model derived from the review. The figure positions brown rice, moderate milling, targeted fortification, biofortification and rice-bran circularity within a common value chain that converges on consumer access and public-health outcomes (Figure 4).

Figure 4. Integrated Nutrition-Sensitive Rice System

A portfolio strategy combines nutrient preservation, targeted restoration, consumer access, and circular recovery.

**Figure 4: Integrated Nutrition-Sensitive Rice System.**

The proposed strategy rejects the assumption that every consumer must receive the same form of rice. Instead, it seeks to maximise nutritional benefit across heterogeneous preferences and needs. Preservation, moderate milling, fortification and bran valorisation operate at different points of the value chain and can therefore be implemented simultaneously.

Proposed Nutrient Retention–Restoration–Accessibility Framework

The NRR framework can be summarised through three linked questions that correspond to retention, restoration and accessibility. Considering the three dimensions together prevents a technically successful intervention from being interpreted as nutritionally effective when it fails at the consumer or implementation level. Retention asks what can reasonably be kept within the edible grain. This dimension concerns fibre, minerals, vitamins, lipids and phytochemicals that can remain through limiting unnecessary removal, with degree-of-milling studies providing the empirical basis. Restoration asks what should be added when population intake is inadequate. This dimension includes conventional fortification and, where relevant, biofortification, while the choice of nutrient and dose should reflect nutritional surveillance rather than marketing opportunity. Accessibility asks whether the nutritionally improved product will actually be consumed. This dimension includes affordability, cooking convenience, sensory acceptance, distribution, cultural preference, public procurement and regulatory credibility. A rice intervention is therefore nutritionally effective only when all three dimensions are considered. Nutrient-rich brown rice with negligible consumer adoption fails accessibility. Cheap polished rice fails retention

when excessive milling unnecessarily removes useful nutrients. Poorly manufactured fortified rice fails restoration despite a strong theoretical rationale.

Conclusion and Recommendations

Rice processing involves a genuine nutritional trade-off. The evidence synthesised in this qualitative literature review demonstrates that increasing degree of milling generally reduces dietary fibre, lipids, minerals, several vitamins and diverse bioactive compounds because these components are concentrated disproportionately in the outer rice tissues and germ. Highly polished rice should therefore not be considered nutritionally equivalent to the intact grain merely because both provide similar caloric energy.

At the same time, the evidence does not support a simplistic rejection of rice fortification. Properly formulated fortified rice can increase the intake of selected micronutrients and has produced measurable improvements in nutritional outcomes in some programme contexts. Fortification is especially valuable because it can use an established staple-food distribution system and can deliver nutrients, such as vitamin B12, that are not naturally supplied by rice in useful amounts. The central distinction is that fortification and whole-grain preservation perform different nutritional functions. The first selectively adds or increases defined micronutrients, the second preserves the fibre, food structure, native lipids, minerals and phytochemicals already present in the grain. One cannot completely substitute for the other. The literature also indicates that the conventional brown-rice versus white-rice dichotomy is unnecessarily restrictive. Moderate milling deserves greater scientific and commercial attention because it may preserve

meaningful proportions of nutritionally valuable outer tissues while delivering sensory properties much closer to those expected by consumers of polished rice.

A further shift is required in how rice bran is conceptualised. Bran should increasingly be treated as a secondary food resource rather than simply a waste product. Rapid stabilisation and appropriate processing can enable its conversion into oil, fibre, protein, fermented ingredients and functional foods, thereby returning displaced nutrients to the human food chain and improving circularity in rice processing.

Based on the synthesis, seven recommendations are proposed. First, rice-quality systems should include nutrient retention alongside whiteness, head-rice yield and visual appearance when evaluating milling performance. Second, research and industry should establish cultivar-specific optimal degrees of moderate milling that jointly evaluate nutrient retention, cooking quality, sensory acceptance and storage stability. Third, fortified-rice programmes should remain targeted to documented nutritional needs and should incorporate rigorous monitoring of nutrient content, blending uniformity, storage, cooking retention and biological outcomes. Fourth, fortification claims should be supported by independent laboratory verification and transparent labelling, and market premiums should be explicable through genuine product quality rather than terminology alone. Fifth, governments and food industries should support scalable rice-bran stabilisation and food-grade valorisation so that nutritionally valuable material removed during milling is not unnecessarily diverted away from human nutrition. Sixth, consumer communication should explain the advantages and limitations of brown, moderately milled, polished and fortified rice without portraying any single product as universally appropriate. Finally, future rice policy should integrate agriculture, food processing, nutrition, consumer behaviour, public health, industrial development and circular-economy objectives. The resulting principle can be stated succinctly, but it should be understood as a system-level rather than a product-level recommendation. Preserve what can reasonably be preserved, fortify what populations genuinely need, recover what processing displaces, and design every intervention around what consumers can realistically access and accept.

Acknowledgement

None.

Conflict of Interest

None.

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