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Systematic Review Article

Determinants of Zinc (Zn) Bioavailability in Rice (*Oryza sativa*): A Systematic Literature Review

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ABSTRACT

This study systematically reviews the determinants of Zinc (Zn) bioavailability in rice (*Oryza sativa*) and evaluates strategies to improve its nutritional contribution. A PRISMA-based systematic literature review was conducted using Scopus, PubMed, SINTA, and Garuda databases. From 768 identified publications, 14 studies met the inclusion criteria and were analyzed. Quantitative evidence from the reviewed studies shows that disrupting phytic acid via genetic mutation increases Zn bioavailability by 1.8- to 2.2-fold, while reducing phytate by >50% through milling or cooking linearly enhances free Zn release by 15–25%. Biofortification strategies could increase Zn content, but their nutritional impact depended on simultaneous reduction of antinutritional factors. Overall, improving Zn bioavailability in rice requires an integrated approach involving genetic improvement, optimized processing techniques, and agronomic strategies to enhance the nutritional quality of rice-based diets.

INTRODUCTION

Zinc (Zn) deficiency is a critical global public health problem that severely affects physiological functions, immune systems, and physical growth, with approximately 17.3% to one-third of the world's population at risk of this micronutrient deficiency (Wessells & Brown 2012). This condition has widespread health impacts, ranging from causing childhood growth retardation (stunting) to causing a significant decline in immune function . Given that the human body lacks a specialized long-term storage system for Zn, meeting the daily requirement for this mineral depends heavily on continuous dietary intake (King *et al.* 2016). Consequently, the risk of deficiency surges sharply in populations whose staple diets are dominated by plant-based foods with low or poorly absorbable Zn content (Kumssa *et al.* 2015).

As one of the world's primary staple foods, rice (*Oryza sativa*) is consumed by more than half of the global population, particularly in Asia where this commodity contributes up to 70% of daily caloric intake (FAO 2017). Rice serves not only as an energy source due to its high carbohydrate content (±70–80% dry weight), but also as a source of essential micronutrients (Juliano 1993). In addition to starch, rice contains various vital minerals such as Iron (Fe), Zinc (Zn), Magnesium (Mg), Calcium (Ca), Phosphorus (P), and Manganese (Mn), which play crucial roles in enzymatic functions, metabolic regulation, the immune system, as well as cell growth and differentiation (Welch & Graham 2004). For populations with a high dependence on this single staple food, the mineral contribution from rice is highly strategic for public nutritional status (Welch & Graham 2004). However, the high consumption of rice without dietary diversification in Asia ironically triggers a high risk of chronic Zn deficiency and hidden hunger.

Bioaccessibility and bioavailability are two sequential and interdependent concepts that determine the efficiency of nutrient utilization within the human body (Kumar *et al.* 2022). Bioaccessibility refers to the fraction of a nutrient released from the food matrix during digestion, making it available for absorption, whereas bioavailability encompasses a broader scope, measuring the proportion of that nutrient that is successfully absorbed through the intestinal wall and enters systemic circulation to be utilized for physiological functions (Kumar *et al.* 2021a). The relationship between the two is highly conditional, as bioaccessibility serves as a strict prerequisite for bioavailability (Kumar *et al.* 2023). However, a high rate of bioaccessibility does not automatically guarantee high bioavailability, since the dissolved nutrients must still navigate cellular transport efficiency, first-pass metabolism, and antagonistic mineral interactions within the body (Kumar *et al.* 2022).

The total mineral content in rice does not directly represent its biological benefits. A more decisive aspect is bioavailability, which is the fraction of minerals that can be released from the food matrix, absorbed through the intestinal mucosa, and utilized in the body's physiological processes (Gibson 2007). Zn is an essential mineral that plays a role in more than 300 enzyme systems, protein synthesis, gene expression regulation, and immune function (Prasad 2013). Zn deficiency remains a global public health problem, especially in developing countries with cereal-based diets (Brown *et al.* 2001).

The low bioavailability of Zn in rice is primarily caused by the presence of antinutritional compounds, particularly phytic acid (myo-inositol 1,2,3,4,5,6-hexakisphosphate), which naturally accumulates in the aleurone and bran layers (Iqbal *et al.* 2005). Serving as the main storage form of phosphorus in plants, this compound acts as a major antinutrient for humans due to its highly potent negative charge affinity toward positively charged divalent minerals such as Zn^{2+} and Fe^{2+} (Kumar *et al.* 2022). Phytic acid aggressively binds these minerals within the human gastrointestinal tract, forming insoluble phytate-mineral complexes that are resistant to digestive enzymes and extremely difficult to absorb (Hurrell & Egli 2010). Consequently, high concentrations of phytic acid drastically reduce Zn bioaccessibility in the small intestine. Although the milling process used to produce white rice can successfully lower phytic acid levels, this mechanical practice simultaneously and drastically reduces the total Zn content, given that the majority of this essential mineral is concentrated within the eroded outer layers of the grain (Iqbal *et al.* 2005)

The factors influencing Zn bioavailability in rice can be systematically categorized into intrinsic and extrinsic factors. Intrinsic factors stem from the internal characteristics of the plant, encompassing the rice variety, grain structure, spatial distribution of Zn, phytic acid content, starch matrix, and specific protein-mineral interactions within the grain. Conversely, extrinsic factors involve external environmental influences and post-harvest interventions, including soil Zn availability, agronomic practices during cultivation, and various food processing methods such as milling, soaking, fermentation, parboiling, and cooking techniques (Welch & Graham 2004). Various strategies have been developed to increase the Zn content and bioavailability in rice, including conventional biofortification, genetic engineering, and Zn-based fertilization (agronomic biofortification) (Bouis & Saltzman 2017).

Although previous reviews such as Gibson (2007) have mapped the general factors influencing mineral absorption, most studies remain limited to testing linear approach models without addressing the absorption paradox in biofortified crops. This Systematic Literature Review (SLR) fills this critical knowledge gap by investigating a novel hypothesis: whether crops with a high baseline Zn content paradoxically result in low bioaccessibility and substantially lower bioavailability. Furthermore, while numerous studies report the total Zn content in rice, very few comprehensively integrate Zn bioaccessibility, the phytate molar ratio, processing effects, and biological validation simultaneously. Therefore, the novelty of this SLR lies in the synthesis of multi-study data to uncover whether increased Zn accumulation specifically in rice mechanically triggers a synchronous increase in phytic acid levels, which ultimately limits the efficiency of mineral release and absorption within the gastrointestinal tract. Through this integrative approach, our SLR can establish a new rationale for predicting the actual efficacy of Zn bioaccessibility and bioavailability. Therefore, there is a gap in research underlying the Systematic Literature Review (SLR) entitled s "Determinat of Zinc (Zn) Bioavailability in Rice (*Oryza sativa*): A Systematic Literatur Review," .

METHODS

Design, location and time

This study employed a Systematic Literature Review (SLR) approach structured in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure transparency and reproducibility in the literature selection process. The design aimed to identify, evaluate, and synthesize scientific evidence related to the determinants of Zn bioavailability in rice (*Oryza sativa*) comprehensively. The literature search was conducted online from September 23, 2025, to December 16, 2025 using four major databases, namely Scopus, PubMed, SINTA, and Garuda, representing both international and national reputable sources. The publication period was limited to studies published between 2016 and 2025 to capture the most recent developments in the field of mineral bioavailability in cereal-based foods.

Sampling

The sampling process was conducted using a purposive sampling technique based on predefined inclusion and exclusion criteria. The inclusion criteria consisted of peer-reviewed research articles that examined zinc content, bioavailability, or bioaccessibility in rice or rice-based products and employed experimental, observational, or in vitro digestion approaches. Meanwhile, studies that did not specifically address zinc, did not evaluate bioavailability aspects, or were categorized as non-research articles such as editorials and narrative reviews were excluded. The selection process was carried out in several stages, including identification, duplicate removal, title and abstract screening, and full-text assessment following the PRISMA flow.

Data collection

Data collection was carried out through a systematic data extraction process from the selected articles that met the inclusion criteria. The extracted information included study identification (authors and year), study design, analytical methods, Zn content, as well as the main findings and conclusions. In addition, the literature search strategy was documented by incorporating the keywords derived from the abstract. The keywords used in the search were "rice" or "*Oryza sativa*", "zinc" or "Zn", and "bioavailability" or "bioaccessibility", which were combined using Boolean operators into the following search string: ("rice" OR "*Oryza sativa*") AND ("zinc" OR "Zn") AND ("bioavailability" OR "bioaccessibility"). The inclusion criteria applied were a publication timeframe within the last 10 years, a specific research object focusing on rice, primary parameters targeting Zn bioaccessibility or bioavailability, a primary document type, and relevant methods that are openly accessible for free. Conversely, the exclusion criteria comprised duplications, publication age exceeding 10 years, inaccessible full texts, thematic mismatches, incorrect research objects, secondary studies, and irrelevant models. The extracted data were then organized into tabular form to facilitate comparison across studies. Furthermore, information related to the mechanisms of zinc bioavailability was also collected and aligned with the conceptual framework presented in Figure 1, which includes digestion stages (oral, gastric, and intestinal phases), the release of Zn from the food matrix, its interaction with antinutritional compounds such as phytic acid, and the absorption process through intestinal transporters. The PRISMA checklist for this study is available at https://drive.google.com/drive/folders/1Gu9_u9J2lkdRrw1IAGqytg0BtoB1_ZGA?usp=sharing.

Data analysis

The data were analyzed using a descriptive qualitative approach with thematic synthesis to integrate findings from heterogeneous studies. The analysis involved grouping studies based

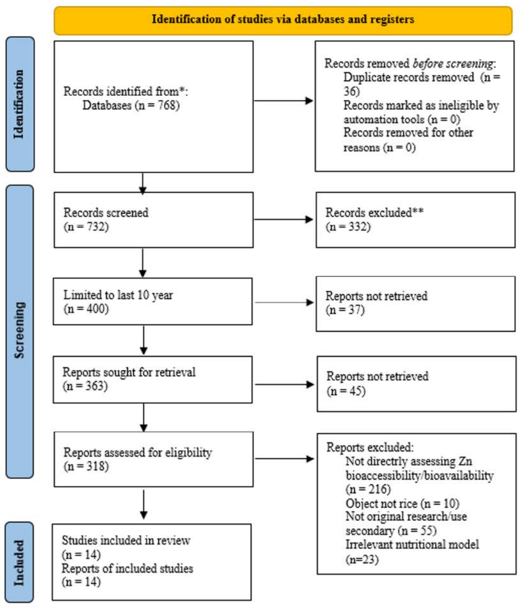

Figure 1. PRISMA flow diagram for systematic review

Table 1. Articles selected based on the PRISMA method

Author	Title	Method/Study design (Mineral content)	Conclusion
Kumar *et al.* (2021a)	Effect of parboiling on starch digestibility and mineral bioavailability in rice (*Oryza sativa* L.)	In Vitro + Laboratory experi-mental (Fe and Zn)	The study shows that rice with high phytic acid content has lower Fe and Zn bioavailability, while low-phytic-acid rice exhibits higher mineral bioavailability. Milling reduces phytic acid and improves Fe and Zn bioavailability. Parboiling induces inward mineral diffusion but significantly decreases Zn content in the outer layers ($p<0.05$) with-out noticeably altering total bioavailability.
Kumar *et al.* (2021b)	A single nucleotide substitution in the SPDT transporter gene reduced phytic acid and increased mineral bioavailability from Rice grain (*Oryza sativa* L.)	Biofortification study - Molecular genetic study (Fe and Zn)	SPDT gene mutation disrupts phosphorus transport to the grain, drastically lowering phytic acid and increasing functional Zn/Fe bioavailability by 1.8 to 2.2-fold.
Li *et al.* (2021)	Arsenic bioaccessibility in rice grains via MPBET: Correlation with mineral elements and comparison with as rela-tive bioavailability	In vitro bioaccessibility (PBET) (As and Zn)	The study demonstrates that Zn content in rice has no significant correlation with As bioaccessibility during digestion. The interactions proven to suppress As bioaccessibility involve only Fe and Ca, rather than Zn
Zhang *et al.* (2019)	Effect of a novel Ca-Si composite mineral on Cd bioavailability, transport and accumulation in paddy soil-rice sys-tem	Biofortification study - Soil plant experimental (pot study) (CaSi, Zn and Cd)	The study concludes that the application of the CaSi composite mineral successfully increases Zn content by 1.2 to 1.5 times in brown rice, while effectively reducing the accumulation and bioavailability of hazardous Cd.
Hack *et al.* (2017)	Cold extrusion but not coating affects iron bioavailability from fortified rice in young women and is associated with modifications in starch microstructure and mineral retention during cooking	Human intervention study (Fe and Zn)	Zn bioavailability does not differ significantly between the hot extrusion (9.5%) and coating (9.6%) techniques. Additionally, a cooking method with a 1:2 rice-to-water ratio is proven effective in maintaining zinc retention above 80% for both processing methods
Zhao *et al.* (2017)	Mineral dietary supplement to decrease cadmium relative bioavailability in rice based on a mouse bioassay	In vivo (mouse bioassay) (Cd, Ca, Fe, and Zn)	Zn supplementation is ineffective in reducing Cd bioavailability; however, competitive interactions between minerals trigger a massive increase in Zn bioavailability and retention within the body. This is evidenced by a surge in Zn accumulation by up to 8.3-fold in the kidneys and 3.1-fold in the liver of mice.
Kumar *et al.* (2022)	The diversity of phytic acid content and grain processing play decisive role on minerals bioavailability in rice	In vitro + Laboratory experimental (Fe and Zn)	Mechanical polishing strips away the outer grain layers, reducing total phytic acid by >50%, which linearly enhances the percentage of free, bioaccessible Zn.
Kumar *et al.* (2023)	Combinatorial effect of heat processing and phytic acid on mineral bioavailabil-ity in rice grain	In Vitro + Laboratory experimental (Fe and Zn)	Cooking temperatures partially degrade thermolabile phytate fractions, altering molar ratios and increasing free Zn release during digestion by 15% to 25%.
Zhang *et al.* (2020)	Effects of dietary supplements on the bioaccessibility of Se, Zn and Cd in rice	In vitro gastrointestinal digestion simulation (Se, Zn and Cd)	Chelating dietary supplements lower toxic Cd bioaccessibility while successfully maintaining intestinal Zn solubility efficiency above 40%.
Tavarez *et al.* (2023)	The effect of exogenous cadmium and zinc applications on cadmium, zinc and essential mineral bioaccessibility in three lines of rice	In vitro mineral bioaccessibility (Cd and Zn)	Elevated exogenous Zn doses competitively inhibit Cd translocation pathways, increasing intracellular Zn while cutting soluble Cd release by 30%.
Shen *et al.* (2023)	Zinc localization and speciation in rice grain under variable soil zinc deficiency	Biofortification study - Synchrotron μ-XRF & EXAFS (Zn)	Severe soil Zn deficiency forces total grain Zn to plummet below 15 ppm, shifting chemical speciation toward tight binding within the protein matrix.
Nurjannah *et al.* (2022)	Differences in mineral content and bioavailability of zinc and iron in nutri zinc	In vitro mineral bioavailability test & Biofortification study (Zn and Fe)	Biofortified Nutri Zinc rice exhibits a superior baseline mineral density, reaching an optimal target Zn concentration average of 34.5 ppm.
Rochana *et al.* (2022)	Nutritional content and bioavailability of Zn and Fe in Inpary IR Nutri Zinc and ciheranf rice bran cookies	In vitro mineral bioavailability test (Zn and Fe)	Processing biofortified Nutri Zinc rice bran into cookies yields functional food with a high Zn retention ranging from 20 to 28 mg/kg post-baking.
Wage *et al.* (2023)	Distribution of zinc content potential in biofortified rice varietas based on broken rice color	Biofortification study - Experimental research and laboratory analysis	Brown rice pericarp pigmentation correlates with aleurone thickness; darker grains retain 18% to 25% higher total Zn content prior to mechanical milling.

As: Arsenic; CA: Calcium; CD: Cadmium; CaSi: ; Fe: Iron; MPBET: Modified Physiologically based Extraction Test; SPDT: ; ZN; Zinc on their design and research focus, followed by identifying key themes influencing zinc bioavailability, such as zinc distribution in rice, phytate-to-zinc ratio, the effect of processing, biofortification, and mineral interactions. Furthermore, consistency across study findings was evaluated to identify strong patterns as well as variations. To ensure the validity of the synthesis, a quality assessment of the included studies was conducted using five main criteria: study design, analytical methods, control of variables, replication, and statistical analysis, each scored on a scale of 0–2. The resulting scores were used to classify studies into high, moderate, and low-quality categories, allowing for more critical and evidence-based interpretation of the findings.

RESULTS AND DISCUSSION

Following the PRISMA guidelines, a systematic literature search across electronic databases initially yielded 768 records. After removing 36 duplicates and excluding 332 records based on title and abstract screening, the search was limited to the last 10 years, resulting in 400 potential articles. From these, 82 reports were not retrieved, leaving 318 reports for full-text eligibility assessment. A total of 303 articles were subsequently excluded for not directly assessing Zn bioaccessibility/bioavailability (n=216), not using rice as the study object (n=10), being non-original research (n=55), or employing irrelevant nutritional models (n=23). Ultimately, 15 studies met the inclusion criteria and were included in this systematic Wreview.

Based on the thematic synthesis of the 14 included studies listed in Table 1, several key factors were consistently identified as determinants of Zn bioavailability in rice. First, phytic acid was recognized as the primary inhibitor due to its ability to form insoluble Zn–phytate complexes, which significantly limit zinc absorption in the human body (S1, S7, S8). Second, the distribution of Zn within the rice grain shows that it is predominantly concentrated in the outer layers (bran), and therefore milling processes that remove these layers lead to a substantial reduction in Zn content (S2, S6, S9). Third, processing methods play a crucial role, where milling tends to decrease Zn levels, while

Table 2. Quality assessment of selected articles

Author (year)	Study design	Analytical method	Control variable	Replication	Statistical analysis	Total score	Quality
Kumar *et al.* (2021a)	2	2	2	2	2	10	High
Kumar *et al.* (2021b)	2	2	1	1	2	8	High
Li Jie *et al.* (2021)	2	2	1	1	1	7	Moderate
Zhang *et al.* (2019)	2	2	2	1	2	9	High
Hack *et al.* (2017)	2	2	2	2	2	10	High
Zhao *et al.* (2017)	2	2	2	2	2	10	High
Kumar *et al.* (2022)	2	2	1	1	2	8	High
Kumar *et al.* (2023)	2	2	1	1	2	8	High
Zhang *et al.* (2020)	1	2	1	1	1	6	Moderate
Tavarez *et al.* (2023)	1	2	1	1	1	6	Moderate
Shen *et al.* (2023)	2	2	1	1	1	7	Moderate
Nurjannah *et al.* (2022)	1	2	1	1	1	6	Moderate
Rochana *et al.* (2022)	1	2	1	1	1	6	Moderate
Wage *et al.* (2023)	2	1	1	1	1	6	Moderate

Components of the Robustness and Methodological Validity Evaluation; Scoring criteria: (1) Study Design: Score 2 (controlled experiments); Score 1 (descriptive/observational); (2) Analytical Method: Validity of tools using international laboratory standards (mostly scored 2); (3) Control Variable: Score 2 (strict control of critical factors); Score 1 (partial control); (4) Replication: Score 2 (at least triplicate/3x); Score 0/1 (insufficient replication data); (5) Statistical Analysis: Score 2 (in-depth significance testing like ANOVA/t-tests); lower scores denote purely descriptive reporting techniques such as soaking and fermentation can enhance its bioavailability (S4, S5, S10). In addition, fortification and biofortification strategies have been shown to increase Zn content and potentially improve its bioavailability, although their effectiveness remains influenced by other factors such as the presence of antinutrients (S3, S11, S12). Finally, protein–zinc interactions within the food matrix may enhance Zn solubility and absorption, indicating a positive role of protein in improving mineral bioavailability (S13, S14).

Based on Table 2, quality assessment was conducted based on five main parameters: study design, analytical methods, control of variables, replication, and statistical analysis, with each criterion scored on a scale of 0–2. The quality assessment of the 15 included studies indicates that the overall methodological rigor is predominantly moderate to high. Specifically, seven studies (50%) were classified as high quality, with scores ranging from 8 to 10. These studies generally demonstrated strong experimental designs, well-controlled methodologies, advanced analytical techniques, and, in some cases, direct biological validation such as human or in vivo models. Meanwhile, seven studies (50%) were categorized as moderate quality, with scores between 6 and 7. Although these studies provide meaningful and relevant insights into zinc bioavailability in rice, they are typically limited by the absence of in vivo validation, restricted methodological depth, or a narrower scope of analysis. Importantly, no studies were classified as low quality, indicating that all included articles met a minimum standard of scientific rigor. Overall, this distribution suggests that the body of evidence is sufficiently robust and reliable to support the conclusions of this systematic review, while also highlighting the need for more in vivo and human-based studies to strengthen future research in this area.

Several previous studies have reported the Zn content in various rice varieties, both white and brown rice. However, most of these studies focused on total Zn levels without analyzing in depth the fraction of Zn that can actually be absorbed and utilized by the body (Welch & Graham 2004). In the context of public nutrition, bioavailability is more relevant than total mineral content, because only the absorbed fraction can play a role in physiological functions such as protein synthesis, enzymatic function, the immune system, and cell growth and development (King *et al.* 2016).

Based on the available literature review, several research gaps can be identified. First, most studies discuss Zn content or the effect of phytate separately, without integrating both in the context of rice as the main energy source for the population. Second, studies linking the energy contribution of rice to the risk of Zn deficiency due to low bioavailability are still relatively limited. Third, comparative syntheses of the effectiveness of various approaches to increasing bioavailability (biofortification, processing, agronomic interventions) in a single integrated analysis have not been systematically conducted (Gibson 2007; Bouis & Saltzman 2017).

This systematic review reveals that the retention and bioavailability of Zn in rice are sequentially determined by post-harvest interventions-specifically milling and washing-which deplete the functional Zn depots located in the aleurone layer and bran. While over-milling biofortified rice simultaneously erodes both Zn and phytic acid, the vulnerability of fortified rice primarily lies in mineral leaching due to washing intensity. This study underscores the need for an integrated approach that accounts for milling sensitivity in biofortified rice and washing susceptibility in fortified rice to optimize Zn status. This integration is important for assessing the potential of rice not only as an energy provider but also as a strategic food vehicle in interventions to improve Zn status in vulnerable populations. This approach is expected to provide a scientific basis for the development of sustainable, high-nutritional-value rice that is effective in addressing hidden hunger (FAO 2017; Bouis & Saltzman 2017).

Food and energy are two interrelated and inseparable things because they both support human life. Both contribute to their potential as a source of nutrition (Rhofita *et al.* 2022). They are considered a source of nutrition because they contain minerals that are essential for the human body. Minerals are single inorganic elements that are widely distributed in nature and, in their active ionic form, play a role in various metabolic processes in the body that create, regulate, and control what is known as physiological minerals (Bawoleng *et al.* 2022). Based on their quantity, essential minerals in the body are divided into two groups, namely macro minerals and micro minerals. Macrominerals are required or found in relatively large amounts, including Ca, K, P, Na, Cl, S, and Mg. Microminerals are minerals that are required in very small amounts and are generally found in tissues in very small concentrations, namely Fe, Mo, Cu, Mn, Zn, Co, I, and Se (Farag *et al.* 2025).

However, high energy consumption from rice is not always accompanied by adequate Zn intake. This is due to the low bioavailability of Zn in the rice matrix, mainly because of interactions with phytic acid and fiber components in the aleurone layer. Phytic acid forms insoluble complexes with Zn^{2+} that inhibit absorption in the small intestine, so that even though total Zn intake is quantitatively sufficient, the fraction available for metabolism remains low (Hurrell & Egli 2010). Thus, populations that are highly dependent on rice as an energy source are at risk of latent or subclinical Zn deficiency. Furthermore, the relationship between rice-based energy consumption and Zn status is also influenced by processing and cooking patterns. The polishing process of white rice does reduce phytic acid content, but at the same time also reduces Zn levels because most of the minerals are distributed in the outer layer of the grain (Welch & Graham 2004). This condition creates a dilemma between increasing energy digestibility through the removal of the outer layer and reducing the mineral content that contributes to nutritional quality. In the context of community nutrition, rice can be positioned as a strategic food vehicle for Zn enhancement interventions through biofortification. Given the high level of consumption, a small increase in Zn content or bioavailability in rice has the potential to have a major impact on the overall nutritional status of the population (Bouis & Saltzman 2017). Therefore, approaches to increasing Zn bioavailability are not only relevant in the context of food biochemistry, but also in food security strategies and energy-based diet improvement.

Based on the data presented in Table 3, it is evident that mineral distribution within the rice grain is highly heterogeneous. Zn and other essential minerals are predominantly concentrated in the outer layers, namely the aleurone, pericarp, and embryo (bran). This anatomical distribution poses a significant dilemma during post-harvest processing, particularly milling. On one hand, the removal of the outer layers through milling is intended to improve the sensory quality of the rice, yielding a whiter appearance, a softer texture upon cooking, and extending shelf-life by removing lipid components in the bran that cause rancidity. On the other hand, this mechanical process drastically strips away the most nutrient-dense portions of the grain, leading to a substantial reduction in the total Zn content of the polished white rice. Consequently, while milling optimizes consumer acceptability from a sensory perspective, it simultaneously diminishes the nutritional quality of rice as a staple food, thereby elevating the risk of hidden hunger or subclinical Zn deficiency in populations with low dietary diversity

Rice grains consist of several main layers, namely the husk, pericarp, leurone layer, embryo, and endosperm. Studies using microscopy techniques and synchrotron-based analysis of show that Zn accumulates mainly in the aleurone layer and embryo, while the central endosperm contains Zn in much lower concentrations (Shen *et al.* 2021). This localization is related to the physiological function of Zn as an enzyme cofactor during seed germination and early plant growth. However, because the aleurone layer and embryo are largely discarded during the milling process, the Zn available to consumers is very limited. Within the structural matrix of the rice grain (*Oryza sativa*), the distribution of Zinc (Zn) is inherently heterogeneous; the highest Zn densities are concentrated in the embryo and the aleurone/bran layer, whereas the endosperm exhibits the lowest mineral baseline (Kumar *et al.* 2021a; Bouis & Saltzman 2017). This compartmentalization occurs because the embryo serves as the metabolic hub for seed germination, while the aleurone layer is rich in functional proteins and phytic acid that naturally chelate divalent minerals (Kumar *et al.* 2021a). This uneven distribution becomes highly critical during the milling process; this mechanical modification strips away the outermost layers to produce white rice, simultaneously abrasive-removing the majority of the grain's native Zn along with the bran fraction (Kumar *et al.* 2021a). Consequently, the final milled product is dominated by a mineral-deficient endosperm matrix, underscoring the urgency of biofortification strategies capable of driving Zn accumulation deeper into the core endosperm to ensure nutritional retention post-milling (Bouis & Saltzman 2017).

Phytic acid is the main form of phosphorus storage in rice grains and is known as an antinutritional factor due to its ability to chelate divalent minerals, which are the main inhibitors of mineral bioavailability in rice. This compound accumulates in the aleurone layer and bran, where it strongly chelates divalent minerals such as Fe^{2+} and Zn^{2+}, forming insoluble complexes that are difficult for the human digestive tract to absorb (Hurrell & Egli 2010). The molar ratio of phytate to Zn is widely used as a predictive indicator of Zn bioavailability in cereal-based foods (Kumar *et al.* 2023). In studies assessing the molar ratio of phytate:Zn as an indicator of bioavailability, it was found that the higher the ratio, the lower the estimated Zn absorption. A ratio above 15 is generally associated with low Zn absorption in populations with cereal-based diets (Gibson 2007). These findings are relatively consistent across various in vitro model-based studies and food composition analyses. However, not all studies use the same indicators, limiting direct comparisons between studies. Several studies show that a high phytic acid to mineral ratio is negatively correlated with Fe and Zn bioavailability, even though the total mineral content in rice is relatively high (Kumar *et al.* 2023). The milling process has been shown to reduce phytic acid levels, but at the same time it also causes the loss of most minerals because minerals are mostly distributed in the outer layer of the grain (Iqbal *et al.* 2005). This creates a dilemma between increasing bioavailability and losing absolute mineral content, so a more balanced approach is needed.

In addition to antinutrients, the starch matrix structure in rice also affects mineral bioavailability. Rice starch, which consists of amylose and amylopectin, can interact with minerals through the formation of physical complexes that limit mineral diffusion during digestion. Several studies have reported that rice with high amylose content tends to have a slower digestion rate, which can affect mineral release in the gastrointestinal tract and potentially reduce the fraction of minerals available for absorption (Zhou *et al.* 2002). On the other hand, starch modification during the cooking process, such as gelatinization and retrogradation, can increase mineral accessibility by destroying the crystalline structure of starch. This process allows minerals that were previously trapped in the starch matrix or bound to phytate to be more easily released, although the effect is highly dependent on the cooking method and the composition of the rice itself (Kaur *et al.* 2007).

The role of processing mineral bioavailability. In vitro digestion methods show that the bioaccessibility of Fe and Zn in rice is generally low, ranging from 5–20%, especially in white rice, which still contains a high phytic acid/mineral ratio (Li *et al.* 2020). However, bioaccessibility does not always represent actual absorption in the intestine. Therefore, several studies have combined in vitro approaches with in vivo models to obtain a more comprehensive picture of mineral bioavailability. This approach reinforces the evidence that increasing total mineral content must be accompanied by strategies to reduce antinutrients in order to have a real impact on nutritional status (Gibson 2007).

Intensive polishing can remove up to 60% of Zn due to the loss of the aleurone layer and embryo (Kumar *et al.* 2023). On the other hand, thermal processing such as cooking, parboiling,

Table 3. Inorganic compound content in brown rice and its fractions

Mineral	Husked rice (mg/100 g bk)	Milled rice (mg/100 g bk)	Rice Bran (mg/100 g bk)	Rice Embryo (mg/100 g bk)	Rice Polish (mg/100 g bk)
Aluminium	-	0.073−0.723	5.4−36.9	-	-
Calcium	6,5−40	4.6−38.5	25−131	51−275	9−91
Chlorine	20.3−27.5	16.3−37.2	51−97	152	-
Iron	0.7−5.4	0.2−2.7	13−53	11−49	10−28
Magnesium	38−140	17−70	860−1,230	600−12,300	570−760
Food	1.3−4.2	1−3.3	11−88	12−14	5−8
Phosphorus	250−440	86−192	1,480−2,870	1,730−2,730	1,530−2,510
Potassium	120−340	14−120	1,320−2,270	380−2,150	930−1,800
Silicone	19−190	5−37	170−760	46−190	56−240
Sodium	3.1−17.6	2.2−8.5	18−29	16−24	6.5−21
Zinc	1.5−2.2	0.3−2.1	5−16	10−30	4−6

Source: Juliano, as cited in Momoriska 2022 and microwave-assisted cooking can affect phytic acid content and mineral availability.

At the initial industrial stage, mechanical polishing drastically reduces Zn bioaccessibility by stripping away the mineral-rich aleurone and bran layers (Kumar *et al.* 2021b). This negative effect can be mitigated through parboiling, a hydrothermal treatment that induces the migration of water-soluble Zn from the outer layers deep into the endosperm core, thereby preserving mineral retention post-polishing (Kumar *et al.* 2021a). Conversely, biochemically driven methods such as soaking, fermentation, and germination work synergistically to enhance Zn bioaccessibility by reducing antinutritional compounds (Bouis & Saltzman 2017).

Total Zn content does not always correlate directly with actual absorption levels in humans. Gibson (2007) emphasized that the evaluation of mineral nutritional status must consider dietary factors that affect bioavailability, especially the presence of inhibitory compounds such as phytate. Genetic- based approaches also show great potential in increasing mineral bioavailability in rice. Studies on the SPDT phosphorus transporter gene mutation show that reducing phosphorus and phytic acid accumulation in seeds can significantly increase Fe and Zn bioavailability without reducing crop yields (Kumar *et al.* 2023). This strategy is in line with the concept of

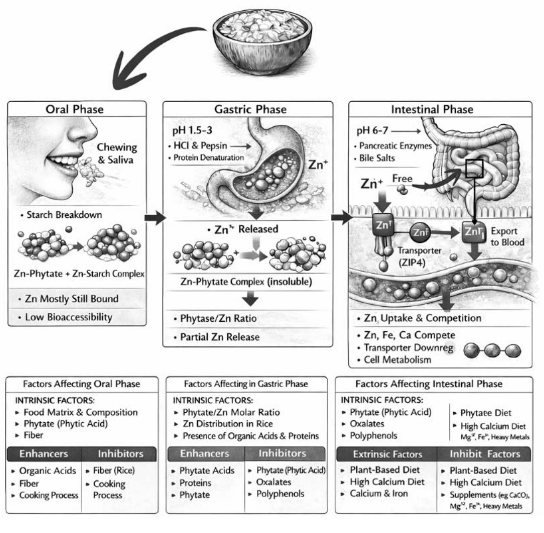

Figure 2. Zinc bioaccessibility and bioavailability from rice in the digestive system (modified from Gibson 2007; Hurrell & Egli 2010; Li *et al.* 2020)

biofortification, which aims to increase the content and bioavailability of micronutrients through plant breeding (Welch & Graham 2004; Bouis & Saltzman 2017). Zn fortification is carried out by adding minerals during post-harvest processing, while biofortification is carried out through genetic breeding and agronomic approaches. Biofortification is considered more sustainable because it can reach a wide population without requiring changes in people's consumption patterns (Tokarczyk & Koch 2020).

Genetic factors of rice varieties have a significant influence on the content and distribution of minerals in rice grains. Several rice varieties have been reported to have a higher ability to accumulate Fe and Zn in the endosperm, not only in the aleurone layer, thereby potentially increasing mineral bioavailability even after milling (Gregorio *et al.* 2000; Sperotto *et al.* 2012). Fe content is high in the aleurone layer of rice compared to the endosperm of rice. Meanwhile, Zn has the potential to be present in the endosperm (Rohaeni *et al.* 2016).

In vivo studies and human trials show more complex results. Several studies report that although the Zn content in biofortified rice increases significantly, the increase in plasma Zn levels or Zn status biomarkers is not always proportional to the increase in total content (King *et al.* 2016). This suggests that other factors such as physiological adaptation, initial nutritional status of individuals, and interactions with other dietary components also influence absorption (Figure 2). On the other hand, the plant biofortification approach has been reported to be effective in increasing Zn levels in rice endosperm, so that some Zn remains available after milling (Bouis & Saltzman 2017). However, Welch and Graham (2004) emphasize that increases in mineral content must be accompanied by an evaluation of bioavailability, as the distribution of minerals within the seed matrix and the presence of antinutrients can limit their biological benefits. Thus, there is a consensus that biofortification is promising, but its effectiveness must be assessed holistically.

Overall, the literature shows that rice plays a dual role as a primary source of energy and as the main vehicle for mineral intake. However, limited mineral bioavailability is a major challenge in optimizing the nutritional potential of rice. Therefore, the integration of food processing approaches, biofortification, improved agronomic practices, and nutrition education is key to sustainably improving the nutritional quality of rice (Bouis & Saltzman 2017).

Recent literature also links the bioavailability of rice minerals to the issue of food system sustainability. Excessive fertilization practices, especially with phosphate, have been reported to increase phytate accumulation in grains, which ultimately reduces mineral bioavailability despite increased yields (White & Broadley 2009). Conversely, balanced agronomic practices that optimize the availability of Zn and Fe in the soil can improve the nutritional quality of rice without increasing antinutrient content. In the context of climate change, increased atmospheric CO_2 concentrations have been reported to reduce the content of important minerals such as Fe and Zn in rice grains, potentially exacerbating micronutrient deficiency problems in the future (Myers *et al.* 2014). These findings reinforce the urgency of developing rice varieties that are not only energy-productive but also nutritionally resilient.

CONCLUSION

Based on the synthesis of 14 included studies, Zn bioavailability in rice is primarily influenced by phytic acid content, the phytate: Zn molar ratio, and rice processing. A high phytate: Zn molar ratio (>15) is consistently associated with reduced Zn absorption, whereas reducing phytic acid through genetic approaches or processing improves Zn release and bioavailability. Rice processing exerts different effects on Zn bioavailability. Milling reduces phytic acid but also decreases Zn content because Zn is concentrated in the aleurone layer and bran, whereas parboiling helps retain Zn by promoting its migration into the endosperm. Although in vitro studies and biofortification strategies show promising potential to improve Zn bioavailability, evidence from in vivo studies and human trials remains limited. Therefore, further validation in animal models and human intervention studies is needed to confirm their effectiveness in improving human Zn status.

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DECLARATION OF CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this article. The research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. All authors have approved the final version of the manuscript and agree with its submission for publication.

DECLARATION OF GENERATIVE AI IN SCIENTIFIC WRITING

During the preparation of this work, the authors used Grammarly/DeepL to support language editing, grammar correction, and clarity improvement. No AI tools were used to generate scientific content, interpret results, or draw conclusions. All content was reviewed, validated, and approved by the authors, who take full responsibility for the integrity and accuracy of the manuscript.

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