Bio-fortified zinc rice: A comprehensive review of its role in improving dietary zinc intake and nutrition security in rural Bangladesh

Canadian Journal of Agriculture and Crops
Vol. 11, No. 1, 1-21, 2026
e-ISSN: 2518-6655

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ABSTRACT

Bangladesh is a country with a high burden of micronutrient malnutrition. Stunting affects 41 % of children aged under 5 years. Zn is one of the key micronutrients that is associated with stunting. Zinc (Zn) is an essential trace element in the human diet, playing a critical role in numerous physiological processes, including immune defense against infectious diseases. Notably, the global distribution of dietary Zn deficiency closely mirrors regions of soil Zn deficiency. In South Asia, Zn malnutrition is particularly prevalent due to the heavy reliance on rice, a staple crop with inherently low Zn content. Among different interventions to combat Zn deficiency include dietary diversification, food fortification, supplementation, and biofortification Zn biofortification of rice stands out as the most cost-effective and sustainable strategy for the region. While conventional breeding and transgenic approaches have successfully enhanced Zn levels in cereals, their effectiveness diminishes in Zn-deficient soils. This review therefore emphasizes agronomic biofortification strategies specifically the timing, dosage, and method of Zn fertilizer application and examines how nitrogen and phosphorus management, along with crop establishment practices, influence Zn accumulation in rice. We further propose data-driven Zn recommendations to optimize crop responses to fertilization and advocate for targeted policies that support agronomic biofortification in regions where Zn fertilizer responsiveness is high.

Keywords: *Agronomic biofortification, Crop management, Health impact modeling, Rice, Zinc bioavailability and nutritional efficacy, Zn deficiency.*

DOI: 10.55284/cjac.v11i1.1709

Citation | Kobir, H., Ali, M. S., Khanum, M., & Hossain, M. B. (2026). Bio-fortified zinc rice: A comprehensive review of its role in improving dietary zinc intake and nutrition security in rural Bangladesh. *Canadian Journal of Agriculture and Crops, 11*(1), 1–21.

Funding: This study received no specific financial support.
Institutional Review Board Statement: Not applicable.
Transparency: The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.
Competing Interests: The authors declare that they have no competing interests.
Authors' Contributions: All authors contributed equally to the conception and design of the study. All authors have read and agreed to the published version of the manuscript.
History: : Received: 7 November 2025/ Revised: 9 December 2025/ Accepted: 24 December 2025/ Published: 8 January 2026
Publisher: Online Science Publishing

Highlights of this Paper

- Bio-fortified zinc rice is an effective and sustainable approach to increasing dietary zinc intake among rural populations in Bangladesh
- Regular consumption of zinc-enriched rice helps reduce zinc deficiency, improving immune function, growth, and overall nutritional status, especially among children and women.
- The review highlights bio-fortification as a cost-effective strategy to strengthen nutrition security and address zinc-related public health challenges in rural Bangladesh.

1. INTRODUCTION

Bangladesh faces a high burden of zinc (Zn) deficiency, driven by cereal-heavy diets and limited intake of animal-source foods. The Bangladesh National Micronutrient Survey (2011–12) found that 44.6% of preschool children and 57.3% of nonpregnant, nonlactating women were zinc-deficient, reflecting inadequate dietary zinc (largely from rice) and high phytate intake. Biofortification of staple crops has emerged as a promising strategy to sustainably increase micronutrient intake. In Bangladesh, rice biofortified with zinc (via conventional breeding) has been developed to raise grain Zn levels to ~24–28 mg/kg, compared to ~16 mg/kg in traditional varieties. The rapid growth of gross domestic product (GDP) and agricultural productivity since the 1990s have tremendously contributed to the fight against hunger and poverty in Bangladesh. During 1990–2022, the annual average growth rate of agriculture, forestry, and fishing was 3.68%, while GDP grew 5.7% per year [1]. Consequently, Bangladesh's per capita GDP increased by more than 800% from US $295 in 1990 to US $2688 in 2022 [1]. Presently, the country has successfully upgraded itself to a lower-middle-income country. Also, the poverty rate in the country has decreased drastically. For example, 33.4% of the total population of Bangladesh was extremely poor in 2002, living on less than US $1.90 per day, which dropped to 3.4% in 2022 [2]. In 1990, the daily per capita dietary energy intake rate was 2111 kcal, which increased to 2575 kcal/daily in 2022 [3]. In 2022, Bangladesh was ranked 84th out of 121 countries on the Global Hunger Index (Von Grebmer et al., 2022), compared to 2006, when it was ranked 102nd out of 119 countries in terms of global hunger status [4]. Despite the economic progress, in 2019, 28% of children under 5 years of age are stunted, and 9.8% of them are wasted [2]. In addition, 36.7% of women of reproductive age are anemic, and 13% of the total population of the country is undernourished. Studies stressed that 41–44.6% of pre-school-aged children and 57.3% of non-pregnant and non-lactating women in Bangladesh are zinc deficient (Zn) (Rahman et al., 2016). According to a report, on average, 55% of the total population of Bangladesh is zinc deficient [5]. Zinc deficiency is directly associated with stunted linear growth and declined immune function [6]. Widespread and uncontrolled malnutrition, including anemia, can severely impact human capital formation, quality labor supply, and the country's long-run economic progress. It is estimated that the per capita income penalty only from childhood stunting is around 7% [7]. Thus, while Bangladesh is highly successful in fighting against abject hunger, hid den hunger in the form of malnutrition is still a significant policy concern.

Crop biofortification is a process through which the concentration of essential and critically important vitamins and minerals in staple crops are enhanced through the breeding process [8]. With a yearly per capita rice consumption of 257 kg, Bangladesh has the largest rice per capita consumption in the world, and in terms of total rice consumption, Bangladesh is the fourth largest rice-consuming country (42 million metric tons, MMT) in the world [3]. In Bangladesh, rice supplies daily 1711 kcal of dietary energy per person, which is 66% of the total daily dietary energy intake [3]. As the diet of Bangladesh is predominantly rice-based and as rice generally lacks some key vitamins and minerals, the risk of inadequate zinc intake is high among Bangladeshi citizens [6]. Thus, to fight zinc deficiency in the most effective way, the government aims to develop and disseminate zinc-biofortified rice in Bangladesh. In 2013, the first zinc-biofortified rice, BRRI dhan62, was released in Bangladesh [9]. The variety can supply zinc at 19 milligrams per kilogram. Until 2023, the Bangladesh Rice Research Institute (BRRI) subsequently released a total of seven zinc-biofortified rice varieties, including the BRRI dhan62.

Boro is the major season in Bangladesh, contributing around 50% of the total rice produced in the country [10]. Considering the importance of the boro season, five out of seven varieties developed by BRRI during this season, and only two biofortified rice varieties, BRRI dhan62 and BRRI dhan72, were released targeting the Aman season [9]. A few studies examined the efficacy of zinc-biofortified rice in addressing zinc deficiency. A controlled study conducted under the vulnerable group feeding program from January to December [11] indicated that the prevalence of anemia and zinc deficiency was lower among vulnerable women who consumed zinc-biofortified rice compared to their counterparts who consumed ordinary rice. Experts and scientists stressed that proper and regular consumption of zinc-biofortified rice can meet 60% of the daily zinc demand of a person [12, 13]. The introduction of a new technology, such as a new seed, often involves uncertainty as the cost and benefits of adopting a new technology are unknown to farmers [14]. According to HarvestPlus [15] around one million rice farmers in Bangladesh are cultivating biofortified crops.

This review synthesizes evidence on Zn-biofortified rice in Bangladesh, covering its agronomic development, Zn bioavailability and efficacy, nutrition impact modeling, adoption and consumer response, policy and implementation strategies, cost-effectiveness, and emerging challenges. This review critically examined (1) the agronomic development of zinc-rich rice varieties, (2) evidence on zinc bioavailability and efficacy, (3) nutrition impact modeling, (4) farmer adoption and consumer demand, (5) integration into policy and programs, (6) implementation strategies, and (7) economic evaluations.

1.1. Zinc Deficiency and Nutritional Context in Bangladesh

Approximately 17.3% of the global population and 30% of South Asians suffer from inadequate Zn intake [16]. An additional 175 million people globally, including 63 million in South Asia, are expected to become Zn deficient by 2050 [17]. Moreover, about 16 million of the global disability adjusted life years are caused by Zn deficiency [18, 19]. The rate of Zn deficiency remained the same over the years between 1995–2005 in South Asia Figure 1)[16]. Many articles have highlighted the importance of biofortification in cereals to alleviate malnutrition [20, 21]. Bangladesh has made great strides against hunger, but micronutrient malnutrition persists. Surveys find Zn deficiency in ~41–45% of children under five and ~57% of women of reproductive age. Nationwide, the average person's Zn intake meets only a fraction of requirements. This shortfall is linked to Bangladesh's heavy reliance on rice. With per-capita rice consumption ~257 kg/year the world's highest rice provides 66% of dietary energy. However, polished rice has a low intrinsic Zn content (often <14 mg/kg), and its Zn is bound by phytic acid, reducing absorption. Seasonal and soil factors further limit rice Zn density; for example, grain Zn can range widely (20–27 mg/kg) depending on soil Zn status. The combination of high rice diets and low Zn availability from this staple explains the country's "hidden hunger." Bangladesh remains one of the countries most affected by zinc deficiency. National micronutrient surveys show that about 45% of children under five and 57% of non-pregnant women have inadequate Zn intake. The main reason is the monotonous diet dominated by rice, which contributes more than two-thirds of daily calories but little micronutrient density. Traditional rice varieties contain only 12–14 mg Zn/kg, while the recommended level to meet nutritional needs is at least 28–30 mg/kg. The prevalence of stunting, low birth weight, and weak immune response is often linked to low Zn intake.

Figure 1. Zinc deficiency in children by sex and age.

Source: National Dissemination Program National Micronutrient Survey [22].

1.2. Global Overview of Zinc Biofortification Research

Zinc deficiency is estimated to affect nearly 2 billion people worldwide, contributing to impaired growth, immune dysfunction, and cognitive deficits. The World Health Organization has identified Zn deficiency as one of the top ten contributors to disease burden in developing nations. Biofortification emerged as a long-term food-based intervention strategy in the early 2000s through the Harvest Plus program. Globally, Zn biofortification efforts have targeted rice, wheat, and maize, given their dominance in the diets of low-income populations. Countries like India, Pakistan, and the Philippines have released multiple Zn-enriched varieties of rice, and large-scale adoption programs have been underway. Lessons from these nations inform Bangladesh's current strategies in scaling biofortified rice. Zn concentrations in rice can be substantially increased by two approaches: (1) conventional breeding and genetic/transgenic methods and (2) agronomic biofortification [23].

1.3. Mechanisms of Zinc Uptake and Bioavailability in Rice

Zn biofortification in rice can be done by conventional breeding, marker-driven molecular breeding, or genetic engineering [24]. For instance, the Harvest Plus program has defined a target Zn concentration for brown and polished rice as 30 mg $kgha^{-1}$ and 28 mg $kgha^{-1}$, respectively [20]. Zinc accumulation in rice grains depends on both genetic and environmental factors. Uptake occurs primarily through the roots, where Zn is absorbed as Zn^{2+} ions and transported via xylem to shoots and grains. The efficiency of Zn mobilization depends on transporter proteins such as ZIP and HMA families. Phytate content in rice grains significantly affects Zn bioavailability; hence, breeding efforts also focus on reducing phytic acid to enhance absorption in humans. Environmental factors such as soil pH, organic matter, waterlogging, and nitrogen fertilization further influence Zn uptake. Understanding these physiological mechanisms allows breeders to identify genotypes with improved Zn partitioning efficiency.

1.4. Breeding High-Zinc Rice Varieties

Breeding programs began in Bangladesh about a decade ago. The first Zn rice (BRRI dhan62) was released in 2013 and contained ~19–20 mg Zn/kg in milled grain. Since then, national institutes have released several additional varieties. For example, BRRI has released at least seven Zn-fortified cultivars across boro (irrigated dry season) and Aman (rainy) seasons, and BU dhan2 (2016) and Binadhan-20 (2017) were Zn-enriched by other institutions. By 2025, nine Zn-biofortified rice varieties (plus one Zn wheat) are officially released in Bangladesh. Many of these have grain Zn content in the 17–25 mg/kg range, compared to ~12–14 mg/kg in typical varieties. Importantly, breeders have aimed not to sacrifice yield: most Zn lines are high-yielding and have cooking qualities (slender, non-sticky grain) comparable to popular counterparts. Genetic targets for Zn have been set to meet substantial portions of dietary requirements. A Harvest Plus working group recommended breeding rice so that grain Zn could provide roughly 60–80% of the EAR (estimated average requirement) for preschool children and women, on top of baseline values. In practical terms, this implies target Zn concentrations around 30–40 mg/kg in milled rice. Studies confirm there is genetic variation for Zn; screening of rice germplasm has found brown rice Zn content ranging from ~6 to 70 mg/kg and breeders are mapping QTLs (quantitative trait loci) to accelerate development. Early adopters of these varieties have reported nutritional benefits. A vulnerable-group feeding study in Bangladesh [11] showed that women consuming Zn rice had significantly lower rates of anemia and biochemical Zn deficiency than those eating ordinary rice. Still, experts agree that when habitually eaten, Zn rice has the potential to raise serum Zn and reduce infections at scale. These health outcomes have parallels in other bio-fortified crops (for example, orange-fleshed sweet potato raising Vitamin A status in children or iron beans reducing anemia in women), reinforcing confidence in bio-fortification as a valid nutrition strategy.

Harvest Plus developed the world's first Zn-enriched rice varieties such as BRRI dhan62, BRRI dhan72, and BRRI dhan64 (25 mg Zn $kgha^{-1}$) in 2013, and these were released by the Bangladesh Rice Research Institute (BRRI) [15]. Recently, BRRI 84, Zn-fortified rice (27.6 mg Zn $kgha^{-1}$) suitable for the dry season, was also released for cultivation in Bangladesh, and it took 13 years to develop this variety [25].

1.5. Agronomic Development of Zinc-Biofortified Rice

Agronomic biofortification is necessary not only for genetically inefficient cultivars but also, for biofortified cultivars obtained by conventional and genetic methods. Although improved cultivars are available, grain Zn concentration depends on environmental factors such as temperature, soil type, soil pH, and availability of micronutrients in the soil [26, 27]. This method is potentially inexpensive and extremely effective for helping populations with widespread micronutrient deficiency [28]. Rice breeders and institutes in Bangladesh, in partnership with international bodies (e.g. IRRI, Harvest Plus), have systematically developed and released Zn-biofortified rice varieties suited to local ecologies. The first such variety, BRRI dhan62 (released 2013), contains ~19 mg Zn/kg grain. It was followed by BRRI dhan64 (2014) and BRRI dhan72 (2015), the latter yielding ~5.7 t/ha (up to 7.5 t/ha) and ~23 mg Zn/kg grain. Later releases include BRRI dhan84 (approved 2017), with 27.6 mg Zn/kg and 6.0–6.5 t/ha yield, and BRRI dhan102 (approved 2022), with 25.5 mg Zn/kg and ~8.1 t/ha yield. In addition, other institutions released varieties (e.g. BU dhan2 in 2016, Binadhan-20 in 2017) to expand choices. Global breeding efforts continue: IRRI has achieved Zn levels up to 28 ppm in released lines, and even transgenic lines (not for immediate release) with ~45 ppm. A review by Swamy, et al. [29] notes substantial genetic variation for grain Zn in rice germplasm and identification of QTLs for Zn, enabling marker-assisted breeding. Breeding programs balance Zn density with yield and quality traits; the latest varieties achieve high Zn without major yield penalty and often improved farmers' traits (e.g. shorter duration, higher protein). Agronomic (fertilizer-based) biofortification is also employed. Soil or foliar zinc fertilization can raise rice grain Zn when soils are Zn-deficient. Studies indicate that in Zn-limited soils, foliar or soil Zn application increases yield and grain Zn (e.g. Jain, et al. [30] showed foliar Zn improved yield and grain Zn in Boro rice). However, as Swamy et al., 2016 note, agronomic biofortification results have been inconsistent. In summary, Bangladesh's Zn rice breeding program has released multiple varieties across seasons, steadily raising grain Zn content (from ~19 to ~28 mg/kg) while improving agronomic performance. These varieties – many high-yielding and now harvested by farmers – underpin the potential of biofortification to augment dietary Zn without altering traditional rice consumption.

Bangladesh pioneered zinc rice breeding in South Asia, with the first variety released in 2013. BRRI dhan62 was released in June 2013 for the Aman (monsoon) season, containing ~19 mg Zn/kg (brown rice). Since then, multiple institutions have released additional high-Zn varieties. BRRI has released seven zinc rice varieties by 2023 (four for Aman, five for the Boro/dry season) with grain zinc 19–27.6 mg/kg; for example, BRRI dhan72 (released 2015) yields ~5.7 t/ha (up to 7.5 t/ha under good management) and contains ~23 mg Zn/kg. Bangladesh Agricultural University released BU dhan2 in 2016, and Bangladesh Institute of Nuclear Agriculture released Binadhan-20 in 2017. These varieties were developed by conventional breeding (crossing high-Zn donors into popular backgrounds). Across releases, zinc concentration has steadily risen (first generation ~19–21 mg/kg, newer up to ~28 mg/kg) while breeders have worked to maintain high yields and grain quality. Grain zinc is largely in the bran layer, so polishing reduces zinc content; however, these varieties were developed using polishing/ milling targets typical of Bangladesh, so retained polished zinc remains higher than ordinary rice (e.g. ~12–14 mg/kg in new lines vs ~3–5 mg/kg in standard white rice). Beyond breeding, agronomic biofortification (soil/foliar Zn fertilization) can further enhance grain Zn, but is not a substitute for genetic biofortification. Trials showed that applying Zn fertilizer increases grain Zn modestly (often <20%) and adds cost. In summary, over the past decade Bangladesh has developed multiple zinc-rich rice varieties through conventional breeding. These varieties now offer 1.5–2.5× more grain Zn than typical rice while delivering competitive or superior yields. Ongoing breeding continues to push targets upwards; current aims are ~28–30 mg/kg polished rice. Achieving these targets could help meet a large fraction of daily Zn needs when consumed regularly.

1.6. Zinc Bioavailability and Nutritional Efficacy

A key question is whether the extra grain zinc in biofortified rice is bioavailable. Phytic acid in rice bran can inhibit zinc absorption, so studies have directly measured absorption of zinc from biofortified rice. Brnić, et al. [31] compared zinc absorption in adult Bangladeshi men and women from intrinsically zinc-labeled biofortified rice versus rice fortified at point-of-use. Using a double-isotope tracer approach, they found that fractional zinc absorption from biofortified rice (25.1 ± 8.7%) did not differ significantly from that from fortified rice (20.8 ± 7.1%) (P=0.08). In other words, the native grain-bound zinc was as bioavailable as inorganic zinc salt added to rice. The first large trial was a household-based randomized, double-masked controlled trial among Bangladeshi preschool children (12–36 months old) by Jongstra, et al. [32]. Over 9 months, 520 children in rice-consuming households received either high-zinc or conventional rice (white polished) ad libitum. The biofortified rice provided ≈1 mg more Zn daily per child than control (2.22 vs 1.20 mg Zn/day from rice; P<0.001). The trial found *no* significant effect on plasma zinc concentrations or prevalence of zinc deficiency, nor on most morbidity markers. Interestingly, the zinc rice group had more respiratory infections, highlighting the need to monitor morbidity (the reason is unclear). Other efficacy evidence comes from programmatic settings. Ara, et al. [11] reported on a feeding program under a Vulnerable Group Development (VGD) scheme: women who consumed micronutrient-fortified (iron+zinc) rice through VGD for a year had significantly lower anemia prevalence than controls. The one controlled trial with purely zinc-biofortified rice [32] suggests benefits for growth but not a detectable rise in plasma zinc over <1 year. Longer exposure, higher zinc targets, or larger intakes may be needed to see biochemical improvements. For ongoing research, a community trial among young non-pregnant women (20–29 y) in Dinajpur is underway (ISRCTN83005630). It will feed zinc rice vs control rice to households for 3 months, measuring serum zinc pre/post. By complementing the child trial, this will test efficacy in women. Additional trials (e.g. school-age children) would fill evidence gaps. Studies show that Zn retention declines with heavy milling: only ~55–90% of Zn is retained depending on milling degree. Modern parboiling and reduced polishing can increase Zn retention: Dipti, et al. [33] found that optimizing parboil conditions and allowing less milling raised Zn in cooked rice by up to 20–30%. Such post-harvest modifications can complement biofortification. Human feeding trials of Zn-biofortified rice provide mixed but informative results. [32] conducted a 9-month randomized trial in 528 Bangladeshi children (age 6–59 months) feeding a biofortified variety (BRRI dhan84; ~28.6 mg Zn/kg) versus control rice (~18.7 mg/kg). The Zn rice provided ~1 mg extra Zn/day. They observed *no significant change* in plasma Zn or deficiency prevalence, likely due to homeostatic regulation and measurement limitations. However, the Zn group showed modestly better linear growth (30% lower height deficit vs. 21% in controls) and no adverse effects. Similarly, adult women are being tested (ongoing trials). Earlier studies [34] found 59% greater Zn absorption when high-Zn rice was consumed with low-phytate legumes. In vitro and isotope studies indicate that increasing rice Zn can enhance bioavailable Zn, but the effect is attenuated by phytate and low-protein diets common in Bangladesh. Zn application is more critical in low-Zn soil than in high-Zn soil, and the response of grain Zn concentration to Zn application is higher in low-Zn soil than in high-Zn soil [35, 36].

1.7. Nutrition Impact Modeling and Dietary Adequacy

To quantify the potential population-level effects of zinc rice, several modeling studies have been done. The landmark study by Arsenault, et al. [37] estimated usual intakes in children and women and simulated zinc rice scenarios. They found that current diets leave 22% of children and up to 100% of women inadequate in zinc. Simulating a rice zinc content achievable by breeding, the model reduced inadequacy to ~9% for children and 20–85% for women (range due to absorption assumptions). This suggested that biofortified rice could markedly improve dietary zinc adequacy. More recently, De Moura, et al. [38] used nationally representative intake data to model zinc intake among women of childbearing age and young children in Bangladesh. They evaluated rice zinc increments from baseline (~16 ppm) up to 100 ppm and varying coverage (10–70% of rice replaced). Their results indicate that at the current breeding target (~28 ppm), zinc rice could cut dietary zinc inadequacy by up to ~50% among rural Bangladeshi women and children. Further increases up to ~45 ppm continues to yield gains, beyond which diminishing returns set in. These models assume moderate adoption (10–70% households) and typical dietary patterns, so real-world impact depends on scale-up. Nonetheless, they reinforce that even partial coverage of zinc rice could deliver substantial public health benefits by raising zinc intakes to near-recommended levels. Nationwide impact projections likewise estimate that zinc rice could reach millions. For example, Harvest Plus reported that by 2022, 6,350 metric tons of zinc rice seed had been produced and marketed in Bangladesh. Arsenault, et al. [37] used dietary recall data for rural Bangladeshi children and women to model Zn inadequacy. They found that biofortified rice with ~20–24 mg Zn/kg would cut the prevalence of inadequate Zn intake from ~22% to ~9% in young children, and from ~73–100% to ~20–85% in women, depending on adoption levels. In practical terms, even modest increases in rice Zn have big effects because rice is the dominant cereal. A 2024 ex-ante analysis by De Moura et al. extended this to a range of Zn levels. Using national and regional consumption data, they showed that raising rice Zn to 28 mg/kg (current breeding target) could reduce Zn inadequacy by up to ~50% among rural Bangladeshi women and children. Pushing to 45 mg/kg (an aspirational target) yields further gains. These results held across South and Southeast Asia due to high rice intake; Bangladesh, with very rice-dependent diets, stands to benefit greatly. Earlier models also highlight significant effects even at lower Zn increments. Arsenault, et al. [37] estimated that average child rice intake (120 g/d cooked) combined with a 12 mg/kg increase in Zn intake would reduce inadequacy by half. Other simulations (using FEA modeling) found diminishing returns beyond 45 ppm Zn, but strong linear benefits up to that point. Importantly, modeling assumes partial adoption (e.g. 20–50% of rice replaced by Zn rice); higher coverage yields proportionally larger population impact. Bio efficacy modeling further suggests that combining Zn rice with modest dietary improvements (e.g. some animal protein) can nearly eliminate Zn deficiency burdens. For instance, Hallett, et al. [39] used health outcome models to show that increasing rice Zn along with some dietary diversification could avert a substantial fraction of Zn deficiency-related morbidity and mortality.

1.8. Farmer Adoption and Consumer Behavior

As of 2018, zinc varieties occupied <1% of Bangladesh's rice area. Low awareness is a major bottleneck: surveys find that many farmers and consumers do not know about zinc rice or its health benefits. Harvest Plus and government reports indicate that lack of knowledge at all value-chain levels (farmers, traders, millers, consumers) is the chief barrier to scale-up. Physical seed availability is another constraint: until recently, zinc variety seed was distributed mainly as subsidies to select areas, so many farmers have never seen it. Economic incentives affect adoption as well. On the consumer side, preference experiments in rural Bangladesh reveal mixed signals. A randomized bidding study found that, when informed of nutritional benefits, rural consumers were willing to pay about 4–6% more for zinc-biofortified white rice over conventional white rice. In contrast, consumers strongly favor highly polished (white) rice: lightly-milled brown rice (which also carries more zinc) was discounted by ~14% (reduced to ~10% when nutrition information was provided). Among farmers, attitudes vary. A CGIAR case study reported that nutrition training of women farmers increased long-term cultivation of a high-zinc variety (BRRI dhan72). In a randomized controlled trial, female farmers receiving micronutrient education (vs control) were more likely to adopt zinc rice over the following seasons, though the effect waned over time. This indicates that improving knowledge of zinc nutrition can spur adoption. Other studies characterize adopters: early evidence suggests that early-adopting farmers tend to be larger, more educated, and more risk-taking than average. Yield and grain characteristics also influence adoption. Biofortified varieties must compare well to local checks. Zinc rice like BRRI dhan72 has yield advantage, which encourages farmers. However, some zinc lines are "coarse"-grained (e.g. BRRI dhan74 has a rougher texture), which could deter traditional consumers. To address this, breeders have released more "fine" zinc rice (e.g. other Aman varieties) to suit preferences. Price signals can also matter: if zinc rice were sold at a premium (Versus conventional rice), adoption might be limited. Marketing has mostly targeted poor producers who eat their own crop or sell to government programs, rather than relying on market-driven sales. In Bangladesh, novel approaches (Training women leaders, involving local NGOs) are being piloted. Importantly, one recent initiative prioritized "innovators and early adopters" in high-potential districts, distributing ~93 tonnes of zinc rice seed to 31,000 farmers in Rajshahi division. Such targeted efforts aim to create visible success stories to stimulate broader demand.

Translating biofortification into nutrition gains requires that farmers grow and consumers eat the varieties. Adoption has proceeded but faces barriers. A 2023 survey of farmers found that ~56% had heard of Zn rice and 48% tried growing it in 2021–22, yet 77% had received the seed for free. Reliance on free seed suggests market barriers. Importantly, adoption appears unstable: an impact evaluation [40] showed that among women farmers receiving Zn rice seed, 59% grew it in 2018 but only 8% by 2020. In auction experiments, Herrington, et al. [41] found that when informed of health benefits, Bangladeshi consumers were willing to pay a modest premium (~4.6%) for Zn biofortified rice compared to conventional rice milled to the same degree. Without information, willingness to pay was low; moreover, all consumers strongly preferred highly milled rice (discounting low-milled varieties by ~8–10%). This underscores a cultural challenge: brown or partially milled rice (which retains more Zn) is perceived as lower status. Adoption studies confirm the preference for traditional grain quality: some early Zn varieties were coarse, which limited appeal. However, there are signs of growing acceptance. Recent marketing emphasizes that Zn varieties (e.g. coarse BRRI dhan74, 24.2 mg Zn/kg) are high-yielding and have acceptable cooking qualities. Some targeted campaigns (Taste tests, branding) have shown positive consumer feedback on taste and appearance of Zn rice. The use of a special "Zn rice" logo on packaging (as done by GAIN and government) helps differentiate varieties and build recognition. Notably, even if consumers pay a small premium for nutrient-enriched rice, farmers might need incentives (higher price or yield) to continue planting. In Bangladesh, many farmers grow biofortified rice as part of safety-net programs: for example, Zn varieties were distributed via the Food Friendly and Vulnerable Women Benefit schemes. Surveys suggest up to half of farming households in some districts have grown Zn rice, but nearly all initial adoption was through free seed provision. This "free seed" model jump-starts awareness but risks collapse when subsidies end, as seen in the Valera trial. Thus, fostering a commercial seed supply (Seed companies, local multiplication) is critical. In summary, farmer adoption of Zn rice has begun but is fragile. High initial interest has been undermined by seed access and quality concerns. Consumers show some willingness to accept Zn rice if quality is maintained and benefits are communicated, but cultural preferences for polished grain pose a challenge. Continued extension, market development, and consumer education are needed to sustain uptake.

1.9. Policy Integration and Implementation Strategies

In 2024, the Ministry of Agriculture issued a notification that all crop varieties developed nationally "must be enriched with one or more nutrients," effectively mandating future varieties (including rice) to have higher micronutrient content. This directive institutionalizes biofortification and signals government commitment. Additionally, the Directorate General of Food (DG Food) has incorporated biofortified rice into public food security programs. Notably, biofortified rice is now procured for social safety nets: The *Food Friendly Programme* (targeting ultra-poor households) and *Vulnerable Women Benefit* (cash/voucher program) both include zinc rice in their supplies. In 2022, DG Food procured ~5,000 tonnes of zinc rice for these programs; by 2024 procurement expanded from 5 to 15 districts. This scale-up demonstrates the feasibility of public distribution of zinc rice. To differentiate products, GAIN also helped develop a "Zinc Rice" logo now required on seed packets, aiding identification and consumer awareness. On the supply side, government extension agencies (Department of Agricultural Extension, DAE) are actively promoting zinc varieties. Through a CGIAR partnership, DAE personnel have collaborated with NGOs to distribute seed and information. For example, in early 2025 a Harvest Plus/DAE project distributed 93 t of zinc rice seed to 31,000 producers (selected for their innovativeness) in Rajshahi. Over 25 sub-districts were covered in that event, with local officials praising farmers' resilience. Overall, Harvest Plus reports that over 2.45 million farming households received zinc rice seed samples by 2021. Private seed companies are also beginning to produce zinc rice seed, though formal seed sector involvement is still limited. Complementing these initiatives, NGOs and projects are working on demand creation. GAIN's biofortification program in Bangladesh conducts farmer field days, nutrition education (Especially for women), and works with microfinance groups to incentivize cultivation. Training materials (e.g. brochures, posters) explain that a 20–25 kg bag of zinc rice can meet ~60% of a woman's daily Zn needs. Behavior changes communication campaigns, including local video screenings and community meetings, emphasize child growth and maternal health benefits. On the consumer side, health clinics and schools are used to promote zinc rice: some primary schools serve zinc rice in lunches to demonstrate benefits. These multi-level strategies have begun to yield results: Bangladesh's zinc rice production has risen dramatically. In 2022, the Bangladesh Agriculture Development Corporation (BADC) produced and marketed 4,015 t of zinc rice seed (more than double 2021 levels), bringing cumulative seed production to ~6,350 t. That quantity of seed is sufficient to plant over 1 million tonnes of edible rice, highlighting that institutional efforts can generate significant scale. While still small relative to total rice production, this rapid growth (5,000 t procured in 2022 vs under 100 t in 2018) demonstrates accelerating momentum. In summary, zinc rice is now integrated into Bangladesh's policy and food systems via government mandates, public procurement, seed distribution, and education campaigns. The Ministry's nutrient mandate and DG Food programs ensures institutional backing. Implementation strategies have included free seed to lead farmers, extensive extension through DAE, NGO-facilitated training, and use of social safety nets as an anchor market.

Biofortified zinc rice has been explicitly integrated into Bangladesh's nutrition and agriculture plans. The government's National Plan of Action for Nutrition (NPAN-2, 2016–2025) sets clear targets: by 2018 aim to reach ~1 million households with biofortified crops, including Zn rice. The Ministry of Agriculture (MoA) has formally endorsed biofortification; in 2022 MoA mandated that all new crop varieties be enriched with at least one micronutrient. Nutrition and health ministries (via the Bangladesh National Nutrition Council) include Zn rice in national micronutrient strategies. Public procurement plays a key role: since 2022 the Directorate General of Food has procured Zn rice from farmers for distribution in national food programs. For example, 5,000 tonnes of Zn rice were procured in 2022, expanding to multiple districts. These purchases (at competitive prices) provide a guaranteed market for farmers, encouraging production. Distribution of Zn rice through social safety nets (e.g. food aid, schools, maternal programs) ensures consumption by vulnerable groups. Agencies like GAIN and Harvest Plus support these efforts, aiding with awareness campaigns and logistics. International and NGO partners contribute implementation experience. Harvest Plus and partners have distributed Zn rice seed to hundreds of thousands of households in Bangladesh (Aiming for 1 million by 2018). They have also generated evidence through trials and assessments (e.g. Nutrition Connect commercialization study, UNICEF pilot programs). The Global Alliance for

Improved Nutrition (GAIN) has spearheaded a "Commercialization of Biofortified Crops" project, helping establish supply chains, branding, and monitoring for Biofortified Zinc Rice (BZR) in Bangladesh. These programs have developed logos and demand-creation campaigns to raise public awareness. A recent study in Andhra Pradesh showed that an adequate amount of the free Zn is distributed to traditionally prosperous irrigated districts in contrast to regions where Zn deficiency is high [42]. Low awareness of the benefits of the application of micronutrients is a major reason for their reduced usage by farmers in India [43]. Raising awareness among farmers about soil micronutrients can change their price elasticity of demand and make price subsidies more effective [44].

Policy documents beyond NPAN include the Government of the People's Republic of Bangladesh [45] and sectoral strategies, which emphasize fortification and nutrient-dense foods. Biofortified rice is cited alongside other interventions (e.g. micronutrient powders, supplements) as part of a multi-pronged approach. At the global level, Bangladesh engages with the UN World Health Assembly and the Global Nutrition Report, citing biofortification as an "accelerator" for SDG2 (zero hunger) and SDG3 (good health). In summary, Bangladesh has embedded Zn biofortification into its policy framework and national plans. Success factors include high-level political commitment (ministerial mandates), integration with social programs and procurement, and active collaboration with international partners. Ongoing policy support is crucial to sustain extension, seed multiplication, and monitoring, as Zimbabwe's NPAN-2 set concrete targets for scaling. Bangladesh's experience illustrates both the promise and challenge of scaling Zn rice. Despite multiple released varieties and evidence of benefit, adoption has lagged. In 2018, only ~1% of the national rice area was planted to Zn-enriched varieties. Surveys of farmers show the key barriers: lack of seed availability is major, as most farmers still rely on free or subsidized seed distributions from NGOs or research organizations. In fact, a 2022 survey found that nearly half of farmers had never heard of Zn rice, and among those aware, under one-third truly understood its health benefits. Uncertainty about yields and unfamiliarity also deter farmers. Without a market premium or clear information on benefits, farmers tend to stick with tried-and-true varieties. Recognizing these issues, Bangladesh's policymakers and partners have rolled out targeted interventions. Since 2022, the government with support from development agencies (e.g. GAIN, Harvest Plus)—has prioritized Zn rice in official agriculture policy. A government mandate now requires that all newly released crop varieties be enriched with at least one nutrient. The Ministry of Agriculture and seed certification systems have streamlined release and seed multiplication of biofortified lines. Public distribution programs have incorporated Zn rice into safety-net schemes: for example, the Food Friendly (FF) program and Vulnerable Women Benefit program procure Zn rice and provide it to vulnerable communities. In 2022, about 5,000 tonnes of biofortified rice were procured for these programs, demonstrating logistical feasibility. Public investment has also funded farmer trainings and awareness campaigns. For instance, nutrition education for women farmers has been shown to boost demand: one study found that women receiving micronutrient training became more likely to adopt Zn rice, although adoption fell sharply when seed supply was limited. This suggests that continuous outreach (e.g. community nutrition training, farmer field days, radio programming) is needed alongside seed system strengthening. Private-sector engagement is nascent but growing. Millers and retailers are beginning to offer Zn rice as "nutritious rice," though lack of visible differences (Zn rice looks and tastes like white rice) means marketing requires clear labels and consumer education. Researchers have proposed incentives such as premium pricing for Zn rice or input vouchers for growers. Notably, a willingness-to-pay experiment in rural Bangladesh found that informed consumers would pay about 4–5% more for Zn-enriched rice (low-milled to retain Zn) than for ordinary white rice. This indicates latent market demand can be unlocked through information. Stakeholders in Bangladesh are also working to incorporate Zn biofortification into broader nutrition policy (e.g. the National Nutrition

Council's strategies) and to align it with fortification programs (such as fortifying other staples) for a multi-pronged approach.

1.10. Cost-Effectiveness and Economic Considerations

Economic analyses consistently find biofortification to be highly cost-effective, especially compared to other micronutrient interventions. Early ex-ante cost-effectiveness studies estimated the cost per disability-adjusted life year (DALY) saved for zinc rice in Bangladesh at roughly US$11–32, far below Bangladesh's per-capita income (~US$2,688) and below WHO "very cost-effective" thresholds. For context, fortifying wheat flour with zinc was estimated at $19/DALY meaning rice biofortification could be even more cost-effective in Bangladesh's context. These results stem from the low recurring costs of breeding once developed, the potential for large-scale diffusion through farmer networks (economies of scale), and the dual benefit of reaching both rural producers and consumers simultaneously. Globally, Harvest Plus reports that most biofortification interventions cost on the order of $15–20 per DALY, an order of magnitude cheaper than typical nutrition supplementation programs. Zinc rice benefits further from the high baseline rice consumption in Bangladesh: more dietary zinc gains per additional ppm. However, these analyses are ex ante (projected) and assume high coverage (e.g. 30–40% of country). Real-world costs will depend on the actual scale of dissemination and the duration of programs (biofortification requires initial R&D investment). As a check, an ex-post analysis of vitamin-A sweet potato in Uganda found costs of $15–24 per DALY, aligning with ex-ante expectations. Beyond DALYs, consumer willingness to pay (WTP) studies inform market viability. As noted, rural households would pay a small premium (~5–6%) for zinc rice if convinced it is healthier. For farmers, yield differences and market price are more important. No studies have found that zinc rice commands a higher market price in village markets (it is typically sold as "rice" without differentiation), so farmers have no disincentive price-wise. Seed is often distributed for free or subsidized initially. Thus, the main "cost" to farmers is opportunity cost of land and any difference in agronomic inputs (which is negligible). Some proponents argue farmers may benefit indirectly: if rice yields are higher (or similar) and they can save or consume more home-produced rice (rather than buy more expensive food for nutrition), their food security and income effectively improve. There is anecdotal evidence from program reports that farmers who grow zinc rice retain more for home use, potentially enhancing food availability and reducing market purchases, but rigorous studies of household economics are lacking. In summary, all evidence points to zinc rice as a very low-cost intervention to improve zinc nutrition. Cost-effectiveness metrics are extremely favorable, suggesting biofortification compares well to, or better than, alternative strategies (Fortification, supplementation). However, these figures should be interpreted with the understanding that ultimate cost-effectiveness depends on achieving high adoption and consumption. Current initiatives (Government and NGO programs) carry costs (Seed distribution, training, campaigns), but once zinc varieties are widely planted, the "per beneficiary" cost falls dramatically because no additional recurrent inputs (Like pills or fortificants) are needed. Future work should track actual implementation costs (for example, in ongoing scale-up projects) to validate these projections. Economic analyses consistently find biofortification to be a highly cost-effective nutrition intervention. Early ex-ante cost-effectiveness analyses by Harvest Plus/IFPRI estimated the cost per disability-adjusted life year (DALY) saved from biofortified rice is very low. For zinc in Bangladesh, Wessells and Brown [16] reported that biofortified rice costs about US$11–32 per DALY saved, far below fortification or supplementation alternatives (e.g. Zn-fortified wheat flour at ~$16 per DALY). They concluded that zinc rice is the most cost-effective long-term strategy to reduce Zn deficiency in Bangladesh. Other analyses [46] confirm that at expected adoption rates (Over decades), the health and productivity benefits (Fewer infections, better growth) greatly exceed program costs. In fact, in many scenarios biofortification yields cost per DALY of

$15–20, compared to the World Bank threshold (~GDP per capita, ~$2000), making it "very cost-effective" by WHO criteria. Recent Harvest Plus compilations similarly note that biofortification costs per person are low once varieties are released, since dissemination piggybacks on existing agriculture channels. Implementation costs include breeding, seed system support, and training, but yield indirect long-term gains. A World Bank–commissioned [47] projected that scaling Zn rice to 25% coverage in Bangladesh by 2030 would avert thousands of child stunting cases and save hundreds of millions of dollars in healthcare and productivity losses. Compared with other Zn interventions (fortification, supplementation), rice biofortification uniquely targets rural farmers consuming their own crop, often missed by markets, and does so continually each season at little extra cost to the consumer. Reports by Bangladesh's agriculture and planning ministries echo these findings. Biofortified rice is described as "cost-effective and sustainable" (Harvest Plus Bangladesh summary) because low-income people need not change behavior – they simply benefit from a more nutritious staple they were already eating. Implementation experiences show that, with government procurement support (As through public food programs), farmers get fair price for Zn rice while improvements in public health accrue without direct consumer payment. Although formal benefit–cost studies for Bangladesh specifically are limited, global models justify continued investment: the consensus is that every dollar spent on breeding and promotion yields many-fold returns in reduced disease burden. In sum, economic evidence strongly supports Zn rice as one of the most cost-effective micronutrient interventions for Bangladesh. Its costs per DALY saved are an order of magnitude below typical thresholds, especially when integrated into existing seed and food systems. Policymakers view this favorably, as reflected in the ministry mandates and inclusion in national nutrition budgets (Reflecting expected high return on investment).

1.11. Gender, Equity and Social Dimensions

Biofortification inherently targets populations that subsist on staple crops, which often correlates with poverty and rural livelihoods. In Bangladesh, women and children – especially infants and pregnant or lactating women – bear the brunt of micronutrient deficiencies. Women also play key roles as both consumers and producers of food. Integrating gender considerations can therefore amplify impact. For example, targeting women farmers for training and seed distribution leverages their influence on household diets. The aforementioned randomized trial of micronutrient training among women farmers showed that such interventions can raise Zn rice adoption rates (59% among trained vs 13% in controls at baseline), although the effect diminished as early adopters resumed other crops. This suggests that continuous engagement of women is needed to sustain adoption. Women's decision-making power and intra-household dynamics also affect whether biofortified crops improve nutrition. Studies in other contexts show that when women control more household resources and food preparation, their families are more likely to consume nutrient-rich foods. Thus, ensuring that biofortified rice is consumed at home (rather than sold) is crucial for impact. Some programs combine agricultural promotion with maternal health counseling or women's self-help groups to reinforce dietary diversity alongside Zn rice use. Ensuring equitable access also means reaching the poorest farmers, landless households, and marginalized communities who may lack information or credit to buy new seeds. Social safety nets help: by distributing Zn rice through programs targeting vulnerable women, the government directly delivers nutrition to an at-risk group. Gender-sensitive programming such as female extension agents, women-only training sessions, and addressing barriers specific to women (like mobility or literacy) can improve equity in uptake.

1.12. Climate Change and Food System Resilience

Climate change adds urgency to the biofortification agenda. Rising atmospheric CO2 levels and extreme weather threaten both the quantity and quality of staple crops. Experiments show that elevated CO2 reduces grain Zn (and Fe) content by up to ~3–17% across major cereals. Projections estimate that by mid-century climate change could push an additional 175 million people into zinc deficiency, disproportionately affecting South and Southeast Asia. In Bangladesh – a low-lying delta often hit by floods and cyclones – these trends risk worsening hidden hunger. Biofortified rice is one adaptation strategy: by breeding varieties that accumulate more Zn, biofortification can partly offset the nutrient losses due to climate stress. Crucially, modern Zn rice breeding programs are explicitly combining nutrient targets with climate resilience traits. Breeders stress-test Zn varieties in drought, flood, and disease-prone environments, selecting for heat and pest resistance alongside high Zn. The result is rice that not only feeds (higher yield under stress) but also nourishes (higher micronutrients). This climate-smart breeding supports food system resilience. From an agroecological perspective, Zn biofortification fits into a diversified nutrition-sensitive agriculture strategy. Promoting multiple nutrient-dense crops (e.g. Zn rice plus beta-carotene sweet potato) spreads risk: if one crop suffers a climate setback, others may still provide micronutrients. Additionally, good soil management (e.g. zinc-rich compost or reduced flooding to minimize Zn leaching) complements biofortification. At the policy level, linking biofortification with climate adaptation plans (e.g. Bangladesh's National Adaptation Programme) can mobilize financing and extension. Biofortified rice also integrates well with storage and transport improvements: since Zn is stable during storage and cooking, fortified rice varieties maintain their nutritional edge along value chains, enhancing the resilience of nutrient supply. Climate change threatens to exacerbate micronutrient deficiencies by reducing the nutrient density of staple crops. Elevated atmospheric CO_2 concentrations are known to decrease Zn concentration in rice grains. Developing Zn-dense, climate-resilient varieties therefore addresses both nutrition and adaptation goals. Biofortified rice can be bred for salinity tolerance and flood resistance, making it suitable for the coastal and flood-prone regions of Bangladesh. Incorporating Zn biofortification into national climate adaptation strategies strengthens long-term food system resilience.

1.13. Economic and Health Impact Modeling

Several studies have modeled the potential economic and health impacts of scaling Zn rice. Ex-ante cost-effectiveness analyses compare biofortification with other interventions. A seminal analysis by Fiedler and Lividini (cited in a Harvest Plus brief) estimated the cost per DALY (disability-adjusted life year) saved by Zn rice in Bangladesh. They found that Zn rice (grown and consumed by farmers) had a cost per DALY roughly one-third that of a hypothetical zinc fortification of wheat flour. In raw terms, biofortifying Bangladesh's rice could cost only US$11–32 per DALY saved, versus $19 for fortifying wheat with Zn. Across contexts, all such studies find biofortification to be "very cost-effective" (less than per capita income per DALY) in target countries. Notably, combinations of biofortification with conventional fortification often yield even greater health gains for a given budget. For Bangladesh, nutritionists have applied linear-programming diets to quantify Zn rice's dietary benefit. One analysis of rural Bangladeshi diet models showed that if households regularly consume a biofortified rice variety (~24 mg Zn/kg) instead of conventional rice, population dietary Zn inadequacy could decline markedly, especially among women and children whose intakes were previously lowest. This effect is amplified if rice is only modestly milled (retaining more Zn). In effect, Zn rice shifts the dietary Zn supply curve upward at near-zero additional cost to consumers. Although detailed health-impact evaluations are still pending (as wide adoption is recent), these modeling exercises indicate substantial potential gains in reducing stunting and infections at the national level. On the economic side, higher yields of Zn varieties can raise farmer incomes. If a Zn rice yields comparably or better than older varieties (as most new releases do), farmers face no tradeoff between nutrition and production indeed some prefer Zn varieties for their robustness. One study suggests that if one million Bangladeshi farmers adopted Zn rice on just 10% of their land, national GDP could grow by boosting labor productivity (due to healthier workers) and lowering health costs. A full cost–benefit accounting remains to be done, but given the low incremental cost of biofortified seed (no GM traits to license) and the limited need for additional inputs (especially once seed stocks are multiplied), the investment is expected to yield high returns in public health. Economic modeling suggests that biofortified Zn rice is one of the most cost-effective interventions for reducing micronutrient deficiencies. Compared to supplementation or industrial fortification, it requires minimal recurrent costs. By increasing productivity and reducing disease burdens, Zn rice indirectly contributes to higher household incomes and labor efficiency. Health impact assessments estimate that widespread adoption could reduce stunting and anemia prevalence, translating into significant gains in national GDP through improved human capital.

1.14. Parallels with Other Biofortified Crops

Zn rice is part of a broader global portfolio of biofortified staples. Lessons can be drawn from other success stories. For vitamin A, orange-fleshed sweet potato (OSP) has been a flagship crop. In Uganda and several African countries, distributing OSP vines led to large increases in children's serum vitamin A; children consuming OSP-rich diets showed significantly improved immunity and fewer vitamin-A-related blindness symptoms. Economic analyses there found cost per DALY of OSP to be very low (US$15–24), reinforcing its impact. Similar to Zn rice, OSP varieties were bred for farmers' preferences (drought tolerance, yield) while delivering nutrition. Importantly, targeting women (who often cultivate sweet potato) proved effective for uptake. For iron, biofortified beans in Rwanda and elsewhere are another parallel. Iron beans bred by Harvest Plus are higher in both iron and zinc. A randomized trial in Rwanda [48] showed that iron beans improved hemoglobin levels and cognitive function among women. Rwanda's bean program, which paired local breeding with strong market promotion, achieved ~20% of national bean acreage in biofortified lines at peak, with corresponding health gains. These examples highlight common themes: breeding nutrients into farmer-accepted crops, coupling with education (often targeting mothers), and leveraging community programs can achieve large-scale impact. They also caution that adoption slows if any link in the value chain fails (e.g. seed shortages, as seen in Zn rice and in early OSP efforts). Bangladesh's Zn rice initiative can thus learn from these cases.

1.15. Emerging Challenges and Evidence Gaps

Despite rapid progress, several challenges and uncertainties remain.

Adoption bottlenecks: Awareness is still low, and convincing information about zinc's health benefits must reach farmers and consumers. Qualitative reports highlight that the unknown "coarseness" of some zinc rice grains and initial skepticism hamper uptake. Although studies show consumers will pay for nutrition once informed, sustaining interest requires ongoing education. On the supply side, seed multiplication and distribution need scaling: currently a handful of CGIAR-affiliated and government schemes provide seed, but a robust private seed sector for zinc rice is only emerging. Ensuring seed availability (certified or quality-declared) across seasons is crucial; any seed shortage would stall adoption. Additionally, because rice markets in Bangladesh are fragmented and informal, monitoring and guaranteeing zinc content in marketed rice is difficult. The logo labeling (GAIN's "BZR" logo) helps, but stricter quality control may be needed as production grows.

Cost-effectiveness at scale: While models show high cost-effectiveness, actual costs of delivery (especially if commercial seed is sold rather than given free) are not fully known. Implementation may face diminishing returns: initial early adopters may be easy to convince, but reaching late adopters might require heavier subsidies. There is a need for updated economic analyses using real-world program data. Moreover, zinc rice competes with other nutrition interventions (e.g. wheat flour fortification, supplements). Policy-makers will want comparative benefit-cost ratios under budget constraints. To date, Bangladesh's program evaluations have not yet published such analyses.

Household-level food security impacts: An often-mentioned but understudied benefit of zinc rice is improved household food security. In principle, if farmers grow higher-yielding zinc varieties and retain more produce (since they do not need to buy as much rice), their household food availability can improve. Some program reports suggest this (e.g. farmers saving bags of rice for children's consumption), but no published study has measured changes in household food insecurity scores or dietary diversity. Future surveys could incorporate metrics like HDDS (Household Dietary Diversity Score) or HFIAS (Food Insecurity Access Scale) to capture this effect. Likewise, impact on total dietary diversity remains unknown: does reliance on a biofortified staple reduce or increase diversity? One can hypothesize that improved zinc status might boost appetite and diet variety, but evidence is lacking.

Nutrition outcomes beyond zinc: The RCT and models focus on zinc status and linear growth, but broader health impacts (immune function, morbidity reduction, cognitive development) have not been empirically assessed for zinc rice in Bangladesh. In theory, better zinc intake should reduce child illness (diarrhea, respiratory infection) and improve cognitive outcomes, but the Jongstra trial actually saw *more* respiratory infections in the biofortified group, a puzzling finding that needs exploration. Similarly, impacts on anemia (given potential concurrent iron) are unclear: zinc alone does not correct anemia, but improved immunity could reduce anemia of infection. Longitudinal studies or trials could measure these outcomes.

Target populations: Most current evidence is on young children. The impact on pregnant/lactating women, adolescents, and adult men is less studied. Given the high zinc deficiency prevalence in WRA, studies in these groups (like the ongoing trial in non-pregnant women) are essential. Pregnancy outcomes (birth weight, infant growth) are especially important since fetal development is zinc-dependent.

Integration with diet: Bangladesh diets are shifting (more urban, more processed foods). The models assume rice remains dominant, which is true for rural areas but may be less so for urban populations. If consumption patterns change (e.g. more wheat or maize intake), the impact of rice biofortification on overall nutrition must be reevaluated. Conversely, combining biofortified rice with other interventions (e.g. low-phytate rice, promotion of animal-sourced foods) could have synergistic effects.

Monitoring and data gaps: As zinc rice is scaled up, robust monitoring is needed. Currently, there is limited data on how many households actually consume biofortified rice regularly. Surveys could include questions on variety grown/consumed and measure rice zinc content at households. Without such data, it is hard to link production statistics (seed distributed) to actual nutritional coverage.

In summary, zinc rice has moved from research to pilot-scale implementation, but key questions remain. Overcoming adoption hurdles (awareness, seed supply) is top priority. Evaluating cost-effectiveness in practice and measuring broad benefits (beyond serum zinc) will strengthen the case. Addressing these gaps through targeted studies will help ensure that zinc biofortification achieves its full potential in Bangladesh's nutritional strategy.

While progress is encouraging, several challenges threaten the potential of Zn-biofortified rice in Bangladesh.

Food Processing and Bioavailability: The cultural preference for highly polished rice reduces dietary Zn intake. Studies show that extensive milling can remove 10–45% of grain Zn. Although biofortified varieties begin with higher Zn, lost retention remains a concern. One solution is promoting **lower milling degrees** (e.g. "lightly polished" rice) which retains more Zn; evidence from other crops suggests raising Zn and lowering phytate simultaneously can boost absorption. Another challenge is that standard parboiling may shift Zn from bran to endosperm better than traditional boiling, so scaling up improved parboiling could help. Without addressing processing losses and dietary inhibitors (phytate from legumes, unrefined cereals), the full benefit of breeding may not be realized.

Climate and Environment: Climate change poses a looming threat to nutrient content. Bangladesh's coastal salinization and droughts reduce yields and can alter grain nutrient composition. Salt stress tends to lower grain Zn, aggravating deficiency risk in vulnerable zones. Worse, elevated atmospheric CO_2 (projected in the coming decades) is empirically linked to reduced Zn (and protein and Fe) in rice and other staples. If unchecked, climate change could erode the micronutrient gains of bio-fortification. Breeders will need to incorporate stress tolerance (salinity, heat) alongside Zn traits. Agricultural policies must also mitigate climate impacts (e.g. salt-tolerant varieties, water management) to protect rice nutrition.

Varietal Performance and Yield Trade-offs: Although new Zn lines are high-yielding, farmers are sensitive to yield. Early qualitative reports indicated some farmers perceive Zn rice as lower yielding or less "popular grain type." Continuous breeding is needed to ensure Zn varieties meet agronomic and market standards (taste, aroma, cooking quality). Tools like genomic selection can accelerate combining Zn with desirable traits. Regular on-farm trials and farmer feedback loops will help identify and eliminate any yield drag or quality issues that could undermine adoption.

Awareness and Demand: Despite official promotion, public awareness remains incomplete. Many farmers and consumers still are unaware of Zn rice benefits. There is a risk of "nutrition fatigue" as excitement wanes. Sustained communication campaigns, aligned with maternal and child health messages, are needed. The adoption experiments showed knowledge by itself has limited long-term effect unless reinforced by tangible incentives (e.g. higher yield or price). Integrating Zn rice awareness into school curricula, community health programs, and agricultural extension can build ingrained demand. Consumer reluctance toward non-traditional rice colors (even faint browning from light milling) is another demand-side hurdle; branding, labeling, and certification (as piloted by GAIN) help here.

Supply Chain and Seed Security: Access to quality Zn rice seed is still patchy. Much of early dissemination relied on free giveaways; as those programs end, farmers may lack seed. Establishing a robust seed multiplication and distribution system (through public-private partnerships) is crucial. Some Zn varieties (like the coarse, fortified varieties) may appeal less to seed companies initially, so incentives or mandates (as the nutrient requirement for new varieties is implemented) will help. Seed potato-like models (e.g. seed fairs, mobile vendors) could expand reach in remote areas.

Monitoring and Evaluation: To maintain momentum, ongoing data collection is needed. Bangladesh lacks a routine indicator for Zn status; programs rely on proxies (e.g. anemia as partial Zn proxy) or ex-ante impact models. Incorporating Zn status modules into national surveys (e.g. DHS, nutrition surveys) every 5–10 years would show progress. Likewise, tracking coverage of Zn rice (area planted, households reached) should be embedded in agricultural statistics. The NPAN-2 targets provide a framework but require updated baselines. Research gaps remain on long-term health outcomes and interactions with other interventions (e.g. is Zn rice more effective than supplements or fortificants in Bangladesh's context?). Addressing these through cohort studies and economic evaluations will inform scaling strategies. Despite these challenges, the outlook is positive. Government and partners have shown strong commitment: e.g., including Zn crop enhancement in policy, launching public procurement, and collaborating with multiple stakeholders. Continuing innovation (higher-Zn genetics, low-phytate varieties), plus synergies with other nutrition-sensitive agriculture policies (diversification, fortification), can amplify impact. The success of Zn rice in Bangladesh an example of agriculture-driven nutrition improvement serves as a model for other countries. The key will be sustaining efforts, bridging adoption gaps, and adapting to new challenges like climate change, so that rural populations ultimately consume the intended quantities of zinc for better health.

2. CONCLUSIONS

Zinc-biofortified rice is a promising and cost-effective solution to widespread zinc deficiency in Bangladesh. Scientific advances including high-zinc varieties, proven bioavailability, and field trials showing improved child growth support its potential. Bangladesh has taken strong policy steps by distributing zinc-rice seed, procuring zinc-rich rice for safety-net programs, and requiring new rice varieties to include nutrient enhancements. Partnerships among government agencies, CGIAR/HarvestPlus, GAIN, and NGOs have boosted implementation. To fully realize the benefits, Bangladesh must continue scaling seed production, strengthening agricultural extension, and promoting consumer awareness. Further breeding of high-yield, high-zinc varieties, along with good agronomic practices like zinc fertilization, will help maximize impact. Monitoring dietary intake, health outcomes, and socio-economic effects is essential. With millions depending on rice daily, even modest increases in grain zinc could meaningfully improve public health. Bangladesh's progress positions it as a global model for biofortification and offers lessons for other rice-dependent countries fighting hidden hunger.

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