Madras Agric.J.,2025; https://doi.org/10.29321/MAJ.10.700SE1

REVIEW ARTICLE

Comprehensive Review on Grain Quality Enhancement and Development of Disease-Resistant Genotypes in Rice (*Oryza sativa* L.): Addressing Food Security Through Sustainable Agriculture

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ABSTRACT

Rice (*Oryza sativa* L.), the seed of life, holds immense nutritional, cultural, and medicinal importance, especially in Asia, where it serves as a staple food for over 90% of the population (Tripathi *et al*., 2020). While white rice is most commonly consumed, it loses significant nutritional components, such as fiber, vitamins, and minerals, during the refining process. In contrast, pigmented rice varieties—such as black, red, brown, and purple rice—retain their bran layers and are rich in essential nutrients, antioxidants, and bioactive compounds, including anthocyanins and γ-oryzanols. These properties make colored rice increasingly popular among health-conscious consumers for addressing micronutrient deficiencies, such as anaemia and zinc deficiency, as well as chronic diseases through its antioxidant intake. Biofortification to enhance zinc and iron content, coupled with improvements in protein (especially glutelin), starch quality, and fiber, is crucial for addressing malnutrition and supporting sustainable health outcomes. Equally important is managing the significant biotic stress—Bacterial Leaf Blight (BLB)—caused by *Xanthomonas oryzae* pv. *oryzae*, which has historically caused yield losses up to 80% and significantly affected grain quality. In India, major outbreaks have been reported in states like Andhra Pradesh, Haryana, Punjab, and Maharashtra. Management strategies encompass genetic, cultural, biological, chemical, and mechanical approaches, with genetic resistance being the most eco-friendly and sustainable. Over 40 resistance (R) genes (e.g., *Xa21*, *xa5*, *xa13*) have been identified, and marker-assisted selection and gene pyramiding have proven effective in developing resistant varieties such as IRBB60. These gene combinations not only provide long-lasting resistance but also preserve grain nutritional traits. Thus, integrating breeding programs for enhanced grain nutritional quality and robust disease resistance offers a dual strategy to improve rice productivity, ensure food security, reduce environmental degradation, and deliver health benefits to consumers. This approach aligns with global efforts to achieve sustainable agriculture and improve nutritional outcomes.

Received: 17 Aug 2025

Revised: 27 Aug 2025

Accepted: 03 Sep 2025

Keywords: *Oryza sativa, Grain quality improvement, Micronutrients, Bacterial leaf blight, Marker-assisted selection*

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INTRODUCTION

Rice is the second most widely consumed cereal crop and is the staple food for over 90% of the Asian population, due to its nutritional benefits, rich history, cultural significance, and medicinal properties. According to the Food and Agriculture Organization (FAO), the major rice-producing countries are China, India, Indonesia, Bangladesh, and Vietnam. These countries are responsible for more than 75 percent of the total rice production worldwide. White rice is widely consumed compared to colored or pigmented rice, even though it is found to be much less nutritious than colored rice. Colored rice possesses a unique color and flavor, and therefore, it is used as an ingredient in many dishes. Pigmented rice is gaining popularity among health-conscious food consumers due to its antioxidants, primarily because it is a rich source of bioactive compounds. However, due to the rising awareness among the population (primarily urban), the demand for pigmented rice is also increasing. Rice bran oil is a good source of essential fatty acids and antioxidants, including tocopherols (Vitamin E), tocotrienols, and ϒ-oryzanols, which have antitumor and blood cholesterol-reducing properties, and thus help prevent heart problems (Arunkumar *et al.*, 2025). According to Ayurvedic treatises, rice can alleviate or subdue the tridoshas (humors) – vata, pitta, and kapha – whose imbalance in the human body causes various types of diseases. Due to its dark colour, black rice bran contains the same anthocyanin antioxidants found in blueberries or blackberries. It has come to light that the population is facing various health problems like stunting, low fertility, anorexia, etc, due to Zn deficiency in their diet. These health and nutritional problems must be addressed urgently to achieve sustainable development goals, including reducing child and maternal mortality and improving overall health by providing a nutritious diet (Descalsota-Empleo *et al.,* 2019). Enhancing the zinc and iron content in rice through biofortification has become important. Alongside the grain quality of rice, it is also crucial to manage the destructive pest and disease cycles in rice to prevent yield losses that threaten the nation's food security. Bacterial leaf blight of rice remains one of the most destructive diseases affecting rice cultivation, as a result of which, drastic loss of production in terms of both quantity and quality can be observed. Therefore, developing rice varieties with improved grain nutritional quality, along with strong resistance to BLB, is equally important and should be prioritized in rice breeding programs.

Grain Nutritional Quality

Understanding the nutritional and chemical properties of rice grain is crucial for addressing nutritional deficiencies and improving human health. Rice grain contains carbohydrates (starch as the main component), proteins (glutelin being the major component), fiber, and various micronutrients like vitamins (vitamin B6, niacin, thiamin) and minerals (iron, zinc, magnesium, potassium, manganese). Each of these compositions is further discussed briefly below.

Carbohydrates: The Wide acceptance of rice in terms of its texture and cooking quality is dependent upon rice starch. The basic attributes associated with rice starch that have given it merit over other cereal and non-cereal starches include hypoallergenicity, digestibility, bland flavour, small granule (3-10 μm), white colour, greater acid resistance, greater freeze-thaw stability of pastes, and a wide range of amylose/amylopectin ratios (Fm, 2023). There are mainly three types of starch based on their rate of digestion: rapidly digestible starch, slowly digestible starch, and resistant starch. Their properties differ from one another due to variations in their amylose content. There are two main polymers in rice starch granules: amylose and amylopectin, along with some minor constituents, including proteins (0.25%), lipids (0.1-0.3%), and phosphorus compounds (Fm, 2023). CR Dhan 310 and CR Dhan 311 are two carbohydrate-improved varieties of rice developed by the ICAR-NRRI, Cuttack, through backcrossing.

Proteins: The major protein component of rice is glutelin (80%). Research has shown that various factors, including the selection of cropping season, location, climate, drying methods, and storage methods, affect the protein content. Protein content ranged from 4.5 to 15.9 per cent in *Oryza sativa* varieties and 10.2 to 15.9 per cent in *Oryza glaberrima* varieties (Muttagi, 2020). The low-expression alleles, *OsAPP6* and the *OsGluA2*^{LET}, are promising target genes for low PC rice breeding through MAS. (Gong *et al.,* 2006).

Micronutrients: Several micronutrients can also be found in rice grains, depending on the type of rice, soil, storage, drying, and milling methods. The mineral content of both black and brown rice is very similar. A serving of either rice meets 8% of the daily value for zinc and 20% of the daily value for phosphorus. However, black rice is a slightly better source of iron, meeting 6% of the daily value, compared to 5% in a serving of brown rice (Abdelsalam *et al.*, 2025).

Fiber: The fiber content found in white rice (0.5-0.1%) is usually lower than that of brown rice (3-4%). Red rice is known to be rich in iron and zinc, while black and purple rice are exceptionally high in protein and crude fiber (Abdelsalam *et al.*, 2025). Gene pyramiding, which involves combining multiple desirable genes into a single plant variety, is a strategic approach for improving fiber quality in rice.

Breeding Strategies to Enhance Nutritional Quality

To effectively enhance grain nutritional quality in rice, breeding strategies such as Marker-Assisted Selection (MAS), Genomic Selection (GS), and CRISPR/Cas9-based genome editing are being widely utilized:

- ***Marker-Assisted Selection (MAS):*** It enables the precise selection of key genes associated with high zinc, iron, and glutelin content, making it particularly useful for traits governed by known QTLs or single genes. For instance, *OsNAS1–3* (nicotianamine synthase genes) and low-expression alleles, such as *OsAPP6*, have been successfully targeted in MAS programs (Wang *et al*., 2013).
- ***Genomic Selection (GS):***It captures both significant and minor gene effects controlling nutritional traits like amylose content, starch structure, and micronutrient levels, and is efficient for improving multiple traits simultaneously (Zafar *et al*., 2023).
- ***CRISPR/Cas9 gene editing*** allows for highly specific improvements in genes involved in protein biosynthesis, phytic acid reduction, and antioxidant production, such as enhancing lysine content or knocking out anti-nutritional factors (Li *et al*., 2020; Fiaz *et al*., 2019).

These advanced breeding tools, when integrated with traditional selection, offer a practical, rapid, and sustainable way to develop nutritionally superior rice varieties.

Factors Affecting the Nutritional Quality of Rice Grain- Tolerance to Abiotic Stress

Maintaining grain quality in rice is crucial for enhancing both the qualitative and quantitative yield. The grain quality of rice depends on several factors, including genetic, environmental, and agronomic factors. The physical and chemical properties of rice grain can be affected by various abiotic factors, as stated below.

Soil: This is a crucial factor that can impact the quality of rice grains. An adequate amount of nutrient availability (such as nitrogen, phosphorus, and potassium) within the soil can interfere with the micronutrient content (essential vitamins and minerals) of the grain. The use of compost and green manure can be beneficial in enhancing soil health. Although rice cultivation has the potential in certain areas, the presence of salinity in coastal Asia makes it unsuitable for rice cultivation. Some varieties tolerant to saline soils include CSR10, CSR13, and CSR23, developed by the Central Soil Salinity Research Institute (CSSRI).

Climatic factors: Several climatic factors, such as rainfall, humidity, pressure, and temperature fluctuations, can influence the quality of starch and its nutrient content. With most high-yielding varieties being susceptible to drought, it serves as one of the principal abiotic stresses for farmers. Sahbhagi Dhan (IR74371-70-1-1) is a promising drought-tolerant variety developed through conventional breeding.

Irrigation: Water availability and its management practices help in maintaining nutrient uptake and can also directly affect the nutritional composition of rice grains. Water stagnation conditions can lead to iron deficiency.

Processing methods: Extreme milling processes can lead to the removal of the outer bran layer of rice, resulting in a loss of nutrients. Other processing factors, such as harvesting (including delaying the harvest), drying, and storage, can also affect the grain quality of rice. Appropriate storage of harvested rice grains can help to prevent nutrient loss and degradation.

Among the biotic factors, diseases (26%), insects (20%), and weeds (23%) are causing a large amount of yield loss, both in terms of quality and quantity (Shekhar *et al.,* 2020). Pest infestations and disease outbreaks are major issues faced by farmers in rice cultivation, resulting in yield loss. The severity of disease cycles is mainly observed at the booting and flowering stages. One such severe disease of rice, bacterial leaf blight, is further discussed below.

Bacterial Leaf Blight in Rice

The primary reason reported for yield loss (up to 26%) is due to diseases caused by the widespread spread of pathogens. There are many different diseases of rice, like brown leaf spot (*Helminthosporium oryzae*), leaf scald (*Rhynchosporium oryzae)*, false smut (*Ustilaginoidea virens*), bacterial leaf blight (*Xanthomonas oryzae* pv. *oryzae)*, etc. Among these, bacterial leaf blight (BLB) is the most destructive disease. Bacterial Blight is one of the oldest recorded rice diseases, first identified by a farmer in the Fukuoka area of southern Japan in 1884 (Nino-Liu *et al*., 2006). In 1990, BLB was named as *Xanthomonas oryzae* pv. *oryzae.* In Japan, this disease has been referred to as “white withering disease” since 1881, when it was previously recorded in various localities of southern Japan (Shekhar *et al.,* 2020). The most important rice-growing states, *viz*., Andhra Pradesh, Punjab, Haryana, and western Uttar Pradesh in India, a major epidemic of this disease occurred during 1979-1980 (Shekhar *et al.,* 2020). The damage caused by this disease was significantly increased due to the widespread cultivation of semi-dwarf and hybrid rice varieties, as well as the massive input of nitrogen fertilizer (Jiang *et al*., 2020). Bacterial leaf blight disease can significantly reduce the nutritional quality of rice grains by directly affecting the starch and nutrient content. The *Xanthomonas oryzae* pv. *oryzae* survive on different hosts, *viz. Brachiaria mutica, Cenchus ciliaris, Cyperus difformis, C. rotundus, Cynodon dactylon, Echinochloa crusgalli, Leersia spp* (*Leersia hexandra, Leersia oryzoides*), *Leptochloa chinensis, Panicum maximum, Zizania aquatica, Z. palustris, Leersia. Oryzoides* and *Zizania latifolia* in the temperate region and *Laptochloa* spp. and *Cyperus* spp. in the tropical region (Shekhar *et al.,* 2020). Exploitation of host plant resistance is considered the most effective, economical, and environmentally safe measure for controlling BLB in combination with management practices (Singh *et al*., 2015).

Symptoms

Bacterial leaf blight is a vascular disease caused by *Xanthomonas oryzae* pv. *oryzae* can significantly affect the crop production and overall yield. The pathogens can enter the host through openings, such as hydathodes, and also through wounds present on the plant’s surface. BLB pathogens cannot enter through stomata. It divides epithelial cell and moves into the xylem vessel. Kresek and leaf blight are the significant symptoms observed in the affected crops. Kresek is typically observed during the tillering stage. In the Kresek phase, due to the blockage of nutrient transfer from the root to different parts of the plant, pale yellow symptoms appear and finally result in wilting of the plant (Shekhar *et al.,* 2020). High humidity, rainfall, and high temperature are favourable conditions for the occurrence of leaf blight. The most favourable temperatures for *Xoo* growth range from 26-30 °C, and 20 °C is the ideal temperature for initial multiplication and growth (Shekhar *et al.,* 2020). The symptoms of leaf blight begin as small, water-soaked stripes from the tips, where water pores are located, and rapidly enlarge in length and width, forming a yellow lesion with a wavy margin along the edge (Shekhar *et al.,* 2020). The sign of *Xanthomonas oryzae* pv. *oryzae is a bacterial ooze and can be seen on the margins or veins of a freshly infected leaf under moist conditions in the morning hours, and it is a source of secondary inoculum (Nino Liu et al.,* 2006). This disease is more likely to occur during the monsoon season in the south-eastern Asian and Indian Ocean regions, particularly from June to September (Shekhar *et al.,* 2020).

Leaf Blight Resistance in Rice

Several management practices, such as pesticide application, crop rotation, balanced fertilizer application, and field sanitation, have been utilized to control BLB, but none of these were 100% effective. This is the main reason why the idea of developing new resistant varieties of rice has come into light. There are more than 40 resistance genes (R genes) that have been identified as dominant against BLB of rice caused by *Xanthomonas oryzae* pv. *oryzae* (*Xoo*). Representatives of a significant class of resistance genes (R genes) against the disease that are prominent in rice are designated with the prefix *Xa* for *Xanthomonas* (Shekhar *et al.,* 2020). The R gene *Xa21*, originating from the wild rice species *Oryza longistaminata*, has provided potential resistance against the bacterial pathogen *Xanthomonas oryzae* pv. *oryzae.* Overexpressing the *Xa21* gene in rice plants builds resistance at both the seedling and adult stages of the plant lifecycle.

Although it has been well known that most plant R genes are dominant, recessive genes have also been recognized in many host-pathogen interactions. Of these, 3 (*xa5*, *xa8,* and *xa13*) occur naturally and confer race-specific resistance (Shekhar *et al.,* 2020). The alleles of the recessive resistance gene *xa13*, identified by gene map-based cloning, occur naturally for resistance to *Xoo* isolates (Yang *et al.,* 2006). Genotypes carrying the *Xa21* and *xa13* resistance genes have successfully shown low disease incidence and superior grain protein quality. By developing resistant varieties with the help of resistant gene combinations like *Xa4* + *xa5, xa5* + *xa21,* and *xa4* + *xa5* + *xa2l, a mindful strategy can be employed* to tackle the problems of bacterial leaf blight disease. Marker-assisted breeding strategy has also been found advantageous in enhancing the resistance of elite cultivars (*e.g., Swarna and IR 64) to bacterial leaf blight by pyramiding specific resistance genes (xa5, xa13,* and *Xa21*) through backcrossing (Shekhar *et al.,* 2020). The resistance gene *xa13*, derived from landrace BJ1 of the Indian subcontinent, is effective both individually and in combination with *Xa21, xa5, Xa4,* and *Xa2* against many pathotypes of *Xoo* (Lore *et al.,* 2011).

The major constraint after the deployment of these R genes is that pathogen populations evolve rapidly to overcome the resistance (Shekhar *et al.,* 2020). Therefore, it is essential to continue finding measures to control bacterial leaf blight disease in the rice crop. IRBB60 variety of rice developed by IRRI, incorporates four BLB resistance genes (*Xa21, xa13, xa5, Xa4*).

CONCLUSION

As discussed in this study, enhancing grain nutritional quality—such as increasing protein content and enriching micronutrients like iron and zinc—alongside developing resistance to bacterial leaf blight (BLB) is crucial for both the quantitative and qualitative improvement of rice crop production. These advancements are crucial to ensuring national food security and delivering better dietary value, thereby improving public health. High-quality rice grain is a vital source of carbohydrates, proteins, fiber, vitamins, and minerals, contributing significantly to balanced diets and overall nutritional well-being. Among the different types, colored rice varieties are superior to non-colored ones in terms of nutritional composition, as they contain a higher concentration of micronutrients and antioxidant compounds. Several studies suggest that black rice exhibits higher scavenging activity compared to red rice, while non-colored varieties possess relatively lower levels of phenolic content and antioxidant activity. Developing resistance to BLB, caused by *Xanthomonas oryzae* pv. *oryzae* (Xoo)—one of the most destructive rice diseases—is essential for minimizing economic losses and maintaining consistent crop yields. The integration of genetic resistance strategies provides a sustainable and environmentally friendly solution for managing BLB, while also enhancing grain quality. In conclusion, the dual approach of enhancing grain nutrition and BLB resistance can significantly benefit consumers by improving their health, support farmers by increasing income stability, reduce the risk of crop failure, and contribute to national food security.

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