



Perspective

Developing green nutritious super rice for a healthy Anthropocene

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Rice is a mainstay of food security for more than half of the global population. For thousands of years, rice as a staple food has provided mainly calories for the human population, and it has been produced with heavy resources and environmental costs, especially in recent decades. Based on the development of Green Super Rice (GSR), which aims to greatly reduce pesticides, fertilizers, irrigation and other resources in rice production while providing high yield and quality [1], we propose to modify the deeply rooted conventions by developing Green Nutritious Super Rice (GNSR) to enhance human nutrition and health. Here we outline the concept, goals, and potential significance, and suggest a technical strategy for developing GNSR assuming the prototype of whole grain black rice (WGBR).

Food security in the contemporary age. Food security has always been of paramount importance worldwide. Food security should be considered as an evolving concept. Currently, three issues must be addressed for the harmonic coexistence of humanity, agriculture, and nature. The first is the quantity of food to meet the world population's demand, which is projected to be around 10 billion by 2050. Numerous predictions have suggested a need for up to a 70% increase in food production by the mid-century compared with the beginning of this century (<https://www.fao.org/4/ap106e/ap106e.pdf>). The second is dietary quality for promoting healthy life, including nutritional adequacy and prevention of non-communicable diseases, which has become increasingly important with the social economic development in many parts of the world. The third consideration is the resource and environmental sustainability of food production. Thus, food security

requires adequate foods, in quantity, quality, and variety, that are healthy for both humanity and the planet.

Willett et al. [2] addressed these issues of food security in alignment with the United Nations' Sustainable Development Goals and the Paris Agreement for climate change. They comprehensively evaluated the health effects of various food products including cereals, vegetables, legumes, fruit, oils, nuts, meat, fish, and dairy products etc., and the environmental impacts associated with their production. They provided scientific targets for healthy diets that would also be benign for the environment. Based on these considerations, a healthy reference diet is recommended to primarily consist of vegetables, fruits, whole grains, legumes, nuts, and unsaturated oils; a low to moderate amount of seafood and poultry, and a low quantity of red meat (but no processed meat), and limited amounts of added sugar, refined grains, and starchy vegetables. They specifically emphasized the importance of whole grains in healthy diets. Thus, diets in line with this recommendation would be healthy for humanity and beneficial for resource and environmental sustainability, thereby ensuring better food security.

From Green Super Rice to green agriculture. The development of GSR was initially intended to tackle problems in rice production in China, a country with an annual yield accounting for 30% of the rice worldwide. For a long time, China has been able to feed 20%–22% of the world's population with only ~8% of the world's arable land, but used >35% of the pesticides and fertilizers produced worldwide. Such a mode of agriculture resulted in high costs in food production and heavy environmental pollution, threatening food safety and resource- and environmental sustainability.

To lessen this tension, Chinese scientists proposed the concept of Green Super Rice (GSR) at the beginning of this century [3]. GSR is characterized by its high yield potential, adequate resistance

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to pests and diseases, tolerance to abiotic stresses including drought, high/low temperature etc., and efficient use of water and nutrients (Fig. 1a). These traits were acquired by incorporating genes of interest from natural rice germplasm, using genomic selection tools (Fig. 2a). Over the past two decades, hundreds of GSR varieties have been developed by integrating traditional breeding methods and functional genomic breeding approaches. The deployment of GSR enables farmers to produce more rice with substantial reductions in pesticides and fertilizers, thereby lowering production costs and minimizing environmental footprints [1]. GSR varieties have helped cope with the impacts of climate change, such as drought and heat extremes, which are becoming increasingly common in many rice-growing regions in China and many African and Asian countries. Moreover, GSR has played a role as a model for developing “green” varieties of other crops, and led the way for China’s green agricultural production system [4].

Climate change and greenhouse gas emissions will significantly impact future food production worldwide. As a response, GSR was suggested as an example of scientific solutions to the challenge of “Nourishing ten billion sustainably: resilient food production in a time of climate change” by the Royal Society for the United Nations Climate Conference 26 (<https://royalsociety.org/topics-policy/projects/climate-change-science-solutions/>). The primary goal of GSR, e.g. “less input, more production, and a better environment”, has now been widely accepted and integrated for the genetic improvement of many crops globally.

Whole grain black rice (WGBR) has the potential to make significant contributions to human nutrition and health. Since ancient times, rice has been a staple food that provides a major portion of calories for human society at a low cost, with the starchy endosperm as the food source. It is not generally recognized that the rice endosperm can also provide significant absolute levels of selected minerals and vitamins in diets due to the relatively high volume of rice consumption. Unfortunately, with the socioeconomic development in recent decades in many parts of the world, especially China, the pursuit of “sensory joy” (i.e. palatability) has pushed the rice grain to be even more refined, leading to very low consumption of whole grain. Consequently, insufficient whole grain consumption has become one of the leading causes of all-cause mortality and reduced disability-adjusted life-year (DALY) globally [5]. In particular, China has suffered the highest age-standardized rate of diet-related cardiovascular disease deaths and the highest rate of diet-related cancer deaths and DALYs [5].

An equally serious health issue is malnutrition because of inadequate nutrient intake, which occurs widely, affecting billions of people, especially in low and middle-income countries [6]. Yet over time seeking ever higher yields, plant breeding has continuously lowered the density of minerals and vitamins in the rice endosperm [7]. Health and nutrition experts identified deficiencies of Fe, Zn, Vitamin A (VA), and more recently also included folate, as the primary cause that can lead to serious health issues inflicting over two billion people globally [6,8]. Thus, an international biofortification program, HarvestPlus, was launched to enhance Fe, Zn, and VA in seven major food crops, including rice [9]. In the past two decades, significant success has been achieved in developing and utilizing biofortified varieties in several targeted regions, but so far only for single nutrients for each staple crop [9]. We estimate that these two health issues, noncommunicable diseases and malnutrition, may affect more than half of the global population in the coming decades.

The whole grain of any cereal consists of the pericarp, seed coat, aleurone, embryo (germ) and endosperm (Fig. 1b). In contrast, refined grain (e.g. polished white rice) retains only the endosperm. In many large studies, whole grain consumption has been associated with lowering risks of all-cause and cause-specific mortality for many diseases, including cancer, cardiovascular disease, coro-

nary heart disease, stroke, diabetes, respiratory disease, infectious diseases and the nervous system disease; adequate intake of whole grains has been estimated to potentially reduce the risks of these diseases by over 30% [10]. This is because insufficient whole-grain intake, or high intake of refined grain, can lead to insulin resistance, which is highly associated with almost all noncommunicable diseases.

Pigmented rice, especially black rice as a whole grain, is rich in diverse nutrients in addition to starch, including proteins, dietary fiber, essential fatty acids, vitamins, mineral elements, and many bioactive compounds [11]. Anthocyanins, synthesized in the pericarp and seed coat of black rice, can offer many benefits that promote human health and longevity [12]. A recent nutriomic assay of WGBR, in comparison to whole grain white rice (WGWR) and their refined counterparts, showed that WGBR can make a comprehensive and rich source of nutrients for human health [13]. Based on the recommendation of 232 g/d for an average active male (weight 70 kg) or female (60 kg) aged 30 yr [2], and according to the dietary reference intake (DRI) of the Chinese Nutrition Society [14], WGBR can provide (on average) 63% of the DRI for dietary fiber. Also, WGBR can supply adequate, or major portions, of the DRIs for all essential mineral nutrients. WGBR can provide 51% of vitamin B-1, and significant portions of vitamins B-2 (17%), B-3 (6%) and B-6 (10%), and 24% of vitamin E and 15% of choline. WGBR is a rich source of bioactive compounds, including 430% of the DRI for anthocyanins [13] and many others. In particular, the β -carotene content at the high end of black rice accessions is comparable to the biofortified “golden rice” and, thus, can contribute up to 33% of the vitamin A DRI requirement. Notably, the average content of Fe and Zn in WGBR is comparable to the targeted levels of these two nutrients for rice in the HarvestPlus project, in addition to a high content of β -carotene.

Given its nutritional value, consumption of WGBR in adequate amounts can contribute important nutritional value and health benefits. Moreover, consuming WGBR would increase by $\geq 20\%$ the edible portion of the rice grain, compared to refined rice thereby amounting to a large yield increase, while also contributing to the major nutritional value of the rice.

Efforts have been made to promote black rice as a nutritious staple food. Currently, rice produced from black rice varieties is difficult to cook and has poor palatability. Recently, breeders at Huazhong Agricultural University have bred a new black rice variety called Huamoxiang 3 that is characterized by high and balanced nutrients in the whole grain, with yields between 5.5 and 11 tons/ha—depending on the production conditions [15]. The grain is easy to cook, has pleasant palatability—receiving high tasting scores comparable to some of the world’s most popular refined rice varieties [16], and has gained favorable responses from consumers. Based on these new developments, the concept of a “Cooking and Steaming Type of Whole Grain Black Rice” was proposed to fill the gap required by consumers to consume rice that does not only provide energy, but is also healthy with respect to its added nutritional content. The availability of such rice cultivars provides the opportunity to unlock the nutritional treasures of black rice for humanity.

Breeding Green Nutritious Super Rice (GNSR). Concept and goals of GNSR. Here we propose that GNSR be developed to meet the future needs of the rice industry and to promote human health for a better planet. To achieve our vision, GNSR should possess the following characteristics: (1) high and stable yields (Fig. 1a); (2) traits for green agriculture including resistance to biotic and abiotic stresses, and other traits that facilitate production with reduced cost and input that benefit the environmental and resource sustainability (Fig. 1a); and (3) whole grain, presumably WGBR that produces anthocyanins in the pericarp and seed coat. WGBR would thus become a healthy and nutritious staple food

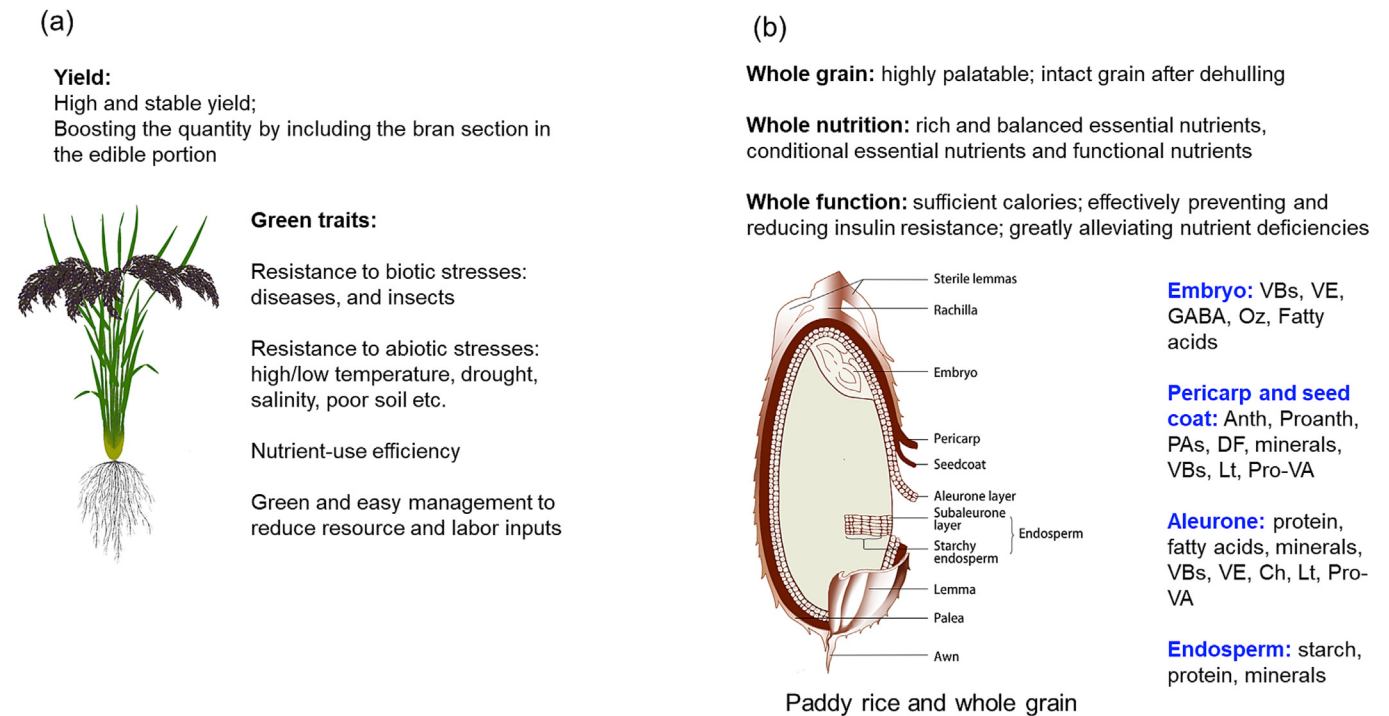


Fig. 1. Traits and goals defined for Green Nutritious Super Rice (GNSR). (a) The traits targeted in the GNSR breeding for high and stable yield and for green agriculture. (b) Definition and targets of *whole grain*, *whole nutrition* and *whole function* based on WGBR. The following nutrients are detected in WGBR at quantities significant for human nutrition [13]: anthocyanin (Anth), B vitamins (VBs), β-carotene (Pro-VA), choline (Ch), dietary fiber (DF), γ-aminobutyric acid (GABA), γ-oryzanol (Oz), insoluble phenolic acids (PA_IN), lutein (Lt), L-carnitine (L-car), phenolic acids (Pas), proanthocyanin (Proanth), soluble conjugated phenolic acids (PA_SC), soluble free phenolic acids (PA_SF), and vitamin E (VE).

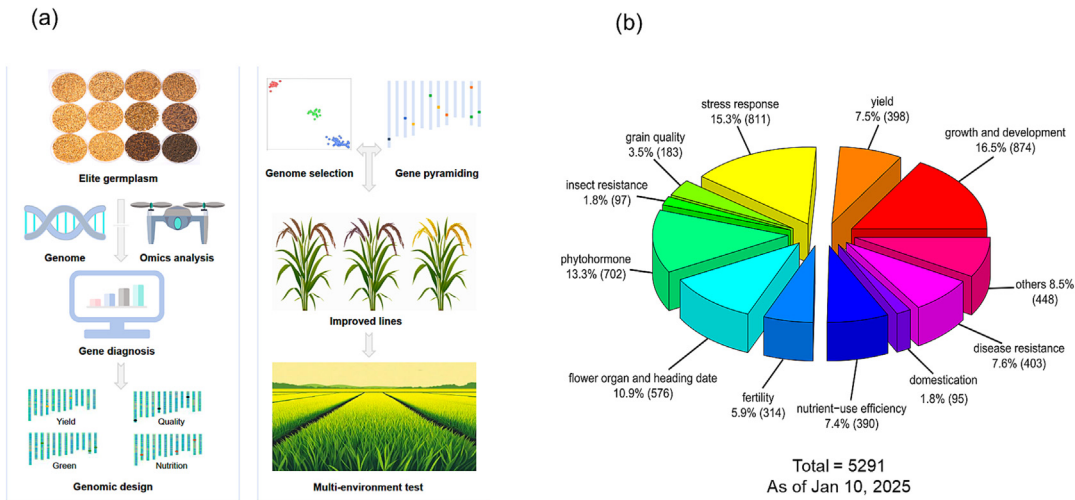


Fig. 2. Genomic breeding of GNSR. (a) Schematic representation of design and implementation of genomic breeding for GNSR. (b) Genes identified in rice functional genomic research by international scientists. Graph showing the number of rice genes functionally characterized in the published literature on PubMed data accessed and analyzed using funRiceGenes [18] on Jan 10, 2025.

as opposed to the endosperm only, and would thereby provide a rich and broad spectrum of balanced nutrients (*whole nutrition*), and *whole functions* in promoting human health (Fig. 1b). High and stable yield refers to yield levels comparable to or higher than the common white rice varieties bred for the same rice-growing regions during the same growing periods. More notably, the inclusion of the bran section (including pericarp, seed coat, aleurone, and embryo) in whole grain rice would considerably boost the quantity in the supply side compared to fine refined grain.

Traits for green agriculture confer to rice varieties the resilience to cope with the varying climate and environmental conditions, including resistance to biotic and abiotic stresses. Biotic stress refers to major diseases and insects that differ from one rice-producing region to another, and rice varieties would be bred for resistance needed in specific rice-producing regions. Abiotic stresses include drought, salinity, and high/low temperatures, especially at the reproductive stage. In addition, nutrient (N, P, and K)-use efficiency should also be incorporated to reduce fertilizer applications. Due to the increasing labor scarcity, there is also a pressing

need for direct seeding, requiring anaerobic germination. Furthermore, GNSR may also include favorable traits for green agriculture or simplified cultivation practices with reduced labor input and environmental impact.

The goals, as defined by *whole grain* traits, are multi-fold (Fig. 1b). Firstly, superior sensory and cooking quality should be a default setting for new whole grain varieties; grain intactness without damage in processing, should include the pericarp, seed coat, aleurone, germ, and endosperm (Fig. 1b). Secondly, whole nutrition refers to the broad spectrum and richness of balanced nutrients in whole grain rice, especially WGBR, including proteins, fatty acids, dietary fiber, vitamins, minerals and diverse bioactive compounds. These nutrients can be classified as essential nutrients, conditionally essential nutrients, and functional nutrients that would promote human health and longevity. Thirdly, the whole function of whole grain for human health may be achieved from two prospects. The first is to greatly reduce the development of metabolic syndrome and risk of type 2 diabetes, which have plagued billions of people, in part due to the high consumption of refined grain. This functional goal can be achieved by decreasing insulin resistance by reducing glycemic load and enhancing insulin sensitivity; this is supported by dietary fiber, unsaturated fatty acids, a reduced glycemic index, and potentially other minerals and phytochemicals that are characteristic of WGBR. Reduction of the glycemic index and increasing fiber by shifting from refined to whole grains can also facilitate long-term weight control [17]. By reducing insulin resistance, the incidence of many major chronic diseases would be significantly reduced [10]. Also, the rich and diverse nutritional composition of WGBR would alleviate malnutrition due to various nutrient deficiencies [6,8], including Fe, Zn, and VA deficiencies as targeted by the HarvestPlus project.

Genomic breeding of GNSR. The first step of GNSR breeding is the genomic design of the target traits for the rice varieties (Fig. 2a). For a specific rice-producing region, the design should consist of the following components: (1) phenology and the targeted flowering time, (2) yield level and associated agronomic traits, (3) resistances to the biotic and abiotic stresses that cause crop loss in the region, and (4) nutrient content in the whole grain. The parental lines, including the core parents of breeding programs and donors for specific traits, should also be included as a design feature. In particular, the target genes for breeding programs should also be listed to match the traits, breeding scheme, and procedures (Fig. 2a).

International rice functional genomic research over the past two decades has identified and characterized thousands of genes for various traits and for a range of biological processes (Fig. 2b) [18]. This effort has provided a solid basis of genes and resources for GNSR breeding, including genes for yield traits and flowering time; resistances to diseases and insects such as fungal blast, bacterial blight, and brown planthoppers; abiotic stresses such as heat/cold, drought and water-use efficiency, and nitrogen-use efficiency; and also, traits for grain quality in the traditional sense based on milled rice. However, genes for some important traits such as resistance to insects like stemborers and leaf-folders, and diseases such as false smut are still not yet available. More importantly, there have been minimal functional genomic studies of whole grain quality traits. Thus, very few genes are available for the genetic improvement of these classes of traits.

Precise improvement of traits with known causative alleles or genes from diverse genetic resources has been realized in GSR breeding [19]. With an elite cultivar as a starting point, a pre-breeding procedure, such as a backcrossing scheme, can be performed using functional markers and genome-wide SNP arrays (Fig. 2a). Many sets of near-isogenic lines (NILs) or pre-breeding lines, each carrying a gene of interest, are generated in a similar

elite genetic background. These NILs can be used directly as improved lines for varietal testing or as intermediate genetic stocks for stacking beneficial alleles to develop GNSR varieties according to specific breeding goals.

Gene-editing techniques provide a powerful tool that can be used for directing the mutation of specific genes, manipulating multiple genes, and targeted replacement in rice. New tools such as artificial intelligence can aid in predicting the potential effects of gene variants and refining traits for optimal gene stacking or editing. All these approaches can further accelerate genomic breeding, from designing to implementation of breeding GNSR.

However, there are still many challenges in GNSR development. In particular, we still lack basic knowledge about biosynthetic pathways and complex interactions for many nutrients in grains. Understanding the coordinated mechanisms and genetic regulatory networks is crucial for improving multi-traits in GNSR development. Specifically, multi-omics approaches should be used to explore the genetic variations of the various classes of nutrients, metabolites, and bioactive compounds; germplasm from diverse sources, populations, and crop wild relatives should be investigated to discover valuable traits and genes.

Secondly, the benefits of many nutrients or phytochemicals on the growth and development of the plant itself and human health have been largely unexplored. In particular, studies involving large human cohorts and animal models are urgently needed to understand the potential impact and mechanism(s) of how cereal metabolomes act on human health.

Lastly, adopting a new type of food depends not only on the product *per se*, but also on human culture, culinary preferences, market development, and farmer capacity building. The long-standing consumer preference for highly polished rice poses a serious hurdle in promoting the widespread adoption of whole-grain rice. Educating consumers about the health benefits of nutritious whole-grain rice and providing them with creative recipes and cooking techniques may help shift this preference. Engaging the culinary leadership may also enhance the prestige and desirability of whole grain rice.

Conclusion and Perspective. There are many potential synergistic and beneficial impacts for the use of WGBR as staple food: (1) strengthening the nutritional value of rice to improve human health, (2) enhancing food security through consumption of the entire grain as opposed to polished rice, (3) reducing the pressure for higher yield thus offering more options for green development for resource- and environmentally sustainable agriculture and, (4) increasing the benefit to rice farmers because of potentially higher prices than conventional white rice, thus making rice production a more attractive industry.

Here we advocate that WGBR become the primary staple food for rice-consuming communities, echoing that proposed by Zhang [20]. Such a change may present a new paradigm for the harmonic coexistence of humankind, agriculture, and nature. However, the realization of such a goal needs concerted actions, including policy support, public education to increase awareness and knowledge across society, cross-disciplinary research involving scientists in different countries, integrating plant science and breeding, food, and nutrition, and health and medicine to advance the scientific frontiers, and industry to produce and promote healthy and nutritious rice products to consumers. The recent development of the “National Whole Grain Action Plan (2024–2035)” has provided very encouraging signals for such movement (https://www.lswz.gov.cn/html/tzgg/2024-12/24/content_285634.shtml).

Conflict of interest

The authors declare that they have no conflict of interest.

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