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The whole grain manifesto: From Green Revolution to Grain Evolution

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ABSTRACT

Grains have historically represented a major component of human diets and were predominantly consumed in whole form until the first half of the 19th century, when a combination of technological innovations and market dynamics made refined grains, hitherto a premium product, affordable and available to the masses. Grains still account for more than half of the total caloric intake among vulnerable populations worldwide, and their dominant consumption in refined form turns a nutrient-dense, protective food into a nutrient-poor one contributing to growing rates of obesity and noncommunicable disease. Shifting a substantial portion of global grain consumption to whole grains is potentially one of the most significant and achievable improvements to diets and food systems worldwide. In countries with significant micronutrient deficiencies, a switch from refined to fortified whole grain foods can enable institutional channels such as school feeding programs to measurably improve diet quality in a budget-neutral way.

1. Introduction

1.1. Historical perspective: the legacy of four revolutions

Four technological revolutions have defined the diets consumed by today's global population and their underlying production systems. The **First Agricultural Revolution** (Neolithic Revolution, dating back to 10,000 BCE) marked humanity's transition from hunter-gatherers to the emergence of agriculture and human settlements. Wild varieties of cereals such as wheat and barley, which had already been harvested for millennia, were domesticated and gradually bred for desirable traits. The **Second Agricultural Revolution**, referred to as the British Agricultural Revolution (mid-17th to late 19th centuries), established the technological and agronomic foundations of modern food production systems, and freed up labor for the **Industrial Revolution**. Machinery including threshers, steam mills, and roller mills made industrial processing competitive by increasing the yield and shelf stability of staple grains compared to traditional milling methods. Finally, the **Green Revolution**, ongoing since the 1940s, successfully increased the yield, availability, and affordability of the "big three" crops – maize, wheat, and rice – in low and middle-income countries, reducing the frequency and severity of famines and improving global food security. Productivity gains were primarily achieved through technological innovations – high-yielding varieties, chemical fertilizers, pesticides, irrigation, and improved agricultural practices – supported by government policies.

These successive revolutions brought multiple gains and decreased the incidence of famines, but have inadvertently contributed to important losses in biodiversity, dietary diversity, and system resilience. Since the 1900s, nearly 75% of plant genetic diversity has been lost as farmers worldwide have left their local varieties and landraces for high-yielding,

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genetically uniform varieties. Of the 27,000 known edible plant species (French, 2019), only about 200 are consumed by the world population in any significant amount, with rice, maize and wheat contributing nearly half of the total caloric intake (Hunter et al., 2020). Primarily due to the combination of consumer preferences and the processing industry's infrastructural investments to satisfy these, and, to a lesser extent, technical constraints, these three staple grains are almost exclusively consumed in refined form. Table 1 describes the predominant geographies, consumption form, and food products prepared with maize, wheat, rice, and other grains consumed worldwide. The very high proportion of unfortified, refined "big 3" grains in global dietary patterns has contributed to carbohydrate-rich, but micronutrient, dietary fiber and bioactive compound-poor diets and their negative health effects, particularly among the more vulnerable. Furthermore, the over-dependence on the "big 3" is contributing to production systems becoming vulnerable to the effects of climate change, especially in developing countries in the tropics and sub-tropics (Pequeno et al., 2021; Ramirez-Cabral et al., 2017; van Oort and Zwart, 2018), jeopardizing their ability to withstand stress while providing nourishment for growing populations.

1.2. Transition from whole to refined grains

The historical transition from whole to refined grains has been influenced by social, political, and economic factors. In the 18th century, Great Britain and the United States consumed most of their grains from coarse, unrefined flour processed by local mills. The advent of the roller mill and the increased global outsourcing of grains facilitated large-scale processing while increasing yields of refined flours. The refined flours produced by roller milling were particularly valuable in the slow-moving supply chains of the time as the grain refining process removed contaminants such as weevil eggs, which can adhere to the bran, and the oil-rich germ, which is responsible for flour rancidity. Therefore, their use in manufacturing food products grew among urban populations, making food production systems increasingly reliant on international food supply chains. The improved stability of refined grains created a food surplus that protected against annual variations in crop yield, promoted a more stable food supply, and lowered prices, making foods available to more people. Moreover, refined white flour had long been perceived by the low-income majority as being aspirational, since white bread was mostly consumed by the affluent. Small mills and bakers were replaced by large production facilities specialized in grain milling and refining, enabling them to achieve economies of scale, reducing cost and hence accessing a much wider consumer market. These facilities were close to port cities to facilitate access to imported grains and export of refined flours to former colonies during the 19th century, reshaping culinary traditions of the recipient nations (Dixon, 2009; Hawkes, 2006). Fig. 1 shows the current average consumption of grains per region and population size and Fig. 2 shows the average grain consumption per region, broken down by whole vs. refined grain. Promoting the consumption and production of whole, locally sourced, and local grains while reversing over-reliance on international food supplies will require a concerted effort by policymakers, institutions, the food industry, and consumers.

1.3. Summary of the evidence

Whole grains are an extensively researched food group. Multiple studies, reviews, and meta-analyses have associated whole grain consumption with benefits to human health. High intake of whole grains has been associated with decreased morbidity and mortality from colorectal cancer, cardiovascular disease, and type 2 diabetes (Aune et al., 2016; Guo et al., 2021; Hu et al., 2020; Reynolds et al., 2019; Tieri et al., 2020; Wang et al., 2021; Zhang et al., 2018). Randomized control trials have demonstrated that higher consumption of whole grains can lead to reduction in bodyweight, total cholesterol, and systolic blood pressure (Reynolds et al., 2019). Other studies have associated whole grain consumption with increased diversity and metabolic capacity of the gut microbiome, suppression of chronic inflammation (Vanegas et al., 2017), and reduction in systemic inflammation biomarkers (Hajihashemi and Haghighatdoost, 2019). The benefits of whole grains are not limited to the adult population; the evidence on health effects of whole grain consumption in children is also positive. Higher intakes of whole grains by children in Iran (Hajihashemi et al., 2014), Denmark (Damsgaard et al., 2017), and Malaysia (Koo et al., 2018) were associated with favorable changes in LDL cholesterol and insulin levels, systemic inflammation biomarkers, systolic blood pressure, body-mass index, and waist circumference. Several countries, including the US, Australia, and Spain, already include whole grain recommendations in their dietary guidelines for infants and young children (Klerks et al., 2019). Conversely, the largest global prospective cohort study to date on associations between diets and health outcomes found high intake of

Table 1
Important grain crop consumption patterns. Data Source: FAOSTAT.

Crop type	Grain	Geographies of major consumption	Annual consumption (global) kg/capita/yr	Predominant consumption form	Food products
Green Revolution cereal crops	Maize	Latin America, sub-Saharan Africa, China, India, Italy	19.6	Refined	Flour, gruel, stiff porridge, dough, dumplings, cornmeal
	Wheat	Global	65.6	Refined	Flour, bread, cake, cookies, pasta and noodles
	Rice	Global	81.4	Refined	Flour, rice, noodles, cake, dumplings, vinegar, milk
Regionally and locally important traditional cereal crops	Sorghum	Africa, India	3.3	Semi-refined	Flour, gruel, porridge, couscous, flatbread, traditional non-alcoholic beverages
	Millets (Pearl, Foxtail, Proso, Finger)	Africa, Eurasia, China, India, Pakistan	2.8	Generally whole	Flour, gruel, couscous, porridge, flatbread, traditional non-alcoholic beverages
	Oats	Northern Europe, Western countries	3.2	Whole	Bread, Breakfast cereal
	Rye	Central and Eastern Europe	1.9	Semi-refined	Bread
	Teff (also a millet)	Africa (Horn of Africa)	29.0 (Ethiopia)	Whole	Flour, flatbread (injera), porridge, gruel
	Fonio (also a millet)	West Africa (Sahel region)	0.08	Whole	Rice, porridge, couscous
	Quinoa (pseudocereal)	South America	0.02	Whole	Flour, rice, porridge, flakes
	Amaranth (pseudocereal)	South America, East Africa	Very low	Whole	Flour, rice, porridge, flakes, popped
	Buckwheat (pseudocereal)	Eurasia	Very low	Whole	Flour, rice, bread, flatbread, noodles

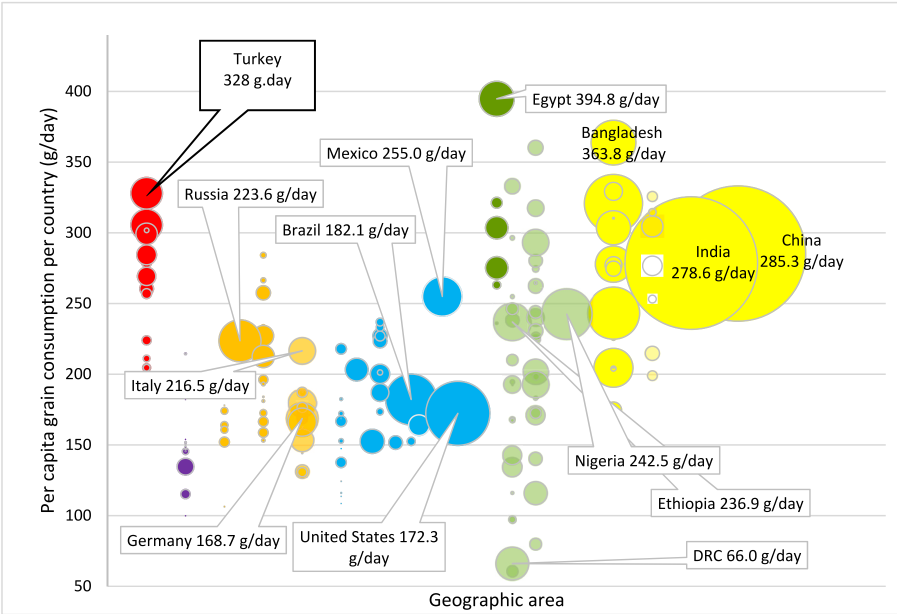

Fig. 1. Average consumption of grains per country on per capita basis (g/day). Circle size represents country population size. Different colors represent the five major geographic areas in the world: red (Middle East), purple (Oceania), orange (Europe), blue (Americas and Caribbean), green (Africa), yellow (Asia). Some countries with large populations are identified in the figure. Data Source: Global Burden of Disease. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

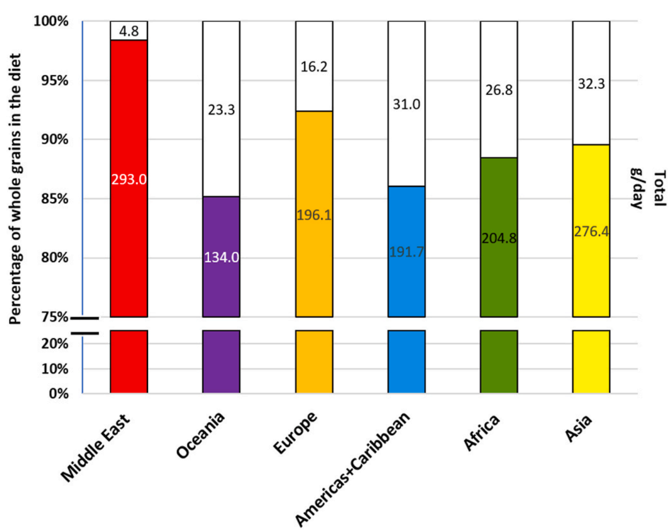

Fig. 2. Average grain consumption per geographic area. Left *y-axis* indicates percentage of whole grain from total amount of grain consumed in the diet. Right *y-axis* indicates quantity of grain (g) consumed per day. Legend in the white portion of the bar indicates quantity of whole grains (g whole grains/day); legend in the colored portion of the bar indicates quantity of refined grains (g refined grains/day). Colors indicate regions as follows: red (Middle East), purple (Oceania), orange (Europe), blue (Americas and Caribbean), green (Africa), yellow (Asia). Data Source: Global Burden of Disease. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

refined grains to be associated with higher risk of mortality and major cardiovascular disease events (Swaminathan et al., 2021).

Fig. 3 describes the health advantages of whole grains.

Several mechanisms underlie the protective effects of whole grains on human health:

- Increased fiber content (mainly insoluble fiber) with beneficial effect on the gut microbiome (Cronin et al., 2021).
- Increased content of various micronutrients and bioactive compounds such as phytoestrogens and polyphenols (Gani et al., 2012).
- Regulation of the glycemic response (Jenkins et al., 1988; Pletsch et al., 2022). Although foods made from whole grain milled to the same fineness as their refined counterparts elicited the same glycemic response, this is not case with foods made from coarsely ground or whole kernel whole grain, which produce a lower glycemic response.
- Greater satiety compared with refined grains, contributing to weight loss and modulation of carbohydrate and lipid metabolism (Karl and Saltzman, 2012).

1.4. *Relevance in the context of current and future public health emergencies*

Obesity, metabolic disorders, and non-communicable diseases (NCDs) are significant comorbidities associated with higher risk of severe illness, hospitalization, and death during public health emergencies, as observed during the COVID-19 epidemic (Bode et al., 2020). A well-nourished, normal weight population improves the chances of healthcare systems to withstand the pressure experienced during epidemics (Browne et al., 2021; Cava et al., 2021). A comprehensive dietary approach, which includes increased whole grain consumption, is necessary to improve the body mass index status of the population. In the US, 30.2% of COVID-19 hospitalizations were attributable to obesity, while 20.5% were attributable to diabetes (O'Hearn et al., 2021). Obese patients present more complications, worse clinical outcomes, and longer stays during hospitalization, significantly increasing resource utilization and healthcare costs (Childs et al., 2015; Moriconi et al., 2020).

Simultaneously, institutional food assistance budgets are further strained by the disruptive impacts of COVID-19, increasing the exposure of vulnerable groups to the double burden of malnutrition. A global assessment performed in 2020 indicated that healthy diets are 60% more expensive than diets that only meet essential nutrients requirements, and 5 times more expensive compared to diets that meet only energy needs through starchy staples (FAO et al., 2020). A shift to whole grains in low and middle-income countries, given their high volumes of grain consumption, is a feasible and timely double-duty strategy. Short of a one-time investment in equipment and technical capacity, whole grain foods can be produced at comparable or lower cost than refined foods. Still, careful calculations accounting for potential losses due to limited shelf-life stability and technical limitations faced when switching from

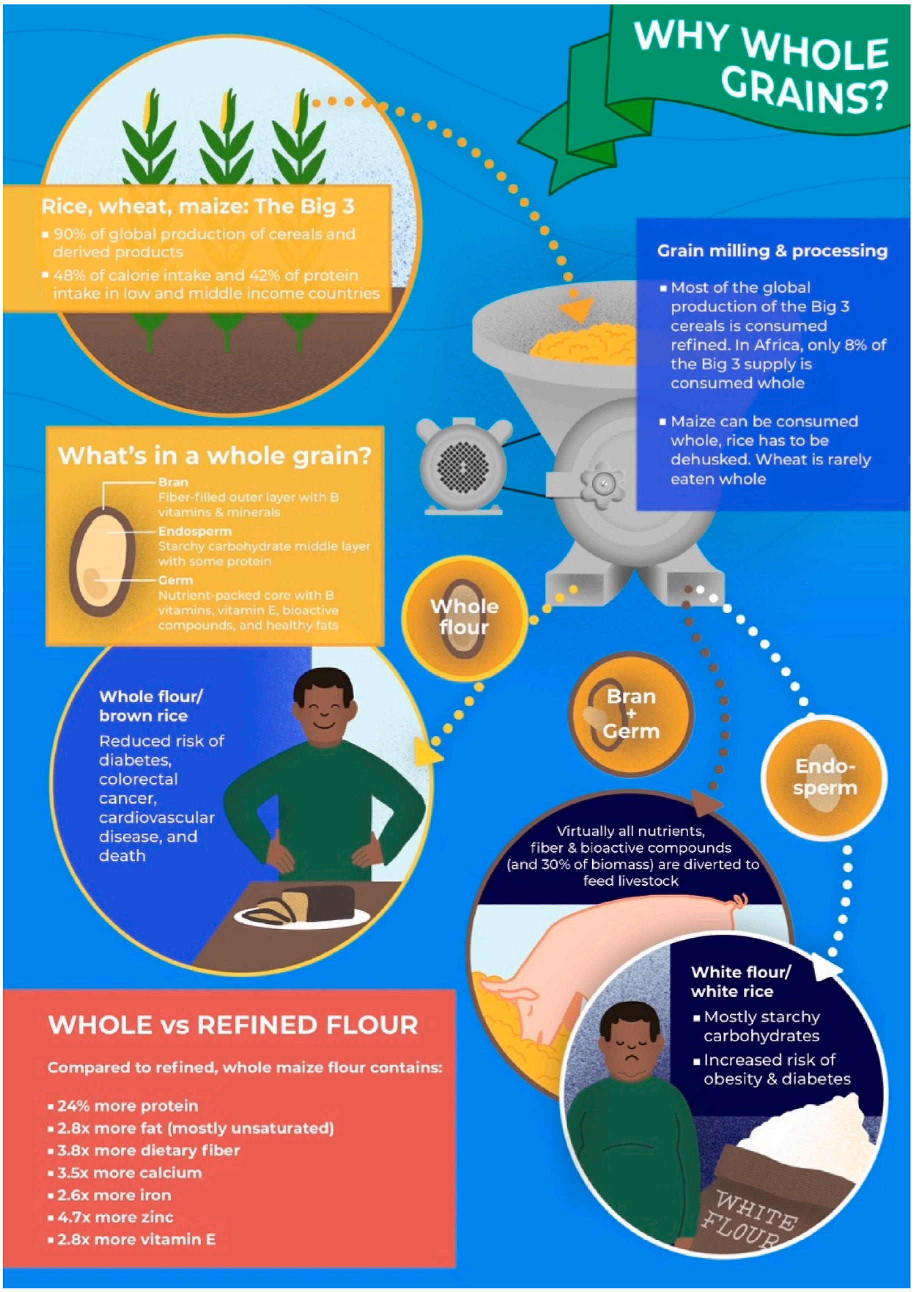

Fig. 3. Anatomical and nutrient differences between whole and refined grains.

refined to whole grains must be included. Overall, by promoting policies that facilitate the switch from refined to whole grains, governments and societies will be making a shift that is nutrition-positive and budget- and environment-neutral.

2. Opportunities and recommended interventions

2.1. Leveraging the cost gain for public health impact

At a fundamental economic level, whole grain foods have an intrinsic cost advantage over their refined counterparts because of the higher yield from raw materials (≥25%). Whole grain foods should be comparable or lower in cost than their refined grain counterparts because of their much higher processing “extraction rate” from the raw grain (i.e., the percentage yield of flour, meal or rice per mass of grain). In order to capitalize from the higher extraction rates from whole grains, investments in milling or other processing equipment to extend whole grain shelf-life by retarding the development of rancidity and food processing technologies, for example with respect to bread dough fermentation, may be required. Whole grain foods are generally more expensive in formal markets, though in some localities some whole grain products have achieved price parity compared to their refined counterparts (Harriman, 2012). Price differences might be attributed to two factors: 1. They are often sold at a premium because their current consumers are willing to pay more for their nutritional and health-promoting attributes, and 2. They are still largely specialty products in affluent societies, and whole grain milling and food processing do not have the same economies of scale as those of refined grain products. However, where these confounding factors are not present, whole grain products are cheaper. Although bran and germ byproducts are sold in secondary markets (animal feed), the price they fetch is significantly lower than that paid for food grade products. Capital investment combined with technical assistance and sustained demand can enable mills to produce whole grain products at a competitive cost. Ideally, cost savings afforded by switching to whole grains should be leveraged for public health benefit. Also, in countries in which flour fortification is not mandatory, policy could mandate fortified whole grain products for public sector procurement. In countries where fortification is mandatory, savings could be deployed to:

- Require addition of secondary and neglected whole grains, legumes, nuts, or seeds, to government-procured foods
- Expand coverage to more vulnerable populations than those currently supported
- Enhance food safety by, for example, compulsory implementation of systems to ensure that grains meet regulatory standards for mycotoxin contamination

It is also important to note that higher costs incurred in processing and commercialization of whole grains could be compensated by the substantial reduction in health care costs related to increased whole grain consumption (Miller et al., 2022).

2.2. Strengthening institutional markets

The interlaced evolution of the milling industry and consumer attitudes towards grains emerging from the Industrial Revolution has entrenched an enduring, strong consumer preference for refined grains. As many societies have historically perceived refined grains as a "food of the rich, their market share grew with development of roller milling which made them affordable to all. Although whole grain consumption is on the rise in high-income countries (Oldways Whole Grains Council, 2022), it is still a fraction of total grain consumption worldwide, despite promotion, public health messaging, and numerous product introductions, particularly in low and middle-income countries. In sub-Saharan Africa and South Asia, whole grains account for only 14 and 10% of grain-based foods, respectively. A better starting point for large-scale transition from refined to whole grains is offered by institutional markets, compared to traditional approaches that have targeted consumer markets.

Institutional food procurement is a powerful demand tool often underutilized in promoting healthy dietary patterns. It comprises food purchases by both public and private sector and provision of food items and meals at institutions including schools, universities, early childhood development centers, healthcare facilities, nursing homes, senior centers, military bases, prisons, and public and private cafeterias. It also covers safety net programs such as in-kind food assistance, restricted cash transfers, and social restaurants and food shops. School feeding alone reaches 305 million children in low- and middle-income countries (World Food Programme, 2020), 47 million in Brazil (Brazilian Ministry of Education, 2022), 30 million in the US (Oliveira, 2019), and 3.3 million, or more than a quarter of the population, in Rwanda (Ministry of Education - Republic of Rwanda, 2022). The European social food service market amounts to $96 billion (Maltese Presidency and the European Union, 2107), and the UK public catering sector spends approximately $3 billion per year (de Schutter, 2014). Nearly $300 billion/year are spent globally feeding workforces and college students. The four largest food outsourcing corporations serve a combined 14 billion meals per year (The Economist, 2020).

Whereas institutional food service plays a complementary role to individual and household food acquisition, it is importantly distinct in three key aspects: access, awareness, and choice. Particularly for low-income and rural consumers, institutional channels can make available and affordable food items these consumers would not otherwise have access to. By operating in a more controlled environment compared to consumer markets, in which consumers are exposed to a broad information spectrum ranging from no information to conflicting and often misleading marketing messages, institutional food service has the opportunity to effectively educate consumers and promote healthier diets. And though not absent in institutional channels, the element of consumer choice is more constrained, which offers opportunities for nudging consumers towards healthier foods and patterns. These channels can be leveraged to enable sustainable consumer demand, thus facilitating whole grain scale-up from processors and distributors, jumpstarting sustainable virtuous cycles that ignite commercial markets and can eventually lead to affordable healthy diets for all (FAO et al., 2020). Although institutional markets represent viable entry points for a whole grain initiative, consumer markets must be an integral part of a whole grain strategy given their larger scale and reach. Integrated thinking across both markets can lead to cross-leverage of insights and efforts and avoid stigmas associated with food assistance.

2.3. Promoting and incentivizing regionally and locally important traditional cereal crops

All cereal and pseudocereal grain species are beneficial to human health due to their broad spectrum of nutrients and deserve investment and promotion. However, not all grains have equal market reach and consumption. Maize, wheat, and rice account for 48% of calorie and 42% of protein intake in low and middle-income countries (CIMMYT, 2019); maize in particular, accounts for 23% of total cultivated area in Africa (Tadele, 2019), 40% of total cereal production and 30% of total calorie intake (Ekpa et al., 2019). Rice also plays a significant role in several West African countries as a staple food. Given the underutilized potential of sorghum and millets in Africa, such regionally and locally important crops represent a vital opportunity to increase intake of whole grains and reach greater populations, particularly in view of their natural resilience to extreme weather events, which are increasing in frequency due to climate change. For example, sorghum is the most drought-tolerant cereal species (Assefa et al., 2010) and pearl millet has better tolerance to high temperatures than most other cereals (Dhankher and Foyer, 2018).

From the resilience, dietary diversification, biodiversity, and sustainability perspectives, a comprehensive strategy to increase consumption of whole grains should include investments towards largely neglected crops (e.g., amaranth, teff, fonio, and quinoa). These crops are naturally adapted to unfavorable soil and weather conditions in their respective regions (Centre for the Promotion of Imports (CBI) & Netherlands Enterprise Agency, 2022; Mabhaudhi et al., 2019), are mostly cultivated by smallholder farmers (National Research Council, 2006) and play an important role in their food security. Several neglected crops, including amaranth and quinoa, provide the added nutritional benefit of edible leaves rich in micronutrients and proteins (National Research Council, 2006). Largely neglected crops also offer a rich gene pool for future crop improvement (Mabhaudhi et al., 2019). Mainstreaming them is an important long-term component of a food system transformation strategy focused on sustainability, climate adaptation, nutrition security, equity, and inclusivity (Willett et al., 2019).

2.4. Investing in innovation

Transitioning a substantial portion of food supply chain and consumption from refined to whole grains is a multi-year journey with risks and opportunities for innovation. It will be important to sustain investments to further improve the whole grain value proposition. Relevant areas for research and innovation include shelf-life extension of whole grain products, aflatoxin reduction, nutrient preservation throughout processing, phytate management, improvement of sensorial attributes, and implementation of good manufacturing practices. Equally important will be to develop an enabling and supportive environment for whole grain products comprising policy, regulation, governance, standards and their enforcement, incentives and disincentives, consumer awareness, leverage of government food procurement, and cross-sectoral collaboration (Poole et al., 2021). Finally, investment in food science and technology research and product innovation to improve consumer acceptability is vital to build demand in both consumer and institutional markets. Table 2 summarizes the key risks involved, their mitigation, and related opportunities for innovation.

2.5. *Africa: Today's challenge and opportunity*

Diets low in whole grains account for 8.3 million years of life lost to disability and premature death (disability-adjusted life years, DALYs) annually in Africa (Global Burden of Disease Collaborative Network, 2017). The single dietary risk that leads to the most DALYs in all of Africa (except Southern Africa) is low intake of whole grains (Branca et al., 2019), particularly among young adults (aged 25–50 years) (Tadele, 2019). Grains are major staples in the diets of 1.3 billion Africans, who consumed nearly 273M MT of grains, cereals, and derived products in 2017 (FAOSTAT, 2022). In sub-Saharan Africa, per capita consumption was 208 g per day, of which only 29 g were in whole form (FAOSTAT, 2). Rates of overweight/obesity among women of childbearing age in sub-Saharan Africa rose from 15.3 to 28.4% between the 1990s and the 2010s, with over half of surveyed countries showing a prevalence over 30% (Reardon et al., 2021). Between 1990 and 2017, of the total burden of disease in sub-Saharan Africa, the proportion attributable to NCDs grew from 18.6 to 29.8%. Prevalence of NCDs across sub-Saharan Africa is now higher than the global average, and almost equivalent to the burden from communicable, maternal, neonatal, and nutritional diseases. Total DALYs due to diabetes increased by 126.4% during the same period (Gouda et al., 2019). Converting 25–50% of the current consumption of refined grains and products to whole grains can reduce the burden of death and disease from NCDs in Africa, help address undernutrition and micronutrient deficiencies, and decrease the incidence of overweight/obesity across different groups. National strategies to increase whole grain consumption can generate substantial government and societal gains due to reduced health care costs and increased labor productivity (Abdullah et al., 2021; Martikainen et al., 2021). Fig. 4 illustrates the journey for the transition from the current to the future state of whole grains in Africa.

As of this writing (January 2022), the Rockefeller Foundation and the World Food Programme have successfully implemented a pilot program in 18 Rwandan schools with nearly 14,000 students whereby fortified whole maize flour has replaced refined flour in meals. Assessments were made on whole grain maize meal acceptability by the school cooks and school learners and the meal porridge product was optimized related to sensory characteristics. The pilot has shown the feasibility of this substitution being budget-neutral to schools and the potential for students and the school community to embrace it. Learnings from the pilot are currently being consolidated to enable scale-up in school feeding and other public procurement channels in Rwanda, as well as in other African countries.

3. Conclusion

Grain consumption by humans preceded agriculture and was the key driver of the development of farming. Successive agro- and processing-technological revolutions, perhaps most significantly the Green Revolution, have bequeathed us the modern agri-food system, which is currently optimized for the production of low-cost calories, mostly from refined grains. We became able to avert famine, at the cost of biological and dietary diversity, nutrition, health, resilience, and sustainability. The time for a course correction – a Grain Evolution — has come. Never has the need for affordable nutritious products to serve vulnerable populations been more urgent; never has the imperative of maximizing nutritional value per dollar spent been more pressing. Substantially shifting refined cereal consumption to whole grains is an overdue journey that will enable us to better nourish humanity while sustaining our planet.

Table 2
Key risks of large-scale transition to wholegrains.

Risk	Likelihood	Impact	Mitigation/Innovation Opportunity
Safety net beneficiaries react negatively to wholegrain products	Medium	Medium	• Gain consumer insight through robust contextual, formative, and market research prior to any product/initiative launch • Feed consumer insight into product formulation, positioning, and marketing • Conduct robust and sustained BCC and social marketing effort with product introduction • Review experiences of other countries (e.g. Denmark)
Consumers reject wholegrain products in the market	Medium	High	
Distribution through safety nets stigmatizes wholegrains as a "food for the poor"	Medium	High	
Shorter shelf life limits procurement of wholegrains in long chain programs	High	Medium	• Prioritize shorter chain programs • Provide technical assistance on processing and packaging to millers • Invest in R&D to extend wholegrain product shelf life in low-resource settings
Millers are reluctant to invest in wholegrain production equipment due to low demand	Medium	Medium	• Start demand building through the institutional market • Incorporate wholegrains into public policy (procurement, fiscal, etc.)

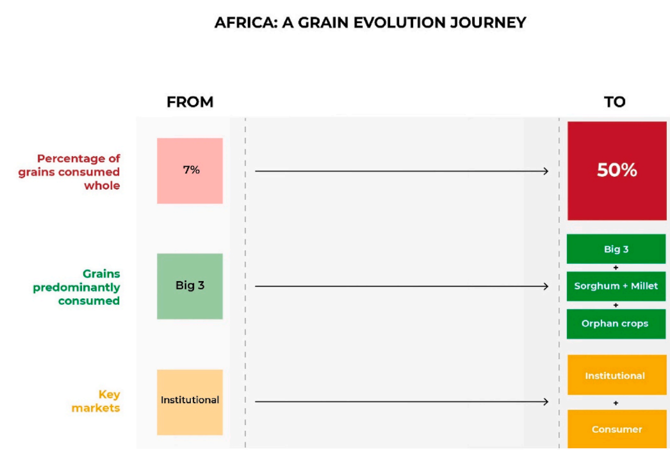

Fig. 4. Illustrative roadmap for transition to whole grains in Africa.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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