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Review Article

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Functional Foods and Food Security in Dryland Communities: Bridging Traditional Knowledge and Modern Innovations - A Review Article

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Abstract

Food insecurity is most severe in dryland regions, where climate stress and limited resources exacerbate nutritional deficiencies and undermine livelihoods. Functional foods enriched with natural bioactive compounds offer a pathway to improve health while supporting sustainable food systems. This review addresses the gap in understanding how traditional dryland food systems can be integrated with modern innovations to enhance food and nutrition security. This review explores the role of functional foods in strengthening food and nutrition security, linking traditional dryland staples such as sorghum, millet, legumes, and camel milk with modern innovations, including fermentation, biofortification, and precision nutrition. A narrative literature synthesis was conducted, drawing from peer-reviewed journal articles, reports, and regional studies relevant to dryland communities. Challenges remain in food safety, postharvest losses, and research investment; however, integrating indigenous knowledge with science enhances dietary diversity, resilience, and community well-being. The review identifies key challenges and opportunities and proposes a conceptual framework linking traditional food systems with modern functional food innovations to enhance sustainable security. Functional foods rooted in both tradition and innovation offer a practical way to reduce malnutrition and disease risks in dryland communities.

Keywords

Food security, Functional foods, Modern innovations, Traditional knowledge

Introduction

In 2023, 2.33 billion people worldwide faced moderate to severe food insecurity, according to the Food and Agriculture Organization, Food Insecurity Experience Scale. Of these, an estimated 864 million were projected to experience severe food insecurity [1], meaning they may have had to eat less or go without food due to insufficient resources [2]. In low-income countries, 64.5% faced moderate-to-severe food insecurity from 2021 to 2023, according to World Health Organization projections [2]. The rates were 43.1% in low- and middle-income countries, 12.9% in upper-middle-income countries, and 8.0% in high-income countries [3]. While food insecurity decreases with economic growth, a strong economy does not guarantee adequate food for all [3]. Functional foods play a considerable role in nutritional science because they are enriched with bioactive compounds that promote health and prevent disease, such as carotenoids, phenolic compounds, antioxidants, omega-3 fatty acids, and specific vitamins

[4, 5]. This concept merges the principles of food science, nutrition, and pharmacology to promote health and well-being [6]. The growing interest in functional foods is fueled by consumers' preference for natural products that enhance health [7, 8]. In arid and dryland regions, functional foods such as sorghum, millet, legumes, and camel milk are vital due to their drought-tolerant properties, their provision of essential nutrients, and their help in maintaining nutrition and resilience under challenging environmental conditions [6, 9]. Agroecosystems in arid regions include pastoral, agropastoral, rain-fed, and irrigated agricultural systems [9]. Farmers and pastoralists utilize food, fodder, and fiber crops, vegetables, rangeland species, fruit trees, medicinal plants, livestock, and fish species to meet their needs. These practices have been adapted over centuries to scarce resources and fluctuating climate typical of dry areas [9]. Agricultural systems in drylands face water shortages, droughts, climate variability, land degradation, desertification, and poverty, which may worsen due to climate change. Dry areas are crucial centers of crop, vegetable, livestock, tree, and fish diversity, with traditional farming systems preserving agrobiodiversity through landraces, local breeds, pastoral flora, and indigenous species. This review aims to examine the role of functional foods in improving nutrition and resilience in dryland communities analyze traditional food systems and their potential for integration with modern innovations and propose pathways for bridging indigenous knowledge with scientific approaches to strengthen food and nutrition security in these vulnerable regions.

Functional Foods and Global Nutrition Challenges

Functional foods play an essential role in food and nutrition security. Functional foods have specific beneficial effects on one or more target functions in the body that go beyond basic nutritional functions, resulting in improved health status and well-being, as well as reduced disease risk [10]. Given this, functional foods have raised consumer interest in healthy diets, thereby occupying a significant place in the global food market [10]. However, despite broad consensus on their health-promoting roles, different authors emphasize different mechanisms and challenges, which require a more critical comparison. Some functional foods are plant-based and contain bioactive components (i.e., flavonoids, catechins, carotenoids, lutein, lycopene, phenolics, quercetin, and anthocyanidins) with health benefits [11]. Some natural food products, such as millet [12], mushrooms [11], microalgae [13], flaxseed, oats, oranges, soybeans, onions, and cherries [11], have been found to contain bioactive components with potential health benefits. Fruits and vegetables are another example of functional foods that are rich sources of essential bioactive compounds, including carotenoids and polyphenols, which have beneficial health properties. Utilizing functional foods to drive transformation enables policymakers to address the dual challenges of undernutrition and non-communicable diseases common in low-income areas, thereby bolstering food and nutrition security [10]. The growing consumer interest in health-enhancing foods underscores the market's rapid growth, though realizing this potential requires addressing bioactive stability, regulatory issues, and consumer confidence [14]. Incorporating plant-based proteins, probiotic strains, and biofortified crops into functional food offerings can further the sustainable development goals (SDGs) by improving nutrient density and reducing disease risk [15-17]. This consumer trend towards foods perceived as health-promoting and sustainably produced supports the market growth of functional products, as recent reviews indicate a rising demand for probiotic-enriched and naturally sourced bioactive [18, 19]. This growing demand is evident in recent studies showing a significant increase in the consumption of functional foods and beverages, driven by health awareness and the global inclusion of plant-derived bioactive [20, 21]. However, these studies also caution that market growth does not automatically translate to improved nutrition outcomes unless affordability and accessibility gaps are addressed in low-income regions. Emerging omics technologies and precision nutrition are accelerating the discovery and optimization of bioactive compounds, thereby enhancing the ability of functional foods to address both human health and environmental sustainability issues [22]. Consequently, the development of functional foods that focus on bioactive enrichment can directly support global nutrition and health goals, aligning with broader sustainable development objectives [22]. By providing bioactive-rich, affordable products, functional foods can simultaneously promote SDG 2 (zero hunger) and SDG 3 (good health and well-being), while also offering economic advantages through reduced healthcare costs [23, 24]. Functional foods are most effective when integrated into broader food systems and policy frameworks that prioritize access, equity, and sustainability (Table 1). It is important to manage trade-offs and unintended consequences, such as over-reliance on single crops and regulatory gaps, to maximize their positive impact on the SDGs [25, 26]. To scale the benefits of functional foods globally, rigorous monitoring and cross-sectoral partnerships are essential.

Traditional Food Systems in Dryland Communities

Global and local workshops demonstrate that policies that support modern agriculture, food and education, industrial development, and globalization are rapidly undermining

Table 1: Functional foods and SDGs.

SDG	Functional food contribution	Example/Impact
SDG 2: Zero hunger	Enhance nutrient density, address micronutrient deficiencies, and support sustainable agriculture	Biofortified grains, ancient grains, wild mushrooms
SDG 3: Good health and well-being	Prevent chronic diseases, improve metabolic and immune health	Probiotics, polyphenols, omega-3s, dietary fiber
SDG 12: Responsible consumption and production	Promote sustainable food systems, reduce waste, and support biodiversity	Macroalgae, plant-based proteins, and sustainable sourcing

indigenous food systems throughout regions, posing numerous risks [27]. Rapid changes in food, diet, and nutrition have resulted from the replacement of traditional farming in many Asian areas by economic development and industrial agriculture [27]. With special emphasis on key staples such as sorghum, millet, local legumes, and camel milk, this summarizes recent research on the resilience and challenges of these systems and highlights their diverse roles in sustaining human populations in hostile environments [27]. These traditional food plants are well-adapted to the diverse biotic and abiotic conditions found in dryland regions, offering a sustainable approach to food security [28]. However, these priority traditional food plants are currently under tremendous strain due to the growth of human and livestock populations in Sub-Saharan Africa, resulting in significant species degradation and loss [29]. They can be incorporated into current farming systems to address this [30]. Incorporating current farming systems will, on the one hand, increase the production of fruits, vegetables, and pulses in Sub-Saharan Africa, which is presently mostly limited to high-altitude areas with moderate to sufficient rainfall [28]. However, because they are less dependent on pesticide inputs, stabilize agroecosystems, increase biodiversity, and aid in carbon sequestration, their management, whether in the wild or on farms, would be advantageous to the environment. Furthermore, integrating these staples into agroforestry parklands, where trees are deliberately retained on cultivated land, represents an innovative and traditional land-use approach to reducing agricultural risks and enhancing food system sustainability [31]. This approach, rooted in traditional ecological knowledge, provides a framework for regenerative food systems that consider both environmental and social well-being [32]. The diverse array of traditional food plants, including indigenous fruit trees such as tamarind, holds significant potential to enhance nutrition, income, and overall sustainability within these communities [28]. However, the full nutritional and health benefits of these underutilized foods often remain obscure due to a lack of comprehensive nutrient composition data, underscoring the need for further research to raise consumer awareness and promote their dietary inclusion [33]. Despite their high nutritional value and cultural importance, these traditional foods often face misperceptions of inferiority compared to conventional staples, hindering their widespread adoption and research investment [28].

Quantitative data

Quantitative research confirms the high nutritional value, yield potential, and economic importance of traditional dryland foods such as sorghum, millet, moringa, and baobab. Below is the summary of nutritional (Table 2), product and yield (Table 3), and financial data (Table 4) for key dryland foods.

Table 2: Nutritional content.

Food	Energy (kcal/100 g)	Protein (g/100 g)	Key micronutrients (per 100 g)
Sorghum	329 - 334	9.9 - 11.6	Iron: 3.94.5 mg; Zinc: 1.7 - 1.9 mg
Millet	347 - 378	10.9 - 11	Calcium: 27 - 29 mg; Mg: 114 - 133 mg
Moringa leaves	64	9.4	Vitamin A: 378 µg; Iron: 4 mg
Baobab fruit	97 - 250	1.7 - 2	Vitamin C: 150 mg; Calcium: 280 mg

Table 3: Production and yield.

Food	Typical yield (kg/ha)	Yield range (kg/ha)	Notes on yield potential
Sorghum	700 - 1,500	Up to 3,000+	Improved hybrids: 8,000 - 9,000 kg/ha
Millet	750 - 2,000	Up to 4,200 (fodder)	Dual-purpose varieties outperform traditional ones
Moringa leaves	5,000 - 10,000	-	High biomass, multiple harvests
Baobab fruit	200 - 500/tree	-	High per-tree yield, variable by region

Table 4: Table economic value.

Food	Market price (USD/kg)	Income potential (USD/ha)	Notes
Sorghum	0.24 - 0.29	240 - 750	Price stable in dryland markets
Millet	0.35 - 0.60	210 - 720	High demand in arid regions
Moringa leaves	1.0 - 2.5	5,000 - 25,000	High-value niche and export markets
Baobab fruit	2.0 - 4.0	400 - 2,000	Value addition increases returns

Modern Innovations for Functional Food Development

The market for functional foods is expected to develop at a compound annual growth rate of 8.5% between 2022 and 2030, from its 2021 valuation of USD 280.7 billion [34]. The market view of consumers has shifted from ordinary traditional foods to more valuable, nutritious, and healthier foods, driven by increased scientific and technical research [18]. This suggests that current advancements in functional food development are driven by a changing consumer mindset that places greater value on nutritional and health-promoting qualities than on basic nourishment. This meal approach, specifically referred to as functional, focuses on probiotics, which enhance immune system activity, cognitive reactivity, and overall wellness [18]. As consumers become more conscious of the impact of nutrition on physical and mental well-being, they are increasingly looking for foods that not only satisfy hunger but also offer additional health benefits. This trend has driven demand for functional foods, and nutritional advances have led to a surge in fortified products that are fortified with beneficial ingredients such as vitamins, minerals, fiber, and omega-3 fatty acids [35]. This growing consumer interest in functional foods that provide health benefits is a key driver of demand for nutritional and fortifying food additives. In the field of food science, functional foods have become a vital area of study and development, providing promising approaches

to the management and prevention of chronic illnesses such as cancer, diabetes, osteoporosis, cardiovascular disease, and hypertension [36]. These meals offer nutritional and medicinal benefits, as they are enhanced with bioactive nutraceuticals. Improvements in food quality, including enhanced organoleptic properties and greater stability against oxidation and emulsification, have been enabled by the interaction between the physiological and technological characteristics of functional ingredients. These developments facilitate the creation of innovative functional food tastes and align with current customer preferences and manufacturing trends [36]. Furthermore, microbial biotransformation, particularly through fermentation, significantly enhances the functional properties and nutritional content of foods by chemically modifying their components, offering benefits for public health [37]. Additionally, advanced food processing methods, including solar drying and extrusion, are being optimized to preserve nutrient integrity and improve bioavailability in these fortified and fermented products [38, 39]. The integration of cutting-edge technologies further enables the creation of food products that not only meet nutritional requirements but also provide additional health benefits, addressing the rising global prevalence of non-communicable diseases [40, 41]. Modern processing methods, such as fermentation and extrusion, bridge traditional food systems with contemporary consumer demands, enabling the creation of safer, more nutritious, and marketable products from local dryland crops. Combining these techniques maximizes both nutritional and functional potential, supporting food security and innovation [42-44]. Biofortification and fermentation initiatives in Africa and Asia are advancing nutrition and food security. African programs, such as the Africa Biofortified Sorghum Project, target vitamin A, iron, and zinc enhancement in sorghum for countries like Kenya and Nigeria, while Indian efforts use local landraces to breed sorghum with higher protein and mineral content [45-47]. Genomic and marker-assisted breeding approaches are being used to increase provitamin A carotenoids in sorghum, addressing vitamin A deficiency in regions where sorghum is a staple [48]. Community-based fermentation models, especially in Africa, use traditional and improved microbial processes to increase the B-vitamin content and bioavailability of staple foods, helping to counter micronutrient deficiencies [42, 49]. Fermentation also reduces antinutritional factors and enhances the functional properties of sorghum-based foods [42, 50, 51]. These innovations combine traditional knowledge with modern science, offering scalable solutions to malnutrition in dryland regions [46, 49]. Despite their potential, scaling these technologies in resource-poor settings encounters significant challenges. High energy requirements for extrusion, along with the necessity for reliable power, water, and cold chains, limit adoption in rural areas [52, 53]. Ensuring consistent product quality and safety demands investments in training, standardized protocols, and equipment [53, 54]. Additionally, high upfront costs, a lack of established value chains, and limited consumer awareness hinder commercialization efforts [53-55]. Furthermore, over-standardization may threaten local food diversity and traditional practices [53].

Food Safety and Quality Challenges

Worldwide, postharvest biodegradation of foodstuffs causes substantial product loss. Food commodities such as cereals and pulses, fruits and vegetables, dairy, bakery, meat, and seafood have substantial losses during their transit and postharvest. Insect pests, microbial pathogens, and oxidation reactions all contribute to these losses [56]. The food supply chain must be managed efficiently to ensure a safer, more sustainable supply of food commodities [56]. This comprehensive approach is essential for anticipating and mitigating risks associated with emerging foodborne pathogens and contaminants [57]. Furthermore, adapting to and mitigating the impacts of climate change, reducing pollution, waste, and biodiversity loss, while simultaneously feeding a growing global population with safe food, necessitates systemic transformation within agricultural systems and the broader agri-food industry [58]. However, these efforts are continually challenged by the emergence and re-emergence of new and re-emerging pathogens, alongside the persistent threat of mycotoxins, whose prevalence is often exacerbated by changing climatic conditions [59, 60].

Postharvest and microbial challenges

The challenges in food safety and quality, particularly the substantial postharvest losses, and the specialized safety protocols required for the development of functional foods [56, 61]. A significant aspect of these challenges is the substantial postharvest losses, which are further exacerbated by fungal contamination and the widespread dispersal of fungal spores across diverse environments [62]. Such losses are not only economically detrimental but also severely compromise global food security, particularly because fungi alone can destroy up to 30% of crop products through disease and spoilage [63]. Moreover, mycotoxin-producing fungi and opportunistic pathogens pose a significant threat to food safety, underscoring the inadequacy of current control measures in the face of the escalating challenges posed by human population growth and climate change [63].

Climate-related safety risks

The exacerbating effects of climate change on food systems are issues compounded by the globalized nature of food supply chains, necessitating robust monitoring and management practices to mitigate risks from production to consumption [64]. Addressing these multifaceted challenges requires a multidisciplinary approach that integrates insights from diverse fields, such as crop production, public health, and advanced computational sciences, to develop predictive models and statistical methodologies [65]. To counteract these emerging threats, proactive and science-based interventions, including continual and dynamic risk assessments, alongside more sensitive and accurate detection methods, are critical [66]. The imperative to address these issues is heightened by the anticipated global population exceeding 9 billion by 2050, which demands either a significant increase in crop production or a dramatic reduction in food waste [67].

Policy and regulatory frameworks

These challenges are further intensified by the rapid pace

of global change, driven by megatrends such as climate change and an aging population, creating an increasingly complex environment for ensuring a safe and secure food supply [66]. Consequently, adaptable and transformative strategies are urgently required to navigate evolving scientific and technological landscapes, alongside shifting socio-economic and demographic realities [58]. Finally, a global estimate of 600 million illnesses and 420,000 deaths annually due to foodborne diseases [68] underscores the urgency of addressing food safety risks, particularly in dryland environments where storage limitations, microbial challenges, and climate vulnerabilities intersect.

Bridging Indigenous Knowledge and Modern Science

The crucial integration of indigenous knowledge with contemporary scientific methodologies, recognizing indigenous knowledge critical role in sustainable development and economic growth, particularly within African contexts [69]. This integration is essential for fostering innovation that is culturally relevant and environmentally sound, leveraging traditional practices like fermentation and sun-drying alongside modern scientific advancements to address localized challenges [69]. Despite elaborate policy efforts in science, technology, and innovation, Africa has yet to optimally integrate indigenous knowledge systems and their stakeholders into the fourth industrial revolution and its bioeconomy components [70]. However, recent scholarship advocates for the equitable recognition of indigenous knowledge systems alongside modern scientific frameworks to enrich the global knowledge pool and foster sustainable community-based environmental resource management [71]. This recognition extends beyond environmental conservation and traditional medicine, encompassing diverse domains such as sustainable livelihoods and social cohesion [72]. Many scholars are now examining how indigenous knowledge can be integrated into educational curriculum, moving beyond its historical marginalization by Western academic perspectives [73]. This shift acknowledges that indigenous knowledge, deeply rooted in local contexts, offers invaluable insights for innovation, particularly in regions striving for knowledge-based economies and sustainable development [74]. The marginalization of indigenous knowledge from formal educational and research platforms in Africa, mainly due to colonial legacies and continued dependence on external funding, has hindered the continent's innovation potential [75, 76]. Therefore, bridging indigenous knowledge with modern science is not merely an academic exercise but a strategic imperative for Africa's transformation toward inclusive, innovative, and sustainable development (Figure 1 and table 5).

Conclusion

This study highlights how both drying methods and extraction techniques significantly impact the recovery of valuable bioactive compounds from kinnow and mosambi peels. Among all the tested combinations, tray drying followed by ultrasonic extraction, especially using 50% methanol or a methanol–ethanol mixture, proved to be the most efficient for enhancing total phenolic content, total flavonoid content, and antioxidant activity. Between the two fruits, kinnow peel was more effective in yielding phenolic compounds and antioxidant potential, while mosambi peel demonstrated stronger antimicrobial activity, particularly in ethanol-based ultrasonicated extracts. The findings confirm that citrus peels, which are typically discarded as waste, can be transformed into a valuable source of natural antioxidants and antimicrobials. With further optimization and validation, these extracts could find application in functional foods, natural preservatives, nutraceuticals, and cosmetic formulations, promoting sustainability and adding value to agro-industrial byproducts.

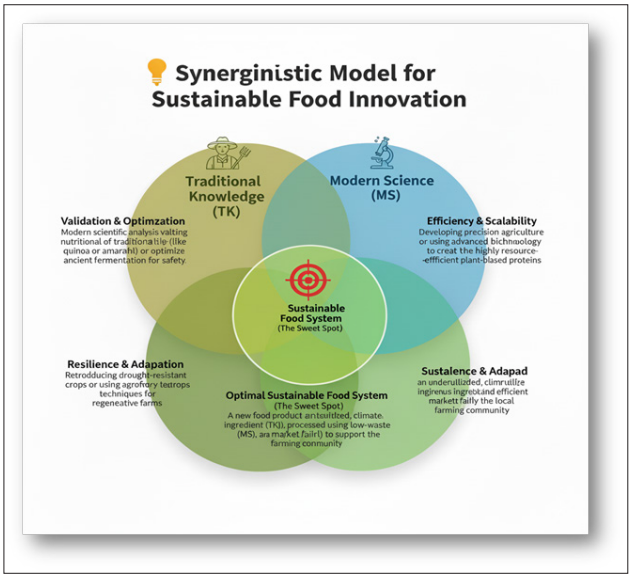

Figure 1: Diagram showing the interaction between traditional knowledge, modern science, and sustainable food innovation.

Table 5: Examples of successful IK-science integration.

Case/Region	Integration approach	Outcome/Impact
Ethiopian sorghum fermentation	Community knowledge + scientific validation	Enhanced food safety, shelf-life, and nutrition
Indian millet fortification	Traditional crop selection + modern biofortification	Improved micronutrient content and child nutrition
West African fermented foods	Local fermentation + research partnerships	Scalable, safer, and more nutritious products

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None.

Conflict of Interest

None.

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