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MILLETS AND THE FUTURE OF FOOD: FROM CLIMATE RESILIENCE TO NUTRITIONAL WELL-BEING

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Millets are a collective term for various small-seeded annual grasses within the Poaceae family, cultivated primarily in dry, marginal lands across temperate, subtropical, and tropical regions (FAO, 2024a). They are highly tolerant to drought and extreme weather, requiring minimal chemical inputs. In India, they are celebrated as "Nutri-cereals" due to their rich nutrient content (ICMR-NIN, 2017).

Millets are broadly categorized into Major Millets and Minor Millets:

- **Major Millets** include Sorghum (jowar), Pearl Millet (bajra), and Finger Millet (ragi). Sorghum is a staple in Africa and South Asia, known for its drought tolerance and high protein, iron, and fiber content (AICRP-Millets, 2017). Pearl Millet, also from Africa, thrives in hot, dry regions and is rich in proteins (12-16%), lipids (4-6%), and dietary fiber (around 11.5%), along with niacin, folate, magnesium, and iron (ICMR-NIN, 2017). Finger Millet, native to East Africa, is exceptional for its calcium content (300-360 mg/100g), the highest among all cereals (ICMR-NIN, 2009/2024).

- **Minor Millets** encompass Foxtail, Little, Kodo, Proso, and Barnyard Millets. Foxtail Millet (kakum) is rich in protein (10-12.3%), fiber (8-19.1%), and various vitamins and minerals, with a low glycemic index. Proso Millet (china) is a good source of B-complex vitamins, magnesium, and dietary fiber (ICMR-NIN, 2017). Little Millet (kutki) is an excellent source of dietary fiber (15.9-18.1%) and minerals like iron, magnesium, and zinc (ICMR-NIN, 2017). Barnyard Millet (jhangora) is noted as the richest source of crude fiber and iron among millets (AICRP-Millets, 2017). Kodo Millet (kodon) is high in protein (8.3-11%), fiber (9-14.3%), B vitamins, and minerals, with strong antioxidant properties (Ghatak et al., 2024). Browntop Millet (korle) is rich

in crude protein (10.72-13.61%), crude fiber (7.2-16.08%), and diverse minerals (ICMR-NIN, 2017).

It's important to distinguish millets (true cereals, members of the grass family Poaceae) from pseudocereals like Amaranth, Buckwheat and Quinoa, which are cultivated for similar purposes but belong to different plant families (FAO, 2024a).

Nutritional Powerhouse and Health Benefits

Millets are a nutritional powerhouse, offering a comprehensive profile of macronutrients, micronutrients, and bioactive compounds. They typically contain 7-12% protein, 2-5% fat, 65-75% carbohydrates, and 15-20% dietary fiber (ICMR-NIN, 2017). They are rich in B vitamins, beta-carotene, vitamin E, and vitamin B12, along with essential minerals like calcium, phosphorus, magnesium, iron, zinc, potassium, and copper (ICMR-NIN, 2024).

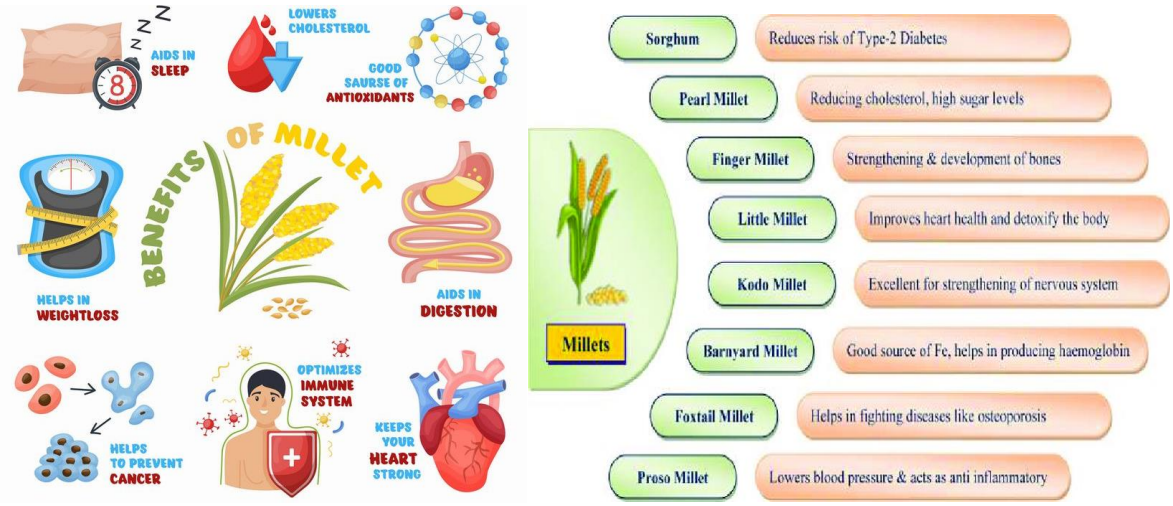
Beyond basic nutrition, millets are abundant in bioactive compounds such as phytates, polyphenols, tannins, anthocyanins, phytosterols and pinacosanols, contributing to their high antioxidant activities (AICRP-Millets, 2017). These compounds offer therapeutic benefits, including anti-microbial, anti-biofilm, and anti-cancer effects (Ghatak et al., 2024).

The consumption of millets is linked to numerous health benefits:

- **Cardiovascular Health:** Millets help decrease triglycerides and C-reactive protein, lower cholesterol (due to niacin), and regulate blood pressure (due to magnesium) (Anitha et al., 2021c).
- **Diabetes Management:** Their low glycemic index (GI) ensures slow glucose release, preventing blood sugar spikes, making them ideal for managing type 2 diabetes.

Minimally processed millets are 30% more effective in lowering meal GI compared to milled rice and refined wheat (Anitha et al., 2021a; University of Reading, 2021).

- **Digestive Health:** High dietary fiber promotes healthy digestion, reduces the risk of inflammatory bowel disease, and acts as a prebiotic, stimulating beneficial gut bacteria (Silva et al., 2024).
- **Weight Management:** The high fiber content promotes satiety, aiding in weight management (Silva et al., 2024).
- **Bone Health:** Millets, especially Finger Millet, are excellent sources of calcium, magnesium and phosphorus, crucial for bone strength and preventing conditions like osteoporosis (ICMR-NIN, 2009/2024).
- **Anti-Cancer and Anti-Inflammatory Effects:** Antioxidants combat inflammation and oxidative stress, factors linked to chronic diseases and cancer (Ghatak et al., 2024).



While millets contain antinutrients (e.g., phytates, polyphenols, tannins, lectins) that can hinder nutrient absorption, traditional and modern processing techniques effectively reduce them. Methods like decortication/dehulling, soaking, germination/sprouting, fermentation, and various heating methods (cooking, roasting, boiling) can significantly enhance nutrient bioavailability (Misra et al., 2016; Sharma & Singh, 2021).

Cultivation and Agricultural Practices

Millets are highly resilient and adaptable, making them crucial for sustainable agriculture (Govindaraj et al., 2022).

- **Climate and Soil Adaptability:** They thrive in low rainfall (200-700 mm annually) and warm climates (20-32°C, tolerating up to 42-50°C), often being the "last crops standing in droughts" (FAO, 2024b). They grow well in various soil types, including poor, sandy, loamy, and clay soils, and even those with low fertility or high salinity. Their deep root systems and C4 photosynthesis contribute to their drought resistance and efficient water use (Ghatak et al., 2024).
- **Water Requirements:** Millets require approximately 70% less water than rice and considerably less than wheat, thriving under rainfed conditions (FAO, 2024a). Adequate moisture is crucial during germination, early vegetative growth, and especially during flowering and grain-filling.
- **Sowing Techniques:** Both traditional (broadcasting, dibbling) and modern (line sowing with seed drills, transplanting) methods are used. Optimal sowing depth is 2-3 cm (AICRP-Millets, 2017).
- **Crop Management:** Millets have low fertility requirements but respond well to balanced nutrient application. They are generally less susceptible to pests and diseases due to natural defences, making Integrated Pest Management (IPM) effective. Effective weed management is critical, as millets compete poorly with weeds in early stages.
- **Harvesting and Post-Harvest Handling:** Grains should be harvested when mature and dry to prevent shattering. Post-harvest processes like threshing and drying (to 10-12% moisture) are vital for quality preservation. The labour-intensive nature of traditional dehulling, especially for minor millets, is a significant bottleneck (ICRISAT, 2022).

Global Production and Market Dynamics

Millets are cultivated in over 100 countries. India is the world's largest producer, contributing approximately 38.4% of global production, with 15.38 million metric tonnes in FY 2024. Other top producers include Nigeria, Niger, Sudan, and Mali. Within India, Rajasthan leads in production and cultivation area (FAO, 2024b). Pearl millet accounts for 60% of cultivated millets in India, followed by sorghum (27%) and finger millet (11%).

Globally, the area under millet cultivation has marginally declined (from 35 to 32 million hectares between 2011-2020), leading to a slight reduction in overall production. However, Asia has seen consistent productivity growth (from 800 kg/ha to nearly 1400 kg/ha between 2000-2019) due to improved cultivars and management, while Africa's productivity has declined. In India, pearl millet productivity increased by 244% between 1963-2020, comparable to wheat, yet cultivation area decreased due to lack of sustained demand and policy support.

The global millet market is experiencing robust growth, valued at USD 11.24-11.31 billion in 2024 and projected to reach USD 15.10-16.93 billion by 2030-2033, with a CAGR of 4.6% to 10.54%. Key growth drivers include:

- Increasing health consciousness and demand for gluten-free and plant-based diets.
- Rising prevalence of lifestyle diseases.
- Government initiatives and policy support (e.g., IYM 2023).
- Environmental sustainability concerns.
- Product innovation and value addition.

Asia-Pacific leads the global millet market (over 60% share in 2025), driven by India, China, and Nepal. Europe and North America are also experiencing steady growth (WITS, 2023).

Global trade in millets reached approximately $258 million in 2023. Top exporters include India ($41 million), Uzbekistan ($40.5 million), and the United States ($33.8 million). Major importers are Pakistan ($37.1 million), Indonesia ($31 million), and Germany ($12.4 million). A significant challenge is that over 80% of India's millet exports are in raw, unprocessed form, and Indian companies hold less than 2% of the global branded millet product market, representing a missed opportunity for higher value capture (WITS, 2023).

Policy Landscape and Research & Development

The global resurgence of millets is significantly shaped by policy and R&D.

- **International Year of Millets (IYM 2023):** Declared by the UN General Assembly at India's initiative, IYM 2023 aimed to raise global awareness of millets' contribution to food security and nutrition, inspire sustainable production, and enhance investment in R&D. It aligns with UN Sustainable Development Goals (SDGs) like Zero Hunger (SDG-2) and Climate Action (SDG-13) (UNGA, 2021).
- **National Government Initiatives:** India declared 2018 as the "National Year of Millets" and classified them as "Nutri-cereals," integrating them into nutrition programs like "Poshan Abhiyaan". Key initiatives include the National Food Security Mission, Rashtriya Krishi Vikas Yojana, and the Millets Mission, aiming to expand cultivation and production. Financial incentives, subsidies for seeds and equipment, and integration into the Public Distribution System (PDS) and Integrated Child Development Services (ICDS) are also part of the strategy. State-level projects like the Odisha Millets Mission (OMM) have shown success in increasing cultivation and yield (Government of India, 2018).
- **Role of International Organizations:** The FAO, as the lead agency for IYM 2023, promotes sustainable production and consumption and collaborates on genetic improvement projects for climate change adaptation. ICRISAT (International Crops Research Institute for the Semi-Arid Tropics) is a pioneering organization in dryland farming, actively involved in millet research and breeding. Their impacts include "Rapid-Ragi" speed breeding protocols for finger millet, reducing its growth cycle from 100-135 days to 68-85 days. ICRISAT has also developed high-protein and high-yielding varieties, improved disease and striga tolerance in pearl millet, and led the pearl millet genome sequencing (Varshney et al., 2017; Kumari et al., 2023).
- **Challenges in Policy Implementation:** Despite efforts, challenges persist, including limited awareness in rural areas, difficulties in processing, lack of established markets, and inconsistent supply and demand. The high cost of millets compared to traditional cereals can also pose accessibility challenges for low-income consumers. The scarcity of high-quality seeds and high-yielding varieties also limits productivity (FAO, 2024a).

Processing, Value Addition, and Product Innovation

Transforming millets into modern food ingredients relies on processing and innovation.

- **Traditional Processing:** Historically, millets were dehulled manually using pestle and mortar, a labour-intensive and time-consuming process, especially for minor millets with tightly adhering husks. Lack of local processing infrastructure remains a challenge (AICRP-Millets, 2017).
- **Modern and Innovative Processing:** Modern techniques aim to remove inedible portions, enhance nutrient bioavailability, and reduce antinutrients. Primary processing includes cleaning, destoning, washing, soaking, germination, and decortication (dehulling), often using modified rice milling machinery like emery or centrifugal mills. Secondary processing converts grains into "ready-to-eat" (RTE) or "ready-to-cook" (RTC) products through extrusion, flaking, popping, and baking. Innovative non-thermal technologies like cold plasma treatment can enhance seed growth, reduce antinutrients (e.g., tannin by up to 57%, phytic acid by up to 18%), and improve nutrient bioavailability. High-Pressure Processing (HPP) can significantly reduce phytate content (up to 80.61%) and increase free iron content (Misra et al., 2016; Sharma & Singh, 2021).
- **Diversification of Millet-Based Products:** Millets are versatile, used in traditional dishes like roti and porridge. Modern value-added products include gluten-free flours for baked goods (breads, pancakes, muffins), breakfast cereals (flakes, puffs, granolas), healthy snacks (puffed millet bread, chips, bars), noodles and pasta, and plant-based milks and smoothies (ICMR-NIN, 2024).
- **Challenges and Opportunities in Value Chain Development:** Challenges include labour-intensive processing, lack of affordable dehullers, inconsistent supply, poor market linkages, low price realization for farmers, and consumer perception issues. Opportunities lie in creating D2C "superfood" brands, leveraging global health trends (clean-label, plant-based, gluten-free), integrating technology (traceability, AI), and strengthening Farmer-Producer Organizations (FPOs) to build robust "farm-to-brand" supply chains.

Environmental Sustainability and Climate Resilience

Millets are a cornerstone of environmental sustainability and climate resilience.

- **Low Water and Input Footprint:** They require significantly less water (approx. 70% less than rice) and fewer chemical inputs (pesticides, fertilizers) than conventional staple grains, making them eco-friendly and cost-effective.

- **Contribution to Soil Health and Biodiversity:** Millets enhance soil fertility by adding organic matter and improving soil structure. Their deep root systems reduce erosion, and they are excellent for crop rotation, promoting soil biodiversity and nitrogen fixation (some varieties).

- **Role in Climate Change Adaptation and Mitigation:** Millets are exceptionally resilient to higher temperatures and extreme weather (droughts, floods). Their short life cycle (60-120 days) allows for "drought escape". As C4 crops, they efficiently use carbon dioxide, contributing to carbon sequestration in the soil and producing lower greenhouse gas emissions compared to high-input crops like paddy rice (Varshney et al., 2017).

Future Prospects and Investment Opportunities

The future of millets is promising, driven by evolving consumer preferences and their critical role in addressing global challenges.

- **Evolving Consumer Preferences:** Growing awareness of millets' health benefits (gluten-free, high fiber, low GI) and a global shift towards sustainable, plant-based diets are driving demand (FAO, 2024b).
- **Investment Avenues:** Significant opportunities exist in (Govindaraj et al., 2022):
    - **R&D:** Developing improved, climate-resilient, and nutritionally superior varieties through genomics and speed breeding.
    - **Processing Infrastructure:** Investing in modern, energy-efficient, and solar-driven processing technologies, especially dehullers for village and micro-enterprise levels.
    - **Startups and Entrepreneurship:** Creating D2C "superfood" brands, developing innovative millet-based products (snacks, cereals, baked goods, beverages), and leveraging technology for traceability and quality checks.
    - **Farmer-Producer Organizations (FPOs):** Strengthening FPOs to build robust "farm-to-brand" supply chains, ensuring quality sourcing and fair prices for farmers.
    - **Market Development:** Facilitating market linkages, establishing quality standards, and promoting millets through consumer awareness campaigns.
- **Contribution to Global Food Security and SDGs:** Millets are vital for combating hunger and malnutrition due to their high nutrient density and affordability. Their

climate resilience ensures food production in erratic weather, making them indispensable for climate change adaptation. Environmentally, they reduce water use, chemical inputs, enhance soil health, and contribute to carbon sequestration. Economically, they provide income and employment for smallholder farmers, contributing to rural development and poverty reduction. Millets directly align with SDGs, including Zero Hunger (SDG-2), Good Health and Well-being (SDG-3), Responsible Consumption and Production (SDG-12), and Climate Action (SDG-13) (FAO, 2024a).

Conclusion and Recommendations

Millets are poised to become a cornerstone of future food systems, offering solutions to global challenges of food security, malnutrition, and climate change. Their exceptional nutritional value, climate resilience, and environmental benefits are undeniable. However, realizing their full potential requires overcoming significant hurdles, particularly in post-harvest processing, market access, and economic viability for farmers.

To accelerate the mainstreaming of millets, a holistic, concerted effort is needed:

- **Governments and Policymakers** must strengthen policy coherence, invest in decentralized processing infrastructure, enhance market linkages (including PDS integration), support farmer empowerment through FPOs and extension services, and increase R&D investment in improved varieties.
- **International Organizations** should sustain the momentum from IYM 2023, facilitate technology transfer to lower-yielding regions, and continue interdisciplinary research into millets' nutraceutical and climate adaptation properties.
- **The Private Sector and Investors** should capitalize on the growing market for health-conscious and convenience foods by investing in modern processing facilities, innovative product development, and D2C "superfood" brands. They should also foster agri-tech innovation and collaborate with FPOs to build robust, remunerative value chains.

By collectively addressing these recommendations, stakeholders can transform millets into a widely consumed, economically viable, and environmentally sustainable food source, contributing significantly to a healthier planet and more secure food future.

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