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FINGER MILLET (RAGI): PROSPECTS IN SUSTAINABLE DEVELOPMENT AS A NUTRIENT-RICH ESSENTIAL

Tanmay Das[1], Anusmita Saha[2], Santanu Kundu[1*], S. Vijay Kumar[3*], Pooja Erapuram[4], Jitendra Majji[3], Vishwajeet Ramesh Avhale[4], Bhambere Hrushikesh Dipak[4], Dhanshri Manishrao Joshi[4], G S Madhu Bindu[5] and Sudhanshu Kasbe Sudhakar[5] and Rajiv Kumar Singh[1]

[1]Division of Agronomy, ICAR-Indian Agricultural Research Institute, New Delhi, 110012, India.
[2]Division of Agronomy, ICAR-Indian Institute of Wheat and Barley Research (IARI Karnal Hub), Karnal, Haryana, 13200, India.
[3]Department of Agronomy, Uttar Banga Krishi Viswavidyalaya, Cooch Behar, West Bengal, 736165, India.
[4]Department of Agronomy, Vasantrao Naik Marathwada Krishi Vidyapeeth (VNMKV), Parbhani, 431402, India.
[5]Department of Agronomy, Professor Jayashankar Telangana Agricultural University, Hyderabad, Telangana, 500030, India.
*Corresponding authors E-mail: sutharivijay@gmail.com; santanukundu120@gmail.com
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ABSTRACT

Finger millet, or ragi (*Eleusine coracana*), a nutrient-rich and climate-resilient cereal, holds a pivotal role in bolstering food and nutritional security in the dryland and semi-dry regions of Asia and Africa. Being enriched with calcium, essential amino acids, antioxidants, and dietary fibers, it offers significant health benefits, such as the management of diabetes, cardiovascular disorders, and malnutrition. Despite its agronomic and nutritional advantages, finger millet remains underutilized due to low consumer awareness, limited market access, and policy neglect. Innovations such as the System of Ragi Intensification, intercropping, and biofortification may enhance its productivity, nutritional quality and resilience. Government initiatives and value-added product development may further promote its adoption. Future research must focus on genetic improvement, precision agriculture, nutrient bioavailability, and post-harvest processing to fully realize it's potential. Repositioning finger millet as a "smart food" is essential for achieving sustainable development goals (SDGs).
***Keywords* :** Nutrient enriched food, Biofortified varieties, Sustainability, Resource use efficiency, SDGs.

Introduction

Achieving food security poses an urgent and complex challenge, especially in developing nations where rapidly growing populations intensify demands on agricultural systems to improve land and crop productivity in a sustainable and environmentally responsible way. Among cereal crops, rice, wheat, maize, sorghum, and various types of millets serve as essential nutritional resources for both human and animal consumption. Finger millet (*Eleusine coracana*)/ragi is particularly popular for its remarkable nutritional profile, making it an invaluable dietary component in low-income regions. In developing nations, finger millet is primarily consumed directly by people, while in developed economies it is more often used as animal feed, contributing to its characterization as a "poor man's food" (Ceasar *et al.*, 2018; Wambi *et al.*, 2020), cultivated predominantly in water-scarce and moderately water-scarce regions of Asia and Africa, this crop is well suited to low-input farming systems, enhancing its relevance for subsistence agriculture (Ceasar *et al.*, 2018; Krishna *et al.*, 2020). Globally, ragi ranks fourth among most produced millet, following sorghum, pearl millet and foxtail millet (Upadhyaya *et al.*, 2007; Maharajan *et al.*, 2019). Its widespread adoption among smallholder farmers is largely due to its remarkable adaptability to diverse climatic conditions and minimal dependence on external inputs, making it highly suitable for marginal environments. Moreover, its low production costs and high tolerance to climatic stress further strengthen its suitability for resource-constrained farming systems.

In response to rising public health concerns, dietary preferences are gradually shifting away from conventional staples like rice and wheat toward more nutritionally rich alternatives such as millets. In this regard, ragi stands out by providing substantially higher levels of vital nutrients including dietary fibre, vitamins, calcium, iron, zinc, magnesium, potassium, phosphorus, and vital amino acids, compared to traditional cereals (Saleh *et al.,* 2013). Additionally, it benefits from a relatively short growth cycle of approximately 90-120 days, strong pest and disease resistance, and exceptional resilience under environmental stress, all of which make it highly relevant for dryland agricultural systems.

Ragi, a member of the *Poaceae* family, is widely cultivated across different states in India, together with Karnataka, Andhra Pradesh, Maharashtra, Odisha, Tamil Nadu, Jharkhand, and Uttarakhand. Despite its proven agronomic and nutritional benefits, its productivity remains relatively low due to unfavourable environmental conditions, limited adoption of agricultural inputs by resource-constrained farmers, and persistent negative consumer perceptions about millets. However, finger millet offers a compelling alternative to major cereals, especially in regions facing water scarcity, soil degradation, and other agro-climatic challenges. Its mild, nutty flavour supports its continued popularity in traditional diets throughout South Asia and Sub-Saharan Africa, where it is commonly processed into porridge, flatbreads, and other staple foods. Due to its superior nutritional value, climate resilience, and low input requirements, ragi is progressively recognized as a key crop for enhancing food and nutrition security, particularly among underutilized minor millets (Maharajan *et al.,* 2022).

Origin and History of Finger Millet

Ragi is an extensively cultivated crop across the dryland and semi-dry regions of Africa and Asia. As a predominantly self-pollinating tetraploid species, and considered to have wild progenitor *Eleusine Africana*. While its origin is frequently linked to the highland areas of Ethiopia and Uganda (Andrea *et al.,* 1999), the precise domestication centre continues to be debated. From its roots in Africa, finger millet is believed to have diffused to the Indian subcontinent approximately 5,000 years ago. Several researchers have advanced different perspectives on its domestication. De Candolle (1886) and Dixit *et al.* (1987) identified India as the centre of origin, referencing the crop's long-established cultivation in that region. Archaeological evidence from Hallur in Karnataka, India, reinforces this viewpoint, with finger millet remains dated to around 2300 BCE (Singh, 2008). In contrast, DeWet (1995) supported an African origin, this evidence suggested that domestication likely took place within the corridor spanning western Uganda to the Ethiopian uplands, a region where *Eleusine coracana* subsp. *africana* (syn. *E. africana*) is widely distributed. The domesticated subspecies, *E. coracana* subsp. *coracana*, encompasses all finger millet varieties grown today. Hilu and De Wet (1976) categorized cultivated ragi into three principal races based on morphological markers, especially inflorescence traits and geographical patterns. The varied nomenclature of finger millet reflects its rich cultural and historical legacy. An alternative hypothesis was proposed by Burkill (1935), who suggested that ragi might have originated from India through the domestication of *Eleusine indica* (L.) Gaertn., illustrating the crop's complex evolutionary pathways. Finger millet has maintained a prominent role in Indian agricultural and culinary systems and it is known by several local names, such as *nachni* in Maharashtra, meaning "dancer," and *umi* in Bihar. Traditionally, red finger millet grains were roasted or sprouted, then dried and milled into a pinkish flour, which is further processed into gruels or dough balls, sweetened or salted according to local preferences, recognized for its high nutritional value, ragi has also been historically utilized as a weaning food for infants (Achaya, 2009).

Botanical Description and Growing Area of Finger millet

Taxonomy and Morphology

Finger millet (*Eleusine coracana*) is an annual grass species typically growing to a height of approximately 30 to 150 cm. It exhibits a relatively short life cycle, with seed development completed within 75 to 160 days (DeWet, 2006). The plant is characterized by green leaves and culms, along with a robust and deeply penetrating fibrous root system. This extensive root architecture not only contributes to the plant's resilience but also plays a crucial role in binding soil particles, thereby minimizing soil erosion. Taxonomically, the species is divided into two principal subspecies: *E. coracana* subsp. *africana*, which represents the wild progenitor, and *E. coracana* subsp. *coracana*, the domesticated form. Hilu and De Wet (1976) further classified the cultivated subspecies into three distinct races based on the morphology of the inflorescence and their corresponding geographical distribution. The inflorescence is composed of spike-like projections arranged in a digitated fashion, resembling fingers an attribute from which the crop derives its common name, “finger millet.” Each spikelet generally contains 4 to 10 florets arranged in succession along each "finger”. Most florets are usually fertile, except for the terminal ones. One distinguishing feature of finger millet grain is the loose attachment of the pericarp to the seed, which facilitates easy separation of the seed coat during processing. The grains exhibit a range of shapes oblong, oval, or round and display a wide spectrum of colours, from reddish-brown to white. In contrast to their wild relatives, modern cultivated varieties are largely non-shattering at maturity, while seed shattering remains a common trait in wild types (De Wet *et al.,*1984). Finger millet exhibits a form of seed dormancy, allowing seeds to remain viable in the soil and germinate only under favourable environmental conditions (Chuah *et al.,* 2004). Like other C4 photosynthetic pathway crops such as maize and sorghum, finger millet efficiently assimilates carbon, enabling it to thrive under a broad range of climatic and environmental stresses. It performs optimally in well-drained sandy soils and exhibits higher nitrogen use efficiency (NUE) than cereals like maize. Research conducted by Thilakarathna and Raizada (2015) has documented considerable genotypic variation in NUE among finger millet accessions, with certain genotypes showing increased responsiveness to nitrogen application. Although the species can endure short-term waterlogging, prolonged exposure to excess moisture or stagnant water has detrimental effects on its growth and productivity. Interestingly, finger millet roots have demonstrated antifungal properties against *Fusarium graminearum*, a significant pathogen in cereal crops. This resistance is linked to the presence of an endophytic bacterium, strain M6, which inhabits the root system and synthesizes natural antifungal compounds that inhibit the pathogen (Mousa *et al.,* 2016).

Major Growing Areas

Finger millet (*Eleusine coracana*) is mainly grown in the semi-arid tropical areas of Asia and Africa, where its potential to sustain in low-input and marginal farming conditions makes it an essential food crop. In Asia, the southern regions of India provide optimal agro-climatic conditions for finger millet cultivation, serving as the primary production zones. The crop plays a key role as a staple food, particularly among rural populations in Southern India, as well as in East and Central Africa. Despite its adaptability across a wide range of altitudes from sea-level plains to the hilly terrains of the Himalayan foothills, finger millet achieves its best yields in well-drained loamy soils. India is among the leading producers globally, with the state of Karnataka alone accounting for approximately 60% of the nation’s production and nearly 34% of the global output (Dhanushkodi *et al.,* 2023). Among millets, finger millet comes at 4th for global production, following sorghum, pearl millet, and foxtail millet. India produces ~ 1.70 MT of ragi annually, with an estimated area of 1.07 mha (Anonymous, 2021). Beyond Karnataka, other significant finger millet-producing states in India include Andhra Pradesh, Telangana, Kerala, Tamil Nadu, Uttarakhand, Haryana, Madhya Pradesh and Jharkhand. These regions contribute substantially to both domestic food security and the preservation of agro-biodiversity through the continued cultivation of this resilient and nutritionally rich crop.

State-of-the-art Technology for Finger millet/Ragi Intensification

In Karnataka (An Indian state), the System of Ragi Intensification (SRaI) locally referred to as *Gulli Ragi* has emerged as an innovative adaptation of the System of Rice Intensification, tailored specifically for finger millet/ragi. This approach incorporates the core principles of SRI (system of rice intensification) into finger millet cultivation, with notable success in enhancing yields and promoting sustainable agricultural practices. The *Gulli Ragi* method has shown potential to significantly increase productivity, reportedly tripling finger millet yields without the application of chemical fertilizers. Central to this technique is the emphasis on resource-efficient management. It involves substantial reductions in the use of seed, irrigation water, chemical fertilizers, and pesticides, while simultaneously encouraging the use of organic matter to improve soil fertility and structure. In contrast to conventional cultivation methods that often rely on continuous flooding, the *Gulli Ragi* system promotes alternate wetting and drying, maintaining moist but not saturated soil conditions. This water management strategy enhances root aeration and encourages deeper root development, thereby improving plant vigour and resilience. By integrating ecological principles into traditional farming systems, the Gulli Ragi method represents a sustainable and climate-resilient approach well-suited to the dryland and semi-arid agro-ecosystems where finger millet is predominantly grown. This technique aligns with broader goals of agroecological intensification, offering a viable pathway for enhancing food security, conserving natural resources, and improving smallholder livelihoods.

Nursery Management and Transplanting for SRaI

Start nursery preparation when the soil is dry by thoroughly puddling the area and incorporating farmyard manure (FYM). Construct nursery beds with a convenient length and a width of 1 meter. Remove soil from both sides of the bed and place it on top to raise the bed height naturally. For added stability, surround the beds with wooden boards supported by bamboo slits to prevent soil erosion during rainfall. To reduce the time and effort required during transplanting, establish the nursery as close as possible to the main field. Soak the seeds in water for 12 hours, then place them in a moist gunny bag and incubate for 24 hours. Level the seedbed before sowing. Apply a thin, even layer of well-decomposed FYM over the seedbed. Broadcast the seeds lightly over this layer. Use 1.25 kg of seed for every 40 square meters of bed area. After broadcasting, cover the seeds with another thin layer of FYM. Water the bed gently every morning and evening. Do not apply any chemical pesticides to the nursery. Under proper care, a healthy and vigorous nursery will be ready for transplanting within 10 to 15 days.

Principles of System of Finger millet/Ragi Intensification

a. **Early Transplanting**: Transplant seedlings when they are 10 to 15 days old and have only two leaves.

b. **Careful Transplanting**: To avoid transplant shock, gently lift seedlings from the nursery with their seed, roots, and soil intact. Transplant without inserting them too deeply. Ensure the seed remains attached and transplant within 15 minutes to prevent drying. Avoid bending the root upward into a “J” shape, as it delays root growth; instead, keep it straight like an “L”.

c. **Wider Spacing**: Transplant seedlings in a square pattern of 25 cm by 25 cm. This spacing allows roots to spread freely and ensures better access to sunlight, air, and nutrients, promoting root development and more tillering.

d. **Weeding and Aeration**: Perform the first weeding 10-12 days after transplanting while weeds are still small. Repeat weeding every 10 days. Mixing weeds into the soil can add up to 1 ton of green manure per hectare and support the development of a diverse soil microbial population.

e. **Water Management**: Use of alternate wetting and drying to create both aerobic and anaerobic soil conditions, improves nutrient mobilization by soil organisms. This also prevents root decay caused by prolonged flooding. Mechanical weeding in non-flooded soil increases soil aeration and root growth, enhancing nutrient uptake.

f. **Organic Manures**: The incorporation of compost or well-decomposed farmyard manure (FYM) at a rate of 10 t/ha, supplemented with diverse organic amendments, enhances soil fertility and ensures balanced nutrient availability. Soil microbiota plays a pivotal role in the mineralization of organic matter, thereby facilitating the release and subsequent uptake of nutrients by plants.

Nutritional Stoichiometry of Ragi and Health Benefits

Finger millet is acclaimed for its remarkable nutritional characteristics (Fig. 1), particularly owing to its significantly high Ca content. According to the National Research Council (NRC, 1996), the calcium concentration in finger millet surpasses that of most other cereal grains to the tune of five to thirty times. The nutrient composition varies across genotypes, with calcium content reaching as much as 450 mg/100 g of seeds (Panwar *et al.,* 2010). Regarding protein, Singh and Srivastava (2006) reported an average content of around 7%, though this can range from 4.88% to 15.58% depending on the variety. Finger millet seeds provide approximately 44.7% of the essential amino acids needed in the human diet (Mbithi-Mwikya *et al.,* 2000). When compared to common staple crops, ragi offers a higher concentration of dietary fiber, P, Fe, Ca, Zn, K, Vit-B, and essential amino acids (Parameswaran *et al.,* 1994; Ceasar *et al.,* 2011). The composition of ragi typically comprises ~3% minerals, ~6.5% protein, ~1.5% ether extractives, ~17.5% dietary fiber (DF), and ~70% carbohydrates (Malleshi NG, 2007). Among all major cereals, finger millet boasts the highest average calcium content at approximately 344 mg per 100 g, making it particularly beneficial for addressing conditions like osteoporosis and calcium deficiency, especially in populations with restricted access to dairy products. This prominent nutrient density underscores finger millet’s potential in improving food and nutritional security (Table 1), especially in malnourished and nutrient-deficient populations.

Carbohydrates

Ragi is largely composed of carbohydrates, making up roughly 70% of the grain’s total weight. Starch accounts for over 72% of this portion, while 15-20% consists of non-starchy polysaccharides (NSPs), which significantly contribute to its high dietary fibre content. The grain contains approximately 1.04% free sugars, 65.5% polysaccharides, and 11.5% DF. According to cultivar-specific studies, lignin content ranges between 0.04-0.6%, cellulose between 1.4-1.8%, and pentosans between 6.2-7.2% (Wankhede *et* *al.,* 1979). The dietary fibre, predominantly composed of NSPs and lignin, cannot be digested by human enzymes but it is essential for gut health (DeVries *et al.,* 1999). Finger millet is also noted for its low glycaemic index. Ragi flour and starch induced a lower glycaemic response vis-à-vis staple cereals in normal and diabetic individuals. *In vitro* analysis further confirmed that ragi starch releases glucose more slowly compared to rice starch, suggesting potential benefits for managing blood sugar levels.

Proteins

Ragi is a rich source of essential amino acids, particularly methionine (3100 mg/g), isoleucine (4400 mg/g), leucine (9500 mg/g), and phenylalanine (5200 mg/g) (Ambre *et al.,* 2020). Its high methionine content distinguishes it from other cereals, which often lack this amino acid a critical dietary requirement in many developing regions (Lande *et al.,* 2017). Methionine and tryptophan are major contributors to the grain's 44.7% essential amino acid profile, exceeding the minimum recommendations by the FAO (Shahidi *et al.,* 2013). The grain's primary storage proteins are prolamins, along with albumins and globulins (Virupaksha *et al.,* 1975). Lysine content in cereals is generally lower than in legumes or animal proteins (ICMR, 2010), however, ragi offers relatively higher amino acid content. Although its prolamins are lower in lysine, arginine, and glycine, they are rich in glutamic acid, proline, valine, isoleucine, leucine, and phenylalanine, which are all vital for human growth and development.

Dietary Fiber (DF) and Antioxidants

High DF content in ragi aids in regular bowel function and promotes digestive health. The DF in this grain is classified into two types based on solubility: soluble dietary fiber (SDF) and insoluble dietary fiber (IDF), each offering distinct health benefits. SDF primarily comprises non-starch polysaccharides such as β-glucan and arabinoxylan, while IDF includes cellulose, lignin, hemicelluloses, and water-unextractable arabinoxylan (Bingham, 1987). NSPs are the major contributors to both soluble and insoluble fibre fractions in millets (Bunzel *et al.,* 2001). Except for arabinoxylan, most fibre compounds decrease progressively from the outer pericarp inward to the endosperm.

Polyphenols

Polyphenols in ragi, act as powerful antioxidants that neutralize free radicals, reduce inflammation, and protect against cellular damage and chronic diseases. The brown seed coat of the grain has a higher concentration of polyphenols compared to other cereals like wheat, barley, and rice (Viswanath *et al.,* 2009). These compounds are primarily found in the outer layers (aleurone, testa, and pericarp), which form the bran. The polyphenol content in the grain ranges from 0.3% to 3%. Hilu *et al.,* (1978) observed that most phenolic compounds in millet exist in glycoside form. There are significant varietal differences in polyphenol concentration. Rao and Muralikrishna (2002) identified ferulic acid as the most common bound phenolic acid, with a concentration of 0.18 g/g, while protocatechuic acid was noted as the major free phenolic acid, at 0.45 g/g. Generally, these polyphenols are heat stable but sensitive to alkaline conditions.

Fats

Finger millet is inherently low in fat, with levels typically ranging from 1.3% to 1.8% (Thapliyal and Singh, 2015), mostly in the form of unsaturated fats. Both brown and white varieties contain about 1.2% to 1.4% fat (Seetharam, 2001). A 100 g serving of finger millet provides approximately 336 Kcal of energy. Sridhar and Lakshminarayana (1994) identified different forms of lipid in ragi comprises structural (~0.6%), free (~2.2%), bound-lipid (~2.4%). The primary fatty acids of ragi includes oleic, palmitic, and linoleic acids, with a smaller amount of linolenic acid.

Antinutritional Factors

Finger millet contains several antinutritional components, including tannins (0.61%), phytates (0.48%), flavonoids, hydrocyanic acid (HCN), oxalic acid, and enzyme inhibitors that impair amylase and trypsin activities (Singh *et al.,* 2016; Nakarani *et al.,* 2021). These compounds, particularly phytates and tannins, may limit nutrient bioavailability. However, they are increasingly known for their health-promoting properties and are now often classified as nutraceuticals. Methods like fermentation and germination can significantly decrease their concentrations. Kumari *et al.,* (2019) observed that unprocessed brown finger millet exhibited higher radical scavenging activity than processed varieties, a trait attributed to the existence of tannins and phytic acid (Devi *et al.,* 2011; Kumari *et al.,* 2019). Green finger millet is traditionally recommended for managing conditions like hypertension, liver disorders, asthma, and cardiac weakness. Additionally, the seed coat is enriched with phytochemicals with potential health benefits. Brown finger millet is distinguished by its superior concentration of phenolic compounds relative to other varieties (Shobana *et al.,* 2009).

Role of Ragi in Climate Smart Sustainable Agriculture

Drought Tolerance and Climate Adaptability

Intercropping millets with pulses or oilseeds enhances natural resource efficiency. Pulses, characterized by their deep taproot systems, are well-suited for intercropping with shallow-rooted, rainfed millets. This complementary root architecture improves overall crop productivity and resource utilization (Jan *et al.,* 2016). Finger millet, in particular, demonstrates moderate drought tolerance and performs well in water-deficient and moderately water-deficient climates, as well as in soils with poor fertility (Maharajan *et al.,* 2021). Finger millet exhibits resilience to drought through three primary mechanisms: drought escape, involving a short life cycle; drought avoidance, which includes enhanced water uptake and retention; and drought tolerance, supported by osmotic adjustments and molecular adaptations. Structural features viz., small seed size, congealed cell walls, abridged leaf area, and profuse root systems enhance stress mitigation and promote efficient water use. The C4 photosynthetic pathway enhances water-use efficiency and enables finger millet to maintain productivity under high-temperature and water-deficit conditions, reduces dependence on irrigation compared to traditional cereals. Moreover, millets contribute significantly to carbon sequestration, with a greater capacity than many cereal and pulse crops, providing substantial ecological, economic, and social benefits. Their adaptability to fluctuating climatic conditions and lower environmental footprint makes them crucial for sustainable agriculture and climate-resilient farming systems. Finger mill*et al*so helps in stabilizing crop yields and supporting the long-term maintenance of carbon levels in natural ecosystems.

Low Input Requirements and Sustainable Agriculture

Millets are fast-growing crops adaptable to multiple seasons and compatible with intensive and relay cropping systems. Despite being labelled as "orphan" or "neglected" crops due to limited global attention and lower production levels, they serve as staple foods in dryland regions and are vital for conserving agricultural biodiversity and supporting rural livelihoods (Belton and Taylor, 2004). With their inherent drought resilience and minimal input requirements, millets are well-aligned with the goals of climate-smart agriculture. They need fewer chemical fertilizers and pesticides, which helps reduce soil degradation and promotes long-term soil fertility. Additionally, their cultivation aids in minimizing erosion and supports the achievement of sustainable development goals (Naresh *et al.,* 2023).

Soil Health Improvement and Intercropping Benefits

Finger millet's ability to withstand adverse climatic conditions makes it suitable plant for intercropping systems. The success of such systems largely depends on the selection of complementary crop species. For instance, when intercropped with deep-rooted pulses, the pulse crops access nutrients from deeper soil layers and redistribute them to the upper soil strata, benefiting shallow-rooted crops like finger millet (Table 2). Studies have demonstrated that millets possess high carbon sequestration potential, with rates ranging from 499.6 to 4024.7 Mg C/ha/year. The values presented here are significantly higher than those found in traditional cereals (0.17-0.52 Mg C/ha/year), pulses (33.0-35.12 Mg C/ha/year), and oilseeds (18.1-45.4 Mg C/ha/year) (Meena *et al.,* 2022). This soil organic carbon accrual enhances soil structure, improves nutrient availability, and boosts microbial activity. Microbial biomass, which is fueled by decomposing organic matter, performs a key role in augmenting soil quality. Furthermore, organic carbon fractions serve as natural binding agents, helping to stabilize soil aggregates while reducing erosion and nutrient leaching. Through these mechanisms finger millet cultivation contributes to healthier soils and promotes sustainable agricultural practices (Fig. 2).

Value-added Products of Ragi

Commercializing value-added enriched ragi and other gluten-free products holds significant potential, especially in industrialized nations where they can aid in reducing obesity and celiac disease prevalence. Finger millet's nutritional value and health advantages make it a desirable and sustainable crop. In order to encourage non-millet consumers to include more millets in their diets, finger millet grains are used to create ready-to-cook or ready-to-use goods. The development of finger millet into practical and user-friendly goods could encourage a wider range of people to consume millets (Ramashia *et al.,* 2018). Nowadays, a wide variety of ready-to-eat ragi products are available in the market (Fig. 3), gaining significant popularity among health-conscious individuals.

Biofortification to Boost Nutritional Values of Finger millets/Ragi

The potential for commercializing value-added, nutrient-enriched finger millet products and other gluten-free alternatives is significant, especially in developed countries, where they can help reduce obesity and celiac disease rates. Owing to its rich nutritional profile and associated health benefits, ragi is increasingly recognized as a sustainable and health-promoting crop. To attract consumers who are unfamiliar with millets, the grain is being incorporated into a range of convenient ready-to-cook and ready-to-use products. Such innovations aim to make millet consumption more accessible and appealing to a broader onlooker (Ramashia *et al.,* 2018). Now-a-days, an expanding variety of ready-to-eat finger millet/ragi products are available in the market, gaining popularity among health-conscious consumers. Some of the important genetic biofortified varieties have been elucidated in Table 3.

However, agronomic biofortification should also be followed in tandem with genetic biofortification. Khobragade *et al.,* (2022) reported that recommended fertilizer (80:40:00 N-P-K kg/ha) coupled with calcium carbonate ($CaCO_3$) at one-fifth of the lime requirement either alone or supplemented with foliar application of iron via 1% $FeSO_4$ resulted in significantly higher quality grain and straw yields in finger millet. Moreover, the integration of the recommended dose of fertilizers (RDF) with either $CaCO_3$ or basic slag led to notable improvements in grain quality. Enhancements were observed across several nutritional parameters, including elevated levels of calcium, iron, protein, crude fibre, and essential minerals. Teklu *et al.,* (2023) showed that application of 25 kg/ha of $ZnSO_4{\cdot}7H_2O$ and 20 kg/ha of $FeSO_4{\cdot}7H_2O$, along with standard NPKS recommendations, significantly increased the zinc and iron concentrations in finger millet grains. This presents an effective strategy for improving dietary micronutrient intake. Further evidence by Manzeke-Kangara *et al.,* (2021) revealed that foliar spray of Fe-EDTA at vegetative and flowering stages resulted into boosted grain iron content by approximately 83%. Supporting this, Kumar *et al.,* (2020) found that among various sources of iron and zinc, foliar spraying of 0.25% zinc humate alongside RDF significantly enhanced zinc uptake, while combining RDF with a 0.5% $FeSO_4$ foliar spray notably improved iron assimilation in the grains. Akbar *et al.* (2018) also observed that exogenous application of calcium nitrate positively influenced grain calcium content, though the response varied depending on the genotype. Rani *et al.* (2022) found that foliar spray of $ZnSO_4$ was more effective than applying it to the soil. The highest zinc concentration was achieved using 150% RDF combined with a 0.5% $ZnSO_4$ foliar spray, which resulted in a 35.9% increase compared to 100% RDF alone. These findings highlighted the effectiveness of nutrient biofortification in augmenting the nutritional superiority in finger millet, thus enhancing dietary quality and public health outcomes.

Ragi: A Catalyst for Livelihood and Government Initiatives

Meeting the nutritional needs of nearly 10 billion people by 2050, while concurrently safeguarding the environment, constitutes a major global challenge. Climate change presents significant challenges to agricultural sustainability and global food security. In this context, millets, particularly finger millet, offer a climate-resilient alternative to major cereals like rice, wheat, and maize. Finger millet grows well in poor soils with low inputs. This reduces cost and improve profitability. Rising demand for gluten free, nutrient rich foods offers market opportunities for value added millet products. Additionally, promotion of finger millet will enhance climate resilience, farmers income and rural development. In order to address the issues of food and nutritional security as well as the threat posed by climate change, the Indian government, state governments, and research institutions have launched a number of programs and projects aimed at boosting ragi and other minor millets production and demand. The following are key policy incentives to boost finger millet production and consumption (Table 4).

Future Prospects and Research Needs

Finger millet is a nutritionally rich and climate-resilient crop, well-suited to thrive in drought-prone, low-fertility, rainfed regions where many conventional cereals fail to perform. Its robust nutritional profile high in iron, calcium, fibre, dietary and essential amino acids make it an effective tool in combating anaemia, diabetes, and malnutrition. With its potential to complement or even replace staple cereals, finger millet offers a promising avenue for food and nutrition security. Future agronomic research should prioritize site-specific nutrient management, sustainable intercropping practices, and water-efficient irrigation systems. Advancing post-harvest technologies and developing value-added products like nutraceuticals and ready-to-eat foods can enhance market appeal and consumer acceptance. Strengthening the entire value chain from production to processing and marketing is essential. This includes improving farmer access to credit, market linkages, and promoting the formation of farmer producer organizations (FPOs) to ensure profitability and scalability.

Although underutilized, finger millet is gaining recognition for its resilience in challenging climates and its contribution to nutritional security. Nevertheless, significant research and development are required to elevate it to the same level as other major cereals. Understanding its genetic diversity, stress tolerance mechanisms, and nutrient bioavailability is critical to realizing its full potential. Collaboration among farmers, industry stakeholders, and researchers is essential for developing innovative, value-added millet products. Modern tools such as artificial intelligence (AI), high-throughput phenotyping, and genomics can significantly enhance genetic improvement. Furthermore, advanced precision agriculture technologies, encompassing unmanned aerial vehicles (UAVs) and digital farm management systems, offer significant potential to enhance productivity and optimize resource utilization. Future research should also emphasize genome editing, molecular breeding, and the development of early-maturing, high-yielding, and biofortified cultivars resistant to pests and diseases. It is imperative to explore the physiological and molecular mechanisms behind tolerance to abiotic stresses such as heat, salinity, and drought. Moreover, nutritional genomics must be leveraged to augment the bioavailability of key micro/macro-nutrients like calcium and iron. In addition, innovations in post-harvest processing and product development are needed to extend shelf life, enhance consumer appeal, and increase farmer incomes. The creation of ready-to-eat and functional food products can significantly expand both domestic and international markets. To maximize the economic and nutritional potential of finger millet, efforts must also focus on strengthening value chains, enhancing financial access, and building market infrastructure. Finally, the mainstreaming of finger millet cultivation requires targeted extension services, participatory breeding programs, and comprehensive farmer training. By combining modern scientific advances with traditional knowledge systems, finger millet can significantly contribute to food security, enhance nutrition, and promote sustainable livelihoods in light of climate change.

Conclusion

Finger millet, once considered a coarse/minor cereals, is now recognized as a "nutri-grain" or "nutraceutical crop" due to its exceptional health benefits and nutritional value. Rich in polyphenols and dietary fibre, it has demonstrated efficacy in addressing hidden hunger and malnutrition, especially in vulnerable populations. Its high calcium and potassium content also makes it beneficial for bone health and blood pressure regulation, positioning it as a vital component of a balanced diet. Owing to its drought tolerance, low input requirements, and ability to grow in marginal soils, finger millet serves as a model crop for sustainable agricultural practices. It is especially suitable for rainfed areas experiencing food insecurity and climate-related challenges. Its adaptability directly contributes to achieving multiple Sustainable Development Goals (SDGs), particularly those focused on ending hunger, improving health, and combating climate change. Despite its numerous advantages, finger millet remains underutilized due to limited market visibility, low consumer awareness, and inadequate policy support. Revitalizing its production and adoption requires an integrated approach involving value chain development, policy reforms, scientific research, and community engagement. Redefining ragi from a "poor man's crop" to a "smart food" of the future is essential to harnessing its full potential. Through concerted and strategic efforts, finger millet has the potential to make a substantial contribution to fostering healthier populations, strengthening resilient agricultural systems, and advancing a more equitable and sustainable production system.

Table 1: Nutritional benefits pertaining to ragi and its reason

Benefit	Reason
Natural weight loss	Higher fiber and tryptophane which lowers blood sugar levels and transforms it to insulin
Body tissue and energy metabolism	Phosphorus aids in energy metabolism
Strengthen bone	Significant amount of calcium (344 mg) needed for bone growth
Prevents cardiovascular diseases	Soluble dietary fiber, hypoglycemic and hypolipidemic effects, lowers serum cholesterol, rich in magnesium
Prevent diabetes	Low glycemic index value and high dietary fiber
	Slow down absorption of glucose, in turn lowering insulin demand
Anti-ageing agent	Methionine and lysine are known to protect skin, antioxidants help in delayed ageing, and vitamin E
Improve digestibility	Slower digestibility, good for pregnant women and diabetics
Boost lactation	Contains amino acids, calcium, and iron beneficial for mother and child
Special therapeutic effects	Contains anti oxidative, anti-inflammatory, and antimicrobial properties

Table 2: Different finger millet based intercropping systems practised in India

Inter/mixed Cropping	Raw-ratio	Benefits	Region
Finger Millet/Ragi + Pigeon pea	8/10:2	Enhanced nitrogen content, deeper root system increases porosity and soil conservation	Karnataka (KA) & Tamil Nadu (TN)
	6:2		Bihar (BR)
	2:8		Chhattisgarh
Ragi + Field bean	8:1	Biological nitrogen fixation, improved soil structure, enhanced fertility	KA and TN
Ragi+ Soybean	6:2	Increased nitrogen content, soil structure, and increased moisture	BR
	4:1		KA
Ragi + Urd bean	8:2/4:1	Cover crop	Maharashtra

Table 3: Important climate resilient/biofortified varieties of finger millet

Variety	Special character	Country	References
Okhale-1 (KAK-WIMBI 1)	Exhibits high productivity with broad panicles, shows strong tolerance to drought, lodging and major diseases like blast and striga. Features brown grain and sturdy plant form	Kenya	http://www.kephis.org/images/VarietyList/april20170525.pdf
P 224	Not prone to lodging or blast, grains are easy to separate and pale in appearance.	Kenya, Uganda, Tanzania	
VL Mandua 347	Early flowering and fair resistance to blast, nutritionally enhance with iron (0.0079–0.0080 mg/100g) and zinc (0.00356–0.0037 g/100g).	India	
KMR 340	White-grained variety ideal for confectionery use, tolerant to blast and blight, stem borer and aphid infestation	India	Gupta *et al*. (2015)
GNN-7 (Gujarat Navsari Nagli-7)	medium-duration, white grain type with easy threshing, strong stem, moderate blast resistance and high calcium content (0.468 g/100g).	India	http://millets.res.in/technologies/finger_millets_varieties.pdf
VL Mandua 347	Resist blast and rich in iron (0.0079–0.0080 g/100g) and zinc (0.00356–0.0037 g/100g).	India	Gupta *et al*. (2015)
VL Mandua 352	Responds well to fertilizer and defends well against blast	India	Gupta *et al*. 2013
VL Mandua 376	Good response to fertilizer application and tolerance to blast disease.	India	Gupta *et al*. (2015)
VL Mandua 348	Resistant to neck and finger blast, lodging resistant, with light Cu-colored grains, and apt for organic systems	India	Patil *et al*. (2016)

Table 4: Government Initiatives for Promoting Millets (Nutri-Cereals)

Initiative	Description
NFSM-Nutri Cereals	Training, seed distribution, and incentives for millet promotion under NFSM. Support for FPOs, seed hubs, tools, and demonstrations
PLI Scheme	Rs. 800 crore (2022–2027) was allotted to promote millet-based value-added products
Millets in PDS	Included in PDS, MDM, ICDS, TPDS for wider availability
Price Support Scheme	Ragi MSP increased from Rs. 3846 (2023-24) to Rs. 4290 (2024-25)
Year of Millets	2018 (National), 2023 (International by UN-FAO) to promote awareness
Millet Parks	Set up across states to boost production & processing
National Millet Museum	Located in Hyderabad to spread awareness
Nutri-Gardens & Campaigns	Millet promotion via SNP, nutri-gardens, global strategy, and G20 MAHARISHI initiative
Millets Experience Centre	Established at Dilli Haat, New Delhi for millet awareness

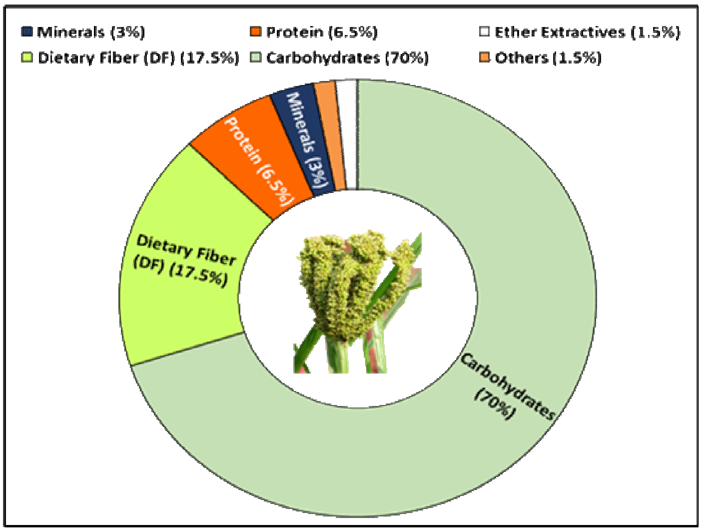

Fig. 1 : Biochemical composition of finger millet seed

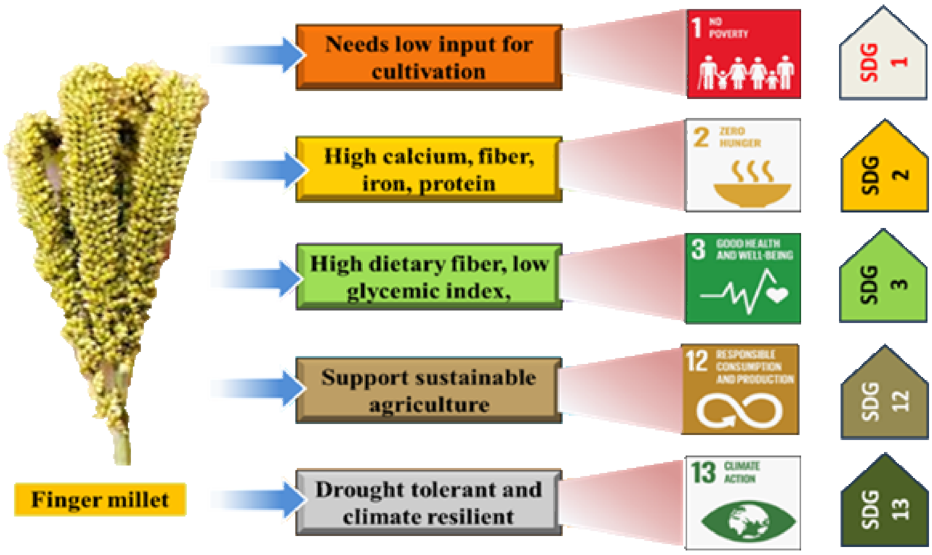

Fig. 2: Potential of finger millet to achieve sustainable development goals (SDGs) in a climate change scenario

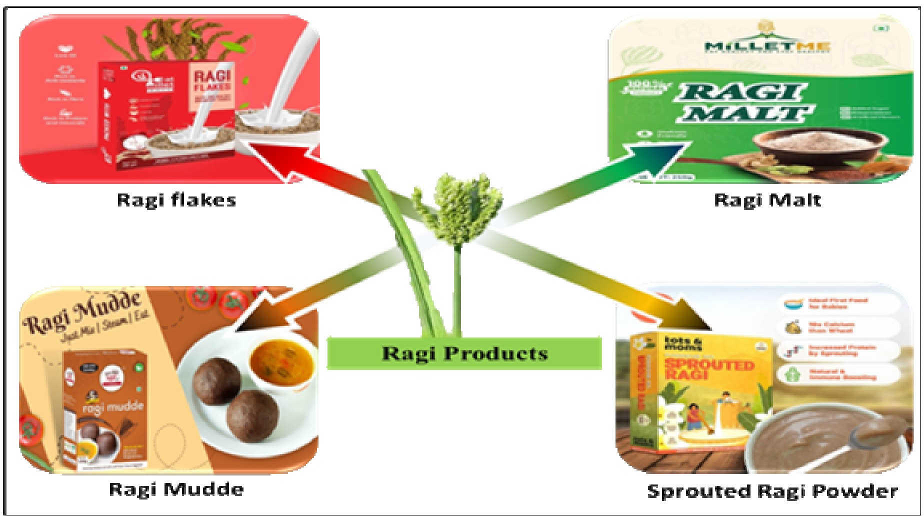

Fig. 3: Commercial and value-added products of finger millet/ragi

Conflict of Interest

The authors declare that there are no conflicts of interest concerning the publication of this article.

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