International Journal for Multidisciplinary Research (IJFMR)
E-ISSN: 2582-2160 • Website: www.ijfmr.com • Email: editor@ijfmr.com

Breeding Approaches in Finger Millet (Eleusine Coracana (L.) Gaertn): A Potential Nutri-Cereal

V. V. Ujjainkar[1], T. H. Rathod[2], P. A. Sonkamble[3], R. D. Lanjewar[4]

[1]Professor (CAS) Genetics & Plant Breeding, College of Agriculture, Dr. PDKV, Akola 444 104
[2]Professor and Head, Department of Agricultural Botany, Dr. PDKV, Akola 444 104
[3]Associate Professor, Department of Agricultural Botany, Dr. PDKV, Akola 444 104
[4]PG Scholar, Department of Agricultural Botany, Dr. PDKV, Akola 444 104

Abstract
Ragi or Finger millet (Eleusine coracana L.) is one of the ancient millets used as a staple food in India. India is one of the World's millet cultivating countries. The most commonly found species includes Finger millet (Eleusine coracana (L.) Gaertn), Little millet (Panicum sumatrense Roth ex Roem. & Schult.), Foxtail millet (Setaria italica (L.) P. Beauvois), and Proso millet (Panicum miliaceum L.). In India, finger millet occupies the largest area under cultivation compared to other small millets. It stands out among cereals like barley, rye, and oats due to its superior nutritional content and exceptional properties as a subsistence food crop. Finger-millet may serve as a nutria-cereal, as it is a prime millet crop with nutritional, therapeutic, and commercial importance. Ragi contains high amounts of calcium, and protein with well-balanced essential amino acids. Thus, ragi is an ideal food for diseases such as diabetes, cardiovascular diseases, chronic obstructive pulmonary disease, and cancer. Its high fiber content prevents constipation, high blood pressure, and gluten intolerance. It has demonstrated the ability to control blood glucose levels.
It is pesticide-free, easy to grow, and cost-effective crop, hence a choice for commercial gains. The development of new finger millet varieties, has proven to be a laborious and resource-demanding endeavor—frequently neglected because of the worldwide focus on the "big three" cereals. These accelerated breeding protocols are particularly beneficial for enhancing crop improvement in resource-limited settings, specifically for Neglected and Underutilized Crops. The "International Year of Millets, 2023" created the demand for nutritious millets to be brought back into the food chain, while it also posed a challenge to breeders to deliver improved cultivars more quickly. Therefore, an attempt has made to focus the health benefits and nutritional qualities of finger-millet and their research updates in field of breeding.

Keywords: Eleusine coracana L., Finger millet, Novel Breeding approach, Nutri-cereal, Ragi

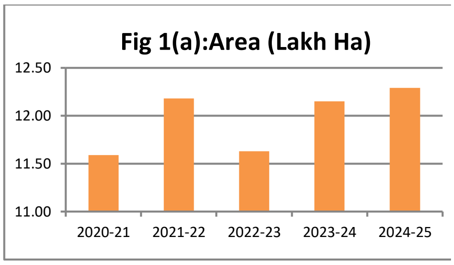
INTRODUCTION

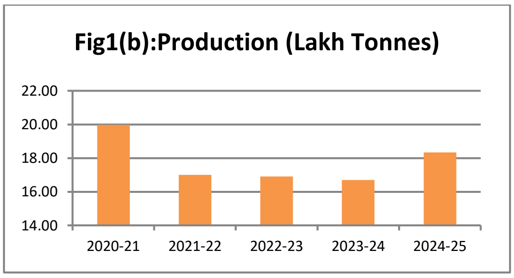
Millets, commonly known as the cereals for the less fortunate, constitute the main dietary staple for a large segment of the impoverished communities in the arid and semi-arid regions of Asia and Africa. Their remarkable ability to flourish in high-temperature, low-moisture environments is a key factor in their cultivation in these areas. The most ancient proof of finger millet's existence dates back to 3000 BC in present-day central Sudan, where it was domesticated. India is recognized as the top producer of finger millet globally. India is well-known throughout the world for its geographical and cultural diversity, which has a big impact on culinary preferences, crop cultivation, and culture. In India, a variety of millet varieties are used extensively as staple foods. These days, millet is considered important because of its many health benefits. On March 5, 2021, the United States proclaimed 2023 to be the International Year of Millets (IYOM), after the Government of India's request was approved by the majority of the UN General Assembly. By high lightening the India's lost grains to the public attention, the GOI hopes to increase the market for Indian cuisine. Finger-millet has gained recognition as a nutri-cereal due to its better nutritional value when compared to other staples like rice and wheat.[4,5]. This nutritional superiority of Finger millet is due to the combination of fibers, carbohydrates, proteins, minerals such as calcium, phosphorous, potassium, magnesium, and vitamins such as thiamine, riboflavin, niacin, tocopherols, and folic acid. The millet kernel's main parts are the endosperm, embryo, and seed coat (testa), among all the different varieties/germplasm lines of finger millets—yellow, white, tan, red, brown, or violet—only the red-colored ones are widely grown worldwide. When compared to other millets like foxtail, pearl, kodo, and proso millet, finger millet is distinct because to its five layered testa. This might be one of the causes of finger millet's higher dietary fiber content. A comparison between finger millet's nutritional profile and that of other minor millets, cereals, and pseudo-cereals in terms of minerals, vitamins, and amino acids [2]. Being nutritionally rich, gluten-free, and having an excellent source of gut-friendly slow digestive starch and fibers. FM and FM-based foods offer various nutritional and health benefits that can be vital in managing non-communicable diseases such as diabetes, cardiovascular diseases, cancer, and chronic obstructive lung diseases [33]. The nutritional attributes of finger millet make it an exceptional food source for individuals of all ages, ranging from weaning children and pregnant or nursing mothers to those dealing with diabetes and coeliac disease. It is particularly attractive to those with gluten sensitivities. The grain is commonly used to create a variety of traditional dishes, such as porridge, flatbread, and fermented foods. Moreover, it is utilized in the production of both alcoholic and non-alcoholic beverages in various African countries, and in India, finger millet malt is employed to prepare nutritious drinks for infants. In addition, the stalks and leaves of the plant are vital sources of feed for cattle and small ruminants, while the grain serves as feed for poultry [7].

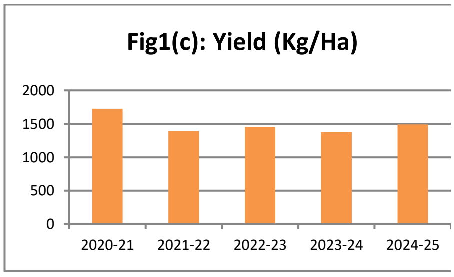
Globally, the finger-millet is grown on a total of about 4 million hectares worldwide, compared with 9.5 million hectares of oats and 47 million hectares of barley in 2022, whereas the total grain yield was estimated at about 3.7 million tones (FAO, 2022). The challenges of crop diversification and food security are paramount in the present age. Recent findings from crop modeling suggest that by 2040, climate change will have a significant impact, causing a substantial drop (over 5%) in the productivity of rice, wheat, maize, and soybean, predominantly in the arid zones across the world. Millions of people rely on finger millet as a staple, and it is commonly cultivated in semi-arid parts of Eastern and Southern Africa and South Asia [24]. It is the third most important millet crop after sorghum and pearl millet and the most important small millet in the tropics covering 12% of the global millet area. In India, finger millet ranks first in importance amongst small millets with a share of 81% of the small millets produced [Meena et al, 2021]. In India, it covers one million hectares, with a total yield of 1.76 million tones and average productivity of 1.74 tones per hectare [3]. Moreover, Maharashtra is one of the important Ragi growing state of the country. (Table 1, Fig 1(a.b.c.))

Year	Area (Lakh Ha)	Production (Lakh Tones)	Yield (Kg/Ha)
2020-21	11.59	19.98	1724
2021-22	12.18	17.01	1396
2022-23	11.63	16.91	1454
2023-24	12.15	16.70	1375
2024-25	12.29	18.34	1492

Table 1: Area, Production and Productivity of Finger-millet (Ragi) kharif in Maharashtra (2020-21 to 2024-25)







Source: Department of Agriculture & Farmer's Welfare (DA&FW), GOI

Biology and Taxonomy of Finger millet

Finger millet was firstly documented by Linnaeus (von Linnaeus 1759) in Systema Naturae, Editio Decima II where he identified it as Cynosurus coracan hence, the basionym Cynosurus coracanus L. The genus Eleusine was later described in detail by Gaertner (1788) in De Fructibus et Seminibus Plantarum and hence the appellation, Eleusine coracana (L.) Gaertn [12]. In cytological perceptive, finger millet is an allotetraploid C_4 plant capable of thriving in fluctuating environmental conditions due to its ability to grow in variety of climatic conditions ranging from coastal plains to highlands and at elevations of 500–2400 meters above mean sea level. The haploid chromosome number in the annual species of finger millet was reported [22] to be 9 in Eleusine indica, 18 in E.coracana, 18 in E. brevifolia Wall. and 17 in E. aegyptica (L.) Desf. Bisht and Mukai (2000) counted the diploid chromosome number in annuals as 36 in E. coracana, 18 in E. indica and E. tristachya, and 16 in E. multiflora while the perennials, E. floccifolia has 18, E. intermedia 18, and E. jaegeri 20 chromosomes [9].

Eleusine coracana is a self-pollinated member of family Poaceae and subfamily Chloridoideae. Cross-fertilization by wind or insects is reported to contribute less than 1% (Seetharam 1998). Different parts and stages of developing inflorescence have been documented. Four principal growth stages (S1, S2, S3, S4) were identified for the developing spike based on a decimal code developed [28 and 43], as shown in Fig.2.

Fig. 2: Principal growth stages of the developing finger millet spike. S1 Booting stage, S2 Flowering or anthesis stage, S3 Grain-filling, S4 Ripening stage (Mirza et al. (2014))[28]

The stage when about one fourth of the inflorescence has emerged is designated as S1 and called the booting stage. The inflorescence is light green in color, the spikelets in the fingers are compactly arranged and florets are not identifiable at this stage. The second stage is anthesis stage. The stage when anthesis is halfway is designated as S2 stage. The inflorescence appears yellowish due to the emergence of anthers. The florets became clear. The S3 stage is the grain-filling stage. It is the late milk stage, once increase in solids in liquid endosperm is notable, when the caryopsis is crushed between fingers. The inflorescence and the developing grains are green in color. The developing grains became swollen but remain covered with lemma and palea. In the S4 stage, 50% of spikelets have ripened and the caryopsis has hardened enough so that it is difficult to divide by thumb-nail. The inflorescence is dried, its color changes to yellow-brown and the grains are clearly visible between the gaped florets (Fig. 3).

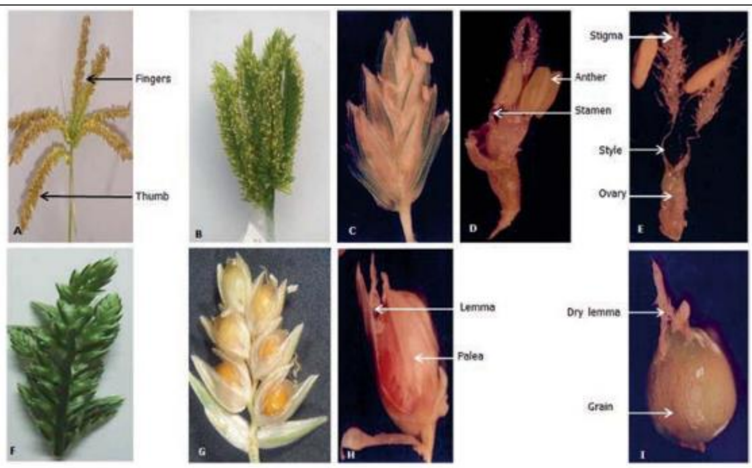


Fig. 3: Different parts of inflorescence in Eleusine coracana (L.) Gaertn. (a) Complete spike or inflorescence, (b) Inflorescence showing flowers on the edge of fingers, (c) Floret (spikelet), (d) Developing embryo in S1 stage, (e) Developing embryo in S2 stage, (f) Finger with developing grains in S3 stage, (g) Single spikelet with maturing grains in S4 stage, (h) Grain with dried lemma and palea still attached, (i) Developed grain with remnants of stigma and stamen attached at the top (Mirza et al. (2014) [28]

The Finger millet inflorescence or spike consists of a whorl with 2–11 (average 5–7) digitate, slightly curved or straight spikes or fingers, with an odd one a little lower known as a thumb, giving the inflorescence a bird-foot appearance (Fig. 3a). The complete emergence of the inflorescence may take up to ten days. Each spikelet consists of 3–13 florets. Flowering takes place simultaneously in all fingers and begins from the top (Fig. 3 b,c). Usually, flowering is complete by third day; however, it varies from place to place depending on temperature and humidity. The terminal floret is mostly sterile. Florets are hermaphroditic having boat-shaped lemma, a smaller palea with two lodicules (Fig. 3g, 6h). Before anthesis florets are compact, the androecium and gynoecium are very small, closely arranged and pale in color (Fig. 3d). The androecium consists of 2–3 stamens with long filaments and short oblong anthers to form the ovary with 2 styles and a plumose stigma forms the gynoecium. After anthesis, the anthers and feathery stigma are visible at the tip of the florets (Fig. 3c); anthers, filaments, stigma and style increase in size, anthers appear yellowish due to pollen grains and the ovary is swollen (Fig. 3e). Pollen viability is very short in finger millet, only 10–15 min and the stigma is receptive for up to 5 h [11]. Opening of the florets and grain filling starts from bottom to top within the spikelets (Fig. 3f). The nonshattering spikelets bear plump grains, usually enclosed in a thin brown pericarp that is exposed between the lemma and palea (Fig. 3g, 6h). Variation in head shapes and grain shapes helps to distinguish closely related species [10]

Physiology of finger-millet

Finger millet is a C4 plant recognized for its durability in challenging environments and its capacity to withstand drought. Its physiological characteristics include a strong, fibrous root system, tillering stems, and a distinctive inflorescence structure. It has erect, light green stems. The leaves of the plant are dark green, linear and mainly smooth with some hair along the leaf edges. The inflorescence of the plant is a cluster of 3–26 'fingers' composed of dense spikelets where the grain, or seed, is produced. Additionally, finger millet demonstrates efficient photosynthesis and possesses a high nutritional profile, particularly in calcium and fiber. Finger millet features a shallow, fibrous root system that branches at lower nodes. This robust root structure aids the plant in anchoring itself and in the absorption of water and nutrients across various soil conditions, including those susceptible to drought. The stems of finger millet are erect, slender, and generally green, with the capability to root at lower nodes. The leaves are linear to linear-lanceolate, predominantly green, and can vary in length. The inflorescence is digitate, meaning the branches extend outward from a central point resembling fingers. These branches, or racemes, can range in number from 4 to 26 and may either spread out or be erect and incurved. The spikelets, which house the flowers and ultimately the seeds, are arranged along one side of the rachis (central stalk).

The Stomatal regulation serves as an additional strategy to cope with heat stress. Stomata, which are tiny openings located on the leaf surface, play a crucial role in gas exchange, including the release of water vapor. Millets possess the capability to manage their stomatal openings to reduce water loss; they can partially close their stomata during daylight hours, thereby decreasing the transpiration rate and conserving water without hindering photosynthesis. Furthermore, millets have developed another protective mechanism against extreme temperatures: they synthesize specific proteins known as heat shock proteins (HSPs) in response to elevated temperatures. These heat shock proteins are instrumental in safeguarding plant cells from damage caused by heat and in preserving their normal functions. Acting as molecular chaperones, these proteins ensure the proper operation of plant cells under conditions of heat stress. Millets also utilize C4 photosynthesis, a more efficient form of photosynthesis in hot and arid environments compared to C3 photosynthesis. This physiological process allows them to effectively utilize carbon dioxide while minimizing water loss through their leaf stomata. Additionally, C4 photosynthesis contributes to the increased biomass of millets, which in turn aids in the regeneration of the soil in which they are cultivated. Moreover, it has been established that millets have a relatively brief life cycle, ranging from 60 to 120 days, allowing them to complete their growth and reproductive phases swiftly. They also display an impressive trait known as drought escape or avoidance, enabling them to mature even more rapidly and finish their life cycle, producing grains before severe drought conditions arise. Certain varieties of millet can also modify their growth patterns in response to limited water availability. Molecular studies identified key drought-responsive genes (EcDehydrin7, EcNAC67, EcbZIP60) and revealed syntenic relationships with Poaceae species, facilitating gene transfer for breeding. Finger millet's diverse genetic traits and stress-tolerance mechanisms make it an essential resource for improving drought tolerance in major crops and developing climate-smart agriculture[16,25,38,39].

Early breeding efforts

Finger millet originated in the highlands of Uganda and Ethiopia and domestication began there around 5000 years ago, as evident from the archaeological records of early African agriculture [2,19,32]. Finger millet arrived in India probably more than 3000 years ago; India has been debated as its origin for a long time due to the presence of several cultivars in different regions. Regarding, finger millet is cultivated under diverse climatic conditions in Asia and Africa, understanding the genetic diversity is vital to identifying genotypes resilient to climate change [27]. In finger millet the hypothesis is assumed that the genotypes tolerant to various biotic and abiotic stresses have more allelic variation compared to susceptible types and thus are very useful for breeding programs. In context of germplasm conservation, targeting towards the crop genetic improvement and subsequent utilization, conservation of the germplasm, evaluation and characterization of the existing diversity is vital. Ex situ conservation prevents the loss of genetic diversity and resources crop breeding programs. For ex situ conservation, seeds are preserved in national crop diversity collections, international genebanks such as those of the Consultative Group for International Agricultural Research (CGIAR), the Millennium Seed Bank, Royal Botanic Gardens Kew and the Svalbard Global Seed Vault (SGSV). SGSV holds 22,000 accessions of millets. Gene banks altogether hold more than 29,000 finger millet germplasms. The International Crop Research Institute for the Semi-Arid Tropics (ICRISAT) Genebank is one of the largest international genebanks that serves as a world repository for the six mandate crops i.e. sorghum, pearl millet, chickpea, pigeonpea, groundnut, finger millet and five small millets with over 126,830 germplasm accessions collected from 144 countries. In addition, the ICRISAT Genebank has also deposited over 111,000 accessions at SGSV, Norway. ICRISAT currently has a collection of 7519 germplasms [31].

Plant breeding is cultivar development, crop improvement and seed improvement of various agriculturally- and horticulturally-important crops, conventionally by selective mating or hybridization. Early finger millet breeding was largely confined to India, particularly in the southern states of Tamil Nadu, Karnataka and Andhra Pradesh. Later, it spread to other Indian states such as Maharashtra, Gujarat, Orissa, Bihar and Uttarakhand. Yield levels were very low due to lack of inputs, poor soil fertility, rainfed farming, low-yielding cultivars and lack of improved agronomic practices. Initial breeding efforts in finger millet were limited due to its self-pollinating nature. Development of emasculation and pollination techniques created the opportunity to improve the crop and create new hybrids. Later, various breeding approaches such as pure-line selection, recombination breeding and mutation breeding were extensively used for the genetic improvement of finger millet. The breeding strategies for selection and genetic improvement have greatly improved since the availability of genomic data and genome editing too.

Conventionally, in India pure line selection method was employed for improvement in crop, followed by hybridization breeding assisted with male sterility and mutation techniques. These conventional approach lead to development of cultivars during 1986-1999 viz., MR-2; MR-6; Indaf-15; VL124; HR911 (UAS 1 x IE 927); L-5 (Malawi x Indaf 9); Gautami (PR 1158–9) (PR 202 x U22) and Gujarat nagli 2 (NS 109) (Pureline selection). After establishment of AICRPs on small millets, emphasis was on developing hybrid cultivars involving productive lines with elite backgrounds. Both early-maturing and long-duration cultivars with high yield potential and suitable for irrigated or rainfed conditions were released. Most of the cultivars were resistant to blast (neck and finger) disease. Numerous blast resistant cultivars of GPU and KMR series i.e. GPU-26, GPU-28, GPU-45, GPU-48, GPU-66, KMR-204, KMR-301 and KMR-340 were released. A somaclonal cv. Dapoli-2 (SCN-6) was developed through tissue culture at Dr. BSKKV, Dapoli, Maharashtra and released in 2017. The parent cv. Dapoli-1 (1985) was mid-late (125–135 days), non-lodging and responsive to nitrogenous fertilizers and with reddish brown grain color. The somaclone Dapoli-2 is a high-yielding cultivar rich in iron and calcium, moderately resistant to blast and
tolerant to aphids and tobacco cutworm.[31]

Table 1. Common Varieties of finger millet grown in different states of India

State	**Varieties commonly grown**
Karnataka	GPU 28, GPU-45, GPU-48, PR 202, MR 1, MR 6, Indaf 7, ML365, GPU 67, GPU 66, KMR 204, KMR 301, KMR 340
Tamil Nadu	GPU 28, CO 13, TNAU 946 (CO 14), CO 9, CO 12, CO 15
Andhra Pradesh	VR 847, PR 202, VR 708, VR 762, VR 900, VR 936
Jharkhand	A 404, BM 2, VL 379
Odisha	OEB 10, OUAT 2, BM 9-1, OEB 526, OEB-532
Uttarakhand	PRM-2, VL 315, VL 324, VL352, VL 149, VL 146, VL-348, VL-376, PES 400, VL 379
Chhatisgarh	Chhattisgarh-2, BR-7, GPU 28, PR 202, VR 708 and VL 149, VL 315, VL 324, VL 352, VL 376
Maharashtra	Dapoli 1, Phule Nachani, KOPN 235, KoPLM 83, Dapoli-2
Gujrat	GN 4, GN 5, GNN 6, GNN 7
Bihar	RAU 8, VL 379, OEB 526, OEB 532

(Source: ICAR-IIMR, Hyderabad, 2018)

Modern trends in finger millet Improvement:

Crop improvement through conventional breeding is slow, especially for traits controlled by quantitative gene action like drought tolerance. Hence, the use of modern crop improvement tools such as genomics to transfer information about genes from model species to the species of interest, and genetic mapping in order to identify genes controlling traits of interest, can provide a more timely and robust response to crop production threats [31]. It also provides added opportunities to develop crop cultivars with multiple stress tolerance. Through molecular techniques, the genetic improvement has been achieved in finger millet for traits viz., herbicide resistance, blast resistance, abiotic stress resistance etc., Finger millet should be prioritized in research and breeding programs as it can help meet all the challenging scenarios of malnutrition, water scarcity, extreme climatic conditions due to global warming and increasing disease susceptibility due to erratic weather. This C4 plant outperforms the C3 plants in harsh conditions and hence is an ideal crop for climate-resilient agriculture. It is allow-input crop and is often grown in infertile soils. This demands the need for identification of genotypes which have high fertilizer use efficiency, particularly N and P. There are only a few early-maturing cultivars which can mature in 90–95 days. The germplasm screening has provided some good cultivars through selection procedures for improving yield and yield contributing traits viz., to develop early-maturing, photoperiod insensitive cultivars suitable for different cropping systems. Breeding of dwarf varieties to avoid lodging and increase grain yield is also important. Finger millet is rich in micronutrients, a good source of essential amino acids and antioxidants also can provide the solution as the most cost-effective approach of mitigating hidden hunger is to introduce varieties with high Ca, Fe, Zn and protein content.

Speed breeding approach in finger millet

Ragi is regarded for its nutritional potential, as rich in calcium, dietary fibre, and phenolic compounds among others family members of poaceae, along with its important source of iron, methionine, and other amino acids, as well as slowly digestible starch and polyphenols. Its gluten-free, low-fat, and easily digestible nature makes it suitable for those with dietary restrictions or sensitivities, earning it the title of "super cereal" [8,17,23]. Climate change has significantly altered the biodiversity of crop pests and pathogens, posing a major challenge to sustainable crop production. At the same time, with the increasing global population, there is growing pressure on plant breeders to secure the projected food demand by improving the prevailing yield of major food crops. Finger millet is an important cereal crop in southern Asia and eastern Africa, with excellent nutraceutical properties, long storage period, and a unique ability to grow under arid and semi-arid environmental conditions. The genetic variability of the existing finger millet genetic resources can be harnessed further to integrate winning and essential traits into candidate varieties through conventional and modern breeding methods. Breeding and genetic innovations such as genomics-assisted breeding, mutation breeding, transgenic approaches and genome editing would accelerate finger millet breeding and new variety design and deployment.

While Finger millet has several benefits, research efforts are minimal compared to three cereal rulers viz., rice, wheat, and maize. In today's contest, the increasing health concerns and climate change challenge breeders to achieve crop improvement faster. Conventionally, the development of improved lines in finger millet involves 4–5 years of breeding and 4–5 years of testing including 1–2 years of multi-environment trials (for promising breeding lines) and three years of national testing (for nominated entries). The adaptation of advanced tools such as selection based on molecular markers (MAS), mapping populations, and phenomics etc., may provide impetus for early line development, however, higher genetic gains require a substantial reduction of breeding cycle time, along with accurate selection for desirable genotypes [21]. The objective of rapid generation advancement can be achieved through the recent method of breeding i.e. 'speed breeding', which can be suitable among the available methods to reduce the breeding cycle time. The Speed breeding may provide the simplest solution to reducing the generation time in a crop to facilitative for the multiple cropping within short window of time. Speed breeding comprises the manipulation of various growing conditions that involves tuning of photoperiod, light intensity, light quality, temperature, and relative humidity which is essential to promote physiologically favouring condition for biologically essential activities of plant lifespan viz., early flowering and subsequent early maturity. Reports has highlighted the success of such adventure of speeding the life-cycle in various agricultural crops including cereals (rice, wheat, barley), oil seed (soybean, brassica) and even in pulses (chickpea and pigeonpea) and fiber crops (cotton) for achieving the rapid generation advancement [1,13,14,20,30,35,36,40,42]. Combining the speed breeding approach with agronomic interventions allowed us to create a robust, efficient, and economical platform for finger millet breeding through rapid generation advancement while keeping it cost-efficient and practical.

Conclusion

Finger millet is a crop of considerable significance for subsistence in Eastern Africa and Asia, including India. This gluten-free cereal has received attention for its exceptional nutritional benefits, which may classify it as a nutria-cereal, making it a key player in the fight against malnutrition. In addition to its health benefits, the cultivation of finger millet serves a dual purpose, addressing the dietary needs of rural families while also supporting their economic livelihoods. Due to the alarming reduction of agricultural land resulting from population growth and industrialization, it is anticipated that the world will face a severe food demand by 2050, prompting agricultural scientists to increase cereal production. The introduction of new genomic resources (WGS) for finger millet, along with knowledge of significant trait-governing genes, can be combined with recent genome editing technologies to create nutritionally rich, climate-resilient cultivars, applicable not only to finger millet but also to other important cereal crops. The replacement of local cultivars with modern varieties, a policy shift towards rice and wheat, and other factors such as environmental degradation, urbanization, deforestation, and bushfires have led to the genetic erosion of indigenous species. Globally, there is now recognition of the health benefits of these once-overlooked coarse grains, leading to a willingness to pay higher prices. Thus, it is imperative to prioritize the promotion of such millets and to focus future efforts on improving the existing gene pool.

References

1. Alahmad S, Dinglasan E, Leung KM, Riaz A, Derbal N, Voss-Fels KP, Able JA, Bassi FM, Christopher J, Hickey LT. Speed breeding for multiple quantitative traits in durum wheat. Plant Methods. 2018;14:1–15
2. Anonymous (1995) Food and Agricultural Organisation (FAO) of the United Nations Sorghum and Millets in Human Nutrition (FAO Food and Nutrition Series, No. 27) 92-5-103381
3. Anonymous (2020): FAOSTAT, Statistics FAO. Food and Agriculture Organization of the United Nations, Rome, 2020.
4. Anonymous (2023a) FAO. International Year of Millets 2023
5. Anonymous (2023b) Ministry of Agriculture and Farmers Welfare Government of India. Nutricereals- IYoM 2023. Available from: dac.gov.in
6. Anonymous (2025a) Knowledge Hub, Crop Trust 2025.
7. Anonymous (2025b) FAO. International Year of Millets 2025.
8. Backiyalakshmi C, Babu C, Deshpande S, Govindaraj M, Gupta R, Sudhagar R, Naresh D, Anitha S, Peerzada O, Sajja S, Singh K, Vetriventhan M.(2023) Characterization of finger millet global germplasm diversity panel for grain nutrients content for utilization in biofortification breeding. Crop Science; 1–20
9. Bisht MS, Mukai Y (2000) Mapping of rDNA on the chromosomes of Eleusine species by

fluorescent in situ hybridization. Genes Genet Syst 75:343–348

10. De Wet JMJ, Rao KEP, Brink DE, Mengesha MH (1984) Systematics and evolution of Eleusine coracana (Gramineae). Am J Bot 71(4):550–557
11. Dodake SS and Dhonukshe BL (1998) Variability in floral structure and floral biology of finger millet (Eleusine coracana [L.] Gaertn.). Indian J Genet Plant Breed 58:107–112
12. Gaertner J (1788) Eleusine Indica (L.) Gaertn. Wire-grass. Crab-grass. Yard-grass. De Fructibus et Seminibus Plantarum 1:8
13. Gangashetty PI, Belliappa SH, Bomma N, Kanuganahalli V, Sajja SB, Choudhary S, Gaviyappanavar R, Bomireddy D, Anil Kumar V, Pranati J, Sharma M. Optimizing speed breeding and seed/pod chip based genotyping techniques in pigeonpea: A way forward for high throughput line development. Plant Methods. 2024;20(1):27
14. Ghosh S, Watson A, Gonzalez-Navarro OE, Ramirez-Gonzalez RH, Yanes L, Mendoza-Suárez M, Simmonds J, Wells R, Rayner T, Green P, Hafeez A. Speed breeding in growth chambers and glasshouses for crop breeding and model plant research. Nat Protoc. 2018;13(12):2944–63
15. Gunturu V.S., R.K. Panda, R.K. Nayak and M. Satapathy (2024): Characterization of the Morpho-Physiology and Yield of Finger Millet (Eleusine coracana L. Gaertn) under the Influence of Lime, Compost, and Micronutrients., Environment and Ecology 42 (2B) : 915-919
16. Gupta SM, Arora S, Mirza N, Pande A, Lata C, Puranik S, Kumar J and Kumar A (2017) Finger Millet: A “Certain” Crop for an “Uncertain” Future and a Solution to Food Insecurity and Hidden Hunger under Stressful Environments. Front. Plant Sci. 8:643.
17. Hasegawa T, Wakatsuki H, Ju H, Vyas S, Nelson GC, Farrell A, Deryng D, Meza F, Makowski D.(2022) A global dataset for the projected impacts of climate change on four major crops. Sci Data.;9:58
18. Heuzé V., Tran G., Hassoun P., and Lebas F., (2019). Finger millet (Eleusine coracana), forage. Feedipedia, a programme by INRAE, CIRAD, AFZ and FAO.
19. Hilu KW, De Wet JMJ, Harlan JR (1979) Archeobotany and the origin of finger millet. Am J Bot 66:330–333
20. Kabade PG, Dixit S, Singh UM, Alam S, Bhosale S, Kumar S, Singh SK, Badri J, Varma NRG, Chetia S, Singh R. SpeedFlower: a comprehensive speed breeding protocol for indica and Japonica rice. Plant Biotechnol J. 2024;22(5):1051–66
21. Kayastha S, Sahoo JP, Mahapatra M, Panda N.(2024) Understanding the molecular breeding and omics approaches for finger millet (Eleusine Coracana L.) improvement towards a global sustainable nutritional security. Crop Des.;3(1):100049.
22. Krishanswami N, Ayyangar GNR (1935) A note on the chromosome numbers of some Eleusine species. Curr Sci 4:106
23. Kudapa H, Barmukh R, Vemuri H, Gorthy S, Pinnamaneni R, Vetriventhan M, Srivastava RK, Joshi P, Habyarimana E, Gupta SK, Govindaraj M.(2023) Genetic and genomic interventions in crop biofortification: examples in millets. Front Plant Sci.;14:1123655
24. Kumar A, Metwal M, Kaur S, Gupta AK, Puranik S, Singh S, Singh M, Gupta S, Babu BK, Sood S, Yadav R. (2016) Nutraceutical value of finger millet [Eleusine coracana (L.) Gaertn.] and their improvement using omics approaches. Front Plant Sci.;7:934
25. Lata, C. (2015). Advances in omics for enhancing abiotic stress tolerance in millets. Proc. Indian Natl. Sci. Acad. 81, 397–417

26. Meena RP, Joshi D, Bisht JK, Kant L. (2021) Global scenario of millets cultivation. Millets Millet Technol. 2021;33–50
27. Mercer K L and Perales H R (2010) Evolutionary response of landraces to climate change in centers of crop diversity. Evol Appl 3:480–493
28. Mirza N, Taj G, Arora S, Kumar A (2014) Transcriptional expression analysis of genes involved in regulation of calcium translocation and storage in finger millet (Eleusine coracana L. Gartn.). Gene 550(2):171–179.
29. Mude LN, Mondam M, Gujjula V, Jinka S, Pinjari OB, Yellodu Adi Reddy N, Patan SSVK.(2020) Morpho-physiological and biochemical changes in finger millet [Eleusine coracana (L.) Gaertn.] under drought stress. Physiol Mol Biol Plants. 26(11):2151-2171
30. Nagatoshi Y, Fujita Y. Accelerating soybean breeding in a CO2-supplemented growth chamber. Plant Cell Physiol. 2019;60(1):77–84.
31. Neelofar Mirza and Soma S. Marla (2019): Chapter 3: Finger Millet (Eleusine coracana L. Gartn.)Breeding in J. M. Al-Khayri et al. (eds.), Advances in Plant Breeding Strategies: Cereals, Springer Nature Switzerland
32. NRC (1996) Lost crops of Africa. National Research Council, Washington, DC
33. Prajakta Sawant and Swagata Tavhare. (2023). A review on the use and scope of finger millet (Ragi) in prevention and management of non-communicable diseases. Journal of Drug Research in Ayurvedic Sciences 8(Suppl 1):p S55-S63
34. Sajja Sobhan, Jwala Pranati, S. Shyamala, K. S. Vinutha, Ramya Reddy, Priyanka Joshi, Srinivasulu Pannem, P. Rakshit, Yashoda Jadhav, C. V. Sameer Kumar and Sean Mayes (2025) A speed breeding protocol for finger millet. Plant Methods **21**, 84
35. Samantara K, Bohra A, Mohapatra SR, Prihatini R, Asibe F, Singh L, Reyes VP, Tiwari A, Maurya AK, Croser JS, Wani SH. Breeding more crops in less time: A perspective on speed breeding. Biology. 2022;11(2):275
36. Samineni S, Sen M, Sajja SB, Gaur PM. Rapid generation advance (RGA) in Chickpea to produce up to seven generations per year and enable speed breeding. Crop J. 2020;8(1):164–9
37. Seetharam A (1998) Small millets research: achievement during 1947–1997. Indian J Agri Sci 68(8):431–438
38. Singh, R. K., Phanindra, M. L. V., Singh, V. K., Raghavendrarao, S., Solanke, A. U., and Ananda Kumar, P. (2014). Isolation and characterization of drought responsive EcDehydrin7 gene from finger millet (Eleusine coracana (L.) Gaertn.). Ind. J. Genet. Plant Breed. 74, 456–462
39. Srikanth K, Asish Binodh, Ravikesavan Rajasekaran, Alagarsamy Senthil, and Narayanan Manikanda Boopathi (2025) "Exploring morpho-physiological, biochemical, and molecular strategies of finger millet (Eleusine coracana) for drought stress tolerance: a review," Crop and Pasture Science 76(4), 1-15
40. Ujjainkar V.V. and V.D.Patil (2020) Marker-assisted selection in American cotton genotypes using biochemical and molecular profiling techniques., Inter J Adv Res Ideas Innov Tech., 6 (1): 989-993
41. Venkatesh, K., Maruthamuthu, E., Srividhya, S., Nayak, S. (2023). Comprehending the Physiological Efficiency of Millets Under Abiotic Stress. In: Harohalli Masthigowda, M., Gopalareddy, K., Khobra, R., Singh, G., Pratap Singh, G. (eds) Translating Physiological Tools to Augment Crop Breeding. Springer, Singapore.
42. Watson A, Ghosh S, Williams MJ, Cuddy WS, Simmonds J, Rey MD, Asyraf Md Hatta M,

Hinchliffe A, Steed A, Reynolds D, Adamski NM. Speed breeding is a powerful tool to accelerate crop research and breeding. Nat Plants. 2018;4(1):23–9

43. Zadok JC, Chang TT, Konzak CF (1974) A decimal code for the growth stages of cereals. Weed Res 14:415–421