***Review Article***

# A Comprehensive Review of Pearl and Small Millets: Taxonomy, Production, Breeding and Future Prospects in Saudi Arabia

## ABSTRACT

Agriculture has seen significant development in the last ten years, but it is also struggling with issues like starvation, malnutrition and climate change in the world. Millet crops from flowering plants of cereals crops belonging to the family Poaceae or Gramineae (herbs). Millets are climate-smart crops that achieve nutritional security, develop sustainable diets, provide multiple health benefits, promote sustainable production agriculture, and the fulfillment of the future needs of the ever-growing population as well as create sustainable market opportunities for producers and consumers. In this review, we have attempted to supply information on millet crops including history and taxonomy, germplasm, world production, economic importance, and breeding approaches, as well as millet challenges and prospects in KSA. We underlined the importance of the collection and conservation of millets germplasm which can be of great use in the identification and development of improved millets cultivars with nutritional and health benefits under harsh and changing climatic conditions using breeding conventional and biotechnology methods. Therefore, the promotion of millet could aid attain achieve food and nutritional security of KSA in alignment with the sustainable development goals in Saudi Vision 2030.

**Key words**:Pearl Millet, Small Millets, Food Security, Future Prospects, KSA

## 1. Introduction

Cereals are annual, herbaceous plants belonging to tribe Triticeae of the grass family Poaceae (Gramineae) and grown for their edible seeds. The term cereal is used to either characterize the grain or the seed itself. Grain is a collective term applied to cereals (El-Hashash and El-Absy, 2019). Over the world, the cereal crops represent an important source of staple foods and directly provide more than 50% of the calories consumed by people (El-Hashash et al. 2022). Wheat, oats, barley, rye, maize, rice, millet, and grain sorghum are important cereals (Decoteau 2005).

Due to their high nutritional value when compared to regularly farmed cereals like wheat, rice, or corn, millets are frequently referred to as "Nutri-Cereals" (FAO, 2023). Millets are a traditional staple food for the rural poor in dryland regions, they can be grown in poor areas (Rao et al., 2021), where there is not enough rainfall subject to low rainfall and drought where other grains are unsuitable for production unless irrigation is available, especially for the growth of maize and sorghum, as well as tolerate a wide range of soils (Nwajei, 2023). Millions of farmers in the arid and semi-arid parts of Sub-Saharan Africa and Asia depend on millets, one of the first plants to be domesticated in these regions (FAO, 2023).

According to a resolution passed by the United Nations General Assembly (UNGA), 2023 as the International Year of Millets (Rao et al., 2021). This reveals the importance of millets and their role in strengthening food security (Ceasar and Maharajan, 2022). Where the millets are highly nutritious and contribute substantially for food and nutritional security, but in recent decades, both millets' production and consumption have drastically decreased (Rao et al., 2021). Millets includes sorghum (*Sorghum bicolor* L.), pearl millet (*Pennisetumglaucum* L.), finger millet

(*Eleusinecoracana* (L.) Gaertn.), foxtail millet (*Setariaitalica* (L.) P. Beauv.), proso millet (*Panicummiliaceum* L.), barnyard millet (*Echinochloa crus-galli* (L.) P. Beauv. and*Echinochloacolona* (L.) Link), kodo millet (*Paspalumscrobiculatum* L.), little millet (*Panicumsumatrense* Roth. ex. Roem. &Schult.), teff (*Eragrostistef* (Zucc.) Trotter], fonio millet (*Digitariaexilis*Stapf and D. iburuaStapf.), job's tears (*Coixlacryma-jobi* L.), guinea millet (*Brachiariadeflexa* (Schumach.) C.E.Hubb. ex Robyns, = *Urochloadeflexa* (Schumach.) H.Scholz), and browntop millet (*Brachiariaramosa* (L.) Stapf.=*Urochloaramosa* (L.) T.Q. Nguyen) (Vetriventhan et al. 2020; Ceasar and Maharajan, 2022).

Food security will be a worry in Kingdom of Saudi Arabia (KSA), as most food products are imported from other nations because domestic demand, particularly for cereals, exceeds local output. Land and water are significant agricultural output constraints, and by 2050, KSA is anticipated to import all of its local requirements (Fiaz et al., 2018).Millet is a wide expression used for various groups of small-seeded annual C4 panicoid grasses whose seeds are utilized as food and biomass as feed. Therefore, it is stapled food in the developing world, especially in the drylands of Africa and Asia. Millets are tolerant to many crop diseases and pestscan thrive on poor soils with few inputs and can withstand harsh climatic conditions (FAO, 2023). Therefore, the addition of drought and heat-tolerant crops like millet in cropping patterns has become necessary due to the rapidly rising livestock population and the increasing scarcity of high-quality feeds with each passing year. It is quite worrying that millet is still underused despite its many advantages and significance (Nwajeiet al., 2019). Millets' genetic diversity presents prospects for economic growth through revenue-generating ventures in the food industry, where they improve human and animal health, or in niche markets for specialized professional uses including therapies, medicines, and specialty chemistry (FAO, 2023).The purpose of this review is to shed light on the value of millets as well as their taxonomy, breeding, production, difficulties, potential, and future prospects in KSA.

Very :[1DAL]Comment

## 2. History and Taxonomy

In Eurasia, some millets have been domesticated in east or central Asia, while others have been domesticated in the Indian subcontinent. The cultivation of millet has a long history, dating back to the ancient world (Zhang et al. 2012). Archaeological discoveries demonstrate that millet was produced 10,000 years ago (Lu et al. 2009). The ancient Vedic Sanskrit text 'Yajurveda' also mentions foxtail millet, barnyard millet and black finger millet, according to Satyavathi et al. (2019). The millet crops were domesticated by the native populations in Asia and Africa and then spread to other parts of the world. Further domestication in other areas led to secondary regions with diversity, adaptation, and a range of possible uses (Bhat et al. 2018). The domestication of millet during the Neolithic and Bronze Ages was facilitated by its innate capacity to thrive and produce in challenging conditions, high genetic flexibility, and high nutritional value (Satyavathi et al. 2019).

The Yangshao region is where the oldest millet in the world was discovered; it predates the Yangshao culture by around 5,000 years. Proso millet was domesticated as early as 8000 BC, whereas foxtail millet may have been used later, around 6600 BC. Early Chinese hunters and gatherers presumably consumed millet. As early as 8000 BC, millet seeds were processed into flour or meal using stone tools, then cooked in earthenware containers. In 3000 BC, the ancient Egyptians discovered how to cultivate millet in the dry Sahara. After learning that millet blossomed during the monsoon season and matured swiftly, the Moors in North Africa began to cultivate it.

It was also grown in southern Arabia and in what was formerly known as Gaul (France) (Bhat et al. 2018). The majority of millets are native to Africa and were domesticated there before spreading to other regions of the world (Meena et al. 2021).

In the field of crop and agricultural sciences, it is crucial that there be a standard and clear system for classifying crops. Plant classification comes before the efforts to simplify plant research, breeding, and specialized development. The availability of standardized plant names makes it easier to communicate, disseminate, and retrieve scientific data (El-Hashash and El-Absy, 2019). The principal ranks of millets classification in descending sequence are:

- Domain: Eukaryota
  - Kingdom: Planta – Plants
    - Subkingdom: Tracheobionta – Vascular plants
      - Phylum: Spermatophyta – Seed plants
        - Subphylum: Magnoliophyta – Angiospermae – Flowering plants
          - Class: Liliopsida – Monocotyledonae
            - Subclass: Commelinidae
              - Order: Cyperales

All millets belong to the family of Poaceae (Gramineae or true grasses). They belong to either of the two subfamilies of Panicoideae (Andropogoneae and Paniceae tribes) or Chloridoideae (Eragrostideae tribe). Small millet crops and their scientific names, common names, origins, chromosome numbers, and economic uses are shown in Table 1. Based on the form and shape of the panicles, races and subraces of the cultivated germplasm of finger millet, foxtail millet, proso millet, kodo millet, small millet, and barnyard millet can be identified (Vetriventhan et al. 2020). However, teff can be classified on the basis of seed color: ivory (white), qey (red/brown) and sergegna (mixed). In fonio, five morpho-types have been recognized namely gracilis, stricta, rustica, mixta, and densa on the basis of morphology (Brink and Belay, 2006). There are nearly ten genera and fourteen species of millets, which belong to Poaceae family (Satyavathi et al. 2019). The morphologies or races of guinea millet and browntop millet are unknown. The chromosome count and ploidy level of tiny millets, which range from the diploid foxtail millet (2n = 2x = 14) to the hexaploid barnyard millet (2n = 6x = 54), are another indication of their differentiation. All of these little millets were domesticated and originated in Asia, Africa, or both. They are now grown all over the world as weeds or grasses, food crops, or both (Vetriventhan et al. 2020).

Table 1. Small millet crops and their scientific names, common names, origins, chromosome numbers and economic uses.

Whatis :**[2DAL]Comment**

| Tribe | Crop | Scientific name | Common names | Origin | Chromosome number | Use |
|---|---|---|---|---|---|---|
| Andropog -oneae | Job's tears | *Coixlacryma-jobi* L. | Adlay, Adlay millet, bodhi bead, six millet, pearl rice, medicinal corn, Coix bead | Southern and eastern Asia | 2n =10,20,30 | Grown for food grain and medicine |
| Paniceae | Pearl Millet | *Pennisetumglaucum* (L.) R. Br (= *P. americium* (L)) | Bajra, cattail, bulrush, candlestick, sanyo, munga, seno | West African Savannah | 2n = 2x = 14 | Grown for food grain in Asia and Africa, for fodder in Americas |
| | Foxtail Millet | *Setariaitalica* (L.) P. Beauv. | Italian, German, Hungarian, Siberian, | Eastern Asia | 2n = 2x = 18 AA | Grown for food grain and fodder |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | kangani, navane, thanahal | (China) | | |
| | Proso Millet | *Panicummiliaceum* L. | Common, hog, broom, samai, Russian, panivarigu, panic, mahameneri | Egypt, Arabia and China | $2n = 4x = 36$ | Grown for food grain and bird seed |
| | Sawa Millet | *Echinochloacolona* (L.) Link ssp. frumentacea (Link) (= *E. frumentacea* Link). | Barnard millet | Peninsular India | $2n = 6x = 54$ | Grown for food grain |
| | Barnyard Millet | *Echinochloa crus-galli* (L.) P. Beauv. (syn. *E. esculenta* (A. Braun) | Japanese, sanwa, sawan, Korean, kweichou | Japan | | |
| | Little Millet | *Panicumsumatrense* Roth. exRoem. &Schult. Subsp. *sumatrense* (syn. *P. miliare*auct. pl.) | Blue panic, heenmeneri, samai | India, especially peninsula | $2n = 4x = 36$ AABB | Grown for food grain |
| | Kodo Millet | *Paspalumscrobiculatum* L. | Varagu, bastard, ditch, naraka, water couch, Indian paspalum, creeping paspalum, amu | India | $2n = 4x = 40$ | Grown for food grain |
| | White Fonio | *Digitariaexilis*Stapf | Fonio, acha, fundi | West Africa | $2n = 36$ | Grown for food grain in Africa |
| | Black Fonio | *Digitariaiburua*Stapf | Hungry rice, raishan, polish millet, iburu, | | | |
| | Guinea millet | *Urochloadeflexa* (Schumach.) H. Scholz (= *Brachiariadeflexa*) | Paguiri, yaquéyaqué | Tropical and subtropical regions in Africa, India, and Pakistan | $2n = 18,36$ | Grown for food grain |
| | Browntop millet | *Urochloaramosa* (L.) T.Q. Nguyen (= *Brachiariaramosa* (L.) Stapf.) | Dixie Signalgrass, makra | South India | $2n = 2x = 18$; $2n = 4x = 36, 72$ | Grown for feed, green manure, and food of terrestrial and water birds |
| Eragrostideae | Finger Millet | *Eleusinecoracana* (L.) Gaertn. | Ragi, African,bird's foot, rapoko, Hunsa, wimbi, bulo, telebun, koracan, kurakkan | East African highlands | $2n = 4x = 36$ AABB | Grown for food grain and beer making in Asia and Africa |
| | Tef | *Eragrostistef* (Zucc.) Trotter | Abyssinian lovegrass | Ethiopian highlands | $2n = 4x = 40$ AABB | Grown for food grain, and fodder |

:[3DAL]Comment

### 3. Important millets germplasm

Breeding cannot be done without germplasm because it is the foundation of plant breeding (El-Hashash and El-Absy, 2019). The genetic material that can be employed to immortalize a species or population is called germplasm. Although it has no intrinsic reproductive value, plant breeding can enhance the germplasm for the highest crop performance (Acquaah 2007). In addition to 30,627 accessions, 133,849 cultivated germplasms of tiny millets are conserved globally, with the majority of them coming from Asia and Africa (Vetriventhan et al. 2020). There are a number of germplasms of small millets with promising characteristics, like nutritional quality and resistance to biotic and abiotic stressors (Maitra et al. 2022). Major millets germplasm collections are presented in Table 2.

The ICRISAT Genebank is one of the biggest worldwide genebanks of millet crops, with millets germplasm accessions gathered from 144 countries through donations and collection expeditions for different crops. Several of the landraces that are now preserved in the ICRISAT genebanks have vanished from their native environments in Asia and Africa. The collection provides protection against genetic deterioration as well as a source of features for improving crop productivity, greater nutritional quality, tolerance to diseases and pests, and environmental challenges (ICRISAT, 2023). At the ICAR-Indian Institute of Millets Research (IIMR) in Hyderabad and the ICAR-National Bureau of Plant Genetic Resources (NBPGR) in New Delhi, vast collections of millets germplasm from 92 nations are preserved (Elangovan et al. 2022).

Table 2.Important millets genetic resources available in the ex situ germplasm collections of ICRISAT, NBPGRand IIMR.

| Crop | ICRISAT | NBPGR | IIMR |
|---|---|---|---|
| Pearl Millet | 24663 | 8369 | 4128 |
| Foxtail Millet | 1542 | 4244 | 4653 |
| Proso Millet | 849 | 1005 | 2128 |
| Barnyard Millet | 749 | 1888 | 1705 |
| Little Millet | 473 | 1885 | 694 |
| Kodo Millet | 665 | 2362 | 344 |
| Finger Millet | 7513 | 11587 | 7806 |

Sources: ICRISAT Genebankhttp://genebank.icrisat.org/, NBPGR, http://www.nbpgr.ernet.in/; IIMR, https://www.millets.res.in/

## 4. **Millets world production**

On the Food and Agriculture Organization (FAO) website, total area harvested and production data for small and pearl millets are available (FAOSTAT, 2023). The average data of millet production and distribution of different continents from 1994 to 2023 are shown in Fig. 1. The total area harvested and production of millets worldwide during the 2021 growing season were 30934728 ha and 30089625.23 tons, respectively.

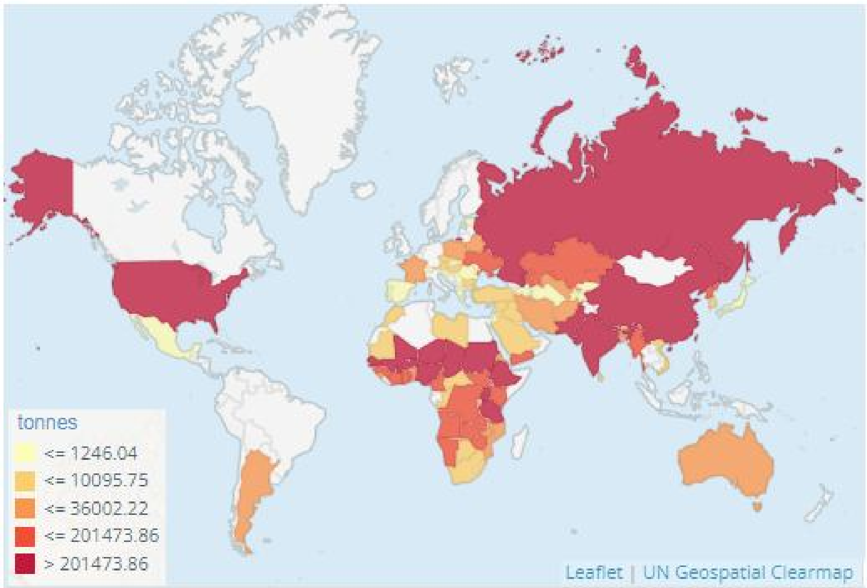

**Fig. 1**. World distribution and production quantities of millets by country: average tonnes, 1994–2021 ( http://www.fao.org; accessed March 22, 2023)

Based on the average from 1994 to 2021, Asia and Africa recorded the highest millet production with 48.5% and 47.5%, respectively, where the two areas contributed around 96% of the world millet production, while other areas contributed around 4%, as shown in Fig. 2.

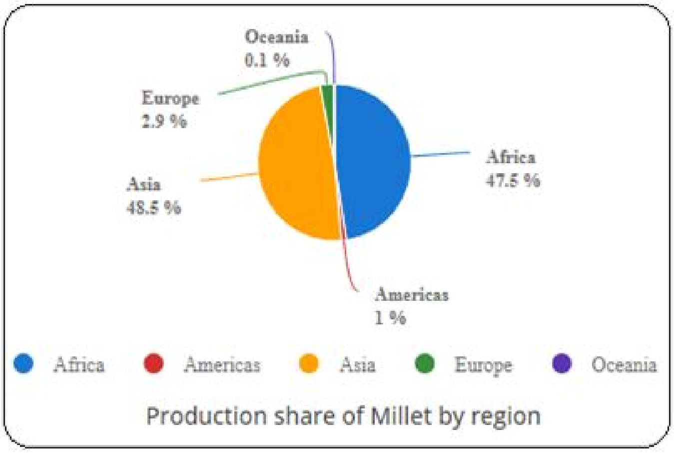

Fig. 2. Production share of Pearl and small millets by region (FAOSTAT 2023).

The top ten countries that produced the most millet are given in Fig. 3 (average 1994 - 2021). These countries are India, Nigeria, Niger, China (mainland), Mali, Sudan, Burkina Faso, Senegal, Sudan (former) and Ethiopia. These countries produced 25534490.12 tons, which was 85% of the total world millet production. India ranks first in millet production in the world, with 36.35% of the total world production, followed by Nigeria (14.74%), Niger (9.21%) and China (7.21%). The remaining ten countries each produce between 1.98% by Ethiopia and 4.26% by Mali.

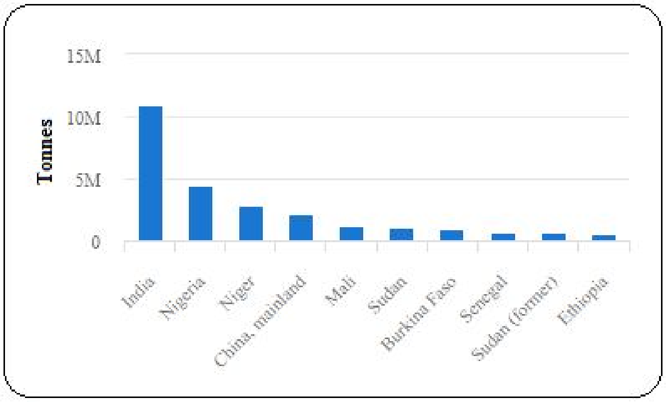

Fig. 3. Top ten countries producers of pearl millet and small millets.

## 5. Economic and Environmental Importance of millets

Millet is a smart and good food that benefits farmers, the environment, planet and contributes significantly to food security. In the developing world, particularly in the dry countries of Africa and Asia, millets are a staple diet (Meena et al. 2021). The characteristics of millets that make them climate-resilient include their ability to adapt to a wide range of ecological conditions, difficult growing conditions, lower water requirements (or drought), lower incidence of insect pests and diseases, and minimal sensitivity to environmental stresses (Bandyopadhyay et al. 2017; Saxena et al. 2018). In rainfed parts of semi-arid countries, small millets are important crops since (Vetriventhan et al. 2020), they produce respectable yields under these circumstances.

Millets can grow in a variety of production environments and don't require a lot of fertilizer or pesticides, promoting sustainable agriculture that doesn't harm the environment, as opposed to conventional agriculture, which can seriously harm the environment due to the indiscriminate use of fertilizers and pesticides (Ceasar and Maharajan 2022; FAO 2023).Ceasar and Maharajan (2022) mentioned that by overcoming the negative effects of global warming and climate change and lowering the negative effects on the environment by reducing the production of synthetic fertilizers and pesticides, millets may assist achieve sustainable development goals (UN General Assembly, 2015).

Millets could play an important role in meeting food demand and strengthening food security as a staple food for the poor and as a human healthy food for those in urban areas. Because they provide high energy, high dietary fibre, protein with a balanced amino acid profile, many essential minerals, polyphenols, vitamins, antioxidants, anticancer, antiinflammatory, antifungal, blood clot inhibition properties, and gluten-free with a low glycaemic index to address intolerances and diabetes (Chandra et al. 2016; Kam et al. 2016; Majid and Priyadarshini 2020). More recently, millet-based meals are advised for a balanced diet and to treat a variety of health conditions (Anitha et al., 2022).

In dryland ago-ecologies and other areas, fodder is a crucial byproduct of millet cultivation that is beneficial to animal health and an essential livestock and poultry feed. Most of these millets' green fodder can also be turned into silage and fed to livestock in the off-season (Bhat et al. 2018).Millet grains are versatile such as cover crop/green manure, biofuel, industrial raw materials, and food industry as major food components in various traditional foods and beverages. They are consumed as fermented beverages making increasing nutrient availability, including protein and mineral bioavailability, and digestibility, and reducing antinutritional factors (Nkhata et al. 2018). Millets are essential to ancestors' customs, cultures, and indigenous knowledge. They also serve as a source of income for marginalized regions engaged in rural, urban, regional, and international trade, and they help to provide women and young people with decent employment opportunities through creative processing and marketing methods (FAO, 2023). Millets are smart foods that are expected to dominate food industries and diets, which opens a new market for small millet demand to achieve nutritional security (Lydia Pramitha et al. 2023).

Generally, millets are an approach to transform local agricultural food systems for improved nutrition, production, a healthier environment, and a better living, without leaving anybody behind, according to the International Year of Millets (FAO, 2023).

## 6. Breeding approaches

Despite their enormous agricultural importance, relative to other major grains, millet cultivation and production have decreased or stalled globally over the past 50 years. This is mostly due to the fact that millets have not yet experienced considerable genetic gain from modern plant breeding (Meena et al. 2021). Little millets can be bred using both biotechnology and traditional breeding methods. Germplasms are the keys to crop development in this aspect since they supply the desired variability (Maitra et al. 2022).

Millets are bred using the same traditional breeding techniques for self-pollinating crops, such as pure line selection, pedigree selection, bulk selection, haploid production, doubled haploids, male sterile-facilitated recurrent selection (MSFRS), diallel selective mating system (DSMS), mutation, interspecific and intergeneric crosses, backcross and single seed descent (El-Hashash and El-Absy, 2019). According to reports on small millet cultivars released over time, several little millet cultivars have already been created using conventional breeding methods efforts across selection and hybridization (Nandini et al. 2019; Vetriventhan et al. 2020).According to AICSMIP (2014), India is a major producer of small millets and has created over 248 varieties of six small millets including finger millet (121), little millet (20), foxtail millet (32), barnyard millet (18), kodo millet (33) and proso millet (24). While in the USA, 11 proso millet cultivars that had been chosen from landraces and 8 that had been chosen through pedigree selection were made available (Santra et al. 2019). The characterization of tiny millets germplasm and their usage in creating and releasing a number of cultivars, especially for resistance/tolerance to biotic and abiotic stressors, have both been successful using traditional breeding methods (Vetriventhan et al. 2020). It is crucial to comprehend the genetic and molecular processes regulating stress tolerance in millets. Working together, modern and conventional breeding should hasten the expedite the dissection and application of these intricate mechanisms (Lydia Pramitha et al. 2023).Traditional plant breeding and selection techniques can take a long time and are frequently inaccurate (Fig. 4). Breeding efficiency is considerably increased when genomic selection and double-haploid technologies are used, and cultivars with several desirable traits can be created quickly, which is not achievable with traditional plant breeding (Santra et al. 2019).

Fig. 4. The difference between conventional and biotechnology methods used in millets breeding programs.

Functional genomics is crucial to the effectiveness of hybrid systems. Multiomics provides more accurate genotype performance prediction than conventional breeding methods (Yang et al., 2021). Molecular breeding tools must be actively used in current breeding programs since traditional breeding products might not be able to match the needs at this time (Eglinton et al. 2006). According to El-Hashash and El-Absy (2019), plant biotechnology techniques include three interacting components: (a) microbial bioprocessing techniques, (b) techniques for culturing somatic and reproductive cells, tissue and organs and (c) molecular and cellular techniques for the characterization and modification of genomes, including techniques for the identification, recombination, cloning, transfer and expression of genetic material. These biotechnology strategies effectively function at the organ, tissue, cell, protoplast, and molecular levels, unlike traditional plant breeding (El-Hashash and El-Absy, 2019). The completion of several whole genome sequencing and transcriptome profiling projects in small millets was made possible by advancements in Next Generation Sequencing and bioinformatics platforms, which resulted in the discovery of a significant number of ncRNAs and an understanding of their expression and regulatory mechanisms (Nallusamy et al. 2022). Fig. 5 shows the bioinformatics methods and tools used in the systems biology of plants, according to El-Hashash and El-Absy (2019). The genome sequence of millets can be effectively used to find candidate genes for abiotic stress tolerance and to further breeding techniques like genomic selection (Satyavathi et al. 2019).

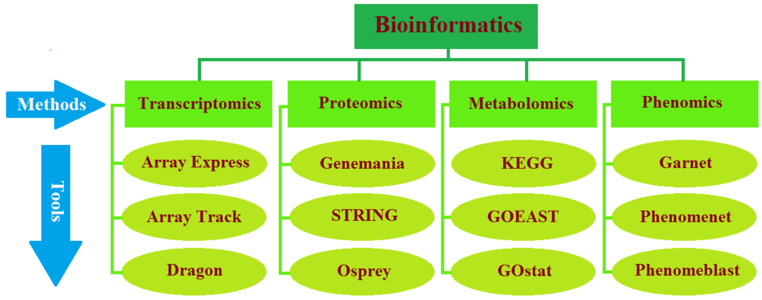

Fig. 5. Bioinformatics methods and tools of bioinformatics used in systems biology of plants Source: El-Hashash and El-Absy (2019).

Enhancing genetic gains in small millets through the use of diverse omics techniques could be made possible by genomics-assisted improvement (Vetriventhan et al. 2020). The development of conventional, molecular, and transgenic plant breeding for the enhancement of essential crops could be greatly aided by advancements in plant phenomics (Araus and Cairns 2014). In order to accelerate and improve crop improvement, future breeding initiatives for millets may incorporate both high-throughput genotyping and high-throughput phenotyping techniques (Santra et al. 2019).

## 7. Economic and nutritional importance of millet in KSA

Vision 2030 is a plan in progress for KSA in alignment with the United Nations Development Program, based on building a sustainable future that will affect all sectors of society (Alnasser and Musallat, 2022), especially ensuring development & food security. Vision 2030 of the KSA states" We will continue to build safe and sufficient strategic food reserves, to better guard against emergencies. We will also continue to collaborate with consumers, food manufacturers and distributors to reduce any resource wastage. The use of water in agriculture will be prioritized for those areas with natural and renewable water sources" (Saudi Vision, 2023). Due to the KSA limited water resources, decision-makers have prioritized the strategic goal of achieving food security as a high priority of Vision 2030 (Alnasser and Musallat, 2022).

One of the millet varieties that is grown most frequently in the area and a staple crop in many parts of KSA is pearl millet. It is a highly nutritious grain that is abundant in protein, fiber, and other necessary nutrients, making it a favorite among people who are concerned about their health. Additionally, there are many uses for pearl millet and it may be used to manufacture a variety of products, such as flour, porridge, and baked foods. Because of its adaptability, it has become a well-liked food ingredient, and the KSA need for products containing pearl millet is anticipated to rise further (MRP, 2023).

The preservation of millet is crucial to establishing national food security in KSA, which are best suited to the arid climate conditions. The Jazan region has many crops, of which millet and other crops represent the most important in the area over a long time. Because millet is a C4 plant, it can withstand heat and drought better than other plant species, therefore restricted to the sand-dune belt in the coastal plain in Jazan region. Twelve millet germplasm accessions from the *Pennisetumglaucum* species, commonly referred to as dukhn, are growing in various locations around the Jazan region, including Al-Hashr mount, Sala mount, Sabya, Faifa mount, Faifa mount, Abu Arish, Sawarya village, Jazan, Al Aredha, and Farasan island (Al-Turki et al. 2019). Also, the millet is introducing as local natural source to be used as staple food to enhance gut ecology health and reduce the severity of celiac patient's symptoms among the Saudi populations (Eid et al. 2018).

Since 2015, the area harvested (ha) with millet has gradually increased until it reached 5,643 hectares in 2021 (Fig. 6). This marked an increase in the area harvested for millet production across the nation compared to the previous years. Despite the increase in the area cultivated in millet in 2021, production has decreased (12,163 tons) compared to 2019, when production was 12,748 tons (FAOSTAT, 2023). With regard to importing millet in KSA, the data in Fig.6 showed a significant decline in the amount of imported millet, as the highest amount imported during 2017 amounted to 14,972 tons, while the lowest amount was imported in 2021 with a value of 3470.85 tons. This means that there was a significant decrease in the amount of millet imported by 62.36% in 2021 (FAOSTAT, 2023).

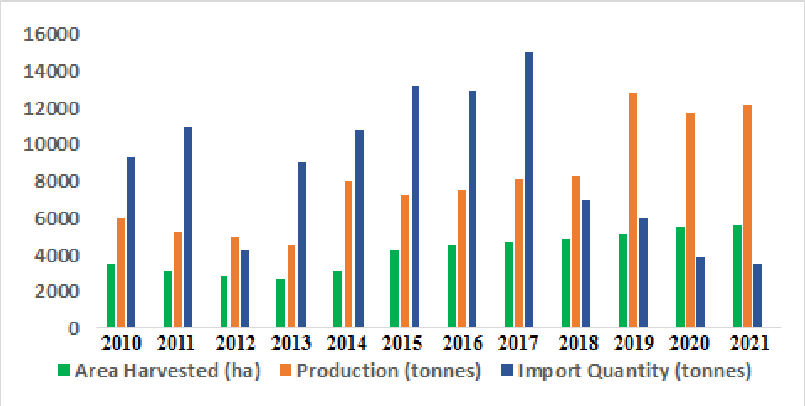

Fig. 6. Area harvested, production, and import quantity of millets in KSA from 2010 to 2021 (FAOSTAT, 2023).

The size of the millets market in KSA was estimated to be USD 334.77 million in 2022. The KSA millets market size is anticipated to increase at a CAGR of 5.04% between 2023 and 2029, reaching a value of USD 472.34 million by that year (Fig. 7). The main growth drivers for the KSA millets market include the increasing popularity of traditional foods, growing demand for gluten-free products, and increasing awareness of the health advantages of millets by KSA people (MRP, 2023). The KSA millet market is divided into five product categories: foxtail millet, proso millet, finger millet, and others. The sector for pearl millet is anticipated to have a sizable market share. Additionally, the KSA millets market is divided into categories for infant food, bakery goods, beverages, breakfast foods, fodder, and others based on application. The KSA millets market is divided into trade associations, supermarkets, conventional grocery stores, online retailers, and others in terms of distribution methods (MRP, 2023).

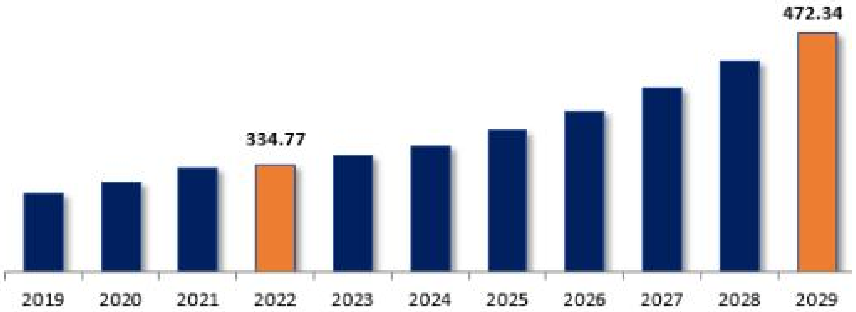

Fig. 7. KSA millets market size by value USD Million from 2019 to 2029 (MRP, 2023).

### 8. Self-sufficiency rate of millet in KSA.

The data shows in Table (3) an increase in the self-sufficiency rate from 39% to 78% during the period (2010-2021), averaged about 48%. The Kingdom importsestimated 8,800 tons. We need in KSA increase the cultivated area from millet to more than 25% to achieve self-sufficiency of millet in KSA.

Table: 3 Self-sufficiency rate of millet in KSA.

| Year | Area Harvested (ha) | Production (tons) | Import | | Consumption (tons) | self-sufficient rate (%) |
|---|---|---|---|---|---|---|
| | | | Quantity (tons) | Value 1000 US$ | | |
| 2010 | 3448 | 5969 | 9249 | 2748 | 15218 | 39 |
| 2011 | 3086 | 5208 | 10977 | 3566 | 16185 | 32 |
| 2012 | 2844 | 4924 | 4190 | 1569 | 9114 | 54 |
| 2013 | 2632 | 4486 | 9007 | 3322 | 13493 | 33 |
| 2014 | 3099 | 8022 | 10799 | 3611 | 18821 | 43 |
| 2015 | 4222 | 7309 | 13170 | 4575 | 20479 | 36 |
| 2016 | 4467 | 7539 | 12886 | 3889 | 20425 | 37 |
| 2017 | 4726 | 8055 | 14972 | 4610 | 23027 | 35 |
| 2018 | 4907 | 8320 | 6996 | 2533 | 15316 | 54 |
| 2019 | 5118 | 12748 | 6000 | 2626 | 18748 | 68 |
| 2020 | 5551 | 11701 | 3897 | 1456 | 15598 | 75 |
| 2021 | 5643 | 12163 | 3471 | 1397 | 15634 | 78 |
| Average | 4145.25 | 8037 | 8801 | 2992 | 16838 | 48 |

Source: FAOSTAT (2023)

## 9. Millet Challenges and Prospects in KSA

In recent years, the KSA achieved impressive social and economic growth. With scarce land and water resources, the amount of food that can be produced domestically is significantly less than what is needed on a daily basis (Fiaz et al. 2018). The millets are excellent dual-purpose fodder crops, which they have known for their role as a shield against food and nutritional insecurity and are better designated as nutritious cereals, also sustain cattle populations in dry tracts, which otherwise have no other alternate fodder source. Despite all this, millet cultivation areas and production have come down with a decline in their consumption in KSA.

A stronger focus on millet research and development is necessary to achieve food, feed, and nutrition security in the KSA and around the world given the changing climate scenario and widespread hidden hunger. For the millet production system to operate well, climatic parameters such as rainfall distribution and pattern, agronomic management, soil type, soil fertility, and socioeconomic status of farming communities are all crucial (Sood et al. 2019).

Although genomic and genetic research on millets has increased recently, high-resolution forward and reverse genetic studies similar to those done on model plants have not yet been applied to millets. This is because many millets don't have complete, annotated genome sequences (Ceasar and Maharajan, 2022). The successful use of their germplasm in crop improvement initiatives is constrained by a very small number of them and a lack of knowledge about the genetic variability of millets. In order to find trait-specific resources, genes, and alleles that can be used in tiny millets breeding projects, it is crucial to prioritize germplasm collection (Vetriventhan et al. 2020). Therefore, Al-Turki et al., (2019) mentioned that several local plant gene banks should be established to conserve the genetic resources of millets and other crops in every major agricultural region in KSA. Additionally, programs and workshops are being planned by experts at the King Abdulaziz City for Science and Technology Gene-Bank (KACST-Gene-Bank) for farmers and employees in various branches of agricultural activity in order to raise awareness of the value of conserving the genetic resources of local agricultural crops and conservation methods (Al-Turki et al. 2019).

As the KSA is located in an arid environment, it is suffering from accelerated groundwater deterioration due to limited precipitation and a warming climate, therefore increasing groundwater depletion and groundwater quality deterioration (Alghamdi et al. 2023). Also, the cultivated soils in KSA have numerous characteristics that may reduce their productivity, such as a predominately light texture, low organic matter contents (i.e., mostly 1%), elevated soil salinity, high levels of total calcium carbonates, and generally poor soil fertility potential (Almadini et al. 2021). Millet with high yield potential (grain or forage) is suitable for growing in saline conditions with treated wastewater irrigation. Millet crops, apart from being nutritionally superior to major cereal crops, are inherently tolerant to abiotic stresses like drought, high temperature, cold, poor soil fertility, and salinity (Singh et al., 2021). Millets can fit very well into multiple cropping systems both under irrigated and rainfed conditions (Vetriventhan et al. 2020). There are various morphological, genetically and biochemical factors, which contribute to potential of millets for being abiotic stress tolerant (Satyavathi, et al. 2019).

The most significant biotic restrictions related to millets include disease occurrence, insect pests, parasitic nematodes, birds, parasitic plants, and weed infestation (Meena et al. 2021). Small millets have a non-preference in ideotype due to the spined hairy shoots and leaves. This causes challenges in managing field activities such as weeding and pesticide spraying. Hence, breeding for reduced bristles, spines in shoots, and leaves helps in proper crop management (Ganapathy and Patil, 2017). So far, millet varieties have been developed mainly through conventional and Biotechnology techniques breeding methods and identification of novel alleles and genes with superior agronomic performance and resistance to biotic and abiotic stresses to accelerate millet improvement, together with better crop management and mechanization (Vetriventhan et al. 2020). Mechanization of millet cultivation in dryland is difficult, and production for high-value industrial applications is not easy.

According to Meena et al., (2021), the lack of well-established millet grain markets in the majority of nations means that farmers receive low economic returns. Additionally, most nations rely on an unofficial seed chain for the supply of millet seeds. This results in the non-availability of improved seeds and large-scale cultivation of less productive and heterogeneous landraces or local cultivars (Rakshit and Wang 2016). A significant barrier to the expansion of the millets market in KSA is the low level of consumer knowledge and availability of millets. Many consumers in the area are unaware of millets and their nutritional worth, despite the fact that millets are healthy and that there is a growing demand for them. Because of this ignorance, millets may not be in high demand, which would limit the market's potential growth. Additionally, some parts of KSA may have a limited supply of millet. Therefore, consumer awareness must be increased and new markets opened for millet and provide in all regions of the KSA. The demand for millet-based infant food products is expected to continue to grow in the region, as the population of KSA is expected to increase in the coming years, which will lead to a higher demand for baby food products.

One of the food security challenges is to facilitate the process of seeking access to capital through various credit schemes (Fiaz et al. 2018). Therefore, supporting farmers in each region of the KSA through the provision of agricultural facilities (Al-Turki et al. 2019). The KSA government has also been generously supporting the agricultural sector, particularly in the promotion of climate-adapted crops like millet. As an illustration, the KSA government created the Agricultural Development Fund (ADF) to finance agricultural projects around the nation. To encourage the expansion and improvement of agriculture, the ADF offers loans and incentives to farmers and agribusinesses. The KSA government has also made investments in R&D projects to support agricultural development and growth. This includes financing for colleges and research organizations to create cutting-edge agriculture technologies and practices, which are anticipated to offer profitable growth prospects for the market throughout the forecast period (MRP, 2023).

Finally, the effective role of agriculture extension in millet production is a current necessity that should be explored and used in a precise and effective manner. Agents' primary tasks will be to assess farmers' current knowledge, raise awareness and motivation, improve capacity through education, transfer site-specific technologies, and raise understanding of the prudent use of inputs, particularly freshwater (Fiaz et al. 2018). Additionally, public–private partnerships, public awareness, farmers' engagement across the countries who are interested in small millets research and promotion will be needed to incorporate small millets-based food products as an important source of nutrients in diets (Vetriventhan et al. 2020).

## CONCLUSIONS

The millet could be a major crop in the future offer a comprehensive solution to the current agrarian challenges and achieve the set goals regarding sustainable agriculture and food security in the KSA, due to its excellent nutraceutical value, unique health benefits, diverse industrial uses, and paramount importance in climate resilience agriculture. To promote millet cultivation in KSA, we need to:

1. Conservation and evaluation of millets germplasm in all adverse agro-climatic conditions in the KSA to identify the best germplasm for millets as a climate-smart crop.
2. Immediate research attention to developing varieties with high productivity and quality, resistance to biotic and abiotic stresses, and high nutrient bioavailability
3. Develop suitable agronomic practices, good storage facilities and create a good market for millets and its products.
4. Awareness campaigns on the benefits of millet and its products.
5. activating the role of agricultural extension in the agricultural practices of millet and supporting farmers through the provision of agricultural facilities for millet production.
6. To make millets competitive in both the production and marketing arenas, we need to refocus the goals of research and development initiatives in the public and private sectors.

## REFERENCES

Acquaah G (2007) Principles of plant genetics and breeding. 1st ed. Blackwell, Malden MA USA.

AICSMIP (2014) Report on compendium of released varieties in small millets [Internet]. Banglore, India; 2014. [http://www.dhan.org/smallmillets/docs/report/Compendium_of_Released_Varieties_in_Small_millets.pdf. Accessed 27 Mar 2023](http://www.dhan.org/smallmillets/docs/report/Compendium_of_Released_Varieties_in_Small_millets.pdf).

Alghamdi, A.G., Aly, A.A., Majrashi, M.A. and Ibrahim H.M.(2023) Impact of climate change on hydrochemical properties and quality of groundwater for domestic and irrigation purposes in arid environment: a case study of Al-Baha region, Saudi Arabia. Environmental Earth Sciences, 82:39. https://doi.org/10.1007/s12665-022-10731-z

Almadini, A. M., Ismail, A. I. H., &Ameen, F. A. (2021). Assessment of farmers practices to date palm soil fertilization and its impact on productivity at Al-Hassa oasis of KSA. Saudi journal of biological sciences, 28(2), 1451–1458. https://doi.org/10.1016/j.sjbs.2020.11.084

Alnasser, A. and Musallat, N. (2022). Food Sustainability Knowledge
among Saudis: Towards the Goals of Saudi Vision 2030. Sustainability 2022, 14, 11398. https://doi.org/10.3390/su141811398

Al-Turki T.A., A.A. Al-Namazi, Y.S. Masrahi (2019). Conservation of genetic resources for five traditional crops from Jazan, SW Saudi Arabia, at the KACST Gene-Bank, Saudi Journal of Biological Sciences, 26(7):1626-1632, https://doi.org/10.1016/j.sjbs.2018.09.007

Anitha, S., Givens, D. I., Subramaniam, K., Upadhyay, S., Kane-Potaka, J., Vogtschmidt, Y. D., Botha, R., Tsusaka, T. W., Nedumaran, S., Rajkumar, H., Rajendran, A., Parasannanavar, D. J., Vetriventhan, M., & Bhandari, R. K. (2022). Can feeding a millet-based diet improve the growth of children?—A systematic review and meta-analysis. Nutrients, 14, 225. https://doi.org/10.3390/nu14010225

Araus JL, Cairns JE (2014) Field high-throughput phenotyping: the new crop breeding frontier. Trends Plant Sci 19:52–61

Bandyopadhyay T, Muthamilarasan M, Prasad M (2017) Millets for next generation climate-smart agriculture. Front Plant Sci 8:1266. https://doi.org/10.3389/fpls.2017.01266

Bhat B.V., B.D. Rao, V.A. Tonapi, Prabhakar, B. Boraiah and P.C. Ganiger (2018). The Story of Millets. Karnataka State Department of Agriculture, Bengaluru, India and with ICAR-Indian Institute of Millets Research, Hyderabad, India. pp 124.

Brink, M. and Belay, G. (2006) Plant Resources of Tropical Africa. Cereals and Pulses. FondationProta, Wageningen, Backhuys Publishers/ CYA0

Ceasar S.A. and T. Maharajan (2022). The role of millets in attaining United Nation's sustainable developmental goals. Plants People Planet. 4(4):345–349. https://doi.org/10.1002/ppp3.10254

Chandra, D., Chandra, S., &Pallavi, S. A. K. (2016). Review of finger millet (Eleusinecoracana (L.) Gaertn): A power house of health benefiting nutrients. Food Science and Human Wellness, 5, 149–155. https://doi.org/10.1016/j.fshw.2016.05.004

Decoteau, D. R. (2005). Principles of plant science. Environmental Factors and Technology in Growing Plants, Pearson, Upper Saddle River, 49-66.

Eglinton J, Coventry S, Chalmers K (2006) Breeding outcomes from molecular genetics. In: Mercer CF (ed) Proc of the 13th Australasian Plant Breeding Conference, Christchurch, New Zealand 18–21 April 2006, pp 743–749.

Eid N.M.S., A. alharbi, F. Al-shaiban, M. alajlani, and R. al ghamdi (2018). The Availability of Prebiotics, Probiotics and Other Gluten Free Natural Sources such as Millet in the Saudi Market to Enhance Celiac Patients' Quality of Life – A Descriptive Study in Jeddah, Saudi Arabia, 2017." Journal of Food and Nutrition Research, 6(3): 187-191. doi: 10.12691/jfnr-6-3-8.

El-Hashash, E.F., El-Absy, K.M. (2019). Barley (*Hordeumvulgare* L.) Breeding. In: Al-Khayri, J., Jain, S., Johnson, D. (eds) Advances in Plant Breeding Strategies: Cereals. Springer, Cham. https://doi.org/10.1007/978-3-030-23108-8_1

El-Hashash, E.F.; Abou El-Enin, M.M.; Abd El-Mageed, T.A.; Attia, M.A.E.-H.; El-Saadony, M.T.; El-Tarabily, K.A.; Shaaban, A. Bread Wheat Productivity in Response to Humic Acid Supply and Supplementary Irrigation Mode in Three Northwestern Coastal Sites of Egypt. Agronomy 2022, 12, 1499. https://doi.org/10.3390/agronomy12071499

Elangovan M, V. Karnam, P. Sushil, P.C. Devi (2022). International Year of Millets 2023: Opportunity for Enhancing the Use of Indian Millets Germplasm. Indian J. Plant Genet. Resour. 35(3): 90–94. DOI:10.5958/0976-1926.2022.00048.1.

FAO (2023). International Year of Millets 2023. Available online: https://www.fao.org/3/cc3253en/cc3253en.pdf (accessed on 20 March 2023).

FAOSTAT (2023) Production-yield quantities of millets in world + (total) 1994–2021. https://www.fao.org/faostat/en/#data/QCL/visualize. (accessed on 23 March 2023).

Fiaz S., M.A. Noor and F.O. Aldosri, (2018). Achieving food security in the Kingdom of Saudi Arabia through innovation: Potential role of agricultural extension, Journal of the Saudi Society of Agricultural Sciences, 17(4):365-375. https://doi.org/10.1016/j.jssas.2016.09.001

Ganapathy, K. N., and Patil, J. V. (2017). Improvement in finger millet: Status and future prospects. Millets sorghum Biol. Genet. Improv., 87–111. doi:10.1002/9781119130765.ch3

ICRISAT (2023). http://genebank.icrisat.org/ (accessed on 23 March 2023).

Kam, J., Puranik, S., Yadav, R., Manwaring, H. R., Pierre, S., Srivastava, R. K., &Yadav, R. S. (2016). Dietary Interventions for Type 2 Diabetes: How Millet Comes to Help. Frontiers in plant science, 7, 1454. https://doi.org/10.3389/fpls.2016.01454

Lu, H., Zhang, J., Liu, K. B., Wu, N., Li, Y., Zhou, K., Ye, M., Zhang, T., Zhang, H., Yang, X., Shen, L., Xu, D., & Li, Q. (2009). Earliest domestication of common millet (Panicummiliaceum) in East Asia extended to 10,000 years ago. Proceedings of the National Academy of Sciences of the United States of America, 106(18), 7367–7372. https://doi.org/10.1073/pnas.0900158106

Lydia Pramitha J, Ganesan J, Francis N, Rajasekharan R and Thinakaran J (2023), Revitalization of small millets for nutritional and food security by advanced genetics and genomics approaches. Front. Genet. 13:1007552. https://doi.org/10.3389/fgene.2022.1007552

Majid, A., &Priyadarshini, C. G. P. (2020). Millet derived bioactive peptides: A review on their functional properties and health benefits. Critical Reviews in Food Science and Nutrition, 60(19), 3342–3351. https://doi.org/10.1080/10408398.2019.1686342

Maitra S, S. Praharaj, A. Hossain, T. S. S. K. Patro, B. Pramanick, T. Shankar, R.N. Pudake, H.I. Gitari, J.B. Palai, M. Sairam, L. Sagar and U. Sahoo (2022). Small Millets: The Next-Generation Smart Crops in the Modern Era of Climate Change. In: Pudake, R.N., Solanke, A.U., Sevanthi, A.M., Rajendrakumar, P. (eds) Omics of Climate Resilient Small Millets. Springer, Singapore. https://doi.org/10.1007/978-981-19-3907-5_1

Market Research Report; MRP (2023). Saudi Arabia Millet Market. Report ID: BWC23219. available online:

https://www.blueweaveconsulting.com/report/saudi-arbia-millet-market. (accessed on 23 April 2023).

Meena, R.P., Joshi, D., Bisht, J.K., Kant, L. (2021). Global Scenario of Millets Cultivation. In: Kumar, A., Tripathi, M.K., Joshi, D., Kumar, V. (eds) Millets and Millet Technology. Springer, Singapore. https://doi.org/10.1007/978-981-16-0676-2_2

Nallusamy, S., Selvamani, S.B., Muthurajan, R. (2022). Genome-Wide Identification and Expression Profiling of Noncoding RNAs in Response to Abiotic Stresses in Small Millets. In: Pudake, R.N., Solanke, A.U., Sevanthi, A.M., Rajendrakumar, P. (eds) Omics of Climate Resilient Small Millets. Springer, Singapore. https://doi.org/10.1007/978-981-19-3907-5_5

Nandini, C., Bhat, S., and Prabhakar, S. J. 2019. Modified crossing SMUASB method for artificial hybridization in proso millet (*Panicummiliaceum* L.) and Little millet (*Panicumsumatrense*). Electronic Journal of Plant Breeding, 10(3), 1161-1170. Retrieved from https://www.ejplantbreeding.org/index.php/EJPB/article/view/3041

Nkhata, S. G., Ayua, E., Kamau, E. H., &Shingiro, J. B. (2018). Fermentation and germination improve nutritional value of cereals and legumes through activation of endogenous enzymes. Food science & nutrition, 6(8), 2446–2458. https://doi.org/10.1002/fsn3.8462018;6:2446–58

Nwajei, S.E. (2023). Effects of planting dates on the crude protein and nutrient uptake of two varieties of millet (*Pennisetumtyphoides* (Burm. f.)) Stapf& Hubbard in a forest-savanna transition zone of Edo state. Sustainability, Agri, Food and Environmental Research, (ISSN: 0719-3726), 11(X):1-14. http://dx.doi.org/10.7770/safer-V11N1-art2332

Nwajei, S.E.; Omoregie, A.U. and Ogedegbe, F.O. 2019. Effects of planting dates on the growth and yield of two indigenous varieties of pearl millet (Pennisetumglaucum (L.) R.Br) in a forest-savanna transition zone of Edo State, Nigeria. ActaAgriculturaeSlovenica 114 (2): 169-181.

Rakshit S, Wang Y-H (2016) The Sorghum genome. Springer International Publishing, Singapore, p 284.

Rao, B. D., Dinesh, T. M., &Nune, S. D. (2021). Policy analysis and strategies. In Millets and pseudo cereals. Woodhead Publishing. https://doi.org/10.1016/B978-0-12-820089-6.00011-2

Santra, D.K., Khound, R., Das, S. (2019). Proso Millet (*Panicummiliaceum* L.) Breeding: Progress, Challenges and Opportunities. In: Al-Khayri, J., Jain, S., Johnson, D. (eds) Advances in Plant Breeding Strategies: Cereals. Springer, Cham. https://doi.org/10.1007/978-3-030-23108-8_6

Satyavathi, C.T., R.K. Solanki, R.K. Kakani, C. Bharadwaj, T. Singhal, J. Padaria, V. Khandelwal, R. Srivastava, R.S. Tomar and M.A. Iqubal (2019). Genomics Assisted Breeding for Abiotic Stress Tolerance in Millets. In: Rajpal, V., Sehgal, D., Kumar, A., Raina, S. (eds) Genomics Assisted Breeding of Crops for Abiotic Stress Tolerance, Vol. II. Sustainable Development and Biodiversity, vol 21. Springer, Cham. https://doi.org/10.1007/978-3-319-99573-1_13

Saudi Vision 2030. Available online: https://www.vision2030.gov.sa/media/rc0b5oy1/saudi_vision203.pdf (accessed on 3 May 2023)

Saxena R, Vanga SK, Wang J, Orsat V, Raghavan V. Millets for Food Security in the Context of Climate Change: A Review. Sustainability. 2018; 10(7):2228. https://doi.org/10.3390/su10072228

Sood, S., Joshi, D.C., Chandra, A.K. et al. Phenomics and genomics of finger millet: current status and future prospects. Planta 250, 731–751 (2019). https://doi.org/10.1007/s00425-019-03159-6

UN General Assembly. (2015). UN General Assembly, transforming our world: The 2030 agenda for sustainable development. Resolut. Adopt. by Gen. Assem. 25 Sept. 2015 16301. (accessed on 24 March 2023)

Vetriventhan, M., Azevedo, V.C.R., Upadhyaya, H.D. et al. Genetic and genomic resources, and breeding for accelerating improvement of small millets: current status and future interventions. Nucleus 63, 217–239 (2020). https://doi.org/10.1007/s13237-020-00322-3

Yang, L., Li, R., Cui, Y., Qin, X., and Li, Z. (2021). Comparison of nutritional compositions of foxtail millet from the different cultivation regions by UPLC-QOrbitrap HRMS based metabolomics approach. J. Food Biochem. 45 (10), e13940. doi:10.1111/jfbc.13940

Zhang J, Lu H, Gu W, Wu N, Zhou K, et al. (2012) Early Mixed Farming of Millet and Rice 7800 Years Ago in the Middle Yellow River Region, China. PLOS ONE 7(12): e52146. https://doi.org/10.1371/journal.pone.0052146