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ORIGIN, DOMESTICATION, TAXONOMY, BOTANICAL DESCRIPTION, GENETICS AND CYTOGENETICS, GENETIC DIVERSITY, BREEDING OF BAJRA [*Pennisetum glaucum (L.)* R.BR.]

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ABSTRACT

Bajra belongs to the Family Poaceae, Subfamily Panicoideae, Tribe Paniceae, Subtribe Panicinae, Section Panicillaria, Genus *Pennisetum* and Species *glaucum*. The word "millet" is derived from the Latin milium, which means "grain." Pearl millet gets its name from the small, round seeds, which are similar in size and shape to pearls. The plant is also sometimes called "bajra" in India and "bulrush millet" in the United States. Further, *Pennisetum glaucum* is the scientific name for pearl millet. The genus name "*Pennisetum*" is derived from the Latin words "penna," meaning "feather," and "seta," meaning "bristle." This refers to the feathery appearance of the plant's inflorescence, or flowering structure. The species name "*glaucum*" is derived from the Latin word "glaucus," which means "grayish-blue." This refers to the color of the plant's leaves and stems. It is also known as 'Bajra' in Hindi, 'Sajje' in Kannada, 'Kambu' in Tamil, 'Saujalu' in Telugu, 'Bajeer' in Kumaoni and 'Maiwa' in Hausa, 'Mexoeira' in Mozambique. 'Baajri' in Marathi, 'Za' in the Dagbani language of Ghana, Mawele in Swahili and mwere in Meru languages of Kenya. Mahangu in Kwanyama of Namibia. It is also popularly known as African millet or barbed millet in various parts of the world. According to archaeobotanical researchers, the cultivation of Bajra dates back to 2000 BC. C. and was first cultivated in the Hallur district of Karnataka. Top 10 bajra producing countries (Byjus, 2023) are India, Nigeria, Niger, China, Mali, Burkina Faso, Sudan, Ethiopia, Chad and Senegal. Top bajra producing states in India (Byjus, 2023) are Rajasthan, Uttar Pradesh, Haryana, Gujarat, Madhya Pradesh, Maharashtra, Karnataka, Tamil Nadu, Andhra Pradesh and Telangana. Pearl millet, also known as bajra, is a type of grain that is widely grown in arid and semiarid regions of Africa and Asia. It is a staple food in many countries, including India, and is often used to make rotis, chapatis, and other flatbreads. Pearl millet is a good source of nutrients, including protein, fiber, and minerals such as iron and zinc (Abbott, 2023). Pearl millet is relatively drought-resistant, making it an important crop in areas with limited access to irrigation. Pearl millet has a nutty flavor and can be used in a variety of dishes, including porridge, bread, and even desserts. It is also sometimes used as feed for livestock. It is a member of the grass family and is closely related to other millet species, such as foxtail millet and proso millet (Abbott, 2023). In this review article on Origin, Domestication, Taxonomy, Botanical Description, Genetics and Cytogenetics, Genetic Diversity, Processing, Uses, Breeding, and Health Benefits of Bajra are discussed.

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INTRODUCTION

Bajra belongs to the Family Poaceae, Subfamily Panicoideae, Tribe Paniceae, Subtribe Panicinae, Section Panicillaria, Genus *Pennisetum* and Species *glaucum* (AICRP, 2023; Abbott, 2023). Many regions of the world are home to bajras. Bajras may have been consumed by people for 7,000 years or more and may have had a significant part in the development of settled farming civilizations and multi – crop agriculture. Bajras are typically warm – weather cereals with small grains that are annual and from the grass family (Byjus, 2023). They have a comparable nutritional profile to other major grains and are quite drought and other extreme weather resilient.

The International Crops Research Institute for the Semi – Arid Tropics (ICRISAT) and the ICAR – Indian Institute of Bajras Research in Telangana, do research on bajras (Byjus, 2023). The word "millet" is derived from the Latin milium, which means "grain." Pearl millet gets its name from the small, round seeds, which are similar in size and shape to pearls (Fig. 1). The plant is also sometimes called "bajra" in India and "bulrush millet" in the United States. Further, *Pennisetum glaucum* is the scientific name for pearl millet. The genus name "*Pennisetum*" is derived from the Latin words "penna," meaning "feather," and "seta," meaning "bristle." This refers to the feathery appearance of the plant's inflorescence, or flowering structure. The species name "glaucum" is derived from the

Latin word “*glaucus*,” which means “grayish-blue.” This refers to the color of the plant’s leaves and stems (Abbott, 2023).

Fig. 1. Pearl millet gets its name from the small, round seeds, which are similar in size and shape to pearls

Bajra is a traditional Hindi name for the *Pennisetum glaucum* crop — also known as pearl millet. It is likewise known as dukn, cumbu, gero, sanio, kambu, babala, or bulrush millet (Snyder, 2023). It is also known as 'Bajra' in Hindi, 'Sajje' in Kannada, 'Kambu' in Tamil, 'Saujalu' in Telugu, 'Bajeer' in Kumaoni and 'Maiwa' in Hausa, 'Mexoeira' in Mozambique. 'Baajri' in Marathi, 'Za' in the Dagbani language of Ghana, Mawele in Swahili and mwere in Meru languages of Kenya. Mahangu in Kwanyama of Namibia (Wikipedia, 2023). The gruel made from millet, the staple of Ancient Tamils, is called *kali*, *moddak kali*, *kuul*, or *sangati* and Telugu: *korralu* or *korra.* It is also called as bullrush millet, cat-tail-millet, mil-a-chandelle, bajra, kambu, duhkn (Plantvillage, 2023). It is known as Bajra in Hindi and Bengali, Sajjalu in Telugu, Kambu in Tamil and Malayalam, Sajje in Kannada, Bajri in Gujarati - Pearl Millet goes by the scientific name *Cenchrus americanus* and is a millet widely cultivated in India and West Africa (Medico, 2021). Bajra is a traditional Hindi name for the cultivation of *Pennisetum glaucum*, also known as pearl millet. Also known as dukn, cumbu, gero, sanio, kambu, babala, or bulrush millet in India. It is a very commonly cultivated grain but is a staple food in many developing countries. The crop is easy to grow and has a variety of nutrients that are beneficial to the human body. It is rich in essential nutrients such as protein, fiber, phosphorus, magnesium, and iron (Medico, 2021). It is also popularly known as African millet or barbed millet in various parts of the world. According to archaeobotanical researchers, the cultivation of Bajra dates back to 2000 BC. C. and was first cultivated in the Hallur district of Karnataka (Medico, 2021). The growth duration of pearl millet is 2.5-4 months, depending on cultivars and the environment under which it is grown. There are three distinct growth phases : vegetative phase GS1, panicle development phase GS2, and Grain-filling phase GS3. The GS1 consists of germination, early seedling growth, tillering; the GS2 consists of boot-leaf, panicle emergence, flowering, and the GS3 includes grain formation, and grain maturation (ICRISAT, 2023).

Pearl millet is grown widely in the arid and semi-arid tropical regions in Indian subcontinent and African continent under the most adverse agro-climatic conditions where other crops like sorghum and maize fail to produce economic yields. Its grains are valued as human food while its dry stover makes important livestock ration in crop–livestock farming system (Yadav and Rai, 2013). In India, pearl millet is the third most widely cultivated food crop after rice and wheat. It is grown on 9 million ha with an average productivity of 1,000 kg ha^{-1} (Yadav and Rai, 2013). India is the largest producer of pearl millet. India began growing pearl millet between 1500 and 1100 BCE. It is currently unknown how it made its way to India. Rajasthan is the highest-producing state in India. The first hybrid of pearl millet developed in India in 1965 is called the HB1. Sajje is the local name of the Pearl Millet in Karnataka and is mostly grown in the semi-arid districts of North Karnataka. Sajje is milled and used for making flatbread called 'Sajje Rotti' and is eaten with Yennegai (stuffed brinjal) and yogurt. *Kambu* is the Tamil name of pearl millet and is an important food across the Indian state of Tamil Nadu. It is the second important food for Tamil people consumed predominantly in the hot humid summer months from February through May every year. It is made into a gruel and consumed along with buttermilk or consumed as dosa or idly. Pearl millet is called *bajra* in Northern Indian states. There was a time when pearl millets along with finger millets and sorghum were the staple food crops in these states but it reduced to a mere cattle fodder crop after the Green Revolution in the 1960s (Wikipedia, 2023). Top 10 bajra producing countries (Byjus, 2023) are India, Nigeria, Niger, China, Mali, Burkina Faso, Sudan, Ethiopia, Chad and Senegal. Top bajra producing states in India (Byjus, 2023) are Rajasthan, Uttar Pradesh, Haryana, Gujarat, Madhya Pradesh, Maharashtra, Karnataka, Tamil Nadu, Andhra Pradesh and Telangana. Indian bajra growing staies or regionszones (Byjus, 2023) are:

Southern Region: This region comprises Karnataka, Tamil Nadu, Andhra Pradesh, Telangana. In this region, bajra is grown in the dry hills or plateau region.

Northern Region: This region mainly comprises Haryana, and Uttar Pradesh. The region experiences low winter temperature and a single crop of bajra is grown here.

Western Region: This region comprises mainly Rajasthan, Gujarat, Maharashtra and some parts of Madhya Pradesh. Bajra is largely grown in Rajasthan contributes to over 80% of total Bajra production in India. The major pearl millet growing states are Rajasthan, Maharashtra, Gujarat, Uttar Pradesh and Haryana which account for more than 90 % of pearl millet acreage in the country. Most of pearl millet in India is grown in rainy (*kharif*) season (June–September). It is also being increasingly cultivated during the summer season (February–May) in parts of Gujarat, Rajasthan and Uttar Pradesh; and during the post-rainy (*rabi*) seaso season (November–February) at a small scale in Maharashtra and Gujarat (Fig. 1a) (Yadav and Rai, 2013).

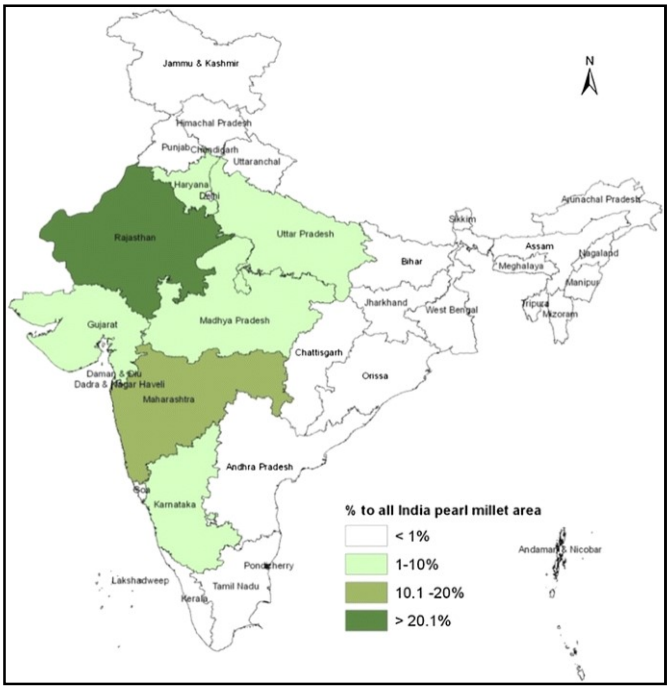


Fig. 1a. Bajra growing States of pearl millet in India

Pearl millet reaches maturity between 50 and 180 days after planting, depending on the variety. The crop is harvested by hand either by cutting the spikes from the plant or by cuting the whole plant (Plantvillage, 2023). Pearl millet (*Pennisetum glaucum* R. Br.) is an important staple and nutritious food crop in the semiarid and arid ecologies of South Asia (SA) and Sub-Saharan Africa (SSA). In view of climate change, depleting water resources, and widespread malnutrition, there is a need to accelerate the rate of genetic gains in pearl millet productivity (Yadav *et al.,* 2021). Pearl millet is a highly nutritious grain that is rich in protein, fiber, and essential vitamins and minerals. According to the Food and Agriculture Organization of the United Nations (FAO), in 2019, global pearl millet production was approximately 17.9 million metric tons. The top pearl millet-producing countries in the world include: 1) India: 9.4 million metric tons, 2) Niger: 2.0 million metric tons, 3) Burkina Faso: 1.5 million metric tons, 4) Mali: 1.3 million metric tons, and 5) Pakistan: 1.2 million metric tons. These five countries together account for around 75% of global pearl millet production. Other significant pearl millet producing countries include Senegal, Chad, and Sudan. In terms of region, Africa is the leading producer of pearl millet, accounting for around 55% of global production. In terms of acreage, India is the leading producer of pearl millet, with an estimated 5.4 million hectares of land devoted to pearl millet production in 2019. Other significant producing countries in terms of acreage include Niger (1.4 million hectares), Burkina Faso (0.9 million hectares), and Mali (0.9 million hectares) (Abbott, 2023). Pearl millet, also known as bajra, is a type of grain that is widely grown in arid and semiarid regions of Africa and Asia. It is a staple food in many countries, including India, and is often used to make rotis, chapatis, and other flatbreads. Pearl millet is a good source of nutrients, including protein, fiber, and minerals such as iron and zinc (Abbott, 2023). Pearl millet is relatively drought-resistant, making it an important crop in areas with limited access to irrigation. Pearl millet has a nutty flavor and can be used in a variety of dishes, including porridge, bread, and even desserts. It is also sometimes used as feed for livestock. It is a member of the grass family and is closely related to other millet species, such as foxtail millet and proso millet (Abbott, 2023). In this review article on Origin, Domestication, Taxonomy, Botanical Description, Genetics and Cytogenetics, Genetic Diversity, Processing, Uses, Breeding, and Health Benefits of Bajra are discussed.

ORIGIN AND DOMESTICATION

Pearl millet was domesticated long ago on the southern margins of the Saharan central highlands at an onset of the present dry phase about 4000–5000 years ago. Soon after domestication, it was widely distributed across the semiarid tropical areas of northern Africa, in the Arabian Peninsula, and Asia. It is believed that pearl millet reached Southern Africa by 900 to 800 BCE. The primary centers of diversity for pearl millet are in Africa where cross-fertile wild species exist. *Pennisetum* violaceum (Lam.) Rich.—also referred to as *Pennisetum glaucum* (L.) R. Br. subspecies monodii (Maire) Brunken—a wild relative and perhaps the progenitor of cultivated pearl millet, is well distributed along the margins of the southern Sahara in West Africa (Muimba-Kankolongo, 2018). Pearl millet (*Pennisetum glaucum* L.) originated in tropical western Africa some 4000 years ago. From there, it divided into globossum race and moved to western side, and a new race typhoid also appeared that reached eastern Africa and travelled to India and southern Africa about 2000–3000 years ago. In between 3000 and 2500 BC, pearl millet spread rapidly to African countries through pastoralists, spurred by the increasing desiccation of the Sahara desert at that time. Vavilov in his classic work on 'Origins of Crops' allotted pearl millet on the Ethiopian centre of domestication, the ancient highlands of Ethiopia are modern agriculturally diverse region in which crops from many parts of the world are continuously grown successfully. There are two evidences which argue against an Ethiopian origin of pearl millet. First, the wild progenitor (Pennisetum americanum subsp. monodii) is rare east of Sudan and has never been collected in the Ethiopian highlands. Wild progenitor is adapted to the sandy semi-arid conditions of the Sahel and very likely would have been absent from the high rainfall and high altitude environment of the Ethiopian highlands. Secondly, the pearl millet of Ethiopia lacks sufficient morphological diversity. Now days, pearl millet is a minor crop in Ethiopia and is probably the product of post domestication introduction (Joshi *et al.,* 2021). Pearl millet (*Cenchrus americanus*, commonly known as the synonym *Pennisetum glaucum*) is the most widely grown type of millet. It has been grown in Africa and the Indian subcontinent since prehistoric times. The center of diversity, and suggested area of domestication, for the crop is in the Sahel zone of West Africa. Recent archaeobotanical research has confirmed the presence of domesticated pearl millet on the Sahel zone of northern Mali between 2500 and 2000 BC (Wikipedia, 2023). Pearl millet is originated from Africa and then it spreads to India and other countries. Bajra is widely grown in Africa and Asia since pre historic times. In Asia, it is an important millet crop of India, Pakistan, China and South Eastern Asia. The important pearl millet growing countries are India, China. Nigeria, Pakistan, Sudan, Egypt and Arabia. India is the largest producer of pearl millet in the world. Principal pearl millet growing states are Rajasthan, Maharashtra, Gujarat, Western Uttar Pradesh, Haryana and Karnataka which accounts for 90 % of the total area and 86% of production In Karnataka, bajra is extensively cultivated as a rainfed crop in red, black and sandy soils during kharif season. It is extensively cultivated in Bijapur, Gulbarga and Belgaum (Agropedias, 2023). Pearl millet originated in tropical Western Africa some 4000 years ago. It is a member of the grass family, originally a wild plant in Africa where largest members of both wild and cultivated forms of this species occur. From there, it differentiated into two races; globosum race that moved to the western side and the typhoides race that reached Eastern Africa and spread to India and southern Africa some 2000–3000 years ago. The evolution of pearl millet under the pressures of drought and high temperatures imparted the ability to tolerate drought, nutrient deprived soil and high temperatures of Indian and African hot deserts more effectively than other cereals like wheat and rice (AICRP, 2023). Pearl millet has been used as a cereal for nearly the last 3000 years in Africa and parts of the Near East. The crop is cultivated for both forage and grain. It is grown on about 26 million ha in many countries of Southern, Eastern Western, and Central Africa, a few countries of Asia, particularly in India, and in some parts of the Americas, and Australia (ICRISAT, 2023).

History and domestication: The origins of pearl millet can be traced back to ancient Africa, where it was first domesticated around 4,000 years ago. The plant is native to the Sahel region of Africa, which stretches across the continent from Mauritania in the west to Sudan in the east. It is believed that pearl millet was first domesticated in this region and then spread to other parts of Africa and Asia through human migration and trade (Fig. 2). There is evidence that pearl millet was an important crop in ancient Africa, particularly in the Sahel region. It is mentioned in ancient texts and depicted in ancient art, and it has been found at archaeological sites in Africa and Asia. Pearl millet was an important food source for many ancient civilizations and played a significant role in the culture and economy of these societies. Over time, pearl millet has undergone significant evolution through the process of domestication and cultivation. It has been selectively bred for various traits, such as increased yield, disease resistance, and improved nutritional content. Today, pearl millet is an important food and feed crop that is widely grown in many parts of the world, particularly in Africa and parts of Asia.

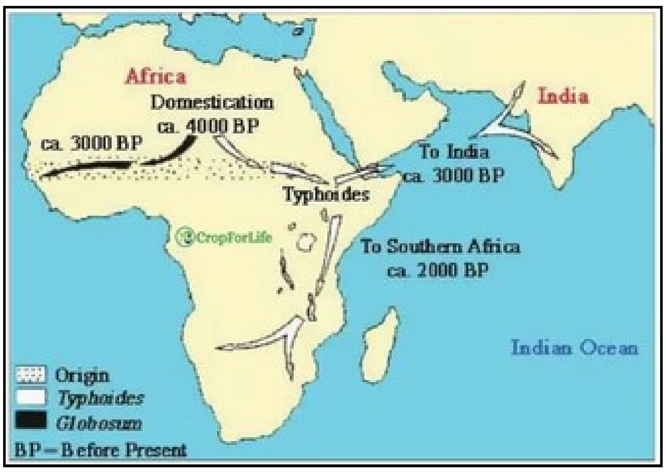


Fig. 2. Domestication of bajra

In terms of its biological ancestors, pearl millet is believed to have evolved from wild grasses that were native to the Sahel region of Africa. In many parts of the world, pearl millet is an important cultural and economic commodity, and it plays a significant role in the livelihoods and wellbeing of many people around the world relay on pearl millet as a source of food and income (Abbott, 2023). The origin of bajra is West Africa and it is distributed in Africa, India, Pakistan, South East Asia, USA and Europe (CUTM, 2023). Most notably in East Asia, South Asia, West Africa, and East Africa, the many species known as bajra were first domesticated. The domesticated types, however, frequently spread far from their initial territory. Based on information like the relative frequency of burnt grains discovered in ancient sites, specialised archaeologists known as palaeoethnobotanists speculate that bajras were more often cultivated in prehistory than rice, particularly in northern China and Korea. Additionally, bajras had a significant role in the prehistoric diets of Indian Mumun, Chinese Neolithic, and Indian cultures. Beginning in the Early Neolithic of China, proso bajra (*Panicum miliaceum*) and foxtail bajra (*Setaria italica*) were significant crops. These two types of bajra were used to make the earliest known Chinese noodles, which were discovered in a 4,000 – year – old pottery bowl at the Lajia archaeological site in north China. The noodles were in excellent condition. Due to its drought tolerance, common bajra was the first dry grain to be cultivated in East Asia, and it has been hypothesised that this helped it spread. By 5000 BCE, Asian bajra types had migrated from China to Europe's Black Sea region. As early as 3000 BCE, bajra was growing wild in Greece, and bulk bajra storage areas from the Late Bronze Age have been discovered in Macedonia and northern Greece (Byjus, 2023).

TAXONOMY

Bajra belongs to the Family Poaceae, Subfamily Panicoideae, Tribe Paniceae, Subtribe Panicinae, Section Panicillaria, Genus Pennisetum and Species Glaucum (AICRP, 2023; Abbott, 2023). It is a member of the grass family (Poaceae) and is classified in the genus *Pennisetum.* The grass family is one of the largest and most diverse families of flowering plants, with over 12,000 species. It includes a wide range of plants, including cereals, grains, grasses, and bamboo (Abbott, 2023). Pearl millet is the most important member of the genus *Pennisetum* in the tribe Paniceae. It has received a variety of taxonomic treatments, and its scientific binomials have been frequently shuffled by a variety of taxonomists. Consequently, it has had many Latin names, perhaps more than any other grass. In the post-Linnaean period from 1753 to 1809, pearl millet was treated as a member of at least six different genera, namely, *Panicum***,** *Holcus***,** Alopecuros, *Cenchrus***,** Penicillaria**,** and Pennisetum. At the beginning of this century, pearl millet was commonly referred to as Pennisetum typhoideum, Penicillaria spicata, Panicum spicatum, and Pennisetum alopecuroides. By the mid-19th century, however, pearl millet was generally called Pennisetum typhoideum L. C. Rich, but this nomenclature was not widely accepted. The name *Pennisetum glaucum* (L.) R. Br., based on Panicum glaucum (L.) R. Br., was adopted by Hitchcock and Chase (1951) in Manual of the Grasses of the United States. Consequently, American scientists currently engaged in research on pearl millet use this name. All annual and perennial members of the section Penicillaria fall under the **x** = 7 group. They have typically penicillate anther tips. Whereas most penicillarias are diploid with 2n = 14 chromosomes, one, viz., Napier grass, is a perennial tetraploid (Jauhar and Hanna, 1998).

Pennisetum is largest genera in the tribe Paniceae with five sections and approximately 140 species that are widely distributed in the tropics and subtropics. *Pennisetum* includes two reproductively isolated species *viz. P purpurium* Schumach, a tetrapolid (2n = 28) perennial species which occurs throughout the wet tropics of the world; and *P. americanum* (syn. *P. glaucum*) (L) Leeke, a diploid annual species, native to the semi-arid tropics of Africa and India. *P. glaucum* (*P. americanum*) contains three subspecies:

a) Sub-sp *glaucum*- cultivated, involucres persistent at maturity, distinctly stalked
b) Plants wild or weedy, involucres readily deciduous at maturity, short stalked or sub-sessile.

i. Subsp, *violaceum* (monodii) - Involucres sub-sessile, stalks less than 0.25 mm long; mature grains 0.6-1.0 mm deep. Considered to be wild progenitor of cultivated pearl millets.
ii. Subsp, *stenostachyum* – Involucre short stalked; stalk more than 0.25 mm long, mature grain 1.0-2.0 mm deep.

Pennisetum glaucum ssp *glaucum* is the only cultivated species for seed purpose, *P. purpurium* and its hybrids with bajra in both directions (bajra x napier and napier x bajra) are cultivated for fodder purposes in some areas of world and India (AICRP, 2023). The genus *Pennisetum* is having more than 140 species. The genus *Pennisetum* is divided in to five sections viz., 1) *Gymnothrix,* 2) *Eupennisetum*, 3) *Penicillaria*, 4) *Heterostachya,*5) *Brevivalvula*. The cultivated *Pennisetum glaucum* belongs to the section *penicillaria.* The progenitors are *Pennisetum purpureum, P. qumulatum* and *P. orientale.* Wild relatives and forms are *P. perottettii, P. mollissimum, P. violaceum, P. versicolor, P. adonense* and *P. gymnothrix.* The cultivated species of *pennisetum* is believed to have originated through hybridization within these six species (CUTM, 2023).

Synonyms (Wikipedia, 2023a)
1) *Alopecurus caudatus* Thunb.
2) *Chaetochloa germanica* (Mill.) Smyth
3) *Chaetochloa italica* (L.) Scribn.
4) *Chamaeraphis italica* (L.) Kuntze
5) *Echinochloa erythrosperma* Roem. & Schult.
6) *Echinochloa intermedia* Roem. & Schult.
7) *Ixophorus italicus* (L.) Nash
8) *Oplismenus intermedius* (Hornem.) Kunth
9) *Panicum aegyptiacum* Roem. & Schult. nom. inval.
10) *Panicum asiaticum* Schult. & Schult.f. nom. inval.
11) *Panicum chinense* Trin.
12) *Panicum compactum* Kit. nom. inval.
13) *Panicum elongatum* Salisb. nom. illeg.
14) *Panicum erythrospermum* Vahl ex Hornem.
15) *Panicum germanicum* Mill.
16) *Panicum germanicum* Willd. nom. illeg.
17) *Panicum globulare* (J.Presl) Steud.
18) *Panicum glomeratum* Moench nom. illeg.
19) *Panicum intermedium* Vahl ex Hornem.
20) *Panicum italicum* L.
21) *Panicum itieri* (Delile) Steud.
22) *Panicum macrochaetum* (Jacq.) Link
23) *Panicum maritimum* Lam.
24) *Panicum melfrugum* Schult. & Schult.f. nom. inval.
25) *Panicum miliaceum* Blanco nom. illeg.
26) *Panicum moharicum* (Alef.) E.H.L.Krause
27) *Panicum panis* (Jess.) Jess.
28) *Panicum pumilum* Link nom. illeg.
29) *Panicum serotinum* Trin. nom. inval.
30) *Panicum setaceum* Trin. nom. inval.
31) *Panicum setosum* Trin. nom. inval.
32) *Panicum sibiricum* Roem. & Schult. nom. inval.
33) *Panicum vulgare* Wallr. nom. illeg.
34) *Paspalum germanicum* (Mill.) Baumg.
35) *Penicillaria italica* (L.) Oken
36) *Pennisetum erythrospermum* (Vahl ex Hornem.) Jacq.
37) *Pennisetum germanicum* (Mill.) Baumg.
38) *Pennisetum italicum* (L.) R.Br.
39) *Pennisetum macrochaetum* J.Jacq.
40) *Setaria asiatica* Rchb. nom. inval.
41) *Setaria californica* Kellogg
42) *Setaria compacta* Schur nom. inval.
43) *Setaria erythrosperma* (Vahl ex Hornem.) Spreng.
44) *Setaria erythrosperma* Hornem. ex Rchb. nom. inval.
45) *Setaria flavida* Hornem. ex Rchb. nom. inval.

46) *Setaria germanica* (Mill.) P.Beauv.
47) *Setaria globulare* J. Presl
48) *Setaria globularis* J.Presl
49) *Setaria itieri* Delile
50) *Setaria japonica* Pynaert
51) *Setaria macrochaeta* (Jacq.) Schult.
52) *Setaria maritima* (Lam.) Roem. & Schult.
53) *Setaria melinis* Link ex Steud.
54) *Setaria moharica* Menabde & Erizin
55) *Setaria multiseta* Dumort.
56) *Setaria pachystachya* Borbás nom. illeg.
57) *Setaria panis* Jess.
58) *Setaria persica* Rchb. nom. inval.
59) *Setaria violacea* Hornem. ex Rchb. nom. inval
60) *Setariopsis italica* (L.) Samp

Synonyms (Plantvillage, 2023).
Pennisetum americanum (L.) Leeke, and
Pennisetum typhoides (Burm.) Stapf. & Hubb.)

BOTANICAL DESCRIPTION

The growth duration of pearl millet is 2.5-4 months, depending on cultivars and the environment under which it is grown. There are three distinct growth phases: vegetative phase GS1, panicle development phase GS2, and Grain-filling phase GS3. The GS1 consists of germination, early seedling growth, tillering; the GS2 consists of boot-leaf, panicle emergence, flowering, and the GS3 includes grain formation, and grain maturation (ICRISAT, 2023). Pearl bajra plant growth and development can be categorised into three major stages (Byjus, 2023):

Growth Stage 1: During this phase, seedling establishment occurs, as well as root, leaf, and tiller development. Panicle initiation is also underway.

Growth Stage 2: During this phase, all leaves lengthen, all tillers emerge, floral initiation in tillers occurs, and the stem lengthens. This phase is characterised by panicle elongation and the formation of floral parts. The appearance of stigmas on the panicle signals the end of this stage.

Growth Stage 3: This stage begins with floret fertilisation and lasts until the plant reaches maturity. The accumulation of dry matter occurs primarily in grain formation and, to a lesser extent, in the expansion of tiller stems and leaves. The development of a dark layer at the bottom of the grain indicates physiological maturity at the end of this phase. Pearl millet being a C4 species is endowed with a very high photosynthetic efficiency and ability for dry matter production. Pearl millet biology includes all growth and developmental features from germination to seed formation. These features include three well defined growth phases i.e. vegetative, reproductive and grain filling. Three well defined growth phases i.e. vegetative, reproductive and grain filling which shall be discussed in relation to crop improvement (AICRP, 2023**)** (Fig.3, 4 ; Table 1).

Table 1. Growth stages in bajra

Growth Phases	Identifying characteristics	Approximate days after emergence*
GP I	**Vegetative phase**	0-21
	Emergence stage	2-3
	Three leaf stage	3-7
	Five leaf stage	7-14
	Panicle initiation stage	14-21
GP II	**Reproductive/Panicle development phase**	21-42
	Flag leaf stage	21-28
	Boot stage	28-35
	Half bloom stage	35-42
GP III	**Grain filling phase**	42-77
	Milk stage	42-49
	Dough stage	49-56
	Black layer formation or physiological maturity	56-63

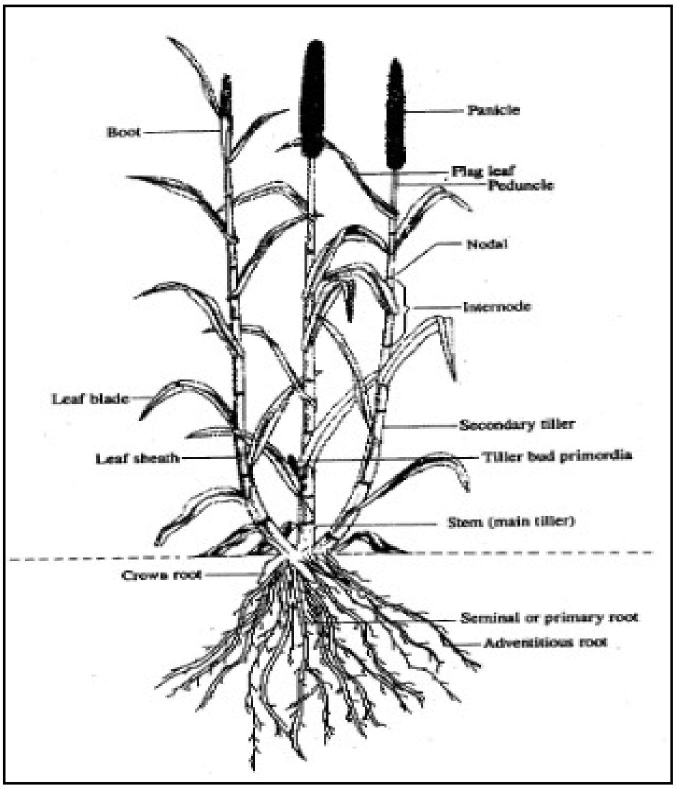


Fig. 3. Parts of pearl millet plant

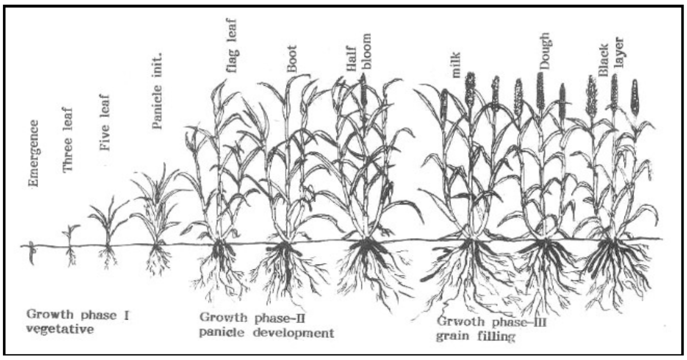


Fig. 4. Major growth stages of pearl millet

Growth stages in bajra

1) Vegetative Phase: Upon germination radicle starts emerging from the hilar region approximately within 16 hours of the initiation of the germination followed by development of plumule and coleoptile sheath approximately two hours later. Radicle grows downwards rapidly and produces fine root hairs. Coleoptile grows upwards slowly through soil until it emerges from the soil surface. Emergence of coleoptile from soil surface depends upon the depth of sowing, soil texture, moisture and temperature. It takes 2-3 days under favourable conditions. Pearl millet has a typical monocotyledonous type of root system consisting of seminal or primary root, adventitious roots, and crown or collar roots. Pearl millet root can penetrate up to 180 cm and attain a total length of 1500 m per m^2 of the cultivated area and touch 3000 m per m^2 at the harvest with a mass of 35 g per m^2. Pearl millet is an erect annual with a good tillering habit. The main stem attains a height of 2 - 4 m with 0.5 - 1.5 cm diameter. It is generally round to oval in shape. Nodes are slightly swollen, may be pubescent with ring of adventitious root primordia at the basal end and its inter-nodes are glabrous. The internodal length increases from the base of the stem upwards. Single leaf appears on each node in alternate orientation. An axillary bud is borne on the node at the base of the groove, which may remain dormant or develop in to a nodal tiller. Soft and thin palatable stem having very low fiber content is desirable for forage. Dry matter accumulation is increased in stem in the long duration pearl millet which limit the increase in grain yield in such types. Genotypic variation exists for stem growth, thickness, internode length and colour. The tiller leaf appears ~ 12 days after seedling emergence from the base of the main stem on both sides, following the alternate arrangement of leaves. Pearl millet has the potential to produce many effective tillers that may increase under wide spacing. Synchrony in flowering coupled with a higher number of effective tillers enhances the probability of producing more seeds from the same plant. Leaves are linear, 20-100 cm long and 0.5-5.0 cm wide, usually sparse to densely hairy or glabrous. The leaf consists of a leaf sheath and lamina or blade. The midrib may or may not be prominent. The leaf margins bear small saw teeth. Stomata are present on both leaf surfaces in equal numbers, varying approximately 45-96 stomata per mm^2. Early maturing genotypes have less number of leaves with faster growth and emergence that helps to escape early drought. The anatomy, a characteristic of C4 pathway in pearl millet makes it adaptive to drought and palatable for grazing cattle (AICRP, 2023).

2) Reproductive Phase/ Panicle development phase: A change from vegetative to reproductive phase is marked by the formation of an apical dome - like structure and a constriction at the base of the shoot meristem leading to a change from leaf primordia to spikelet primordia, development of spikelets, florets, glumes, stigmas and anthers. The period between panicle initiation to anthesis is critical in determining the grain number. Panicle emerges in ~35-70 days from the day of sowing depending upon the early or late genotypes. Panicle emergence is marked by the rapid elongation of the peduncle and the inter-node below it, and by the appearance of the flag leaf or boot leaf. Panicle takes nearly six days to emerge from the leaf sheath, with the maximum emergence on the fourth or fifth day. Hybrids generally take less time for panicle emergence than their parents indicating heterosis for the early panicle emergence. Pearl millet inflorescence is a compound terminal spike called panicle and its length generally varies between 20-25 cm with a circumference of 7-9 cm. The panicle shape varies considerably but, the common shapes are either cylindrical or conical. Inflorescence consists of a central rachis covered with soft/short hairs and bears fascicles on rachillae. The density of fascicles and the length of rachillae determine the degree of compaction of the panicle. Each fascicle contains spikelets surrounded by a wall of bristles (*i.e*., involucre). The prolongation of the fascicle axis determines the length of bristles. A spikelet may contain 2-4 flowers or florets, but generally two. The lower floret is staminate and the upper floret is bisexual or hermaphrodite. Pearl millet is a protogynous species. The styles start protruding two to three days after the emergence of the panicle. The stylar branches protrude first from the florets in the upper middle region of the panicle and then proceed both up and downwards. In the hermaphrodite flowers, the stigmas emerge earlier than the anthers and hence stigmas receive pollen from inflorescence of other plants. The time required for complete stigma emergence varies from 2 to 3 days and they remain receptive for next two to three days. By the time anther emergence commences, the stigma would have emerged and also pollinated, avoiding selfing. The emergence of the first anther usually begins about three to four days after the first stigma has emerged. The anther emergence occurs in two phases. The first phase involves solely the hermaphrodite flowers, and the second phase includes the staminate flowers. When the first phase of the emergence of anthers has reached the basal spikelets, the second phase begins when the staminate flowers are functional from the upper part of the panicle. A panicle continues shedding pollen for about 3 days. The anther emergence continues throughout the day and night. The anthesis occurs between 8 am and 2 pm with a peak at about 10 am. The increase in humidity and a decrease in temperature have been noted to reduce anther emergence, while lowering of humidity and a rise in temperature enhances up the anthesis. Pearl millet is a highly cross-pollinated species. Wind is supposed to be the major cross pollinating agent. However, insects also effect cross pollination. Protogyny and the time lag between stigma emergence and anther dehiscence favor cross pollination, but asynchronous flowering prevents its full realization. The protogyny in pearl millet is exploited for controlled cross pollination without resorting to emasculation (AICRP, 2023).

3) Grain filling phase: Pearl millet seed is a caryopsis and its shape is highly variable, ranging from globular to conical shape. The seed colour varies from ivory to purplish black, with light to deep gray being the most common seed colour. A small embryo is present on the depressed or flat surface at the tapering end of the seed. The size of the grain depends on its position in the panicle, being largest at the base, medium in the middle, and smallest at the apex. Variations exist in grain size among varieties generally ranging from 4-12 g per 1000 grains. Seed viability and seedling vigor are dependent upon the extent of grain development. Selection of varieties with higher percentage of seed filling and larger seed size may lead to higher yields. The temperature at which the seed developed did not affect seed viability, but it did affect the vigour. Post-harvest dormancy has been reported for at least 14 days in pearl millet (AICRP, 2023).

Description: Pearl millet has ovoid grains of 3–4 mm length, the largest kernels of all varieties of millet (not including sorghum). These can be nearly white, pale yellow, brown, grey, slate blue or purple. The 1000-seed weight can be anything from 2.5 to 14 g with a mean of 8 g. The height of the plant ranges from 0.5–4 metres (Wikipedia, 2023). Pearl millet varieties from the world collection probably have more variation in physical characteristics than any other millet. Kernel shape has different classifications: obovate, exagonal, lanceolate, globular and elliptical. In Africa, pearl millet is classified as either globular or lanceolate and hexagonal (Wikipedia, 2023). Bajra refers to the edible seeds of pearl millet plants. They grow in various shades of white, yellow, gray, brown, and bluish-purple (Snyder, 2023). Bajras are typically annuals that grow to be 30 to 130 cm tall, with the exception of pearl bajra (*Pennisetum glaucum*), which has stalks that grow to be 1.5 to 3 metres tall and 2.5 cm thick. The inflorescences can be spikes or racemes with flowers on stalks of roughly equal length along an extended axis, or panicles with closely packed clusters of small florets. Except for pearl bajra, seeds are still enclosed in hulls after threshing. Hulled seeds are typically creamy white in colour (Byjus, 2023).

The pearl millet plant is a tall, erect annual grass that ranges from 6 to 14 feet in height and is a highly tillering, cross-pollinating diploid tropical C4 cereal with grain on the surface of erect candle shaped terminal spikes. Grain size varies from 0.5 to over 2.0 g/100 seeds, and, depending on ear head size, grain number per ear head ranges from 500 to 3,000. Pearl millet plant is stoloniferous, annual or perennial. Stem or culm is herbaceous, stout, erect or ascending or decumbent or mat forming, glabrous or pubescent; internodes solid or hollow, terete. The leaves: not differentiated into two kinds (basal rosette absent), basal and cauline, not distinctly distichous; sheaths terete or with compressed keels; ligules a ciliate membrane; blades flat with prominent mid-rib with dense hair. Inflorescence is a false spike with spikelets on contracted axes, The fruit is caryopsis, bigger than bracts, various shapes (oblong, ovoid, hexagonal), 3-4 mm in diameter, bluish or whitish (Agropedias, 2023). Pearl millet is an annual grass in the family Poaceae which is grown widely in Africa and India for its grain which can be used to make flour and other foodstuffs. Pearl millet is a very robust grass which tillers widely and grows in tufts. It has slender stems which are divided into distinct nodes. The leaves of the plant are linear or lance-like, possess small teeth and can grow up to 1 m in length. The inflorescence of the plant is a spike-like panicle, made up of many smaller spikelets where the grain is produced. Pearl millet can reach 0.5 to 4 m in height depending on the cultivar and is an annual plant, harvested after one growing season. Pearl millet may also be referred to as bulrush millet, cat-tail millet or yellow bristle grass and originates from the Sahel zone of Africa (Plantvillage, 2023).Pearl millet is an annual. It is a bunch grass growing 1-2 m tall, on smooth 1.25-2.5 cm diameter stems, with upright side shoots (tillers). The inflorescence (10- 50 cm) is a terminal spike, resembling that of cattail. Seeds are cylindrical, typically white, or yellow, but there are varieties with colors ranging from brown to purple. Leaf blades are long and pointed. Pearl millet's deep root system grows relatively fast and can scavenge residual nutrients. It is a good choice for low-input sustainable agricultural systems (USDA, 2023). The pearl millet plant is an annual grass that grows to a height of 1-2 meters. It has a robust, upright stem and long, slender leaves that are typically green or bluish-gray in color. The leaves are arranged in a spiral pattern around the stem and are typically 30-50 cm long and 1-2 cm wide. The leaves are attached to the stem by a sheath, which is a tubular structure that encloses the base of the leaf. The sheath is typically open at the top and closed at the bottom, and it serves to protect the base of the leaf and help the plant retain moisture. The plant produces clusters of small, inconspicuous flowers that are arranged in a terminal inflorescence, or flowering structure. The inflorescence is a spike-like structure that is typically 20-30 cm long and consists of numerous small flowers arranged in rows along a central axis. The flowers are typically green or yellow in color and are surrounded by small, leaf-like bracts.

similar in size and shape to pearls, hence the name “pearl millet.” The seeds are typically 3-5 mm in diameter and are surrounded by a hard, outer coating. The seeds are typically yellow or brown in color and are contained within a seed head, which is a spiky structure that is formed from the dried flowers and bracts (Abbott, 2023). A robust, quick growing, summer cereal with large stems, leaves, and panicles. Plants are tall and vigorous, with exceptional grain and fodder yielding potential, and are regarded as a coarse cereal in the category of maize and sorghum. Pearl millet plants have variable number of tillers, variable panicle length, seed size, seed color, and plant height, depending on the cultivars and environments. The seeds or caryopses of pearl millet are highly variable (from 3 to 15g per 1000 seeds). Some seeds are as broad as long, but may range from almost globose to subcylindrical and conical in shape.

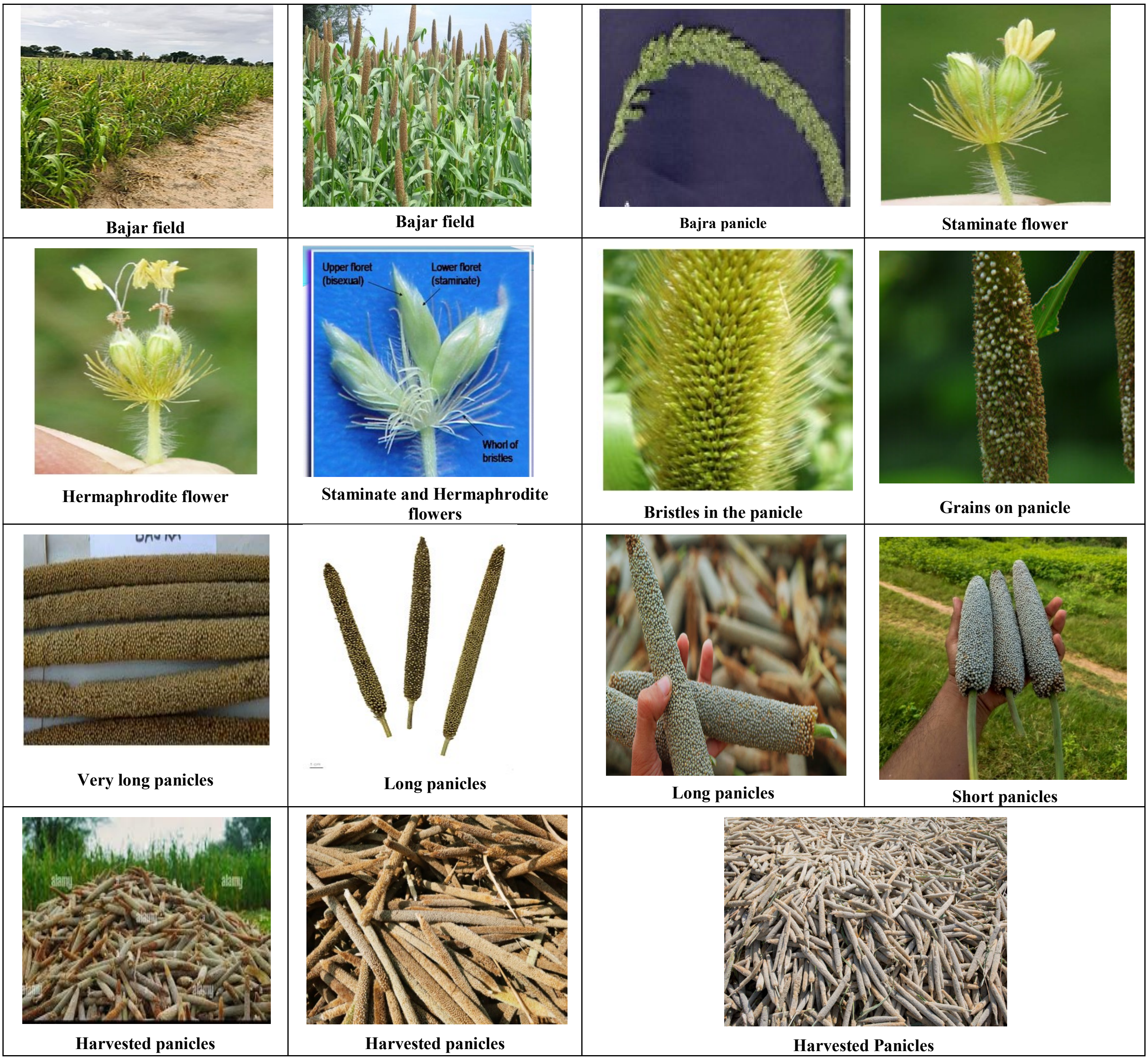


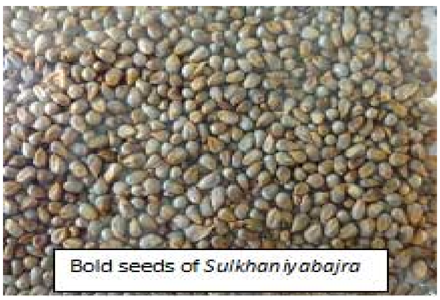
Fig. 5. Botanical Description

The bracts are typically green or purple in color and help to protect the flowers. Each flower consists of a calyx, which is a group of small, green or yellow sepals that enclose the flower bud, and a corolla, which is a group of small, green or yellow petals. The calyx and corolla are attached to a receptacle, which is a structure that supports the flowers and seeds. The receptacle is typically elongated and cylindrical in shape, and it is surrounded by a ring of small, leaf-like bracts. The flowers are followed by small, round seeds that are

They are most often ash gray or steely blue in color, and also of purple, grayish brown, yellowish brown, and pearly-amber white. Sometimes, the embryo has a reddish tinge. The color of the glumes may range from deep purple to brownish gray or straw color. Seed surface may show striations or microscopic protuberances, depending on the genotypes. The stems are often densely villous below the panicle, 1-2 cm or more in diameter, and solid. Sometimes secondary or even tertiary culms arise from the nodes. The internode is usually light green and sometimes shows a purple pigment when exposed. The nodes are often marked by a ring of long white cilia pointing upward, which bear a ring of adventitious roots on the basal side. The main stalk gives rise to one or more primary tillers arising at or below ground surface and about the height of the main tiller. Secondary branches arise from the main and primary tillers. Tertiary, and rarely, quaternary branches may be produced. All the tillers can bear productive panicles, and become an important factor for survival in times of adversity. Surface area measured for panicles from different origins averaged 115 sq cm for main panicles, 90 sq cm for primary, 50 sq cm for secondary, and 20 sq cm for tertiary panicles. The leaves are long, scabrous, and slender, with smooth or hairy surface, and hairy ligules. The blades are lanceolate, cordate, and measure 90-100 cm or more in length and 5-8 cm wide. The midrib may be prominent, upright or drooping. The leaf sheaths are open and hairy, while the ligule is short. Stomata are found on both leaf surfaces in equal numbers, 50-80 per sq mm. Leaves and culms may vary in color from light to deep purple. Spikelets and bristles are borne on rachilla with 30-40 bristles about as long as the spikelets. Each bristle is broader at the base than the apex. Usually there are 870-3000 spikelets per panicle. Averaging 1600 spikelets per panicle. There are different types of spikelets: unifloret, bifloret, trifloret, and tetrafloret. The panicles are often similar in size and shape for a particular genotype. They are stiff, compact, cylindrical, conical or spindle-shaped; 2-3 cm in diameter, usually 15-45 cm long, although some varieties may have 150-cm long panicles. The rachis is straight, cylindrical, solid, often 8-9 mm thick, and unbranched. It extends the entire length of the inflorescence, tapering gradually from base to apex, and is covered with short, soft, villous hairs (Fig. 5) (ICRISAT, 2023).

Bajra Variety- Sukanya: Sulkhaniya bajra is suitable for sandy loam soil of the dry and semi-arid climate. It is an early sowing variety sown during the pre-monsoon rains. In around 50-55 days 50% ear heads are formed whose average length ranges between 60-90 cm. The total number of tillers per plant range between 6-10 and the percentage of productive tillers ranged between 90-100%. The crop matures in around 90 days and the total yield ranges between 20 -25 quintals/hectare and average biological yield is 40 quintals/hectares. The variety is drought tolerant and can withstand long gaps of dry season. The productivity is good even in dry period as compared to commonly cultivated varieties (Fig. 6) (Innovation, 2023).

60-90 cm earhead



Bold seeds

Fig. 6. Sukanya bajra – A local type from Rajastan

Floral Morphology

The inflorescence of foxtail millet has a main stalk with shortened side branches bearings spikes and bristles. The inflorescence is a terminal spike, 8- 32 cm long , drooping, dense, cylindrical lobed, borne on a thin and very short pedicel. Each spikelet consists of a pair of glumes that embraces two minute flowers. The lower one is sterile whereas the upper one is fertile or bisexual with three stamens and a long oval smooth ovary with two long styles ends feathery. The anthers are yellow or white, ovary surmounted by two long styles and feathery stigmas. The lodicules are two in number. The grain is oval in shape, shiny, 2 mm in length, tightly enclosed within the thickened lemma and palea; varying in colour from cream to orange, yellow brown to black (Gupta *et al.,* 2012). It is a highly cross-pollinated crop. The pollinating agent is wind. The flowers are protogynous. The spike emerges about 10 weeks after sowing, The styles begin to protrude 2-3 days later first at the top of the inflorescence and proceeds. They take two days to complete the entire spike. Exerted stigma remains receptive for 12-24 hours. Anthers usually emerge after the styles are dry. The anther emergence starts from middle of the spike and proceeds upwards and downwards. Anthesis occurs throughout the day and night with the peak between 8.00 p.m. to 2.00 a.m. (Fig. 7, 8, 9) (Eagri, 2023a).

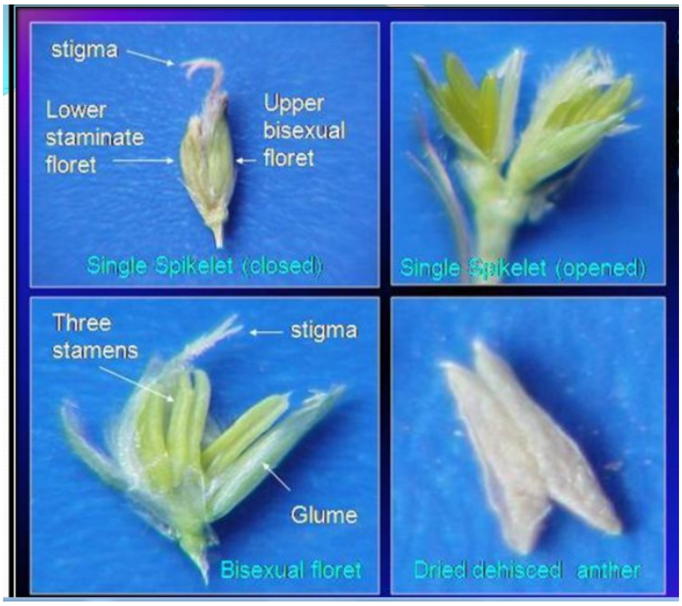
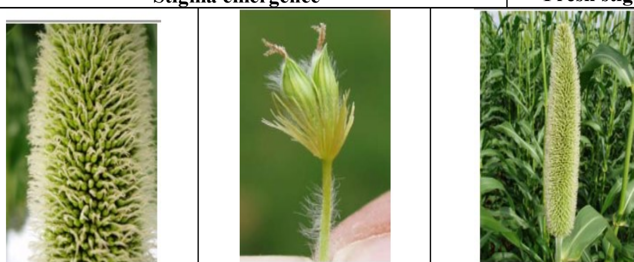


Fig. 7. Parts of pearl millet flower

Stigma emergence **Fresh stiga**



Withered stigma **Protogynous flowering** **Full protogyne**

Fig. 8. Stigma emergence and receptiveness

Fig. 9. Protogynous flowers

Anthesis and Pollination: The flowers below the apex of the head begin to open when about three-fourth of the head emerges out of the sheath,. Flowering proceeds from the top to downward in the main spike. A head takes 8 to 16 days to complete flowering. A single floret remains open for about 30 minutes, and it may take about 80 minutes for complete blooming, which is hastened by high temperatures and low humidity. During pollination tips of stigmatic branches and the anthers protrude through the slit between the incurved edges of the palea. The stigmatic branches emerge first followed by emergence of anthers. The anther after emergence starts dehiscing by longitudinal slits from the top to bottom. As the glumes began to spread, the stigmas and the anthers developed and pushed out of the slit between the incurved edges of the palea. The feather like stigmas were first to emerge, but were quickly followed and overtaken by the anthers. Sometimes, some anthers remained adhered in the curved edges of the palea. This pattern is generally associated with round shaped flowers or moisture deficient soil. In general, the anthers shed pollen after they are fully extruded outside the glumes. After dehiscence, the glumes began to close, leaving the shriveled anthers and the tip of the stigmas outside. After pollination, the lodicules shrink and glumes begin to close. Anthesis in foxtail millet generally takes place near midnight and in the morning, but varies significantly with the environment. Most of the flowers opens during the midnight and between 8-10 a.m.

The duration for an ear head to complete its flowering varies from 10-15 days. Maximum number of floret opens on sixth day of emergence. Humidity and temperature are the main factors that affect pollination. The foxtail millet is highly autogamous and the extent of out crossing varies from 1.4-4% . Natural crossing occurs between the cultivated and the wild taxa of foxtail millet, derivatives of such hybrids are obnoxious weeds. In general, tetraploids are more vigorous but colchicines induced auto-tetraploids in foxtail millet were smaller, late in flowering and had a two-fold reduced level of fertility. However in another study 20% increase in grain weight was observed in polyploids, but the total grain yield decreased by 46%. A genetic male sterile line controlled by dominant gene 'Ch A' and photoperiod sensitive male sterility are being used in hybridization programme in China (Gupta *et al.,* 2012).

Selfing and Crossing Techniques: Controlled pollination without resorting to emasculation is a common phenomenon in pearl millet. Usually, there are 900-3000 spikelets per panicle, averaging 1600 spikelets. Each spikelet has two florets, one bisexual and the other, staminate. The bisexual or hermaphrodite floret consists of a pistil and three anthers while the staminate floret has three anthers. Looking to tender, large number and small structure of florets, it is difficult to follow emasculation in pearl millet. Protogynous nature is exploited for effecting cross-pollination; protogyny, is a unique feature in which the stigmas emerge and become active earlier than anthers or pollen dehiscence and receive pollens from other plants. This sequence of flowering practically excludes self pollination in the same inflorescence. The inflorescence to be used as a female or male is covered with the glassine paper bag before any stigma is visible. Generally, the safest stage is when about one third of the inflorescence is out of the flag leaf sheath. When all stigmas have emerged, the panicle can be considered ready for cross pollination. If selfed seed of the male parent is not required, fresh pollen from dehiscing anthers, visible as yellow powder in the transparent selfing bags can be collected by tapping even in the inflorescences in which stigmas have completely emerged. The pollination is carried out by quickly removing the bag from the female inflorescence, dusting the pollen collected from the male infloresence, and then rebagging the pollinated inflorescence (AICRP, 2023).

GENETICS AND CYTOGENETICS

Genetic symbols and genetic control of morphological mutants in pearl millet is furnished in Table 2. Kumar and Andrews, 1993).

Genetically, pearl millet is a diploid species, which means that it has two copies of each chromosome in its cells. The basic chromosome number for pearl millet is 2n = 14, which means that it has 7 pairs of chromosomes. However, there is also evidence of higher ploidy levels in some pearl millet varieties, with some studies reporting the presence of triploid (3n = 30) and tetraploid (4n = 40) individuals (Abbott, 2023; CUTM, 2023).

Like all living organisms, pearl millet has a genome, which is the complete set of genetic material present in its cells. The genome of pearl millet is relatively large, with an estimated size of about 730 million base pairs. Studies of the genomic ancestry of pearl millet have revealed that it is a hybrid species, resulting from the crossing of two ancestral grass species. This hybridization event is thought to have occurred around 4000 years ago in Africa, and has contributed to the adaptability and diversity of pearl millet. Genomic studies of pearl millet have provided valuable insights into the genetic basis of important agronomic traits, such as grain yield and drought tolerance. These studies have also helped to identify genes and genetic pathways that are involved in the development and function of various plant organs and processes, including photosynthesis, stress responses, and plant-microbe interactions (Abbott, 2023).

GENETIC DIVERSITY

The flowers of pearl millet are followed by small, round seeds that are similar in size and shape to pearls, hence the name "pearl millet." The seeds are typically 3-5 mm in diameter and are surrounded by a hard, outer coating. The seeds are typically yellow or brown in color and are contained within a seed head, which is a spiky structure that is formed from the dried flowers and bracts (Abbott, 2023). Pearl millet has ovoid grains of 3–4 mm length, the largest kernels of all varieties of millet (not including sorghum). These can be nearly white, pale yellow, brown, grey, slate blue or purple. The 1000-seed weight can be anything from 2.5 to 14 g with a mean of 8 g. The height of the plant ranges from 0.5–4 m (Wikipedia, 2023). The fruit of pearl millet is caryopsis (fruit and seed fuse in a single grain), bigger than bracts, various shapes (oblong, ovoid, hexagonal), 3-4 mm in diameter, bluish or whitish (Agropedias, 2023). Pearl millet seed is a caryopsis and its shape is highly variable, ranging from globular to conical shape.

Table 2. Genetic symbols and genetic control of morphological mutants in pearl millet

Table 1. Gene symbols and genetic control of morphological mutant phenotypes reported in pearl millet, 1934 to 1991.

Character or mutant phenotype	Gene symbol	Genetic effect†	References
		Chlorophyll deficiencies (CD)‡	
Albina or white	*w*	1 r	Rangaswami Ayyangar, 1934
			Rangaswami Ayyangar and Hariharan, 1935
			Kadam et al., 1940
			Krishnaswamy and Rangaswami Ayyangar, 1941
			Al-Fakhry et al., 1965
			Burton and Powell, 1965
			Koduru and Krishna Rao, 1980
			Burton, 1986
			Dev et al., 1987
Albino-terminalis	*at*	1 r	Appa Rao et al., 1984
Patchy white	*pw*	1 r	Koduru and Krishna Rao, 1980
White virescent	*wv*	1 r	Koduru and Krishna Rao, 1980
Virescent white		2Dde	Kadam et al., 1940
White-tipped green	*wt*	1 r	Koduru and Krishna Rao, 1980
Light green		2 r	Al-Fakhry et al., 1965
	lgn_1	1 r	Hanna et al., 1978
	lg_1 lg_2	2 r	Koduru and Krishna Rao, 1980
Chlorina	*c*	1 r	Koduru and Krishna Rao, 1980
Chlorina virescens	*chv*	1 r	Appa Rao et al., 1984
Pale green		2 re	Rangaswami Ayyangar, 1934
			Rangaswami Ayyangar and Hariharan, 1935
		1 r	Krishnaswamy, 1962
Yellow green	*yg_1 yg_2*	2 r	Koduru and Krishna Rao, 1980
Greenish yellow	*gy*	1 r	Appa Rao et al., 1984
			Burton, 1986
Green yellow		1 r	Burton, 1986
Greenish medium yellow		1 r	Burton, 1986
Pale green yellow	*pgy*	1 r	Burton and Powell, 1965
Pale yellow	*py*	1 r	Burton and Powell, 1965
			Appa Rao et al., 1984
			Burton, 1986
Pale yellow 2	*py*		Burton and Powell, 1965
Light yellow		1 r	Burton, 1986
Medium yellow	*my*	1 r	Burton and Powell, 1965
Yellow	*y*	1 r	Burton and Powell, 1965
		1,2 r	Kadam et al., 1940
		1 r	Al-Fakhry et al., 1965
	yn_1	1 r	Hanna et al., 1978
Bright yellow	*by*	1 r	Appa Rao et al., 1984
Deep yellow		1 r	Burton, 1986
Very deep yellow		1 r	Burton, 1986
Virescent yellow		1,2 r	Kadam et al., 1940
		1 r	Al-Fakhry et al., 1965
Yellow virescent	*yv*	1 r	Koduru and Krishna Rao, 1980
			Dev et al., 1987
Dwarf pale yellow		1 r	Burton, 1986
Golden yellow		1 r	Kadam et al., 1940
Golden	*g*	1 r	Burton, 1986
Zebra	*z*	1,2 r	Kadam et al., 1940
		2 r	Al-Fakhry et al., 1965
		1 r	Appa Rao et al., 1984
		1 D	Werner and Burton, 1991
Zebra virescens	*zv*	1 r	Appa Rao et al., 1984
White striping$_1$	*wst_1*	1 r	Koduru and Krishna Rao, 1980
White striping$_2$	*wst_2*	1 r	Koduru and Krishna Rao, 1980
White striping$_4$	*wst_4*	1 r	Koduru and Krishna Rao, 1980
Yellow striping	*yst_1 yst_2*	2 r	Koduru and Krishna Rao, 1980
Fine striping	*fst*	1 r	Koduru and Krishna Rao, 1980
Bleached leaf	*bl*	1 r	Appa Rao et al., 1990
White sheath	*ws*	1 r	Appa Rao et al., 1990
		Foliage striping	
Striping (variegated)		1 r	Ratnaswamy, 1960
Yellow striping in purple foliage	*gys_1 gys_2 gys_3*	3 r	Gill et al., 1969
Yellow striping in green foliage	*gys_1 gys_2 gys_3*	3 r	Gill et al., 1969
White striping$_3$		Plastid inheritance	Krishna Rao and Koduru, 1978a
Stripe	*sp*	Sectorial chimera	Appa Rao and Mengesha, 1984
Abnormal plastid development	*vi*	1 r	Reddy and Subrahmanyam, 1988
		Leaf characters§	
Weak midribs		2 Drc	Krishnaswamy and Rangaswami Ayyangar, 1942
Drooping lamina		2 Dc	Singh et al., 1968
Narrow leaf		1 r	Desai et al., 1959
Midribless	*mrl_1 mrl_2*		Appa Rao et al., 1988a
Glossy	*gl_1 gl_2 gl_3*	1 r	Appa Rao et al., 1987

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		Pubescent mutants	
Hairy leaf	*hl*	1 r	Singh et al., 1967 Burton and Powell, 1968 Singh et al., 1968 Gill et al., 1971 Khan and Bakshi, 1976 Krishna Rao and Koduru, 1979 Appa Rao et al., 1988c
Hairy node	*Hn*	1 D	Gill et al., 1971
Hairy lamina	*hl*	1 r	Krishna Rao and Koduru, 1979
Hairy leaf sheaths and blades		1 r	Appa Rao et al., 1988c
Hairy leaf surface	*Hr*	2 Dre	Lal and Singh, 1971
Hairy sheath	*hs*	1 r	Krishna Rao and Koduru, 1979
Hairy stem	*hst*	1 r	Krishna Rao and Koduru, 1979
Hairy leaf margin	*Hm*	1 D	Krishna Rao and Koduru, 1979
Trichomeless	*tr*	1 r	Powell and Burton, 1971
		Plant form	
Wavy stem	*ws*	1 r	Krishna Rao and Koduru, 1979 Burton, 1981
Thick stem		1 D	Al-Fakhry et al., 1965
Dwarf plant stature	d_1	1 r	Burton and Fortson, 1966
Dwarf plant stature	d_2	1 r	Kadam et al., 1940 Burton and Fortson, 1966
Dwarf plant stature (other than d_2)		>2 r	Burton and Fortson, 1966
Dwarf plant stature	d_3	1 r	Appa Rao et al., 1986
Dwarf plant stature	d_4	1 r	Appa rao et al., 1986
Dwarf plant stature		2 Dc	Al-Fakhry et al., 1965
Semidwarf (translocation dwarf)		1 r	Koduru and Krishna Rao, 1984
Brachytic dwarf	d_b	2 re	Gupta et al., 1985
		Plant pigmentation	
Purple coleoptilar leaf		1 D	Yadav, 1976
Purple seedling base	Pb_1 Pb_2	2 Dc;	Koduru and Krishna Rao, 1979
✓ Golden plant color		1 r	Burton, 1968
Red plant color	–	1 D	Burton, 1968
Purple plant color	*P*	1 D	Burton, 1968 Lal and Singh, 1971
Purple plant color	*PP*	1 D	Appa Rao et al., 1988c
Purple foliage	Pp_1 Pp_2	2 Dc	Athwal and Gill, 1966 Gill, 1969 Gill and Athwal, 1970
Purple midrib, margin, and sheath		1 D	Manga et al., 1988
Brownish leaf type-1		1 D	Al-Fakhry et al., 1965
Brownish leaf type-2		2 D	Al-Fakhry et al., 1965
Purple apicule		1 r	Manga et al., 1988
Purple leaf sheath		1ic	Singh et al., 1967
Purple leaf junction		1 D	Singh et al., 1968
Red stem	*Rp*	2 Dre	Gill, 1969
Purple stem	Ps_1 Ps_2	2 Dc;	Koduru and Krishna Rao, 1979
Purple internode		1 D	Al-Fakhry et al., 1965
		1 D	Manga et al., 1988
Purple (red) node	*Rn*	1 D	Krishnaswamy, 1962 Al-Fakhry et al., 1965 Singh et al., 1968 Koduru and Krishna Rao, 1979
	Pn_1 Pn_2	2 Dc	Appa Rao et al., 1988c Manga et al., 1988
Red node	Rn_1 Rn_2	2 Dc	Gill, 1969
Orange node	*on*	1 r	Degenhart et al., 1991
Purple node and auricle	*Pna*	1 D	Appa Rao et al., 1968c
Purple auricle	Par_1 Par_2	2 Dc	Manga et al., 1988
Yellow spikelets		1 r	Appa Rao and Mengesha, 1984
Purple glumes	Pg_1Pg_2	2 D	Gill, 1969
Purple glume tip	*pap*	1 r	Manga et al., 1988
Purple lemma, palea, bristle		1 D	Singh et al., 1967
Purple bristle	Bep_1 Bep_2	2 Dc	Gill, 1969
		1 D	Singh and Pandey, 1973
Purple anther		1 Dc	Athwal and Gill, 1966
		Earhead characters	
Exsertion of nodes from leaf sheath		1 D	Al-Fakhry et al., 1965
Exsertion of head from flag leaf		1 D	Al-Fakhry et al., 1965
Flag leaf interlocking		3 r	Singh et al., 1969
Curly spike	*Cl*	2 Dre	Singh and Pandey, 1972
Goose-neck peduncle		1 r	Krishnaswamy and Rangaswami Ayyangar, 1942
Complete sterility		2 Dde	Kadam et al., 1940
Spikeletless	*sl*	1 r	Rai et al., 1987
Basal branching		1 r	Rangaswami Ayyangar et al., 1935a
Branched earhead base	*Beb*	1 D	Gill and Athwal, 1970 Gill et al., 1971
Tapering earhead tip	Te_1Te_2	2 Dc	Gill and Athwal, 1970 Gill et al., 1971
Tufted earhead tip	*tet*	1 r	Gill and Athwal, 1970 Gill et al., 1971
Branched earhead tip	*bet*	1 r	Krishnaswamy and Rangaswami Ayyangar, 1942 Gill and Athwal, 1970 Gill et al., 1971
√ Bizarre earhead	be_1 be_2	2 rd	Dev et al., 1987
Curved earhead tip		1 D	Singh et al., 1968
		3 r	Singh et al., 1969
Naked earhead tip		2 Dre	Singh et al., 1969
	Net_1 Net_2	2 D	Gill et al., 1971
Bristling	*Br*	1 D	Rangaswami Ayyangar and Hariharan, 1936 Krishnaswamy, 1962 Ahluwalia and Shankar, 1964 Athwal and Gill, 1966 Lal and Singh, 1967 Gill and Athwal, 1970 Gill et al., 1971
		1 ic	Yadav, 1974a
		>1+	Appa Rao et al., 1988c
Semicompact earheads		1 D	Singh and Pandey, 1973
Floret-bearing bristles	*Fbb+Br*	1 D	Gill et al., 1971
Rough spike surface		2 Dre	Singh et al., 1969
Earhead tip sterility		2 Dc	Krishnaswamy and Rangaswami Ayyangar, 1942 Singh et al., 1969
		1 D	Singh et al., 1967

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Gappiness in earheads		1 r	Krishnaswamy and Rangaswami Ayyangar, 1942
		Reproductive structures	
Multiple carpels		1 r	Manga, 1977
Pistilless		1 r	Pokhriyal et al., 1967
Large pollen grains		1 D/2 Dc	Verma et al., 1969
Dummy pollen		1 r	Rangaswami Ayyangar and Panduranga Rao, 1935
Stubby head		1 r	Hanna and Powell, 1973
		Sterility	
Cytoplasmic male sterility	*ms, ms, ms*	1 r	Burton and Athwal, 1967
Restoration of pollen fertility (A_1 cytoplasm)		2 Dc	Siebert, 1983
Restoration of pollen fertility (A_2 cytoplasm)		2 Dde	Siebert, 1983
Genetic male sterility		1 r	Krishnaswamy and Rangaswami Ayyangar, 1942 Gill et al., 1973
	ms_1 ms_2	1 r	Krishna Rao and Koduru, 1978a,b
Triggering of male-sterile genes, C-2 cytoplasm	R_1 R_2	2 Dde	Krishna Rao and Uma devi, 1989
Female sterility	*fs*	1 r	Hanna and Powell, 1974
		Seed characters¶	
Yellow grain color	*Y*	1 D	Patel, 1939 Burton and Powell, 1968 Lal and Singh, 1971 Madhava Rao and Kulliaswamy, 1975
Purple seed color		1 D	Al-Fakhry et al., 1965
		2 Dc	Al-Fakhry et al., 1965
Pearly amber grain		1 D	Khan and Bakshi, 1976
Yellow endosperm	*y*	1 r	Phul et al., 1969
Amber endosperm	y^a	1 r	Phul et al., 1969
Deep slate endosperm	y^{ds}	1 r	Phul et al., 1969
Light slate endosperm	y^{ls}	1 r	Phul et al., 1969
Purple pericarp	*Prp*	1 D	Phul et al., 1969
Sugary grain	*su*	1 r	Patel, 1941
		Earliness and maturity#	
Early maturity	e_1	1 r	Burton, 1981
Early maturity	e_2	1 r	Hanna and Burton, 1985
		Resistance to diseases	
Downy mildew resistance		1/2 D	Appadurai et al., 1975
	DM_1 DM_2	2 Dde	Gill et al., 1978
Smut resistance		1 ic	
		1 D	
		2 Dde	Yadav, 1974b
Rust resistance	Rpp_1	1 D	Andrews et al., 1985
	Rr_1	1 D	Hanna et al., 1985
		1 D	Sokhi et al., 1987
		2 Dc	Sokhi et al., 1987
Pyricularia grisea resistance		2 D	Wilson et al., 1989
		3D	Hanna and Wells, 1989
Bipolaris setariae resistance	Bp_1 Bp_2 bp_3 bp_4	4 gs	Wells and Hanna, 1987, 1988
		Gamete formation	
Desynapsis	*ds*	1 r	Minocha et al., 1975 Pantulu and Rao, 1976 Subba Rao, 1980
Desynapsis and fragmentation	*ds ds*	2 rd	Lakshmi et al., 1979
Multiploid sporocytes	*mu*	1 r	Pantulu and Manga, 1971

† 1 r = single recessive gene; 2 r = two recessive genes; 3 r = three recessive genes; 1 D = single dominant gene; 2 D = two dominant genes; 3 D = three dominant genes; 1 ic = single gene, incomplete dominance; 2 Dc = two dominant genes with complementary action; 2 rd = two recessive duplicate genes; >1+ = more than one gene with additive action; 2 re = two genes, recessive epistasis; 2 Dde = two genes, duplicate dominant epistasis; 2 Dre = two genes dominant and recessive epistasis; 4 gs = two duplicate genes, 1 inhibitory gene, 1 antiinhibitory gene.
‡ Other CDs reported include: maculata (Chandola et al., 1963; Tara Mohan et al., 1973); striata (Chandola et al., 1963; Joshi, 1968; Tara Mohan et al., 1973); viridis (Tara Mohan et al., 1973; Singh et al., 1978); xantha (Chandola et al., 1963; Tara Mohan et al., 1973; Singh et al., 1978); and virido-albina, xantha-alba, and tigrina (Chandola et al., 1963).
§ Brown-midrib trait (Cherney et al., 1988) not included, as genetics of the trait not worked out.
¶ Endosperm colors described by Phul et al. (1969) form multiple allelic series.
# Response to photoperiod (Burton, 1966) and studies on earliness and lateness of landraces (Bilquez, 1963; Bilquez and Clement, 1969; Bharadwaj and Webster, 1971; Appa Rao et al., 1988b) not included.

The seed colour varies from ivory to purplish black, with light to deep gray being the most common seed colour. A small embryo is present on the depressed or flat surface at the tapering end of the seed. The size of the grain depends on its position in the panicle, being largest at the base, medium in the middle, and smallest at the apex. Variations exist in grain size among varieties generally ranging from 4-12 g per 1000 grains (AICRP, 2023). The small seeds of pearl millet, around 2 mm in diameter, are encased in a thin, papery hull which is easily removed in threshing. Seed color varies greatly between varieties (Wikipedia, 2023a**).** Pearl millet plants have variable number of tillers, variable panicle length and shape, seed size, seed color, and plant height, depending on the cultivars and environments. The seeds or caryopses of pearl millet are highly variable (from 3 to 15g per 1000 seeds). Some seeds are as broad as long, but may range from almost globose to subcylindrical and conical in shape. They are most often ash gray or steely blue in color, and also of purple, grayish brown, yellowish brown, and pearly-amber white. Sometimes, the embryo has a reddish tinge. The color of the glumes may range from deep purple to brownish gray or straw color. Seed surface may show striations or microscopic protuberances, depending on the genotypes (ICRISAT, 2023) (Fig. 10, 11). DNA based markers have emerged as a robust genomic tool for the estimation of genetic diversity and cultivar identification. We are reporting genetic diversity among 20 commercially released pearl millet cultivars comprising of hybrids and open pollinated varieties. Twenty one polymorphic SSR primer pairs, selected after initial screening of 60 were used to study the diversity which amplified 64 alleles. The number of amplified alleles among the cultivars ranged from 2–6 per locus with a mean value of 3 alleles per locus.

Fig. 10: Variability for seed shape, color and size in pearl millet

Conicle	Spindle	Cylindrical	Candle

Fig. 11. Panicle shapes

UPGMA cluster analysis differentiated all the cultivars and eighteen of them were found to be clustered into three major groups at similarity coefficient of 0.43 while two, JBV-3 and BAIF Bajra-1 remained ungrouped and were quite distinct from others. Interestingly, all the cultivars developed at IARI, New Delhi, were present in a subgroup within group I. Similarly, majority of hybrids developed at HAU, Hisar were grouped in the another subgroup within the group 1. BAIF Bajra 1 an exclusive forage purpose variety was genetically most diverged. Besides, a set of five polymorphic primers were found to differentiate all the cultivars. The results have demonstrated presence of moderate level of genetic diversity among the pearl millet cultivars (Kumar *et al.,* 2013).

A total of 97 pearl millet genotypes were grown at Hisar during Kharif 2013 season. The objectives of the investigation were to study genetic variability, correlation and path analysis for eight characters viz., days to 50% flowering, plant height (cm), effective tillers, panicle length (cm), panicle diameter (mm), number of nodes/main tiller, internode length (cm) and grain yield (g/plant) among 97 diverse pearl millet genotypes. Significant differences were observed among the genotypes for all the characters studied. The characters namely grain yield, panicle diameter, panicle length and plant height showed high phenotypic (PCV), genotypic (GCV) coefficient of variation, heritability and genetic advance. Genotypic and phenotypic coefficients of variation were highest for the trait grain yield. Estimates of heritability ranged from 18.15 per cent for effective tillers to 94.80 per cent for plant height, while grain yield showed 88.75 per cent heritability. High heritability coupled with high genetic advance as per cent of mean was observed for days to 50% flowering, plant height, panicle length, panicle diameter and grain yield indicating the importance of these traits in selection and crop improvement. The result from character association indicated that grain yield (g/ plant) had significant and positive correlation with plant height and panicle diameter at phenotypic level. The genotypic correlation estimates showed significant positive association of grain yield with panicle length, panicle diameter, number of nodes and internode length. Panicle length and plant height exhibited the highest positive and significant direct effect on grain yield. Hence, these traits could be considered as suitable selection criteria for the development of high yielding pearl millet genotypes. Panicle diameter, plant height, internode length and panicle length showed highest positive direct effect on grain yield at genotypic level. Hence, main emphasis should be given to these traits in breeding programme for development of high yielding pearl millet hybrids (Kumar *et al.,* 2014).

The observation on 36 genotypes of fodder bajra collected from divers sources were data recorded on fodder yield and its components for 11 metric traits. Green fodder yield exhibited highly significant and positive association with grain yield per plant, 1000-grain weight and number of tillers per plant it indicate that tillers in fodder bajra is major yield contributing characters. Grain yield per plant followed by dry matter yield per plant exhibited high and positive direct effects on green fodder yield per plant. Grain yield per plant, 1000-grain weight, number of tillers per plant, plant height, dry matter yield per plant and leaf stem ratio were the most important characters contributing to green fodder yield in pearl millet and can be strategically used in the selection process for green fodder yield improvement in fodder *bajra*. Thirty six genotypes were grouped into five clusters. On the basis of inter cluster distance, clusters III and V were identified as more divergent clusters. The hybridization programme has been suggested on the basis of inter cluster divergence and cluster means for the character studied (Bind *et al.,* 2015). An evaluation of 34 germplasm of pearl millet for genetic variability, heritability, genetic advance as percent of mean along with the association of grain yield with component traits was performed. The ANOVA showed highly significant differences among the genotypes for all the characters studied, indicating the presence of sufficient variability in the experimental material. The PCV were slightly higher than GCV indicating little influence of environment on the expression of characters. High PCV and GCV were recorded for all the characters. High heritability with high genetic advance as per cent of mean for ear girth, protein content and seed density suggested the prevalence of additive gene action in their inheritance indicating the selection based on these traits to be quite effective. The traits, number of effective tillers per plant, ear length, ear girth and seed density showed positive association with grain yield for which indirect selection can be made in future breeding programme to enhance grain yield (Sharma *et al.,* 2018).

Genetic variability which is the basic material for selection and improvement of any crop is fast eroding in pearl millet as natural habitats of wild cultivated species are being destroyed and modern cultivars replacing the traditional cultivars. On this premise collection and characterisation of the crop germplasm was carried to identify elite accession(s) for the crop improvement. Thirty five (35) pearl millet accessions collected from the major cultivated states in Nigeria were evaluated for morphological and yield parameters using a Randomised Complete Block Design (RCBD) with replicate three each. Wide range of significant ($P < 0.05$) variability was observed in all the morphological characters assessed with different trait been favoured by different genotypes. The highest plant height was recorded in KD-CK-01 (371.85 cm) and the least height in accession NG-ZA-05 with the value of 170.58 cm. Accession NG-ZC-03 had the highest weight of seeds per plot and weight of seeds per hectare with the value of 738.52 g and 1318.78 kg/ha respectively. Phenotypic coefficient of variance was higher than the corresponding genotypic coefficient variance for all the traits studied. Moderate (30-60%) to high (>60%) heritability was obtained among the traits studied while genetic advanced ranged from 21.92 to 127.27. Cluster analysis grouped the accessions into four major clusters based on their morphological similarity; cluster I consisting 14.29% of the genotypes, 17.14% in cluster II, 40.00% in cluster III and 28.57% were clustered in IV. The high variability recorded in the germplasm couple with high heritability and genetic advance in most of the parameters studied, indicate that the accessions and traits could be explored in the crop improvement (Abdulhakeem *et al.,* 2019). Pearl millet is an important millet crop of semi-arid regions in India and Africa. To study the genetic variability present among the newly effected fifty four hybrids an experiment was conducted in randomized block design with three replication. Yield parameters *viz.*, days to fifty per cent flowering, plant height, number of productive tillers, ear head length, ear head girth, test weight, single head grain weight, single plant yield and quality traits such as crude protein, crude fibre, beta carotene, iron and zinc were studied. The phenotypic coefficient of variation (PCV) was greater than genotypic coefficient of variation (GCV) for all the characters studied which shows the little influence of environment. High phenotypic (PCV) and genotypic variability (GCV) was obtained for plant height, single plant yield, single head grain weight, crude fibre, beta carotene content, iron and zinc. Highest heritability (h2) conjunction with genetic advance (GA) was observed for all the characters studied and moderate for number of productive tillers per plant and earhead girth Therefore, the presence of high variability among the genotypes can be utilized for nutritional enrichment in future millet breeding programs (Subbulakshmi *et al.,* 2019).

The present investigation was conducted to study variability parameters and character association in 50 pearl millet single cross hybrids which were generated by crossing five male sterile lines with 10 genetically diverse restorers in line x tester mating design at ICRISAT, Hyderabad during Summer, 2018. These crosses were evaluated during Kharif, 2018 at College of Agriculture, Swami Keshwanand Rajasthan Agricultural University, Bikaner. The material was evaluated in randomized block design with three replications. The analysis of variance indicated the presence of significant genetic variability among the single crosses for all the characters studied. The characters like number of effective tillers per plant, plant height, ear head length, ear head diameter and grain yield per plant were highly variable and correlated to each other. Hence, major emphasis should be given on these characters for selection of genotypes in breeding programmes for developing high yielding cultivars in pearl millet (Kumawat *et al.,* 2019).

Population genomic analysis of pearl millet inbred lines derived from diverse geographic and agroecological features identified five subgroups mostly following pedigree differences with different levels of admixture. It also revealed the prevalence of high genetic diversity in pearl millet, which is very useful in defining heterotic groups for hybrid breeding, trait mapping, and holds promise for improving pearl millet for yield and nutritional quality. The short LD decay observed suggests an absence of persistent haplotype blocks in pearl millet. The diverse genetic background of these lines and their low LD make this set of germplasm useful for traits mapping (Kanfany *et al.,* 2020). The present investigation was carried out at Agricultural Research Station, Perumallapalle, Tirupati, with 10 maintainer (B) and 27 restorer (R) lines of pearl millet during summer, 2020 in randomized block design with three replications to estimate genetic parameters viz., genetic variance, heritability (broad sense) and genetic advance as per cent of mean for 15 quantitative traits. The analysis of variance revealed highly significant differences among the genotypes for all the characters studied. The phenotypic coefficient of variation (PCV) was higher than genotypic coefficient of variation (GCV) and the difference between PCV and GCV was narrow for most of the characters, implying little influence of environment on expression of the traits. High values of PCV, GCV and heritability estimates coupled with maximum genetic advance over mean were obtained for panicle length, green fodder yield per plant, dry fodder yield per plant, panicle weight, 1000 grain weight, harvest index and grain yield per plant indicating the preponderance of additive gene action and selection based on these characters could be effective (Saikumar *et al.,* 2020). The study was initiated to determine the genetic variability, heritability and genetic advance analysis for yield and yield related traits. The materials comprised of nine parents *viz*., RVS-08/6, R-16419, R-15114, R-15134, R-15261, R-15510, R-15762, R-18428, ASRT-111 and their 36 F1's developed through half diallel cross.

The trial was carried out in randomized block design (RBD) with two replications. Heritability is a measure of possible genetic advancement under selection. Some characters recorded high value of heritability and genetic advance, indicating effectiveness in selection of these traits. Higher heritability was observed for Seed setting %, panicle length, panicle index per plant, plant height, days to 50% flowering and effective tiller per plant, pollen viability %, grain yield per plant while moderate heritability exhibited for canopy temperature at vegetative stage, canopy temperature at post anthesis and flag leaf temperature. Higher genetic advance as per cent of mean was found for three characters that is for effective tillers per plant, panicle length and grain yield per plant. The moderate genetic advance was found for plant height that makes simple selection should lead to a fast genetic improvement of the genotypes used in this study (Chauhan *et al.,* 2020). The study was aimed to ascertain the magnitude of variability in a core germplasm collection of diverse origin and predict pearl millet biofortification prospects for essential micronutrients. Germplasm accessions were evaluated in field trials at ICRISAT, India. The accessions differed significantly for all micronutrients with over two-fold variation for Fe (34–90 mg kg^{-1}), Zn (30–74 mg kg^{-1}), and Ca (85–249 mg kg^{-1}). High estimates of heritability (> 0.81) were observed for Fe, Zn, Ca, P, Mo, and Mg. The lower magnitude of genotype (G) × environment (E) interaction observed for most of the traits implies strong genetic control for grain nutrients. The top-10 accessions for each nutrient and 15 accessions, from five countries for multiple nutrients were identified. For Fe and Zn, 39 accessions, including 15 with multiple nutrients, exceeded the Indian cultivars and 17 of them exceeded the biofortification breeding target for Fe (72 mg kg^{-1}). These 39 accessions were grouped into 5 clusters. Most of these nutrients were positively and significantly associated among themselves and with days to 50% flowering and 1000-grain weight (TGW) indicating the possibility of their simultaneous improvement in superior agronomic background. The identified core collection accessions rich in specific and multiple-nutrients would be useful as the key genetic resources for developing biofortified and agronomically superior cultivars (Govindaraj *et al.,* 2020).

There are 40 genotypes of pearl millet that were gathered from ICRISAT in Hyderabad for the study. The experiment was performed in triplicate using Randomized Block Design. With an average D2 value of 398.08, the experimental material was divided into seven clusters, indicating the presence of diversity across the lines for the attributes being studied. Among different clusters the maximum cluster lines i.e., ten lines were observed in cluster V followed by cluster IV, cluster III, cluster I, cluster II, cluster VII, and cluster VI. Cluster V has the greatest intra cluster distance, followed by Cluster II, Cluster IV, and Cluster I. As a result, within these clusters, selection might be based on the greatest mean for desirable characteristics. The relative divergence shows the degree to which each cluster differs. The highest order of divergence was observed in cluster VIII and cluster X, followed by cluster V and cluster VIII. The results revealed that the parents are genetically heterogeneous in these clusters. The high heterotic response may have been achieved when used in a hybridization programme. Cluster VI and Cluster VII had the shortest inter-cluster distance, indicating low genetic diversity. Plant height had the highest cluster value in cluster VIII and the lowest in cluster X, whereas phenological parameters like days to flowering and days to maturity had the highest cluster value in cluster II. Days to flowering were the most important factor in genetic divergence, followed by the number of panicle length, fodder yield per plot, and productive tillers per plant (Shashibhushan *et al.,* 2022). An experiment comprised of fifty diverse accessions of forage was conducted at Anand Agricultural University, Anand to study the genetic variability, heritability, genetic advance, characters association and path coefficient analysis. The magnitude of phenotypic coefficient of variation was observed higher than corresponding genotypic coefficient of variation for all the characters under study. High genotypic and phenotypic coefficient of variations were observed for crude protein yield per plant, green forage yield per plant and dry matter yield per plant, which indicated the presence of sufficient amount of variability for these traits. High heritability coupled with high genetic advance for green forage yield per plant, plant height, stem thickness, leaf width and number of leaves per plant indicated good response of selection. Plant height, leaf length, leaf width, stem thickness, dry matter yield per plant, crude protein yield per plant and neutral detergent fiber content showed positive and significant correlation with green forage yield per plant and its quality at both genotypic and phonotypic levels. Path analysis indicated dry matter yield per plant, crude protein yield per plant, number of tillers per plant and stem thickness exerted a strong positive direct effect on green forage yield per plant (Parmar *et al.,* 2022).

A set of seventy-five germplasm lines were evaluated in Randomized Complete Block Design during Kharif 2021 to study different genetic parameters and associations among different yield accrediting characters. Analysis of variance indicated significant differences for all investigated traits in the experimental materials. The values of PCV were higher than GCV but in a narrow range indicating the least influence of environment on the expression of traits. Estimates of high heritability along with higher genetic advance as a percentage of mean were observed for grain yield plant-1, test weight, harvest index, numbers of productive tillers plant-1 and biological yield indicating the presence of additive gene action signifying for improvement of this trait by applying diverse selection methods. Correlation and path analysis studies revealed that the harvest index, biological yield, and numbers of productive tillers plant-1 could be considered good selection indices for selecting genotypes for yield improvement. The percent contribution of individual characters toward the total divergence was found high for biological yield (g). Based on D2 values, 75 genotypes were grouped into five clusters. Intra cluster distance ranged from 0.00 to 67.34. The highest inter-cluster divergence was documented between genotypes of clusters III and V (Rajpoot *et al.,* 2023). Present study on thirty six genotypes of fodder bajra [*Pennisetum glaucum* (L.) R. Br.] revealed wide spectrum of variation for various characters. Out of 11 characters studied, green fodder yield per plant has wide difference between GCV and PCV. Grain yield per plant, panicle length, dry matter yield per plant had close proximity between GCV and PCV, high heritability coupled with high genetic advance as per cent of mean. Therefore, these characters might be under the control of additive gene effects (Bind *et al.,* 2015a). Pearl millet is known to have a high level of genetic diversity, which is thought to be due to its wide range of adaptation to different environments and its long history of cultivation. This genetic diversity has been exploited by plant breeders to develop improved varieties of pearl millet with desirable traits such as higher yield, improved disease resistance, and better nutritional content (Abbott, 2023).

BREEDING

Germplasm

Pearl millet is gaining importance as a climate-resilient and health-promoting nutritious crop. Recent evidences using microsatellites suggest the monophyletic origin of pearl millet and its further migration and secondary diversification leading to enormous diversity. Genetic erosion of landraces has been evident in different pearl millet growing regions due to replacement with modern cultivars. Large variability found in pearl millet germplasm has been conserved in several gene banks. Toward enhancing the utilization of pearl millet germplasm, available subsets like core and minicore collections and reference sets should be extensively evaluated to identify trait-specific germplasm and also develop genomic resources to associate sequence differences with trait variations. Although transfer of desirable traits from primary wild relatives has been successful, concerted efforts are needed to broaden cultivated genepool by utilizing secondary and tertiary genepool toward developing climate-resilient cultivars. Development of genomic resources is expected to rise as the genome sequence of pearl millet is due for release and also due to faster developments in NGS technologies that could be efficiently utilized for management and utilization of pearl millet germplasm and in turn for crop improvement (Pattanashetti *et al.,* 2016).

Breeding objectives (CUTM, 2023)
1. Breeding for high grain yield
2. Breeding for improved grain quality
3. Breeding for drought tolerance
4. Breeding for disease resistance
5. Breeding for alternate source of cytoplasm in male sterile plants
6. Breeding for to have high forage Value

Breeding procedure (CUTM, 2023)
1. Introduction: Hybrid bajra from Punjab. Tift 23 A from USA
2. Selection : Pure line selection : Co 2, Co 3,
3. Hybridisation and selection
Interspecific hybridisation
Pennisetum glaucum X P. purpureum
Cumbu napier hybrids

4. Heterosis breeding: Hybrid bajra
In earlier days before the identification of male sterile lines utilising the protogynous nature hybrids were released. The hybrids were produced by sowing both parents in the ratio of 1:1. After the discovery of cytoplasmic genic male sterile line Tift 23A by Burton in Tifton, Georgia led to development of hybrids. Earlier hybrids of India viz., HB1, HB2 to HB5 were produced utilising Tift 23 A

5. Population improvement: ICRISAT entry WCC 75 is an example for population improvement. This was developed from world composite by recurrent selection method. It was developed from derivatives of numerous crosses between diverse sources of germplasm and Nigerian early maturing land races known as 'Gero' millets. Another example is ICMV 155 of ICRISAT.

6. Synthetic varieties: Synthetics are produced by crossing in isolation a number of lines tested for their GCA. E.g. ICMS 7703. It is a result of crossing between 7 inbred lines of India x African crosses

7. Mutation breeding: At IARI Tift 23 A was gamma irradiated and 5071 A resistant to downy mildew was evolved. With this the hybrid NHB 3 was evolved (5071 A x J 104).

Breeding centers (CUTM, 2023)

1. International Crops Research Institute for Semi Arid Tropics (ICRISAT,) Hyderabad
2. All Indian Pearl Millet improvement project (AIPIP) Jodhpur, (Rajasthan).

Breeding Achievents: Enormous progress has been made in the genetic improvement of pearl millet in India during last several decades. The genetic improvement programme evolved strongly starting from selection in local and traditional material and reaching development of high-yielding hybrids with in-built resistance to diseases and tolerance to climatic stresses like drought and heat. The major approach in hybrid breeding has been to strategically utilize germplasm from Africa and Indian subcontinent with the result that a large number of genetically diverse hybrids have been developed with different combinations of phenotypic traits that are important for adaptation to different ecological regions. The genetic diversification of hybrids has proved very critical to contain downy mildew epidemics which had threatened hybrid technology per se in mid-1970s. A great deal of work has been done on understanding the epidemiology of different diseases and crop response to moisture stress that helped in developing disease-resistant and stress-tolerant cultivars. More than 100 cultivars with a combination of diverse phenotypic traits have been released in the last 25 years, providing a wide range of choice to farmers in different production ecologies of the crop. These cultivars have been widely adopted by Indian farmers with the result that the crop productivity has gone up from 305 kg ha^{-1} during 1951–1955 to 998 kg ha^{-1} during 2008–2012, registering a 227 % improvement which assumes greater significance given that more than 90 % of pearl millet is grown as rainfed and often on marginal lands. In future, pearl millet is likely to play a greater role in providing food and nutritional security. Pearl millet would also be an excellent genomic resource for isolation of candidate genes responsible for tolerance to climatic and edaphic stresses for accelerating further genetic improvement of this crop as well as for their possible deployment in the genetic improvement of other crops (Yadav and Rai, 2013).

Pearl millet breeding in India has historically evolved very comprehensively from open-pollinated varieties development to hybrid breeding. Availability of stable cytoplasmic male sterility system with adequate restorers and strategic use of genetic resources from India and SSA laid the strong foundation of hybrid breeding. Genetic and cytoplasmic diversification of hybrid parental lines, periodic replacement of hybrids, and breeding disease-resistant and stress-tolerant cultivars have been areas of very high priority. As a result, an annual yield increase of 4% has been realized in the last three decades. There is considerable scope to further accelerate the efforts on hybrid breeding for drought-prone areas in SA and SSA. Heterotic grouping of hybrid parental lines is essential to sustain long-term genetic gains. Time is now ripe for mainstreaming of the nutritional traits improvement in pearl millet breeding programs. New opportunities are emerging to improve the efficiency and precision of breeding. Development and application of high-throughput genomic tools, speed breeding, and precision phenotyping protocols need to be intensified to exploit a huge wealth of native genetic variation available in pearl millet to accelerate the genetic gains (Yadav *et al.,* 2021). The major focus of research at ICRISAT is improving the crop productivity and adaptation by breeding for: increased grain and biomass yield, resistance to insect pests, disease and *striga*, and tolerance to heat and drought. Both hybrid and population breeding approaches are followed. Several new male-sterile lines, and pollinator lines have been developed which have been and are being used to develop high yielding disease resistant F1 hybrids by private and public sectors, particularly in India. A number of populations with wide genetic base have been created to derive open-pollinated varieties and parental lines of hybrids. This has been possible because of easy access to the rich and diverse germplasm collections available at ICRISAT Asia Center. A large number of open-pollinated varieties have been released for cultivation by farmers in several countries in Africa and Asia, mainly through collaborative breeding with national programs. Using molecular marker techniques genes for downy mildew resistance have been identified in collaboration with Cambridge lab funded by ODA. Resistant genes are now being transferred by marker-assisted selection technique (ICRISAT, 2023).

Pearl millet breeding and biotechnology: Pearl millet breeding and biotechnology are important tools for improving the yield, quality, and disease resistance of the crop. Breeders use a variety of techniques to improve the traits of the crop. These techniques may include the use of genetic markers to select for desired traits, the use of advanced breeding methods such as genomic selection, and the development of hybrid varieties through crossbreeding. There have been numerous studies on pearl millet breeding, including research on the genetic basis of important traits, the use of molecular markers to improve breeding efficiency, and the development of new breeding methods. For example, a study published in the journal Euphytica in 2010 found that pearl millet breeding has resulted in significant improvements in yield, disease resistance, and other traits over the past few decades. Another study, published in the journal Plant Breeding in 2015, used molecular markers to identify sources of resistance to downy mildew, a major fungal disease of pearl millet. Further, pearl millet biotechnology refers to the use of modern biotechnology techniques to improve pearl millet. These techniques can include genetic engineering, tissue culture, and molecular biology. For example, a study published in the journal Plant Molecular Biology in 2002 used genetic engineering to introduce a gene for insect resistance into pearl millet. The gene, known as Bt, encodes a protein that is toxic to certain insects but is safe for humans and other animals. The researchers found that the genetically engineered pearl millet plants were resistant to stem borers, a major pest of pearl millet (Abbott, 2023).

In addition to genetic engineering, pearl millet biotechnology also includes the use of tissue culture to propagate elite varieties. Tissue culture involves the use of small pieces of plant tissue to grow new plants in a laboratory setting. This can be used to produce large numbers of plants that are genetically identical to a parent plant. Furthermore, molecular biology techniques, such as DNA sequencing and gene expression analysis, are also used in pearl millet biotechnology to study the genetics and genomics of the crop. This research can help to identify the genes responsible for important traits, such as yield and disease resistance, and can inform the development of new breeding strategies. For example, genetic engineering can be used to introduce genes that provide resistance to pests and diseases, which can reduce crop losses and improve yields. Tissue culture can be used to produce large numbers of elite varieties, which can help to distribute improved varieties more widely and efficiently. Molecular biology techniques can provide insights into the genetics and genomics of pearl millet, which can inform breeding efforts and improve our understanding of the crop (Abbott, 2023).

Bajara /Pearl millet Varieties

Bajara /Pearl millet Varieties (Kumar, 2013):

Giant Bajra: The variety was developed by MPKV, Rahuri by intervarietal hybridization between Australian and local bajra from Dhule district followed by selections. The variety has been recommended for cultivation in entire bajra growing area. Plants are leafy with profuse tillering and have 9-10% protein at boot stage. The variety is good for hay and silage making. It is moderately resistant to downy mildew and ergot diseases. The green fodder yield is 50–75 t/ha. (CVRC Notification no. 295(E) dated 9th April 1985).

Raj Bajra Chari-2: The variety was developed by RAU, Jobner after two cycles of full sib selection in a population created through random mating among 20 crosses of four inbreds (originating from west Africa). It has been notified for cultivation for entire bajra growing area. The green fodder yield is 30–45 t/ha and is resistant to foliar diseases and insect-pests. At ear emergence stage, internodes are completely covered (enclosed) in the leaf sheath and the leaves are broad and shining. (CVRC Notification no. 386(E) dated 15th May 1990).

CO-8: The variety was bred by TNAU, Coimbatore by hybridization (732 A × Sweet Giant Bajra) followed by pedigree selection. It was released for entire bajra growing areas of the country. It is ready for fodder harvest in 50–55 days and produces green fodder to the tune of 30 t/ha. It has soft stem with high leaf stem ratio and is highly palatable. The variety has pale yellow green bristles on panicles at flowering. (CVRC Notification no. 615(E) dated 17th August 1993).

TNSC-1: The variety was bred by TNAU, Coimbatore and recommended for cultivation in the entire bajra growing area of the country in 1995. The variety provides 27–40 t/ha green fodder and is resistant to foliar diseases and insect-pests.

APFB-2: The variety was developed by recurrent selection in the randomly mated population at ANGRAU, Hyderabad in 1997. It was recommended for cultivation in Andhra Pradesh. It belongs to early maturity group, non-lodging, fertilizer responsive, best suited to summer and early Kharif sowings. The plant height is 160–180 cm providing green fodder yield 25 t/ha and dry fodder yield 5.5 t/ha in a single cut. The variety is useful for multi-cut also in the summer season.

Proagro No. 1 (FMH-3): This variety was developed by Proagro Seed Company, Hyderabad through hybridization of PSP-21 × PP-23. The variety is recommended for cultivation throughout the pearl millet growing areas of the country. The plants require 50- 55 days for flowering and matures in 90-95 days. The variety is highly resistant to downy mildew and provides 75 t/ha green fodder in multi cut system and 36 t/ha in single cut system. (CVRC-Notification no 401(E) 15th May 1998).

GFB-1: The variety has been bred by GAU, Anand and released in 2005.

PCB-164: The variety has been developed by PAU, Ludhiana from five late maturing lines. It was released and notified for cultivation in north west India. (CVRC Notification no. 1178(E) dated 20th July 2007).

FBC-16: The variety has been bred by PAU, Ludhiana and notified for cultivation in the entire north-west India. This is a multi-cut variety, resistant to major diseases. The variety has low concentration of oxalates and high voluntary dry matter intake by the animals. The green fodder yield potential is 70–80 t/ha. (CVRC Notification no. 1178(E) dated 20th July 2007).

Avika Bajra Chari (AVKB-19): The variety has been bred by IGFRI-RRS, Avikanagar by selection from material collected from Nagore, Rajasthan in 2006. The variety is recommended for cultivation in the state of western Uttar Pradesh, Rajasthan, Haryana, Punjab and Tarai region of Uttarakhand. The variety is a dual purpose with green fodder yield potential of 36.7 t/ha, dry fodder 8.8 t/ha and 10.2 q/ha seed yield.

Narendra Chara Bajra-2 (NDFB- 2): The variety has been developed by NDUA&T, Faizabad and is recommended for cultivation in pearl millet growing areas in north-east zone under salt-affected soils. (CVRC Notification no. 449(E) dated 11th February 2009).

State wise status of popular Hybrids/Varieties of pearl millet released in India are furnished it Table 3 (NUTRI, 2023):

Table 3. State wise status of popular Hybrids/Varieties of pearl millet (NUTRI, 2023)

State Name	Season	varieties Released(Recommended during last 15 years)	Hybrids varieties
PUNJAB	Kharif	RHB-58, Pusa-444, MLHB-267, JKBH-26, GHB-316, Pusa-605, Nandi-32, Pusa-415, Proagro-9443, HHB-146, BHB-577, Nandi-52, GHB-744, PHB-2168, JKBH-676	RHB-58, Pusa-444, MLHB-267, JKBH-26, GHB-316, Pusa-605, Nandi-32, Pusa-415, Proagro-9443, HHB-146, BHB-577, Nandi-52, GHB-744, PHB-2168, JKBH-676
HARYANA	Kharif	CZ-IC-923, Pusa Bajri – 266, Jawahar Bajra Variety-2, Pusa composite-334, HC-10, GICKV-96752, Pusa composite-383, HC-20, MP-406, Pusa composite-443 , RHB-58, Pusa-444, MLHB-267, JKBH – 26, GBH-316, 7886, Pusa – 605, Nandi-32, Pusa-415, HHB-94, 7688, Proagro-9443, RHB-121, Proagro-9445 GHB-558, HHB-146, GHB-577, HHB-117, GHB-538, HHB-67, GHB-719, HHB-197, GHB-757, GHB- 732, Nandi-52, GHB-744, PHB-2168, JKBH-676, RHB-154, HHB-216, RHB-173, HHB-223	RHB-58, Pusa-444, MLHB-267, JKBH – 26, GBH-316, 7886, Pusa – 605, Nandi-32, Pusa-415, HHB-94, 7688, Proagro-9443, RHB-121, Proagro-9445 GHB-558, HHB-146, GHB-577, HHB-117, GHB-538, HHB-67, GHB-719, HHB-197, GHB-757, GHB- 732, Nandi-52, GHB-744, PHB-2168, JKBH-676, RHB-154, HHB-216, RHB-173, HHB-223
HARYANA	Fodder	Proagro No.1, Avika Bajra Chari	Proagro No.1, Avika Bajra Chari
RAJASTHAN	Kharif	RHB-58, Pusa-444, MLHB-267, JKBH-26, GBH-316, 7886, Pusa-605, Nandi- 32, Pusa-415, HHB-94, 7688, Proagro-9443, RHB-121, Proagro-9445, GHB-558, HHB- 146, GHB-577, HHB-117, GHB-538, HHB-67, GHB-719, HHB-197, GHB-757, GHB-732, Nandi-52, GHB-744, PHB-2168, JKBH-676, RHB-154, HHB-216, RHB-173, HHB-223	RHB-58, Pusa-444, MLHB-267, JKBH-26, GBH-316, 7886, Pusa-605, Nandi- 32, Pusa-415, HHB-94, 7688, Proagro-9443, RHB-121, Proagro-9445, GHB-558, HHB- 146, GHB-577, HHB-117, GHB-538, HHB-67, GHB-719, HHB-197, GHB-757, GHB-732, Nandi-52, GHB-744, PHB-2168, JKBH-676, RHB-154, HHB-216, RHB-173, HHB-223
UTTAR PRADESH	Kharif	Jawahar Bajra Variety-2, GICKV-96752, Pusa composite-383 , RHB-58, Pusa-444, Nandi-32, 7686, 7688, Proagro-9443, Proagro-9445, RHB-121, RHB-173, GHB-558, GHB-577, GHB-744, Nandi-52, Nandi-62, HHB-146, HHB-197, HHB-223, PHB-2168	RHB-58, Pusa-444, Nandi-32, 7686, 7688, Proagro-9443, Proagro-9445, RHB-121, RHB-173, GHB-558, GHB-577, GHB-744, Nandi-52, Nandi-62, HHB-146, HHB-197, HHB-223, PHB-2168
UTTAR PRADESH	Rabi	Nandi-32, Nandi- 52, Nandi-62, Nandi-64	
ODISHA	Kharif	RHB-58, Pusa-44, Proagro-9443	RHB-58, Pusa-44, Proagro-9443
ODISHA	Fodder	Proagro No.-1	
MADHYA PRADESH	Kharif	RHB-58, Pusa-444, MLHB-285, JKBH-26, GBH-316, 7886, Pusa-605, Nandi- 8, Nandi-32, Pusa-415, 7688, Proagro-9443, RHB-121, Proagro-9445, GHB-558, HHB-146, GHB-557, Nandi-62, HHB-197, GHB-732, Nandi-52, GHB-744, PHB-2168, RHB-173	RHB-58, Pusa-444, MLHB-285, JKBH-26, GBH-316, 7886, Pusa-605, Nandi- 8, Nandi-32, Pusa-415, 7688, Proagro-9443, RHB-121, Proagro-9445, GHB-558, HHB-146, GHB-557, Nandi-62, HHB-197, GHB-732, Nandi-52, GHB-744, PHB-2168, RHB-173
GUJARAT	Kharif	CZ-IC-923, Jawahar Bajra Variety-2, Pusa composite-334, GICKV-96752, Pusa composite-383, MP-406 , RHB-58, Pusa-444, JKBH-26, GBH-316, 7876, Pusa-605, Nandi- 8, Nandi-32, Pusa-415, 7688, RHB-121, Proagro-9445, GHB-558, HHB-146, GHB-577, GHB-538, GHB-719, Nandi-62, HHB-197, GHB-757, GHB-732, Nandi-52, GHB-744, JKBH-676, RHB-154, HHB-216, RHB-173, HHB-223	RHB-58, Pusa-444, JKBH-26, GBH-316, 7876, Pusa-605, Nandi- 8, Nandi-32, Pusa-415, 7688, RHB-121, Proagro-9445, GHB-558, HHB-146, GHB-577, GHB-538, GHB-719, Nandi-62, HHB-197, GHB-757, GHB- 732, Nandi-52, GHB-744, JKBH-676, RHB-154, HHB-216, RHB-173, HHB-223
GUJARAT	Rabi	GHB-526	GHB-526
GUJARAT	Fodder	Proagro No.1	
GUJARAT	Summer	Guj-Hybrid, Nandi-32, GHB-526, Proagro-9444, Proagro-9555, Nandi-62, Nandi-52, Nandi-62	Guj-Hybrid, Nandi-32, GHB-526, Proagro-9444, Proagro-9555, Nandi-62, Nandi-52, Nandi-62
MAHARASHTRA	Kharif	AIMP-92901, Prabhni Sampda, Pusa composite-612 , RHB-58, Pusa-444, MLHB-267, Nandi-30, Saburi, GK-1004, PAC-903, MLBH-504, Proagro-9443, Nandi-35, GHB-558, B-2301, B-2095, GK-1051	RHB-58, Pusa-444, MLHB-267, Nandi-30, Saburi, GK-1004, PAC-903, MLBH-504, Proagro-9443, Nandi-35, GHB-558, B-2301, B-2095, GK-1051
MAHARASHTRA	Rabi	GHB-526, Saburi, GK-1004, Nandi-64, Nandi-35, Proagro-9444, Proagro-9555	GHB-526, Saburi, GK-1004, Nandi-64, Nandi-35, Proagro-9444, Proagro-9555
ANDHRA PRADESH	Kharif	Ananta, Pusa composite-612, RHB-58, Pusa-444, Nandi-360, GK-1004, PAC-903, MLHB-504, Proagro-9443, Nandi-35, GHB-558, B-2301, B-2095, GK-1051	RHB-58, Pusa-444, Nandi-360, GK-1004, PAC-903, MLHB-504, Proagro-9443, Nandi-35, GHB-558, B-2301, B-2095, GK-1051
ANDHRA PRADESH	Rabi	Ananta	
ANDHRA PRADESH	Fodder	Proagro No 1	
ANDHRA PRADESH	Summer	GK-1004, Nandi-35	GK-1004, Nandi-35
KARNATAKA	Kharif	Pusa composite – 612, RHB-58, Pusa-444, MLHB-267, GK-1004, PAC – 903, MLHB-504, Proagro-9443, Nandi-35, GHB-558, B-2308, B-2095, GK-1051	RHB-58, Pusa-444, MLHB-267, GK-1004, PAC – 903, MLHB-504, Proagro-9443, Nandi-35, GHB-558, B-2308, B-2095, GK-1051
KARNATAKA	Rabi	GHB-526	GHB-526
KARNATAKA	Fodder	Proagro No.1	
KARNATAKA	Summer	GK-1004, Nandi-35, GHB-526	GK-1004, Nandi-35, GHB-526
TAMIL NADU	Kharif	CoCu-9, Pusa composite-612, RHB-58, Pusa-444, X-6, X-7, GK-1004, PAC-903, Proagro-9443, COH (Cu)-8, Nandi-35, GHB-558, B-2301, B-2095, K-1051	RHB-58, Pusa-444, X-6, X-7, GK-1004, PAC-903, Proagro-9443, COH (Cu)-8, Nandi-35, GHB-558, B-2301, B-2095, K-1051
TAMIL NADU	Rabi	X-6, X-7, COH (Cu)-8, GHB-526, GK-1004, Nandi-35, Proagro-9444, Proagro-9555, GK-1051	X-6, X-7, COH (Cu)-8, GHB-526, GK-1004, Nandi-35, Proagro-9444, Proagro-9555, GK-1051

High yielding hybrids and varieties recommended for different states are furnished in Table 4 (Vikaspedia, 2023):

Table 4. High yielding hybrids and varieties recommended for different states (Vikaspedia, 2023)

Region/ State		Recommended Hybrid	Recommended Variety
Rajasthan	Kharif	KBH 108, GHB 905, 86M89, MPMH 17, Kaveri Super Boss, Bio 448, MP 7872, MP 7792, 86M86, 86M66, RHB-173, HHB 67	MBC 2, PC 443, JBV 3, PC 383, ICMV 221, Raj 171
	Summer	Nandi 70, Nandi 72, 86M64	
	Kharif – arid parts	HHB 234, Bio 70, HHB-226, RHB-177	CZP 9802
Gujarat	Kharif	KBH 108, GHB 905, 86M89, MPMH 17, Kaveri Super Boss, Bio 448, MP 7872, MP 7792, 86M86, 86M66, RHB-173, HHB 67	MBC 2, PC 443, JBV 3, PC 383, ICMV 221, Raj 171
	Summer	Nandi 70, Nandi 72, 86M64	
	Kharif – arid parts	HHB 234, Bio 70, HHB-226, RHB-177	CZP 9802
Haryana	Kharif	KBH 108, GHB 905, 86M89, MPMH 17, Kaveri Super Boss, Bio 448, MP 7872, MP 7792, 86M86, 86M66, RHB-173, HHB 67	MBC 2, PC 443, HC 20, JBV 3, PC 383, HC 10, ICMV 221, Raj 171
	Kharif – arid parts	HHB 234, Bio 70, HHB-226, RHB-177	CZP 9802
Punjab	Kharif	KBH 108, GHB 905, 86M89, MPMH 17, Kaveri Super Boss, Bio 448, MP 7872, MP 7792, 86M86, 86M66, RHB-173	PCB 164, ICMV 221, Raj 171
Delhi	Kharif	KBH 108, GHB 905, 86M89, MPMH 17, Kaveri Super Boss, Bio 448, MP 7872, MP 7792, 86M86, 86M66, RHB-173	JBV 3, PC 383, ICMV 221, Raj 171
Uttar Pradesh	Kharif	KBH 108, GHB 905, 86M89, MPMH 17, Kaveri Super Boss, Bio 448, MP 7872, MP 7792, 86M86, 86M66, RHB-173	JBV 3, PC 383, ICMV 221, Raj 171
Madhya Pradesh	Kharif	KBH 108, GHB 905, 86M89, MPMH 17, Kaveri Super Boss, Bio 448, MP 7872, MP 7792, 86M86, 86M66, RHB-173	JBV 4, JBV 3, PC 383, ICMV 221, Raj 171
Maharashtra	Kharif	Kaveri Super Boss, Pratap, PKV Raj, Shine, MP 7792, 86M86, PAC 909, 86M64, 86M53	ABPC-4-3, PC 612, Parbhani Sampada, Samrudhi, ICMV 221, Raj 171, ICMV 155
	Summer	Nandi 70, Nandi 72, 86M64	
Tamil nadu	Kharif	Kaveri Super Boss, Pratap, Co 9, Shine, MP 7792, 86M86, PAC 909, 86M64, 86M53	PC 612, CoCu 9, Samrudhi, ICMV 221, Raj 171, ICMV 155
	Summer	Nandi 70, Nandi 72, 86M64	
Andhra Pradesh	Kharif	Kaveri Super Boss, Pratap, Shine, MP 7792, 86M86, PAC 909, 86M64, 86M53	PC 612, Samrudhi, ICMV 221, Raj 171, ICMV 155, Ananta
Karnataka	Kharif	Kaveri Super Boss, Pratap, Shine, MP 7792, 86M86, PAC 909, 86M64, 86M53	PC 612, Samrudhi, ICMV 221, Raj 171, ICMV 155

USES

Pearl millets are used largely to prepare traditional, thick or thin, fermented or unfermented porridges in Africa. The second major use in Africa is malting for the brewing of traditional beers and wines. In west African countries, *e.g.,* Senegal, millet is used for making couscous, pap, and fritters. In Cameroon, pearl millet-based gruels and steamed cakes are prepared for feeding infants and preschool children. Malted pearl millet in combination with legumes has been used to prepare malted weaning foods. Pearl millet has also been used in composite flour with wheat for making bread. Up to 30% pearl millet was used successfully in making bread in Senegal. Pearl millet is traditionally milled by hand-pounding in a wooden mortar, yielding a flour of about 85% extraction. Experimental milling systems, such as the Storamil process, have given 65–75% yields of fine flour. Pearling or debranning of pearl millet has also been achieved with a vertical cone polisher of the type normally used for polishing rice. Pearl millet can be malted and used wholly or partially in place of sorghum malt in the traditional or industrial brewing of opaque beer. However, the small size of the grain is a disadvantage in large-scale industrial malting plants. Pearl millet is also grown as a forage crop in the southeastern USA and in some parts of southern Africa (Gomez and Gupta, 2003). Pearl millet is primarily grown for food and dry fodder. Its grains are highly nutritious with high levels of metabolizable energy and protein, have high densities of iron and zinc, and more balanced amino acid profile than maize or sorghum. Grains are mainly used for human consumption in the form of diverse food, mostly as leavened and unleavened flat breads and porridges. Dry stover of pearl millet is a major component of livestock ration during the dry period of year.. Pearl millet is also an excellent forage crop because of its lower hydrocyanic acid content than sorghum. Its green fodder is rich in protein, calcium, phosphorous and other minerals with oxalic acid within safe limits. A significant portion of pearl millet grain is also used for non-food purposes such as poultry feed, cattle feed and alcohol extraction (Yadav and Rai, 2013). Pearl millet is commonly used to make *bhakri* flatbread. It is also boiled to make a Tamil porridge called *kamban choru* or *kamban koozh*. In Rajasthani cuisine *bajre ki khatti rabdi* is a traditional dish made Flatbreads made of pearl millet flour, known as *bajhar ji maani* or *bajre ki roti* in Punjab, Rajasthan and Haryana, bajrichi bhakri in Maharashtra and bajra no rotlo in Gujarat, India, are served with various types of kadhi and bhaaji in meals. Bajhar ji maani prepared in Tharparkar, Sindh is served with various types of kadhi and bhaaji. In Namibia, pearl millet flour is used to make Oshifima, a staple food in northern part of Namibia (Wikipedia, 2023). The seeds are typically cooked as a cereal grain or sometimes finely ground and used as a flour (Snyder, 2023). Bhakri flatbread is frequently made from pearl millet. Additionally, it is cooked to create the Tamil dish known as kamban choru or "kamban koozh." Bajre ki khatti rabdi is a traditional Rajasthani dish made with yoghurt and pearl millet flour. It is typically prepared in the summer and served with meals.

The Pearl Millet is known locally in Karnataka as Sajje and is primarily grown in the semi – arid regions of North Karnataka. Sajje is ground and used to make flatbread, which is then served with yoghurt and stuffed brinjal. Pearl millet is known as kambu in Tamil, and it is a staple cuisine throughout the Indian state of Tamil Nadu. It is the second most significant cuisine for Tamils and is primarily enjoyed from February through May during the hot, muggy summer months. It is either turned into a gruel and eaten with buttermilk or eaten as a dosa or an idly. In the northern Indian states, pearl millet is known as bajra. Bajra and Jowar used to be the main food crops in these states, but following the Green Revolution in the 1960s, they were reduced to being just cattle fodder crops (Byjus, 2023). Bajra is common minor millet of India with wider industrial and household utility. It is used a feed, food and raw material in soft drink industry. Botanically it is known as *Pennisetum typhoides* L. and belongs to the family poaceae (Eagri, 2023a). Pearl millet grain can be ground into flour and used to produce porridge, or a type of flat bread. It can also be cooked and prepared in a manner similar to couscous or rice. The plant stems can be used for roof thatch and building construction. In countries other than Africa and India it is most widely grown as fodder (Plantvillage, 2023). Some of the preparations made by using ragi are furnished in Fig. 12.

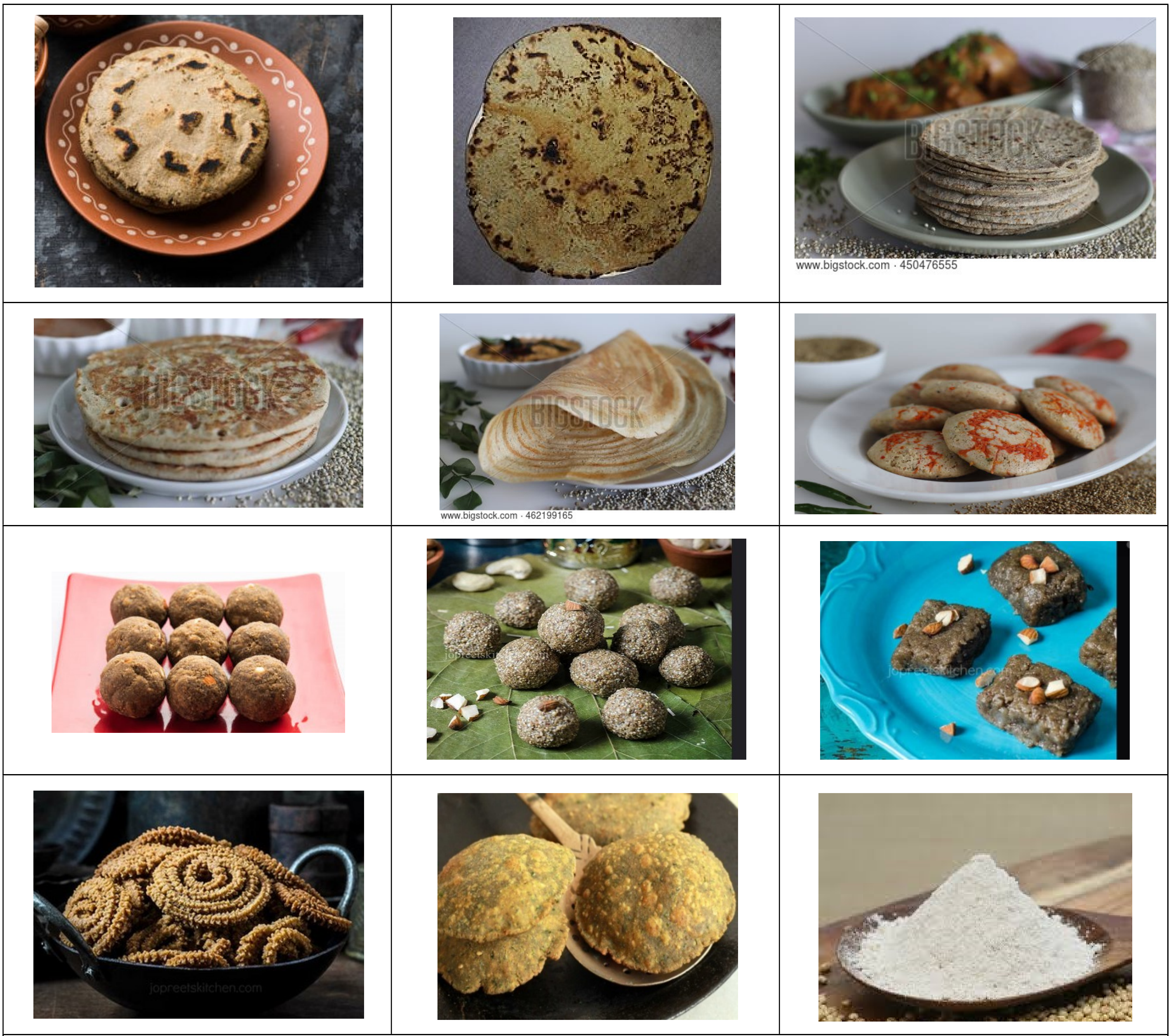

Fig. 12.

By-products of pearl millet: In addition to the grain, which is used as a source of food and feed, pearl millet also has several by-products that can be used for a variety of purposes. Here is more detailed information on pearl millet by-products **(**Abbott, 2023).

1. Pearl millet flour: Pearl millet flour is made by grinding the grain into a fine powder. It is a nutritious and versatile ingredient that is used in a variety of dishes, such as breads, porridges, and flatbreads. It is also a good source of protein, fiber, and micronutrients, making it a healthy alternative to wheat flour for people with gluten sensitivities.

2. Pearl millet bran: Pearl millet bran is the outer layer of the grain that is removed during the milling process. It is a good source of dietary fiber and contains a variety of nutrients, including vitamins and minerals. It is often used as a supplement in animal feed or as an ingredient in breakfast cereals and other processed foods.

3. Pearl millet husk: Pearl millet husk is the outermost layer of the grain that is removed during processing. It is a good source of fiber and is often used as a natural alternative to synthetic fibers in animal feed. It can also be used as a soil conditioner in agriculture.

4. Pearl millet straw: Pearl millet straw is the dried stalks of the plant that remain after the grain has been harvested. It is a versatile by-product that is used as animal bedding, as a construction material, and as a biofuel. It is also used in the production of paper and other products.

5. Pearl millet seed oil: Pearl millet seed oil is extracted from the seeds of the pearl millet plant. It is a good source of essential fatty acids and has a high smoke point, making it suitable for cooking at high temperatures. It is also used in the production of soap, cosmetics, and other personal care products.

6. Pearl millet hay: Pearl millet hay is made from the dried leaves and stems of the pearl millet plant. It is a nutritious feed for livestock and is often used as a supplement to other types of hay. It is also used as a natural alternative to synthetic fibers in animal bedding.

7. Pearl millet silage: Pearl millet silage is made by ensiling (fermenting) pearl millet straw and other plant materials. It is a highly nutritious feed for livestock and is often used as a supplement to other types of silage.

8. Pearl millet malt: Pearl millet malt is made by germinating pearl millet grains and then drying them. It is used in the production of beer and other alcoholic beverages, as well as in the production of malt extract and other food products.

9. Pearl millet syrup: Pearl millet syrup is made by extracting the sugars from pearl millet grains and concentrating them into a thick, sweet syrup. It is used as a natural sweetener and as an ingredient in a variety of food products, including baked goods, sauces, and confectioneries.

10. Pearl millet tea: Pearl millet tea is made by brewing the leaves of the pearl millet plant. It is believed to have a variety of health benefits, including the ability to reduce inflammation.

Side effects of pearl millet

Like all foods, pearl millet may have some potential side effects and disadvantages that it is important to consider. Here are potential side effects and disadvantages of pearl millet, along with evidence and purpose and effect (Abbott, 2023).

1. ***May cause allergic reactions:*** Some people may be allergic to pearl millet, and consuming it may cause allergic reactions such as itching, swelling, and difficulty breathing.

2. ***May cause gastrointestinal symptoms:*** Consuming large amounts of pearl millet may cause gastrointestinal symptoms such as bloating, gas, and diarrhea. This may be due to the fiber content of pearl millet, which can cause increased gas production and bowel movements.

3. ***May interfere with medication:*** Pearl millet may interact with certain medications, such as blood thinners, and may interfere with their effectiveness. It is important to speak with a healthcare provider before consuming pearl millet if you are taking any medications.

4. ***May contain toxins:*** Some varieties of pearl millet may contain naturally occurring toxins, such as fumonisins, which may cause a range of health problems, including liver damage and kidney failure. It is important to ensure that pearl millet is properly processed and stored to minimize the risk of exposure to toxins.

5. ***May contain gluten:*** Some types of pearl millet may contain gluten, which may cause digestive problems and other health problems in people with gluten sensitivity or celiac disease. It is important to choose gluten-free pearl millet products if you have a gluten sensitivity or celiac disease.

6. ***May cause weight gain:*** Consuming large amounts of pearl millet may contribute to weight gain due to its high calorie and carbohydrate content. It is important to consume pearl millet in moderation and as part of a balanced diet to avoid weight gain.

7. ***May contain anti-nutrients:*** Some types of pearl millet may contain anti-nutrients, such as phytates and tannins, which can interfere with the absorption of certain nutrients, such as calcium and iron. Proper cooking methods, such as soaking and sprouting, can help to reduce the levels of anti-nutrients in pearl millet.

8. ***May cause nutrient deficiencies:*** Consuming a diet that is high in pearl millet and low in other grains may lead to nutrient deficiencies, as pearl millet is not a complete protein source and is low in certain nutrients, such as essential amino acids. It is important to consume a varied diet that includes a range of grains and other protein sources to avoid nutrient deficiencies.

9. ***May contribute to environmental degradation:*** The cultivation of pearl millet may contribute to environmental degradation if it is not done sustainably and responsibly. This may include issues such as water depletion, soil erosion, and pesticide and fertilizer runoff. It is important to consider the environmental impacts of pearl millet production and to adopt sustainable and responsible farming practices.

10. ***May contribute to social and economic issues:*** The cultivation and trade of pearl millet may contribute to social and economic issues, such as land use conflicts and labor abuses. It is important to consider the potential negative social and economic impacts of pearl millet production and to address these issues in a responsible and sustainable manner.

NUTRITIONAL VALUE

The nutritional advantages of pearl millet are its high fat content and a relatively high lysine content, comparable with that of high-lysine corn in some varieties. Antinutritional factors, however, have been reported in several studies. A thionamide-like substance has been identified that interferes with the formation of thyroid hormones, which in turn leads to undesirable goitrogenic effects (Gomez and Gupta, 2003). Average nutritional profile of 1 cup (170 g) of cooked pearl millet is given in Table 5 (Medico, 2021).

Table 5. Average nutritional profile of 1 cup (170 grams) of cooked pearl millet

Calories	201
Protein	6 grams
Fat	1.7 grams
Carbs	40 grams
Fiber	2 grams
Sodium	286 mg
Folate	8% of the Daily Value (DV)
Iron	6% of the DV
Magnesium	18% of the DV
Thiamine	15% of the DV
Niacin	14% of the DV
Phosphorus	14% of the DV
Zinc	14% of the DV
Riboflavin	11% of the DV
Vitamin B6	11% of the DV

Pearl millet/Bajra is an energy-packed grain and can also be called a superfood. Loaded with insoluble fiber that helps you lose weight, lower cholesterol, and lower blood sugar levels. If you are trying to lose weight, adding low-calorie density whole foods to your diet can be beneficial. The caloric density of food measures its caloric content in relation to its weight (in grams) or volume (in ml). For example, a food that has 100 calories per 100-gram serving would have a caloric density of 1. A food that has 400 calories per 100-gram serving would have a caloric density of 4. Foods with a low-calorie density help you feel full but with fewer calories. Foods with a caloric density greater than 2.3 are generally considered high. Bajra has a caloric density of 1.2. Therefore, foods like bajra with a low-calorie density can help you lose weight. As a bonus, it is rich in essential vitamins, especially vitamin B6, potassium, and magnesium, making the grain good for the heart. It is a gluten-free grain and superfood, which helps you lose weight. It is loaded with insoluble fiber that helps burn extra fat (Medico, 2021). Nutritional value of bajra as given by Byjus (2023) is furnished in Table 6.

Bajra and the majority of millets have excellent nutritional characteristics. In general, cooked millet is a rich source of fibre, carbohydrates, and protein. Additionally, it is a wonderful source of minerals and vitamins. Overall, millet is a healthy source of carbohydrates. Furthermore, it is gluten – free, making it a good option for anyone with celiac disease or those on a gluten – free diet. Bajra contains significant amounts of phytochemicals, polyphenols, and antioxidants, all of which are recognised to improve human health in a variety of ways. However, the presence of advantageous polyphenols may also prevent the body from completely absorbing some elements in bajra, like iron and zinc (Byjus, 2023). Pearl millet is a nutritious grain that provides a number of important nutrients, including protein, fiber, and a variety of vitamins and minerals. Here are the nutritional properties of pearl millet, along with the daily value (DV) based on a 2000 calorie diet (Abbott, 2023): Protein: 3 grams (6% DV), Fiber: 2 grams (8% DV), Thiamin (B1): 0.5 milligrams (33% DV), Niacin (B3): 2 milligrams (10% DV), Folate (B9): 70 micrograms (18% DV), Vitamin B6: 0.1 milligrams (5% DV), Iron: 1 milligram (6% DV), Magnesium: 75 milligrams (19%

DV), Phosphorus: 105 milligrams (11% DV), Potassium: 115 milligrams (3% DV), and Zinc: 1 milligram (9% DV).

Table 6. Bajra Nutritional Information

	Nutritional value per 200 g	Quantity
Basic Components		
	Proteins	22 g
	Water	17.3 g
	Ash	6.5
Calories		
	Total Calories	756
	Calories From Carbohydrates	600
	Calories From Fats	71
	Calories From Proteins	85.3
	Carbohydrates	
	Total Carbohydrates	146
	Dietary Fiber	17 g
Fat and Fatty Acids		
	Total Fat	8.4 g
	Saturated Fat	1.4 g
	Monounsaturated Fat	1.5 g
	Polyunsaturated Fat	4.3 g
	Omega – 3 Fatty Acids	236 mg
	Omega – 6 Fatty Acids	4 g
Vitamins		
	Vitamin E	100 mcg
	Vitamin K	1.8 mcg
	Thiamine	842 mcg
	Riboflavin	580 mcg
	Niacin	9.4 mg
	Vitamin B6	768 mcg
	Foliate	170 mcg
	Pantothenic Acid	1.7 mg
Minerals		
	Calcium	16 mg
	Iron	6 mg
	Magnesium	228 mg
	Phosphorus	570 mg
	Potassium	390 mg
	Sodium	10 mg
	Zinc	3.4 mg
	Copper	1.5 mg
	Manganese	3.3 mg
	Selenium	5.4 mcg

Side Effects: Although bajra or pearl millet is one of the most consumed foods in our country, it has a large number of side effects. If you are eager to add this millet to your daily diet plan, there are a few things to keep in mind. Pearl millet is not recommended for those with thyroid gland dysfunction, as it can further compromise the functioning of this butterfly-shaped gland and lead to various metabolic disorders. The oxalates in Bajra, if not cooked properly, can result in kidney stones and the phytic acid can interfere with the absorption of food in the intestine. Therefore, if you have any of these health problems, talk to your doctor or nutritionist before consuming pearl millet (Medico, 2021).

HEALTH BENEFITS

Use bajra control diabetes, keeps the heart healthy, safe for people intolerant to gluten, weight control, packed with omega-3 fats, polycystic ovary syndrome, improves digestion, natural detoxifier, increases lung power, fight heartburn, strengthens bones, improve eyesight, overcome fatigue, helps in preventing loss of hair, strengthens hair follicles, prevents hair loss with patterns , prevents hair breakage (Medico, 2021).

Snyder (2023) reported the following health benefits of bajra

May aid weight loss: If you're trying to lose weight, adding whole grain foods with a low calorie density like bajra to your diet may be beneficial. The calorie density of a food measures its calorie content relative to its weight (in g) or volume (in ml). For example, a food that has 100 calories per 100-gram serving would have a calorie density of 1. A food that has 400 calories per 100-g serving would have a calorie density of 4. Foods with a low calorie density help you feel full but for fewer calories. Foods with a calorie density greater than 2.3 are generally considered high. Bajra has a calorie density of 1.2. Thus, foods like bajra with a low calorie density may aid weight loss.

May be a good choice for people with diabetes: Overall, most types of millet are considered to be a good grain choice for people with diabetes. Foods that are high in fiber, especially cereal fibers like bajra, have also been associated with improved outcomes in the management of type 2 diabetes and other chronic diseases. What's more, millet has a lower glycemic index (GI) than some refined grain products like white rice and white bread. Plus, some emerging research in animals and humans has found that millet proteins may contribute to improved blood sugar levels. On average, most types of millet have a GI value of 43–68. Foods with a GI value of 55 or below are typically considered to be low. The GI is a measure of how much certain foods affect blood sugar levels. Foods that are lower on the glycemic index are usually better choices for people with diabetes. In some cases, glycemic load (GL) may be a better measure of how a food affects blood sugar levels. GL differs from GI by also considering the typical serving size of a food. A GL of 10 or below is considered low, while a GL of 20 or more is high. One study noted that millet flakes have a GL of 9.2, meaning they have a low GL. That said, some of the research that supports these claims did not use bajra specifically, and the use of both GI and GL in diabetes management is controversial. Therefore, more research is needed to understand exactly how millet affects blood sugar levels.

Contains nutrients that may support healthy hair, skin, and nails: You may have heard that bajra is good for your hair, but the millet itself has not been studied as a hair treatment. However, bajra is a good source of many nutrients known for contributing to healthy hair, skin, and nails, including protein, vitamin B6, niacin, folate, iron and zinc. Regularly eating bajra as part of your diet could help prevent deficiencies in these nutrients. Eating bajra on a regular basis may have a number of positive health effects, including weight loss, better diabetic control, and a higher intake of nutrients that support healthy skin, hair, and nails. High – fiber foods, particularly those found in cereals like bajra, have also been linked to better outcomes in the treatment of type 2 diabetes and other chronic conditions. Additionally, compared to some refined grain products such as white rice and white bread, millet has a lower glycemic index (GI). Additionally, several recent studies in both humans and animals have discovered that millet proteins may help to lower blood sugar levels. The body finds it more difficult to digest the fibre found in whole grains like bajra. As a result, it prevents the blood sugar surge that processed carbohydrates might bring about. The body uses insulin more effectively when blood sugar is stabilised. A diet rich in whole grains, such as bajra, can lower levels of triglycerides, blood sugar, low – density lipoprotein (LDL), or bad cholesterol. Magnesium is necessary for the body's cells. It helps the body make new proteins, regulate the neurological system, and turn food into energy. Fatigue is one of the initial signs of a magnesium shortage. Magnesium – rich foods, like bajra, can help us receive enough of the mineral in our diet and boost our level of energy (Byjus, 2023).

Health advantages and benefits of pearl millet (Abbott, 2023):

1. Good source of nutrients: Pearl millet is a good source of several important nutrients, including protein, fiber, and a variety of vitamins and minerals. It is particularly high in B-vitamins, including thiamin, niacin, and folate.

2. May support weight loss: Some research suggests that consuming pearl millet may help to support weight loss. One study found that participants who consumed pearl millet had significantly lower body weight and body mass index (BMI) compared to those who did not.

3. May improve digestion: Pearl millet is a good source of fiber, which can help to improve digestion and reduce the risk of constipation. It may also help to promote the growth of beneficial bacteria in the gut, which can support overall gut health.

4. May lower blood pressure: Some research suggests that consuming pearl millet may help to lower blood pressure. One study found that participants who consumed pearl millet had significantly lower blood pressure compared to those who did not.

5. May improve heart health: The nutrients in pearl millet, including fiber and B-vitamins, may help to improve heart health by lowering blood pressure and reducing the risk of heart disease. Pearl millet is also a good source of antioxidants, which may help to protect against oxidative stress and reduce the risk of heart disease.

6. ***May improve brain function:*** Pearl millet is a good source of thiamin, a B-vitamin that is important for brain function. Some research suggests that thiamin may help to improve memory and cognitive function.

7. ***May reduce the risk of cancer:*** Pearl millet is a good source of antioxidants, which may help to protect against oxidative stress and reduce the risk of cancer. Some research suggests that pearl millet may have anti-cancer properties and may be effective in preventing the growth and spread of cancer cells.

8. ***May improve exercise performance:*** Some research suggests that consuming pearl millet may improve exercise performance by increasing the body's ability to use oxygen and by reducing fatigue. One study found that participants who consumed pearl millet had significantly improved cycling performance compared to those who did not.

9. ***May improve skin health:*** Pearl millet is a good source of antioxidants, which may help to protect against oxidative stress and improve skin health. Some research suggests that pearl millet may have anti-aging properties and may be effective in reducing the appearance of fine lines and wrinkles. In addition, pearl millet is a good source of B-vitamins, which may help to improve skin health by maintaining the skin's natural moisture barrier and reducing inflammation.

10. ***May improve immune function:*** Pearl millet is a good source of various nutrients, including vitamins and minerals, that are important for immune function. Some research suggests that consuming pearl millet may help to improve immune function and reduce the risk of infections. It is important to note that more research is needed to confirm these potential health benefits of pearl millet and to determine the optimal amounts and forms of pearl millet to consume for different health outcomes. It is also important to maintain a balanced and varied diet and to speak with a healthcare provider before making any changes to your diet or taking supplements.

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