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Millets: Robust Entrants to Functional Food Sector

Sagar Maitra[1], Sandipan Pine[2], Pradipta Banerjee[3], Biswajit Pramanick[4] and Tanmoy Shankar[5]

[1] *Professor, Department of Agronomy and Agroforestry, Centurion University of Technology and Management, Paralakhemundi – 761211, Odisha, India*
[2] *Associate Professor, Department of CSE, Centurion University of Technology and Management, Paralakhemundi – 761211, Odisha, India*
[3] *Assistant Professor, Department of Biochemistry and Plant Physiology, Centurion University of Technology and Management, Paralakhemundi – 761211, Odisha, India*
[4] *Assistant Professor, Department of Agronomy, Dr. Rajendra Prasad Central Agricultural University, Pusa – 848125, Samastipur, Bihar, India*
[5] *Associate Professor, Department of Agronomy and Agroforestry, Centurion University of Technology and Management, Paralakhemundi – 761211, Odisha, India*

CHAPTER MENU

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1.1 Introduction

The word "millet" derives from the "mil" or "thousand," which refers to the huge number of grains that can be produced from a single seed. Millets are coarse cereals with a heritage of consumption since early human civilizations from the Neolithic age. Presently, these crops are cultivated in arid and semi-arid regions of Asia and Africa as staple food and animal feed (Brahmachari et al. 2018; Maitra 2020). Millets are considered as miracle crops, because cultivation of millet has multiple benefits (Figure 1.1). The grains are used as food and the stover is used as fodder. Millets are diversified cereals; hence their cultivation enriches biodiversity in the agro-ecosystem. In erosion prone steep and arid regions, short statured millets provide grassy cover, thus restricting soil and nutrient loss. Soil organic carbon depletion is a major problem in drylands and cultivation of millet with less water assures carbon sequestration (Srinivasarao et al. 2014). Millets are less nutrient demanding, are cultivated with low chemical input and emit less greenhouse gas emissions; thus, millets reduce the carbon footprint in agriculture. Under extreme weather conditions, including higher temperatures, C_4 millet plants assure CO_2 abatement opportunities and, in the future, with elevated CO_2 levels these crop will perform better than other major cereals. Food and nutritional security is a major concern,

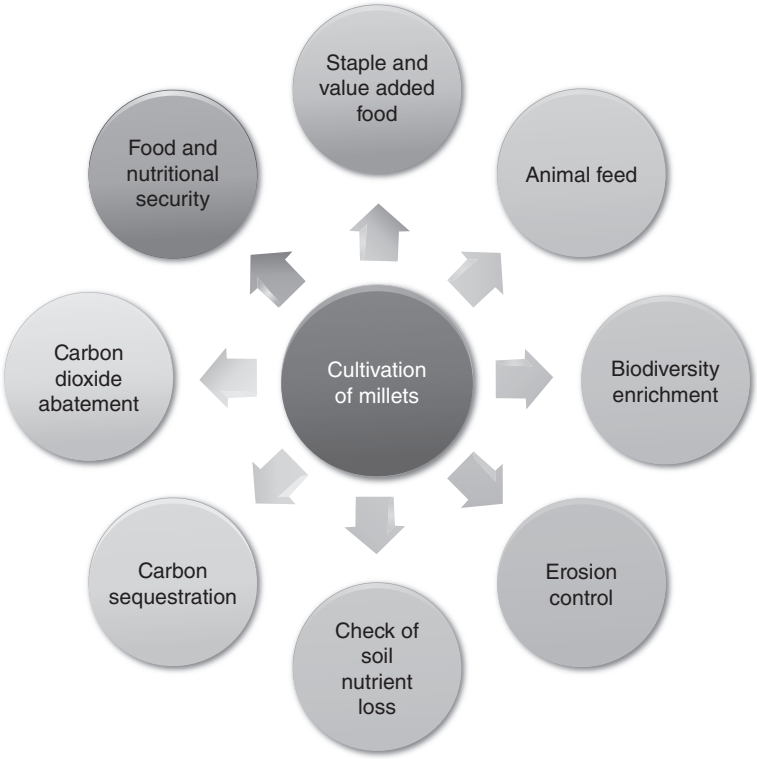

Figure 1.1 Multifaceted benefits of millet cultivation.

even in today's world, and nutrient-rich millets can fulfill this requirement. Moreover, millets are non-gluten foods richer in dietary fiber and essential macro- and micro-nutrients compared to other cereals. The world population will be 9.7 billion by 2050 and 11.2 billion by 2100 and agriculture will play a crucial role in feeding these huge populations with deteriorating and shrinking natural resources. Industrialization and urbanization have already changed the food consumption pattern and in future the transformation to value-added and energy-rich food will further intensify, leading to tremendous challenges to agriculture. The world cereal equivalent food demand is projected to be around 14,886 million tons in 2050 (Islam and Karim 2019). Food and nutritional security will add another dimension to the global food supply system. Considering all the above issues, including climate change, there is an urgent need to shift from ongoing crop production to ecologically sound and nutrient-rich crops. In this regard, millets can fulfill future requirements, because they have the desired qualities to cope with future climatic conditions. But, obviously, there is still the scope for adoption of smart technologies of precision agriculture (PA) to create a hunger-free world with sustainable agricultural production.

1.2 Nomenclature and Use

"Millet" is a generic term comprised of different coarse cereals and forage crops (Weber 1998). The millets can be placed as per prehistoric classification into mainly nine genera, namely, *Brachiaria, Digitaria*, *Echinochloa*, *Eleusine*, *Panicum*, *Paspalum*, *Pennisetum*, *Setaria* and *Sorghum*. Additionally, *Coix* and *Amaranthus*, and *Eragrotis* and *Fagopyrum* genera are also included as millets or coarse cereals. Among millets, the most prominent belong to the genera *Sorghum* and *Pennisetum*, which account for major world production, but the contribution of millets to the world's food basket is still negligible and these are essential food grains for mainly warm environments of the rainfed arid and semi-arid regions (Maitra 2020; Saxena et al. 2018). The classification of presently cultivated millets is essential to realize their uses and importance in agriculture in harsh agro-ecological regions (Table 1.1). Though the acreage of millets is less, these are a vital source of energy and staple food for sizeable populations dwelling in the dry regions of Asia and Africa. Out of total millet production in the world, about 50% of sorghum and 80% of millet are used as human food (Venkatesh Bhat et al. 2018). Grains of millets are common ingredients of animal feed and these are grown as green forage. The stover, or straw, of millets is used in animal feed, brewing, manufacturing of alcohol and for other industrial purposes. However, the use of millets varies in different countries; for example, in West African countries, a fermented thick porridge is made from pearl millet and sorghum. Finger millet and pearl millet are used for production of beer in Eastern Africa. However, these are also ingredients in Eastern European fermented drinks. Also breads are a very common food item prepared from millet in different countries like China, India, Mexico, Scotland, the United States and Ethiopia. In China, use of foxtail millet as an ingredient in soup is often observed. In cold regions of Japan, Japanese barnyard millet is used as a food. Flour from different millets is blended and used in the preparation of various value-added products such as pudding, breads, biscuits, sweets, cakes, chips,

Table 1.1 Nomenclature of millets.

S. No.	Common name	Scientific name
Major millets under cultivation		
1	Sorghum/Giant millet	*Sorghum bicolor* L.
2	Pearl millet	*Pennisetum glaucum* L.
Small millets under cultivation		
3	Finger millet	*Eleusine coracana* L. Gaertn.
4	Barnyard millet	*Echinochloa frumentacea* L.
5	Proso millet	*Panicum miliaceum* L.
6	Foxtail millet	*Setaria italic* L.
7	Kodo millet	*Paspalum scrobiculatum* L.
8	Little millet	*Panicum sumatrense* L.
Lesser known millets		
9	Brown top millet	*Brachiaria ramosa* L.
10	Crap grass	*Digitaria cruciata*
11	Tef	*Eragrotis tef*
12	White fonio	*Digitaria exilis*
13	Black fonio	*Digitaria iburua*
Extinct millet		
14	Job's tear millet	*Coix lacryma* (L.)
Pseudo millet		
15	Purple amaranththus	*Amaranthus cruentus*
16	Buckwheat	*Fagopyrum esculentum*; *F. tataricum*

Source: GOI 2020

rolls and noodles. Moreover, due to their gluten-free nature and non-allergenic properties, these millet products have gained a rapid momentum, especially in the developing countries. Millets are mainly grown in the rainy season (June–July sown), but during recent times improved varieties and hybrids have been developed which can be cultivated in winter (October–November sown) and even in summer (February sown) under irrigated conditions. These hardy crops require less water and can more easily combat extreme weather conditions, including higher temperatures. As C_4 plants, millets can utilize more CO_2 and thus assure environmental benefits (Brahmachari et at. 2018). The agriculture in India faces many constraints, like the threat and variation of the monsoon season, but millets are ecologically sound crops which can withstand different weather aberrations with greater storability (Maitra 2020). However, millets have not received much attention from researchers and policy-makers compared to other major cereals like rice, wheat, maize and barley.

1.3 Description of Important Millets

Millets exhibit diversity in grain size, structure and threshing characteristics. The edible grains of sorghum, pearl millet and teff are the naked kernels, but in finger, foxtail and proso millet, the loose husk is removed easily to reveal the edible portion. Millets are diversified crops with heterogeneous botanical characteristics. Taxonomic description of some important millets is included in Section 1.3.1 below.

1.3.1 Sorghum

Sorghum (*Sorghum bicolor* L. Moench) is a member of the subfamily *Andropogoneae*, originated in Africa, diploid in nature with 10 chromosomes (2n = 20), comprised of several subspecies and the cultivated one is *bicolor* (Oblana 2004). Sorghum is cultivated widely throughout the world, mainly for four different purposes, namely, grain crop, forage, sweet sorghum and bioenergy crop (Mullet et al. 2014). Basically, sorghum is self-pollinating with the possibility of cross-pollination to some extent (Rooney and Wayne-Smith 2000; Taylor 2019). The plant height varies from 0.5–4.0 m and has a fibrous root system and a solid stem with nodes and internodes. The leaves have parallel veins with a midrib and are 30–135 cm long. The inflorescence is known as the panicle or head, 7.5–50 cm in length and 4–20 cm in width. The grains are rounded, pointed at the base with a slight depression near the end, and color is white, pink, yellow or brownish yellow. The crop is hardy in nature, tolerant to drought, mainly cultivated as a rainfed crop during the monsoon season, requiring 25–30 cm water. Presently, a hybrid sorghum is widely cultivated and is of complex genetic origin with a high production potential. Sorghum is cultivated over an area of 42.14 million ha with a total production of 59.34 million tonnes. The United States ranks top as a sorghum producing country.

1.3.2 Pearl Millet

Pearl millet (*Pennisetum glaucum*) belongs to the family *Panicoideae* and earlier was called *Pennisetum typhoides*. Pearl millet originated in Africa and is a diploid plant (2n = 14), a self-pollinating crop, but outcrosses may occur and cause heterozygosity (Poncet et al. 2000). There are two types of pearl millet, forage and grain types (Blümmel et al. 2003). Pearl millet is a tillering annual plant with a height of 1–3 m and above, having a fibrous root system, solid stem with nodes and internodes, and long and fairly broad leaves held erect by thick midribs. The inflorescence comprises of an almost cylindrical spike packed with spikelets containing 800 to 3000 grains in each spike. The seed is caryopsis, oval in shape, with one of its ends tapering, 3–4 mm long and 2.0–2.5 mm wide. The crop is mainly grown under rainfed conditions and requires 25–30 cm water to produce a satisfactory yield. The cultivated area under pearl millet is about 31 million ha, including Africa and Asia. India is the largest producer of pearl millet (8.3 million tonnes from 9.3 million ha).

1.3.3 Finger Millet

Finger millet (*Eleusine coracana* L. Gaertn) originated in the East African highlands and entered into India during the Bronze Age (Fuller et al. 2011). The genus *Eleusine* has about 10 species including annuals and perennials. The widely cultivated finger millet is self-pollinated and tetraploid (2n = 36), an annual cereal of the *Poaceae* family, mostly grown as food in dry areas of different African countries and India. The plant is erect, growing to a height of 60 to 130 cm, with a fibrous root system and profuse tillering habit and compressed stem. The leaves are linear with a distinct midrib, ligule with a fringe of hairs. The effective tillers hold earheads comprised of spikes, named as fingers (two to eight in number) in which spikelets are arranged. The seeds are small, whitish, pale yellow or reddish brown in color. Finger millet is an ecologically sound and drought tolerant crop. It has been reported that finger millet requires less water for its cultivation and thus can withstand water stress (Harika et al. 2019).

1.3.4 Foxtail Millet

Foxtail millet (*Setaria italica* L.) was domesticated in central China during ancient periods as food grain and forage (Miller et al. 2016). It is an annual grass of the *Poaceae* family, member of the subfamily *Panicoideae*, and a diploid plant (2n = 18) grown in dry regions. The stem is slender and erect, which can grow up to a height of 80 to 150 cm. The leaves are narrow, flat and about 30 to 45 cm long. The inflorescence is cylindrical with bristling panicles often arching toward the tip. Generally each spikelet contains 1 to 4 bristles looking like the tail of a fox. The seeds are small, convex and enclosed in glume, creamy white, orange red and even purple in color. Foxtail millet is mainly cultivated in dry regions as a rainfed crop, as it shows great tolerance to drought conditions.

1.3.5 Proso Millet

Proso millet (*Panicum miliaceum* L.) is an ancient cereal first domesticated in Northern China and presently cultivated mainly in India, China, Afghanistan, Turkey and Romania, in soils with marginal and poor fertility (Hunt et al. 2008). It is an annual grass crop of the *Poaceae* family, with 2n = 36, mainly self-pollinating, but cross pollination may also take place for about 10% or more. The plant is an erect herb with profuse tillers and a plant height of 45 to 100 cm. The roots are fibrous and shallow and the stems are slender. The leaves are linear and the inflorescence is branched with spikelets at the tip of branches. The glume and palea are firmly attached to the grain and grains are white, yellow, reddish or black in colour. The crop is grown in warm regions of the world, is highly drought resistant and can easily be grown in areas with scanty rainfall.

1.3.6 Barnyard Millet

Japan is considered as the centre of origin of barnyard millet (*Echinochloa frumentacea* L.) and evidence shows that it was domesticated in China around 10,000 years ago (Sood et al. 2015). Presently, the cultivation of barnyard millet is concentrated on the Indian subcontinent and China. Barnyard millet is an annual grass of the *Panicoideae* subfamily of the family

Poaceae (Clayton et al. 2006), hexaploid (2n = 54) (Yabuno 1962; 1966), and can be cultivated up to an altitude of 2000 m above msl and possesses tolerance to water shortage.

1.3.7 Little Millet

It is believed that the origin of little millet (*Panicum sumatrense* Roth.) is peninsular India and archaeological evidence favors an Indian origin (Venkatesh Bhat et al. 2018; De Wet et al. 1983; Fuller 2011; Maitra and Shankar 2019). At present, it is cultivated mainly on the Indian subcontinent, China, Malaysia and the Philippines. Little millet is a crop of the family *Poaceae*, subfamily *Panicoideae*, tribe *Paniceae* with 2n = 36. It has two subspecies, subsp. *sumatrense* (cultivated little millet) and subsp. *psilopodium* (wild progenitor). Little millet is cultivated in the tropics and subtropics, even at an altitude of 2000 m above msl. It is a short duration crop and can withstand both drought and water stagnation for some periods of time. Like other millets, it is an annual grass that grows straight. The leaves are linear with straight and folded blades, 30 cm to 1 m long. The panicles are awned and grains are round and smooth, and brown in colour.

1.3.8 Kodo Millet

Kodo millet (*Paspalum scrobiculatum* L.) is a tetraploid species (2n = 40) and was domesticated in India around 1000 BC, belonging to the subfamily *Panicoideae*, tribe *Paniceae* (Jarret et al. 1995). Kodo millet has three races, namely, *regularis, irregularis* and *variabilis*, of which the race *regularis* is the most common. The plant is an erect herb, growing up to a height of 45–90 cm or more. The leaves are narrow, stiff and thick with hairy ligules and possess purple pigmentation. The inflorescence is raceme and spikelets are one-flowered. The crop is self-pollinated and the caryopsis is enclosed by lemma and palea and brown in color. Kodo millet has the capability to tolerate stress and is widely cultivated in drylands.

1.3.9 Brown-Top Millet

Brown-top millet (*Brachiaria ramosa* L.) is a lesser known warm-season annual or perennial grass of the *Poaceae* family originating in India (Maitra 2020; Kingwell-Banham and Fuller 2014), and cultivated mainly in the southern states of India. Besides India, brown-top millet is also grown in Africa, western Asia, Arabia, Australia and China. The plants are erect with a prostrate culm 90 cm long, with minutely hairy nodes, leaf blades of 2 to 25 cm length and 4 to 14 mm width (Clatton et al. 2006), indeterminate and stalked white flowers with open and spreading inflorescence of 1–8 cm long, and with colored ellipsoid seeds. The crop matures at 60 to 75 days after sowing (Maitra 2020).

1.4 Millets: The Ancient Crops

Millets are among the oldest foods known to humans, but due to more preference being given to rice and wheat during the second half of the previous century, they lost the respect that they deserved, considering their utility, nutritional value,

compatibility in cropping systems and environmental benefits. The majority of the millets are renowned in the Old World in different countries of Asia and Africa (Weber and Fuller 2007; Jaison 2018). In China, during the Neolithic age, millets were domesticated and cultivated, as is evidenced from samples recovered from the Cishan site showing their existence at around 10,000 years ago (Lu et al. 2009). There are arguments on origin of millet in China and it is also believed that millets originated in tropical western Africa during ancient times (FAO 1995). Archaeo-botanical research from Neolithic south Indian sites indicate that brown-top millet originated in the Deccan region of south India (Maitra 2020; Kingwell-Banham and Fuller 2014). Sorghum is a native of Africa and domestication took place around 5000–8000 years ago. The Indian subcontinent is considered as the secondary center of origin of sorghum, as evidence shows cultivation at about 4500 years ago. The domestication of pearl millet was noted in north-central Sahelian Africa during 4500 BC. Finger millet is of African origin, but entered into Asia during the prehistoric period (Venkatesh Bhat et al. 2018). Other millets mostly originated in Asia and Africa (Table 1.2) and later spread and were adapted to other regions of the world. In the Neolithic age of China, proso and foxtail millets were considered as vital food crops. Foxtail millet also is an ancient cereal of Eurasia (Hunt et al. 2008; De Wet et al. 1982; Jiaju and Yuzhi 1994). The farming of foxtail millet is found mainly in China and neighboring countries as food grains, but also used as grain, bird seed, feed and forage in the United States and Australia (Sheahan 2014). The origin of proso millet is considered as Manchurian (House et al. 1995), but it has also been found in Western Asia and Europe during ancient periods (Hunt et al. 2008), presently known as an important crop of China, the central and southern states of India, Kazakhstan, Afghanistan, Turkey, Romania, the USA and Australia.

1.5 Current Scenario of Millets Production

Millets are the staple food of a large number of populations throughout the world, especially in arid and semi-arid tropicals regions, mostly located in Africa and Asia. India is the largest producer of millets in the world. India, Nigeria and China together account for 55% of global millet production. The global production of millets is about 31 million tonnes and India shares 37.5% (Table 1.3). African countries, namely, Nigeria, Mali, Burkina Faso and Sudan, are the world's leading consumers. Considerable vast acreage under millet is found in Burkina Faso, Chad, Mali, Nigeria and Sudan among the African countries (Table 1.4). About a decade back, the estimated demand for millet in 2025 was fixed at 30 million tonnes (NAAS 2013). But during recent times, millets are recognized as nutri-cereals and increasing demand is noted among the health-conscious urbanites in developing as well as developed countries. which focuses further on enhancement of production. As per the market dynamics, demand pushes production and considering the environmental issues, it may be stated that future agriculture of arid and semi-arid regions will thrive on boosting millet production.

Table 1.2 Regions of origin of different species of millets.

Scientific name	Common name	Origin
Brachiaria ramosa (L.) Stapf. (syn. *Urochloa ramosa* (L.) R.D. Webster)	Browntop millet	Deccan region, South India
Coix lacrhyma-jobi L.	Job's tears millet	Northeast India, Southeast Asia, Southern China
Digitaria exilis (Kippist) Stapf.	White fonio	West Africa
Digitaria iburua Stapf.	Black fonio, hungry rice	West Africa
Echinochloa colona (L.) Link ssp. *frumentacea* (Link) (= *E. frumentacea* Link).	Sawa millet	Peninsular India
Echinochloa crus-galli (L.) P. Beauv. (syn. E. *esculenta* (A. Braun)	Barnyard millet	Japan
Eleusine coracana (L.) Gaertn.	Finger millet	East African highlands
Eragrostis tef (Zucc.) Trotter	Tef	Ethiopian highlands
Panicum miliaceum L. ssp. *miliaceum*	Proso millet	China
Panicum sumatrense Roth. ex Roem. & Schult. Subsp. *sumatrense* (syn. P. miliare auct. pl.)	Little millet	Peninsular India
Paspalum scrobiculatum L.	Kodo millet	India
Pennisetum glaucum (L.) R. Br (= P. *americium* (L))	Pearl millet	West African Savannah
Setaria italica (L.) P. Beauv ssp. *italica*	Foxtail millet	China
S. verticillata (L.) P. Beauv	Bristley foxtail millet	South India
Sorghum bicolor (L.) Moench ssp. *bicolor*	Sorghum	African Savannahs

Source: Weber and Fuller 2007; Venkatesh Bhat et al. 2018

Table 1.3 Millet production statistics.

Sl. No.	Region/Country	Area (ha)	Yield (kg ha^{-1})	Productions (tonnes)
1	Africa	22,099,632	7180	15,867,785
2	Asia	10,971,060	13,108	14,381,318
3	India	9,107,000	12,781	11,640,000
4	World	33,560,087	9243	31,019,370

Source: FAOSTAT 2020

1.6 Nutritional Importance of Millets

Millet contains all essential nutrients like carbohydrates, dietary fibres, proteins, fats, vitamins and minerals and is comparatively nutritious to fine cereals like wheat, barley, rice and maize (Table 1.5). Interestingly, all millets are superior to fine cereals in terms of

Table 1.4 Area, yield and production of millets (except Fonio) in leading millet growing countries (2018).

Sl. No.	Country	Area (ha)	Yield (kg ha^{-1})	Production (tonnes)
1	Angola	241,059	2154	51,915
2	Australia	35,161	10,216	35,922
3	Bangladesh	32,651	3894	12,713
4	Benin	28,856	9060	26,143
5	Burkina Faso	1,393,878	8531	1,189,079
6	Burandi	8837	11,281	9969
7	Cameroon	8837	11,281	9969
8	Central African Republic	9132	11,101	10,137
9	Chad	1,221,948	6192	756,616
10	China	617,407	25,370	1,566,363
11	Congo	16,109	8832	14,227
12	Cote d'ivoire	77,673	8261	64,169
13	Democratic People's Republic of Korea	73,584	10,666	78,486
14	Democratic Republic of the Congo	60,897	6701	40,807
15	Eritrea	69,544	3440	23,921
16	Ethiopia	515,613	19,064	982,958
17	France	10,948	37,250	40,914
18	Gambia	114,568	8632	98,894
19	Ghana	179,332	10,124	181,564
20	Guinea	167,404	12,828	214,747
21	Guinea-Bissau	12,577	11,758	14,788
22	India	9,107,000	21,781	11,640,000
23	Kazakhstan	43,420	9267	40,239
24	Kenya	115,806	7215	83,556
25	Malawi	54,230	5774	31,315
26	Mali	2,158,250	8527	1,840,321
27	Mauritania	11,906	2766	3239
28	Mozambique	37,665	4521	16,995
29	Myanmar	244,113	10,155	247,895
30	Namibia	244,113	10,155	247,895
31	Nepal	263,497	11,916	313,987
32	Niger	7,033,751	5483	3,856,344
33	Nigeria	2,795,829	8015	2,240,744
34	Pakistan	455,818	7679	350,010
35	Poland	13,721	15,989	21,938

(Continued)

Table 1.4 (Continued)

Sl. No.	Country	Area (ha)	Yield (kg ha^{-1})	Production (tonnes)
36	Russian Federation	187,144	11,606	217,200
37	Rwanda	11,370	4500	5116
38	Senegal	817,901	7018	574,000
39	Sierra Leone	41,769	10,687	44,639
40	South Africa	10,225	4916	5027
41	Sudan	3,753,000	7053	2,647,000
42	Uganda	147,625	14,224	209,979
43	United Republic of Tanzania	332,637	9845	327,467
44	United States of America	163,090	20,010	326,340
45	Yemen	97,596	5926	57,836
46	Zambia	41,463	7785	32,278
47	Zimbabwe	222,032	1733	38,473

Source: FAOSTAT, 2020

mineral content and other essential constituents. Furthermore, millets are considered as functional food and consumption of millets among health-conscious people has recently increased.

1.6.1 Millets as Functional Food

Millets provide an alternative source of food and nutrition, particularly in developing countries like India and Africa, where they are now used for human consumption but were primarily restricted to animal feed in developing countries. Millets are generally gluten-free, thus considered appropriate for people who suffer from gluten allergy and celiac disease. In general, millets are rich in dietary fiber, resistant starch, oligosaccharides, lipids, antioxidants, minerals and B-complex vitamins (Banerjee and Maitra 2020). However, the anti-nutritional factors like phytates and tannins in millets affect the mineral bioavailability (Rao et al. 2017). Millets are enriched with important phytochemicals such as polyphenols, lignans, phytosterols, phyto-oestrogens and phytocyanins, which have potential health promoting benefits. Millet can be considered as a functional food, as it acts as antioxidants, immune modulators, detoxifying agents, etc. and thus protects human beings from degenerative diseases like cardiovascular diseases, hyperglycaemia, tumors, respiratory health, Parkinson's diseases, etc. (Rao and Qaim 2011; Chandrasekara et al. 2012). Thus, millets meet the necessary criteria of nutraceuticals, which are defined as any food that contains bioactive ingredients and exerts beneficial effects on human physiology to combat chronic diseases, and so can be termed as functional foods or nutraceuticals (Banerjee and Ray 2019). The vitamins, minerals and essential fatty acids that are obtained from millets are non-acid forming, easy to digest and non-allergenic in nature (Saleh et al. 2013).

Table 1.5 Nutritional value of millets and fine cereals (per 100 g of edible portion).

Crop	Carbohydrate (g)	Crude fibre (g)	Protein (g)	Fat (g)	Mineral (g)
A. Fine cereals					
Barley	69.6	3.9	11.5	1.3	1.2
Maize	66.2	2.7	11.5	3.6	1.5
Rice	78.2	0.2	6.8	0.5	0.6
Wheat	71.2	1.2	11.8	1.5	1.5
B. Millets					
Barnyard millet	74.3	14.7	11.6	5.8	4.7
Brown-top millet	71.3	–	9.0	1.9	3.9
Finger millet	72.0	3.6	7.3	1.3	2.7
Foxtail millet	60.0	8.0	12.3	4.3	3.3
Kodo millet	65.9	9.0	8.3	1.4	2.6
Little millet	75.7	8.6	8.7	5.3	1.7
Pearl millet	67.5	1.2	11.6	5.0	2.3
Proso millet	70.4	2.2	12.5	1.1	1.9
Sorghum	72.6	1.6	10.4	1.9	1.6

Source: GOI 2020; Banerjee and Maitra 2020

1.6.2 Anti-Oxidant and Anti-Aging Properties

Several human diseases are linked to oxidative stress by the action of reactive oxygen and nitrogen species. Phytochemicals which act as antioxidants can protect from oxidative damage to maintain proper physiological function in humans. Plant extracts like polyphenols can reduce the risk of neurodegenerative diseases, cancer, aging, diabetes, infections, etc. (Kaur and Kapoor 2001; Scalbert et al. 2005, Tsao 2010). The seed coats of most millets contain various phenolic compounds which exhibit antioxidant properties (Hegde et al. 2005; Chandrasekara and Shahidi 2010). The antioxidants are found mainly in free or bound form in millets. Rao and Muralikrishna (2007) found protocatechuic acid as the key free phenolic acid in finger millets. Most of the total phenolic compounds in millets are derivatives of benzoic acid (gallic acid, protocatechuic acid, *p*-hydroxybenzoic acid, vanillic acid, syringic acid), while others are either flavonoids (quercetin, proanthocyanidins like condensed tannins) (Chethan and Malleshi 2007) or derivatives of cinnamic acid (ferulic acid, *trans*-cinnamic acid, *p*-coumaric acid, Caffeic acid, sinapic acid). In bound phenolic acids, ferulic and *p*-coumaric acid are the main components (Devi et al. 2014). An *in-vivo* study in rats showed that millets in a regular diet can enhance the activities of antioxidant enzymes such as catalase, glutathione peroxidase, glutathione reductase (Hegde et al. 2005) and block cross-linking of collagen (Hegde et al. 2002), resulting in decreased stiffness of elastic tissues in tendons, skin and blood vessels. The reduction of stiffness is one of the key mechanisms of anti-aging. The processing of millets reduces the bioavailability of polyphenols. Thermal or hydrothermal

treatments, germination, decortication or fermentation generally reduce the polyphenol levels (Rao and Muralikrishna 2007; Shobano and Malleshi 2007). There is an ample scope of research to increase the bioavailability of natural antioxidant in millet and to present it as a functional food ingredient.

1.6.3 Protection Against Cancer

Healthy diet and life style can prevent several health hazards, including cancer. There are several underlying causes of cancer, including genetic mutation, inheritance, etc. It has been reported that the bioactive constituents in millet like lignans possess the ability to prevent cancer. Furthermore, the frequency of spontaneous or induced tumors is diminished by consumption of anti-carcinogenic foods on a regular basis. Phytochemicals, especially antioxidants and polyphenols, are potential anti-carcinogenic agents which act as terminators of singlet oxygen species and free radicals (Banerjee and Maitra 2020). *In-vivo* experiments performed on rats using ferulic acid were found to be effective against induced carcinogenesis in tongue and colon (Kawabata et al. 2000) as well as in breast cancer cell lines (Choi and Park 2015), indicating that ferulic acid can be used as a chemotherapeutic agent against tongue, colon and breast cancer. Some millet contains nitriloside (Vitamin B_{17}), which specifically targets the cancer cell without having any detrimental side effects on human health. Previously, it has been reported that risk of esophageal cancer can be reduced by consumption of sorghum and millets. because the initiation and progression steps of cancer in tissues can be lowered by phenolic components (tannins and phytate) found in millets as reported by various authors (Chandrasekara and Shahidi 2011a; 2011b; Kumar et al. 2016). Singh et al. (2015) reported anti-carcinogenic properties of finger and pearl millet via a cyto-toxicity assay on HepG2 hepatic cancer cell lines. A good number of studies demonstrate that the dietary fibres can be used as functional food to combat breast cancer (Cade et al. 2007).

1.6.4 Anti-Diabetic Properties

Diabetes mellitus is a chronic metabolic disorder caused by a lack of sufficient insulin secretion (Type-1) or due to mutual endurance to insulin production and action (Type-2). Phenolic compounds found in the seed coats of millets (finger millet) were found effective in preventing diabetes due to their antioxidant properties and it has been revealed that the antioxidants help to lower the blood glucose levels (Shobana et al. 2009; American Diabetes Assocation 2010; Kim et al. 2006). The anti-nutrients such as tannins, phenolic and phytates found in millets decrease the glycemic response due to reduced starch digestibility and absorption.

1.6.5 Protection Against Gastro-Intestinal Disorders

Millets are a rich source of soluble and insoluble dietary fiber, or roughage, that are not degraded during digestion, but rather used as food by probiotic bacteria which in turn prevents gastro-intestinal disorders (Anderson et al. 2009). The high percentage of insoluble fibers found in millets results in stimulation of bowel mobility, prevents

constipation and promotes peristalsis movement. The soluble fibers help lubrication of an inflamed alimentary tract. Moreover, the polyphenols are known to decrease peptic inflammation and exhibit anti-ulcerative properties (Chethan and Malleshi 2007). Another important fact about millets is that they contain low amounts of fat which is beneficial against obesity.

1.6.7 Protection Against Osteoporosis

Osteoporosis is caused by calcium deficiency and the costly mineral supplements available on the market for treatment possess considerable side effects (Straub 2007). Dietary intake of high amounts of naturally occurring calcium prevents osteoporosis. Millets are a rich source of calcium, containing five to ten times higher calcium content than compared to other cereal crops (Sanwalka et al. 2011; Kumar et al. 2013). It has been reported that millets have more calcium content when compared to cow's milk (Wijesinha-Bettoni and Burlingame 2013). Cow's milk is unsuitable for people who suffer from lactose intolerance and so millets prove to be a safe substitute. The value-added products developed from millet are part of an essential diet for children and older individuals for the development of their bones.

1.7 Changes in Food Consumption Pattern and Future Demand

Human civilization has witnessed massive advancements during the last century due to technological development, urbanization and improved production systems. However, there is a limitation in the supply of nutritious foods to the world population, particularly those who have comparatively less access to a healthy diet. The problem is more crucial in the developing countries of Africa and Asia, where majority of malnourished people reside (FAO 2017). The estimates show that the world population will be 9.7 billion by 2050 and 11.2 billion by 2100 and agriculture will face a tremendous challenge in the future with declining and shrinking natural resources. Interestingly, urbanization is flourishing on a rapid scale and at present 54% of the global population is urban dwelling. In 2050, about two-thirds of populations will be urbanites (UN 2015) and the rate of urbanization is more in the developing world. Earlier, in the developing countries, the majority of the population lived in rural areas and were mostly dependent, either directly or indirectly, on agricultural activities. But over the years, agriculture became less profitable due to climatic uncertainties, volatility of the market and improper progress in rural infrastructure in the agriculture-based countries. On the other hand, some technological development on the agriculture front, particularly with the use of more efficient farm machinery, reduced the use of the human workforce in agriculture, which also triggered urbanization that in turn lead to the changes in the food consumption patterns. The population of the higher income group prefers processed, value-added and animal-sourced foods, which require more energy and other inputs. Undoubtedly, the flourish in consumption of these energy diets changed the food production system where processing, value-addition, marketing and logistics started to provide employment for more

people, with a subsequent decrease in the population being involved in farming activities (FAO 2017). In urban and peri-urban areas, supermarkets and value chains have increasingly shown a vertical growth during the last decade. But there is still the presence of a diversified distribution system in developing countries (The Nielsen Company 2015), with some ecological and ethical presence. Both forms of market dynamics notably realize the importance of millets. For rural populations of drylands in developing countries, consumption of millets is of local significance of their heritage, and for urbanites these are healthy and nutritious foods. Smallholders are also gaining benefits as producers of the nutritious foods and so they become part of the value chain (Rao and Qaim 2011).

Therefore, the demand for food is driven not only by population growth, but also by income growth (Valina et al. 2014). To meet future demand, farm productivity should be increased with sustainable intensification (Garnett et al. 2013), because earlier agricultural output was increased by increasing chemical inputs and non-judicious use of water at a cost to the environment. By 2050, agricultural productivity will need to be increased by about 50% of the present time (World Bank Group 2016); another estimate suggests global crop production could increase by 45 to 70% (Mueller et al. 2012). Furthermore, considering the food waste and adverse impacts of climate change with its associated uncertainties, there will be a need to produce more food to meet the food and nutritional security of the people (FAO 2018). The world cereal equivalent food demand is projected to be around 14,886 million tons by 2050 (Islam and Karim 2019), in which India and China will acquire the major share. In the present context of climate change and dwindling natural resources, it may be stated that growing populations, trending globalization and blooming urbanization have made sustainable agriculture and food, as well as nutritional security, an extraordinary challenge. The sustainable targets are to be considered at international and national level to reach the sustainable developmental goal, considering the socio-economic and ecological landscapes (Davis et al. 2016; Calicioglu et al. 2019).

1.8 Food and Nutritional Security

Worldwide, different nations and leading international organization have adopted initiatives to eliminate hunger, but still it persists in the developing world (Fraser and Rimas 2010). Besides, due to the increasing population, urbanization, mal-agricultural practices, shrinking of agriculture land and over-exploitation of resources, it is of prime importance to adopt a proper action plan for the sustainable future (Garnett 2014; Gladek et al. 2016). The issues related to climate change have an added hindrance in reaching the goal of food security. During the last five decades, the concept of food security was limited to availability and accessibility of food to all; but nowadays, food security denotes sufficient access to nutritious food to lead to a healthy life (Committee on World Food Security 2012). The recent data indicates that there were 815 million people of Africa and Asia who suffered from food insecurity (El Bilali et al. 2019), primarily due to natural calamity, worsened by climate change. Adoption of sustainable agricultural practices can only assure sustainable food system and nutritional security (El Balali 2018; Maitra and Ray 2019). The current food production system comprises of a number of limitations

like deterioration of land and water resources, increased emission of greenhouse gasses, environmental degradation and erosion of genetic diversity, resulting in food insecurity (FAO 2017). Food security as well as changeover from the present system to sustainable food system is the main topic of consideration in the field of food production. Creation of attractive opportunities for enhancing farm output, reduction of food insecurity and transformation of present-day agriculture in developing countries to sustainable food production, need to be considered in a holistic manner, targeting economic prosperity of the smallholder farmers. The majority of the smallholders in dry areas of the world produce millets by subsistence farming. Cultivation, processing and value addition and consumption of millets can accomplish the food and nutritional security to the malnourished populations dwelling in the developing world.

1.9 Climate Change and Associated Threat to Agriculture

The term "climate" denotes the long-term characteristics of weather conditions of a geographical area. The concerns relating to the Earth's climate of today are not of natural origin, but rather manmade and may be defined as the change that can be accredited directly or indirectly to human interference that modifies the atmospheric composition other than natural variation over a comparable time (UNFCCC 2017). In the Earth Summit (1992), held in Rio de Janeiro, agriculture was revealed through a reference of food security and the impact of climate change on agriculture was realized for the first time (Muldowney et al. 2013; Loboguerrero et al. 2019). Over the years, it became clear that agriculture and the food value chain is one of the major contributors to different greenhouse gases (GHGs), with an estimated emission of 5.1 to 6.1 Gt CO_2-eq year^{-1} (Smith et al. 2007). Climate change is already in progress and global warming and irregular rainfall patterns have already shown negative impact on farm output, with fewer yields of maize decreasing by 3.8% and wheat by 5.5% (Lobell et al. 2011; IPCC 2013). Due to climate change the concentration of ozone (O_3) increases and negatively influences crop growth. At the global scale, 2.5 billion smallholders have been severely affected by the ill effects of climate change (Niles et al. 2017). In developing countries, about two-thirds of the population is directly or indirectly dependent on agriculture and will be adversely affected by the negative impacts of climate change (Yadav et al. 2019). Increasing temperature may cause harm to several crops if it reaches beyond the threshold level (Yadav et al. 2019). There will be a 550 ppm concentration of CO_2 in the atmosphere by 2050, which will reduce yields of C_3 plants like rice, wheat and barley. On the other hand, maize and millets (C_4 plants) can produce more photosynthates under elevated CO_2 conditions. However, protein concentrations will be reduced in some cereals and forages with more CO_2 concentration in the atmosphere (IPCC 2001). Increase in O_3 concentration also adversely affects crop yield (Avnery et al. 2011). Furthermore, water scarcity will reduce crop yield unless more drought tolerant crops or varieties are grown (Maitra and Pine 2020). Considering the future demand for food security, climate smart agriculture should be adopted with sustainable farm productivity, building resilience to climate change and reduction of GHGs emission (FAO 2019). The negative impact of climate change in terms of food insecurity will be more prominent in the ecologically

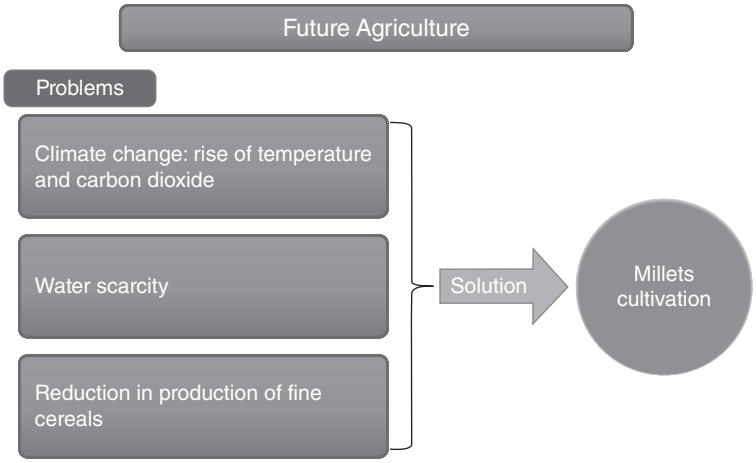

Figure 1.2 Problems of future agriculture and millets cultivation as a probable solution.

vulnerable areas, where incidence of hunger and malnutrition is common and cultivation of ecologically sound and nutritious crops may be a suitable alternative (Figure 1.2).

1.10 Millets: As Climate Smart Crops

Future agriculture will face some common environmental changes like enhanced temperature, uncertainties in rainfall, elevated CO_2 and GHGs levels, and more frequency in natural calamities (mainly drought and flood). Under these conditions, climate resilient agriculture should be adopted in which cultivation of climate smart crops will play a pivotal role. There is no doubt that millets are the climate smart crops which can simultaneously mitigate the ill effects of climate change and adapt to the changed and wider agro-climatic conditions (Bandyopadhyay et al. 2017). Millets have some efficient morphological, physiological, molecular and biochemical traits which can withstand abiotic stresses. As millets are short-duration crops, thus completing a cycle within a short time span, they can escape the possibility of environmental stress conditions under early or late sowing conditions. Besides, millets possess less leaf area (except pearl millet and sorghum), a thickened cell wall and a dense fibrous root system which facilitates their capability to tolerate abiotic stress (Li and Brutnell 2011). Being C_4 plants, millets can utilize more atmospheric CO_2 and by the process of photosynthesis can produce more assimilates, even under elevated CO_2 levels into the atmosphere (Aubry et al., 2001)). The nitrogen use efficiency of C_4 plants are higher compared to C_3 plants (like rice and wheat). The C_4 pathway of photosynthesis allows millets to perform better under hot weather conditions, including enhanced flexible allocation patterns of biomass and reduced hydraulic conductivity per unit leaf area (Sage and Zhu 2011). Furthermore, water use efficiency (WUE) of millets are higher than major cereals and in the future, under the crucial situation of water deficit in a major portion of the world, millets will automatically be chosen to combat water shortage. For

example, foxtail millet needs only 257 g of water to produce 1 g of dry biomass and the water requirement is half that of maize (470 g) and wheat (510 g) to produce the same quantity of dry biomass (Bandhyophyay et al. 2017). Wheat and rice have a global warming potential of around 4 tons CO_2 eq/ha and 3.4 tons CO_2 eq/ha, respectively. Wheat, rice and maize also have high carbon equivalent emissions of 1000, 956 and 935 kg C/ha for wheat, rice and maize, respectively (Jain et al. 2016). The carbon footprint of millets is comparatively less than major cereals and therefore cultivation of millets can reduce the carbon footprint (Saxena et al. 2018). Furthermore, in the process of chemical nitrogen fertilizer production, CO_2 is generated and as per an estimate to fulfill the present requirement of chemical nitrogen fertilizers in the world, annually 300 teragram (Tg = 10^{12}g) of CO_2 is released into the atmosphere (Jensen et al. 2012). Millets are less nutrient demanding crops and promotion of millet cultivation will indirectly save the environment. Erosion of genetic diversity is another important issue which is the result of industrialized agriculture, and agricultural sustainability can only be achieved by assuring greater ecosystem services in which genetic diversity plays a crucial role. In this way, the rich diversity of millets will lead future farming toward sustainability.

1.11 Future Agriculture: Smart Technologies in Millet Farming

With the advancement of science and technology, agriculture has also become smart and precise. Precision agriculture (PA) is a new concept where crop management has been made easier with the latest technologies and, in future, smart technologies will enhance input use efficiency in agriculture and more production to feed the growing population. PA is actually information and technology-enabled farming practices to identify, analyze and manage the variability within the field and it aims to register optimum productivity and profitability, protection of natural resources and sustainability (Saiz-Rubio and Rovira Más 2020). In PA, new information technologies (ITs) are used to make better decisions for managing the variability in several aspects of crop production and management. Use of remote sensing, Internet of Things (IoT), different sensors, artificial intelligence, machine learning, different apps and drones for crop management will make farming more precise for a target yield output. In the smart farms of the future, there will be sensing technology, hardware and software applications with IoT-based management, data analytics and smart crop management. Presently, millet cultivation is practiced by the small and marginal farmers in dry regions of the world and in these areas investment in agriculture is less. Millets are undernourished crops managed by smallholders in developing countries. But the situation will be changed over time with proper realization of the importance of millets in food and nutritional security under changed climatic conditions. There is an urgent need of research initiatives like other major cereals in the areas of site-specific crop management with the help of PA technologies to face and fulfill the future food demand. In the advent of technological flourish it may be expected that over a period of a few decades, the orthodox millet farming may be shifted into the concept of Agriculture 5.0 that implies unmanned operations and decision support

systems in which robots, drones and other forms of artificial intelligence will be used (Saiz-Rubio and Rovira Más 2020; Zambon et al. 2019).

1.12 Conclusions

At present, agriculture is facing great challenges due to the adverse effects of climate change, which have further resulted in slow progress in production enhancement with narrowed profit. The ongoing inefficient agricultural practices as well as over reliance on major cereals, urbanization and consumption of value-added processed foods and industrialization are the main causes of the increased carbon footprint triggering global warming. On the other hand, millets have the qualities to combat the ill effects of climate change and can be adapted to extreme weather conditions. Furthermore, millets are nutritionally superior and can be treated as a functional food. Considering these advantages, ancient millets can now be nutured as future food. In the near future, taking advantage of latest technological developments, millet cultivation can be intensified with smart technologies with proper transformation into Agriculture 5.0. Millets, the ancient and forgotten food, may regain its pride as an important staple of future food.

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