Small Millets: The Next-Generation Smart Crops in the Modern Era of Climate Change

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Sagar Maitra, Shubhasisha Praharaj, Akbar Hossain, T. S. S. K. Patro, Biswajit Pramanick, Tanmoy Shankar, Ramesh Namdeo Pudake, Harun I. Gitari, Jnana Bharati Palai, Masina Sairam, Lalichetti Sagar, and Upasana Sahoo

Abstract

Millets are coarse cereals belonging to the family Poaceae, which is cultivated since the ancient period of civilization. Among different millets, small or minor millets are treated as neglected crops due to their low-yield potential compared to major millets (sorghum and pearl millet) and fine cereals (rice, wheat and maize). In spite of their versatile qualities, small millets remained underutilized due to institutional promotion in favour of fine cereals. Recently, these coarse cereals are re-evaluated as 'nutri-cereals' considering their composition and nutritional value. In the present consequences of adverse impacts of climate change, the small millets also attracted the attention of growers and policy-makers as they are less demanding to external inputs, drought-tolerant and register a comparatively lower carbon footprint than other cereals. These beneficial impacts ensured the

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S. Maitra (✉) · S. Praharaj · T. Shankar · J. B. Palai · M. Sairam · L. Sagar · U. Sahoo
Department of Agronomy and Agroforestry, Centurion University of Technology and Management, Paralakhemundi, Odisha, India
e-mail: sagar.maitra@cutm.ac.in

A. Hossain
Bangladesh Wheat and Maize Research Institute, Dinajpur, Bangladesh

T. S. S. K. Patro
Agricultural Research Station, Acharya N. G. Ranga Agricultural University, Vizianagaram, India

B. Pramanick
Department of Agronomy, Dr. Rajendra Prasad Central Agricultural University, Pusa, Samastipur, India

R. N. Pudake
Amity Institute of Nanotechnology, Amity University Uttar Pradesh, Noida, India

H. I. Gitari
School of Agriculture and Enterprise Development, Kenyatta University, Nairobi, Kenya

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comeback of small millets after the institutional neglect for a few decades in the developing countries. Considering the food and nutritional security of the common people, small millets can be considered as suitable staples. The emerging health consciousness and food demand for the future pushed small millets to the forefront because of their ecological soundness and mitigating ability to climate change. However, the successful harvest of small millets warrants an integration of proven and climate-smart technologies for the fulfilment of the future needs of the ever-growing population. The chapter focused on all these aspects. Moreover, the research scope mentioned in the chapter implies future directions for enhancing small millet-based agriculture viable in diversifying food baskets and achieving food and nutritional security in a hunger-free society.

Keywords

Small millets · Climate-smart agriculture · Food security · Nutritional security · Cultivation technologies

1.1 Introduction

The agricultural production system has evolved over time and many significant changes have happened in the field of agriculture. The growing population and low resource base necessitate resource efficient yet high-yielding agricultural production system (FAO 2017; Struik and Kuyper 2017). Though productivity has been given utmost focus in the past, nutritional security holds equal importance (Swaminathan and Bhavani 2013; Garcia et al. 2020; FAO, IFAD, UNICEF, WFP and WHO 2021). Providing safe, sufficient and nutritious food have to be achieved sustainably without damaging the resource base (El Bilali et al. 2019; FAO and WHO 2019). With the advent of green revolution in India, the production of cereals like rice and wheat increased significantly (Maitra et al. 2018; Maitra 2020a, b). Moreover, assured market price for these cereals, government procurement system and institutional support, high productivity etc. prompted the farmers to focus largely on fine cereals-based cropping system. This has led to the further simplification of crop diversity and the genetic diversity has become even narrower.

Climate change is one of the major issues challenging present-day farming. Rising temperature, uncertainty in rainfall events, increasing carbon dioxide levels and frequent weather anomalies have made agriculture highly risk prone (Hossain et al. 2021; Bhadra et al. 2021). Since agriculture is the primary occupation of a large section of the population in India, the threat of climate change puts agriculture as well as the livelihood of millions in vulnerable conditions (Mbow et al. 2019). As agriculture in developing or low-income countries are subsistence type, with the food consumption pattern of farm families closely matching the food they grow, the food and nutritional security becomes a function of crop productivity and nutritional quality of their own farm produce (Brahmachari et al. 2018; FAO 2019; Pradhan et al. 2021). In this context, growing nutrient-rich crops as a part of crop production

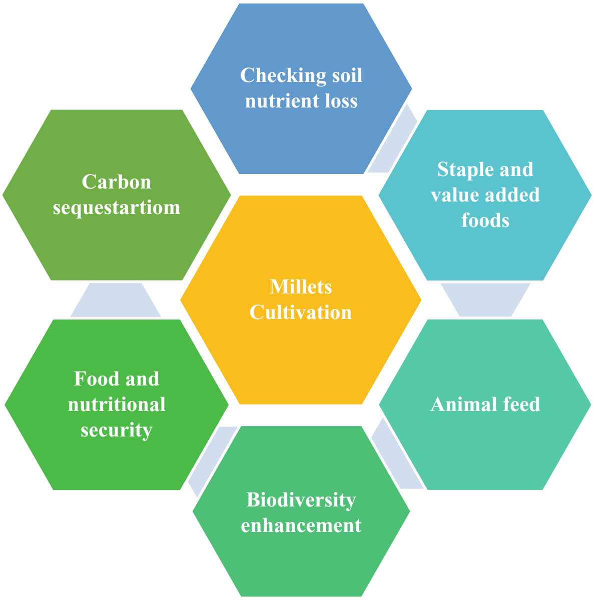

Fig. 1.1 Multiple benefits of millet cultivation

holds a greater significance in improving the health and well-being of farm families (Pradhan et al. 2019).

Millets, the term derived from 'mil' or 'a thousand' denotes the number of grains generated from a single seed (Maitra 2020a, b). They are small-grained coarse cereals and consumed for a long time. Due to the multiple health benefits millets provide and their resilience to unfavourable climatic conditions, they are considered as 'miracle crops' (Banerjee and Maitra 2020). Millets produce nutrient-dense and gluten-free grains with high dietary fibre, while, the stover can be used as nutrient-rich fodder (Maitra and Shankar 2019). These low water-consuming millets offer an excellent option to utilize water-scarce dryland region for its cultivation and also add organic matter to the soil, thus enhancing carbon sequestration. In addition to being low water requiring, the production of millets also emits very less amount of GHG (greenhouse gas), use very less chemical or industrial inputs and hence has a very low carbon footprint (Saxena et al. 2018). Millets can also reduce the erosion problem in sloppy lands. Incorporation of the stover into soil can also replenish the nutrients to a certain extent, add organic matter and improve the infiltration capacity of the soil, thus sustaining the soil health in long run (Fig. 1.1). Among a rich diversity of millets, sorghum (*Sorghum bicolor* L. Moench) and pearl millet (*Pennisetum glaucum* L.) are considered as major millets; while small or minor millets are foxtail or Italian millet (*Setaria italica* L.), finger millet or ragi (*Eleusine coracana* L. Gaertn), kodo millet (*Paspalum scrobiculatum* L.), barnyard millet (*Echinochloa frumentacea* L.), proso millet (*Panicum miliaceum* L.), little millet (*Panicum sumatrense* L.) and brown-top millet (*Brachiaria ramosa* L. Stapf; *Panicum ramosum* L.) (Table 1.1). In the global small millets production map, India

Table 1.1 Common small millets and their botanical name

Small millets	Botanical name
Finger millet	*Eleusine coracana* L. Gaertn.
Barnyard millet	*Echinochloa frumentacea* L.
Proso millet	*Panicum miliaceum* L.
Foxtail millet	*Setaria italica* L.
Kodo millet	*Paspalum scrobiculatum* L.
Little millet	*Panicum sumatrense* L.
Brown-top millet	*Brachiaria ramosa* L. Stapf; *Panicum ramosum* L.

ranks at the top covering an area of 7.0 lakh ha with about 80% of Asia's production (Rao et al. 2011). Due to the presence of different antioxidants, detoxifying agents and immune modulators in the grains, these small millets are known as nutri-cereals (Rao et al. 2011). The major small millets growing states in India are Karnataka, Tamilnadu, Uttarakhand, Maharashtra, Madhya Pradesh, Andhra Pradesh, Odisha and Bihar.

Even though minor millets are highly nutritious and possess high-stress tolerance ability as discussed above, their low productivity and lack of assured market price have made them relatively less popular among farmers. Developing agro-industries that can use millets, developing value-added and market-friendly nutritious products etc. can help in improving the market demand for the crop further and hence the farmers may get a relatively higher price for their produce. Improved agricultural technologies inclusive of smart agriculture or the concept of 'Agriculture 5.0' further create a potential for enhancement of small millet production and productivity (Zambon et al. 2019; Saiz-Rubio and Rovira-Más 2020).

Considering the above points, it can be assumed that millets can be an excellent option for climate-smart agriculture that can address the issues of food and nutritional security to a great extent. Moreover, it helps in diversifying the agroecosystem. Being less input-intensive, climate-resilient and nutritionally super-rich, it can be the answer to climate change, malnutrition and unsustainable resource use.

1.2 Salient Features of Small Millets

The salient features of the small millets have been briefly discussed below.

1.2.1 Finger Millet (*Eleusine coracana* L. Gaertn)

East African highlands is considered as the origin of finger millet. In India, it is also commonly known as *ragi*, *mandua*, *marua*, *nagli* and *kapai*. It is only during the bronze era that finger millet found its entry into India (Fuller et al. 2011). Ten different species (including annuals and perennials) come under the genus *Eleusine*.

Fig. 1.2 Finger millet standing crop (**a**) and (**b**) seeds

The most widely cultivated species of *Eleusine*, i.e. *E. coracana* is tetraploid ($2n = 4x = 36$) and self-pollinated in nature. Finger millet has an erect plant type with a height ranging from 60 to 130 cm. The crop has a shallow and fibrous root system. It has profuse tillering habit and the stem is compressed. The ear heads have spikes, in which the spikelets are arranged. The seeds of this crop are small (Fig. 1.2) and its colour varies from whitish, red-yellow to pale brown. Being a drought-tolerant crop, it can be grown in water-scarce environments and produce a sizable yield (Harika et al. 2019).

1.2.2 Foxtail Millet (*Setaria Italica* L.)

The historical evidence suggested that foxtail millet was domesticated in central China for harvesting grain and fodder yields (Miller et al. 2016). It is also known as Italian and German millet. The millet has several vernacular names in India such as *kakun*, *kangni*, *navane*, *thinai*, *kang* and *rala*. Foxtail millet is a member of the family *Poaceae* and *Panicoideae* subfamily, and is a diploid ($2n = 18$) plant. Like other small millets, it can also be grown in the dryland region. The stem length varies from 80 to 150 cm. The stem is slender and erect. Leaves are narrow, flat and length varies from 30 to 45 cm. The inflorescence is cylindrical. Each spikelet comprises a single or maximum of four bristles, looking like foxtail. The seed is small, convex and enclosed in a glume. Colour variation is observed in the seeds, but creamy white and orange red-coloured seeds are more common (Fig. 1.3). Some varieties also produce purple-coloured seeds. As foxtail millet is tolerant to drought, it can be cultivated in moisture scarce situations as a rainfed crop considering its ability to withstand soil moisture stress.

Fig. 1.3 Foxtail millet standing crop (**a**) and (**b**) seeds

Fig. 1.4 Proso millet standing crop (**a**) and (**b**) seeds

1.2.3 Proso Millet (*Panicum miliaceum* L.)

Proso millet is reported to be first domesticated in North China (Hunt et al. 2008). Recently, it is being grown in some Asian countries such as India, Afghanistan and China and European countries, namely Romania and Turkey. It has some other common names such as broomcorn millet, common millet and hog millet. In India, proso millet is commonly known as *cheena*, *panivaragu*, *variga* and *baragu* in different states. The crop is usually grown in low fertile soils with minimum use of external inputs. It belongs *Poaceae* family ($2n = 36$). Basically, proso millet is a self-pollinated crop, but cross-pollination may occur to an extent of 10% or a little higher. The plant is erect with profuse tillering. The plant is 45–100 cm tall with a fibrous root system. The stem is slender and the leaves are linear. The inflorescence is branched; spikelets are located at the tip of the inflorescence branch. Proso millet produce grains of different colours, namely, yellow, white, yellow, black and reddish (Fig. 1.4). Being a less water-requiring crop, it can be grown in warm regions of the world, where rainfall is low or scanty.

1.2.4 Barnyard Millet (*Echinochloa frumentacea* L.)

The origin of barnyard millet is considered as Japan and historical evidence indicated that the cultivation of barnyard millet was there in China around 10 thousand years ago (Sood et al. 2015). Currently, the area under barnyard millet is largely confined to the Indian subcontinent and China. In Indian vernacular languages, it has some other names such as *madira*, *sawa*, *sawan*, *kudraivali* and *oodalu*. Barnyard millet comes under *Panicoideae* subfamily (family *Poaceae*) and it is hexaploid (with $2n = 6x = 54$) (Clayton and Renvoize 2006). Barnyard millet has wider adaptability and can be grown in higher altitudes also (2000 m above MSL) (Gupta et al. 2009). The crop has the quality of drought tolerance (Maitra et al. 2020). The variation in colour and shape is observed in the panicles of barnyard millet (Kuraloviya et al. 2019) with raceme numbers of 22–64 in every inflorescence (Renganathan et al. 2020). Each spikelet has two florets. It is self-pollinated, however, there is the possibility of cross-pollination. The seed colour is whitish to grey and the seeds are soft (Fig. 1.5) (Maitra et al. 2020).

1.2.5 Little Millet (*Panicum sumatrense* Roth. ex Roem. and Schult)

The probable origin of little millet is India (Maitra and Shankar 2019). Archaeological evidence showed that it was grown in western India during 2000 BC (Venkatesh Bhat et al. 2018). Presently, the crop is cultivated in India, the Philippines, China and Malaysia. In India, it is also known as *kutki*, *sawai*, *samulu* and *same*. It belongs to the family *Poaceae* and is grown in tropical and subtropical climates. Being a drought-tolerant and short-duration crop, it has wider adaptability even at high altitudes. The leaves are 30–100 cm long. The crop has awned panicles and round-shaped brown grains (Fig. 1.6).

Fig. 1.5 Barnyard millet standing crop (**a**) and (**b**) seeds

Fig. 1.6 Little millet standing crop (**a**) and (**b**) seeds

Fig. 1.7 Kodo millet standing crop (**a**) and (**b**) seeds

1.2.6 Kodo Millet

The domestication of kodo millet (*Paspalum scrobiculatum* L.) began in India about 3000 years back. In the Indian language, kodo millet is also known as *varagu*, *haraka* and *arikalu*. Like other millets, it also comes under *Poaceae* family with the subfamily of *Panicoideae*, and it is a tetraploid crop ($2n = 4x = 40$) (Jarret et al. 1995). Kodo millet plants are erect, 45–90 cm tall with purple-coloured leaf pigmentation. It is self-pollinated with single-flowered spikelets. Brown-coloured grain is covered by lemma and palea (Fig. 1.7). Under severe drought conditions, it exhibits a high tolerance to abiotic stresses, namely, scanty soil moisture and heat; and thus, it is considered a suitable crop for drylands.

1.2.7 Brown-Top Millet

The probable region for the domestication of brown-top millet is the Deccan of India (Kingwell-Banham and Fuller 2014) and it has the heritage of an important cereal

Fig. 1.8 Brown-top millet standing crop (**a**) and (**b**) seeds

since 3000 BCE (Fuller et al. 2010). In the ancient period, in agro-pastoral practices, it was a common crop with legumes (Maitra 2020a). At present, it is grown in India, China, Arabia, Australia and a few African countries (Clayton and Renvoize 2006). Presently, in Karnataka–Andhra Pradesh adjacent dry areas this millet is cultivated as a food crop and it is commonly known as *karole* in the Deccan. The *Rayalseema* region of Andhra Pradesh (especially in *Ananthpur* district) and *Chitradurga*, *Gulbarga*, *Tumkuru*, *Dharwar* and *Chikkaballapura* districts of Karnataka are known for its cultivation. The Bundelkhand region of Central India is also recognized for growing this crop (Niyogi 2018) in marginal lands. Unlike other small millets, it is suitable for production in partially shaded areas, ensuring suitability to grow in fruit orchards under limited sunlight conditions. Moreover, in a little millet field, its presence is observed as a weed (Sakamoto 1985).

Brown-top millet is an annual and perennial coarse cereal that belongs to the *Poaceae* family (Fig. 1.8). The crop has an erect stem (culm) or prostrate type growing laterally on the ground. The plant height may be up to 90 cm (Maitra 2020b) and experimental results showed that the plant height of this crop was 68–74 cm in Chhattisgarh, India (Thakur et al. 2019). In another experiment, Saikishore et al. (2020) recorded the plant height of 134–153 cm. The crop has fibrous roots with a maximum of 60 cm depth. The nodes have minute hairs, but leaf blades do not contain hairs (Maitra 2020b). In general, the length and width of leaf blades are 2–25 cm and 4–14 mm, respectively (Clayton and Renvoize 2006). Brown-top millet bears indeterminate white flowers, which are stalked. The inflorescences are 3–15 with a length of 1–8 cm long, originating from a central axis, open and spreading. Panicles are looser and non-bristly. The seeds are ellipsoid and tan coloured. Grains of brown-top millet are ovate to round with a long embryo. The husk is fine-beaded and rough (Kingwell-Banham and Fuller 2014). The average duration of the crop is 75–90 days.

It is clear from the above paragraphs that all the small millets have abiotic stress tolerance ability to a large extent. This feature can be exploited to make it a suitable crop under climate-resilient agricultural practice.

1.3 Small Millets as Functional Foods

As discussed in the introduction, small millets are nutritionally rich and hence can alleviate the issue of malnutrition and nutrient deficiency to a great extent. Their nutritional superiority is not only due to the presence of a high amount of macro- and micronutrients, but also the presence of other compounds of nutraceutical significance that act as a protectant against different diseases. The nutritional values of small millets are presented in Table 1.2.

Millets are an excellent source of nutrition. As millets are generally gluten-free, hence it can be a food alternative for people with gluten allergies. Millets also contain some important phytochemicals like polyphenols, phytosterols and lignans, which have potential health benefits. Millets are also rich in dietary fibres and vitamin B complexes. The antioxidants and immune-modulator activities of millets act as a protective barrier against diseases like Parkinson's disease, cardiovascular disease and respiratory diseases (Rao et al. 2011; Chandrasekara et al. 2012). Several studies have reported on the beneficial role of low glycaemic index (GI—a measure of carbohydrate quality) foods and diets in the nutritional management of diabetes and several other chronic diseases. The rate of glucose absorption is usually decreased by low GI foods causing reduced insulin demand (Shobana et al. 2013). The small millets have low GI than rice and wheat and hence, can be considered a good dietary choice for diabetic people (Patil et al. 2015; Rao et al. 2017). The fibre richness of finger millet helps in the reduction of blood cholesterol and slow release of glucose to the bloodstream during digestion and prevents constipation (Rao et al. 2017).

Considering all the benefits millets can also be considered as nutraceuticals (Banerjee and Ray 2019). Millets are also easy to digest and non-allergenic. Phytochemicals such as polyphenols act as antioxidants and give protection against oxidative damage. Seed coats of most of the millets are found to have phenolics with antioxidant properties (Chandrasekara and Shahidi 2010).

Table 1.2 Nutritional value of small millets (per 100 g of edible portion)

Crop	Carbohydrate (g)	Crude fibre (g)	Protein (g)	Fat (g)	Mineral (g)
Finger millet	72.0	3.6	7.3	1.3	2.7
Barnyard millet	74.3	14.7	11.6	5.8	4.7
Proso millet	70.4	2.2	12.5	1.1	1.9
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
Brown-top millet	71.3	16.1	11.5	1.9	3.9

Sources: Baptist and Perera (1956); Kering and Broderick (2018); Maitra (2020a); Banerjee and Maitra (2020); Hemamalini et al. (2020), IIMR (2021)

1.4 Small Millets as Climate-Smart Crops

In the present context of climate change and associated aberrations, there is an urgent need for the consideration of climate-smart crop production technologies for uninterrupted and sustainable farm output. In this regard, climate-smart crops are to be chosen that can withstand various ill effects of climatic abnormalities and ensure satisfactory farm outputs. Small millets are of automatic choice as they are climate resilient because they can tolerate high temperature and soil moisture deficit to a large extent, which is very common in tropical and subtropical conditions in developing countries. Being less nutrient-demanding crops, they are grown under minimal management ensuring less carbon footprint in agriculture. The small millets possess a C_4 type of photosynthesis and sequester carbon, thereby adding CO_2 abatement opportunities under the elevated CO_2 levels in the future (Bacastow and Keeling 1973; Prentice et al. 2001; Balbinot et al. 2021). Further, small millets enrich the agro-biodiversity (which has been lost due to the adoption of industrialized agriculture-dominated monocropping) and are suitable for intercropping with other important crops inclusive of legumes (Maitra 2020a) millets-based intercropping.

In general, climate-smart agriculture has three basic objectives (Fig. 1.9) and these are as follows:

1. Productivity: Sustainably improving productivity and income.
2. Adaptation: Strengthening the resilience of food systems to climate changes and variability.

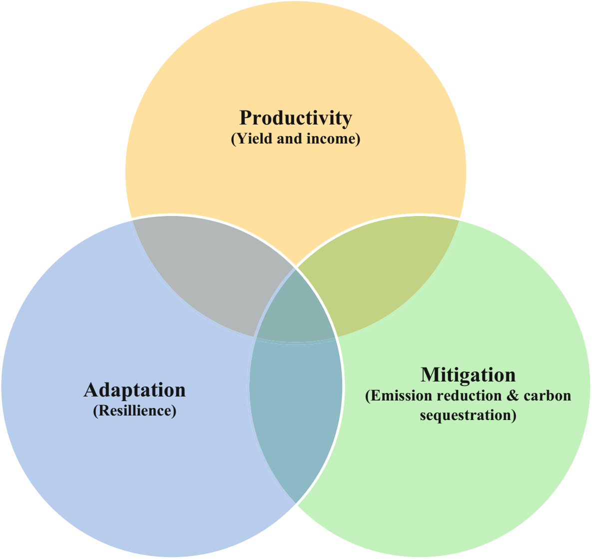

Fig. 1.9 Objectives of climate-smart agriculture

3. Mitigation: Reduce GHG emissions from agricultural activity and sequester carbon in the farmland.

1.4.1 Millets as a Driver of Climate-Smart Agriculture

As discussed in the previous section, climate-smart agriculture aims at attaining sustainable crop production and income generation in the face of changing climatic scenarios by adapting to the changing climate as well as mitigating climate change (FAO 2013; IPCC 2018). These factors are discussed here in detail.

1.4.1.1 Productivity of Small Millets

The small millets have low productivity which can be attributed to poor agronomic management. They are mostly grown in dryland regions where other crops cannot be grown successfully and with very low or minimum use of external inputs (Prasanna Kumar et al. 2019). Proper irrigation and nutrient management can help in improving millet productivity further in these regions. The stress resistance attribute of millets makes it a perfect choice for dryland regions. Considering climate change scenarios, where abiotic stresses such as drought and heat stress are expected to be more frequent, millets can provide production stability and food and nutritional security (Maitra et al. 2022). In addition to agronomic management, genetic interventions can also be extremely useful in improving small millet productivity. The small millet varieties can be bred for high productivity, especially under stressed environments.

1.4.1.2 Adapting to Changing Climate

Climate change is expected to negatively affect freshwater availability for agricultural activity (Singh et al. 2014; Zaman et al. 2017; Boretti and Rosa 2019). Dryland agriculture or rainfed agriculture is expected to be even more affected by the vagaries of climate change events (Ashalatha et al. 2012; Hossain et al. 2021; Tui et al. 2021). Recurring drought, uncertain rainfall events such as the late onset of monsoon, early withdrawal of monsoon and the prolonged dry period within the crop season are going to affect the rainfed agriculture more as compared to irrigated agriculture where there is assured irrigation to counteract the shortage of water at any stage (Turral 2008; Miyan 2015; Sanjeevaiah et al. 2021). However, it is not appropriate to say that the negative influences of climatic aberration will be confined to dryland regions (Hatfield et al. 2011). In fact, due to changing climate, the hydrological balance is supposed to be disturbed, which will also have a negative impact on the irrigation water availability in the irrigated region (Bhave et al. 2018; Zeng et al. 2021). Freshwater availability is expected to decrease further due to inter-sectoral competition and competition for other alternate uses (OECD 2009). Under such conditions, growing crops with inherently less water demand can provide a sustainable solution (Zeng et al. 2021). All millets inclusive of small millets have very less water demand as compared to cereals (Maitra et al. 1997; Ramya et al. 2020; Saxena et al. 2018). Hence, growing millets may result in higher productivity per unit amount of freshwater consumed and hence, they enhance water productivity (Mekonnen and Hoekstra 2014). The performance of millets under the water-scarce condition in the dryland region can also be due to their adaptation at the physiological level because of their C_4 photosynthetic mechanism (Wang et al. 2018; Hatfield and Dold 2019; Ghatak et al. 2021). Small millets, because of their C_4 mechanism, can fix sufficient carbon dioxide for photosynthesis even when the stomata are partially closed in response to moisture stress (Hao et al. 2017). This allows for better photosynthetic activity under moisture stress.

Change in soil fertility is another outcome of climate change. As the temperature is expected to rise due to climate change, there will be rapid oxidation of soil organic matter (Eric et al. 2013; Karmakar et al. 2016). Moreover, due to heavy and intense rainfall events, soil fertility may be lost because of leaching of nutrients and erosion of fertile topsoils. Millets can counteract this negative impact of climate change in two ways. First, being capable of growing well under less fertile conditions, millets can give some yield. Secondly, millets can protect against erosion and save fertile topsoil (Saxena et al. 2018). Small millets when grown in those soil can also add organic matter through degraded root biomass after crop harvest. Moreover, retaining millet residues on the soil surface can also enhance organic matter and nutrients in the soil. Further, it can improve water infiltration, thus enhancing in situ soil conservation. With the addition of organic matter, better soil moisture promotes better microbial activity, which further improves soil fertility through nutrient addition or solubilization. Further, intercropping small millets with legumes helps in the improvement of soil quality because of the combination of cereal legumes in polyculture (Maitra 2020a, b).

As small millets are better adapted to harsh climatic conditions, they provide better stability in production over years/seasons as compared to fine cereals. Also, millets are getting proper attention in the recent past due to their high nutritional quality and health benefits (Saleh et al. 2013; Kumar et al. 2020). This has led to a decent market price for these produces and their associated processed and value-added products. Considering the market demand, yield stability and low cost of cultivation, millets can be a safe bet for resource-poor farmers under resource-starved growing conditions. Production of value-added products can further improve the economic prospect of millet production. To a great extent, it can help in breaking the vicious circle of dearth. It is significant to record that, while calculating the economics, the benefits of good health and well-being are often ignored. As good health brought about by food and nutritional security improves the human resource potential further, it further improves wealth creation. Moreover, good health and well-being also reduce expenditure associated with health-related issues.

Considering the above positive facts associated with small millets, it is clear that they can be an excellent option for adapting to conditions under changing climates. In addition to food security and nutritional security as well as economic profitability, small millets also provide much-needed agroecosystem diversity. Diversity in agroecosystem provides resilience, improves productivity, minimizes risk and provides multiple sources of income as well as profit (Parmentier 2014; Altieri et al. 2015).

1.4.1.3 Mitigating Climate Change

The mitigation of climate change may be achieved by reducing GHG emissions and enhancing soil carbon sequestration (Amelung et al. 2020; Fawzy et al. 2020; Navarro-Pedreño et al. 2021). The rice production system is one of the major contributors to GHG emission when GHG emission from croplands is considered (Boateng et al. 2017; Vetter et al. 2017; Arenas-Calle et al. 2019). The anaerobic environment in the paddy ecosystem is favourable for the emission of GHG such as methane and nitrous oxide (Oertel et al. 2016; Wang et al. 2019). Additionally, frequent tillage also oxidizes the soil organic carbon and hence carbon dioxide emission from cropland increases (Haddaway et al. 2017; Krauss et al. 2017). Unlike cereals, small millets emit lesser GHGs. Also, millets have a comparatively lesser carbon footprint as compared to fine cereals (Kane-Potaka et al. 2021). Moreover, fine cereals use a huge amount of chemical fertilizer, which in its due course of industrial production produces a high amount of GHG (Maitra et al. 2022). An estimate mentions that for fulfilling the global chemical N fertilizers, annually 300 teragrams (Tg) of CO_2 is released into the atmosphere (Jensen et al. 2012). Unlike cereals, millets being less nutrient demanding have a lesser carbon footprint. Millets can also help in sequestering carbon through their shoot and root biomass production and addition to the soil post-harvest. The technological developments facilitated all aspects of farm sector to align towards the direction of smart or precision agriculture. The smart technologies have enough potential to maximize input use efficiency and the productivity of crops can be enhanced with an efficient management. There is enough scope for inclusion of the concept of Agriculture 5.0 with the advent of technological supports such as Internet of Things (IOT) in smart irrigation, robotics and drones and some forms of artificial intelligence and machine learning (AI and ML) in crop management targeting a higher productivity of climate-smart small millets (Zambon et al. 2019; Saiz-Rubio and Rovira-Más 2020; Maitra et al. 2022).

1.5 Climate-Smart Small Millets Production Practices

Climate-smart agronomic practices largely rely on good agriculture practices (GAP) that improves input use efficiency, reduce emission from the system, saves resource, avoid agroecosystem pollution and promotes ecosystem services. The targets are achieved through many practices such as integrated nutrient management (INM), integrated pest management (IPM) and conservation agriculture. In addition to these, available precision agriculture tools and decision management systems can further improve in making decisions regarding climate-smart crop production practices.

1.5.1 Integrated Nutrient Management (INM)

INM integrates all the available nutrient sources judiciously and compatibly to supply essential plant nutrients. It reduces the overdependence on chemical fertilizer and utilizes all the available low-cost local resources to meet the crop nutrient requirement. INM improves soil structure, improves soil fertility, improves soil biological activity, reduces cost of nutrient management, promotes ecosystem services and makes better utilization of inherent soil fertility (Kumara et al. 2007).

Considering the fact that, production of chemical fertilizer emits huge amount of greenhouse gas, INM, through substitution of chemical fertilizers, can help in the reduction of total carbon footprint of the production system. It can also help in soil carbon sequestration through the addition of organic matter. Unlike other crops, where nutrient demand is very high, the application of organic manure can practically replace a large portion of crop nutrient demand in millets. Research evidence suggests the beneficial effects of INM (Table 1.3).

Table 1.3 Beneficial effects of INM in small millets

Crop	Salient findings	References
Finger millet	Manures applied previously yielded more grains of finger millet than only chemical fertilizers	Pilbeam et al. (2002)
	Application of farmyard manure (FYM) enriched with P and recommended dose of N produced more grain yield than the recommended dose of fertilizer (RDF) in clay loamy soil	Jagathjothi et al. (2011)
	A combined application of FYM (10 t ha^{-1}) +100% NPK and maize residue incorporation (5 t ha^{-1}) + 100% NPK produced more grain yield in semi-arid tropical Alfisol	Sankar et al. (2011)
	FYM (10 t ha^{-1}) + bioinoculant consortia (60 g kg^{-1} seed each) + $ZnSO_4$ (12.5 kg ha^{-1}) + borax (kg ha^{-1}) + 100% RDF (50:30:25) yielded more grain and straw of kharif finger millet than recommended dose of nutrients	Roy et al. (2018)
Foxtail millet	50% RDF + 25% N as neem cake + biofertilizer (*Azophos*) recorded more growth and productivity than RDF	Monisha et al. (2019)
	Adoption of INM with FYM + RDF + 3% *Panchagavya* resulted in maximum grain yield	Kumaran and Parasuraman (2019)
	Application of 75% recommended dose of nitrogen (RDN) through chemicals +25% N through poultry manure + biofertilizer (*Azospirillum* seed inoculation) enhanced the grain yield	Selectstar Marwein et al. (2019)
Little millet	INM with FYM @ 7.5 t ha^{-1}, N 40:P 20:K10 kg ha^{-1}, calcium carbonate, zinc sulphate and borax resulted in more grain yield	Parihar et al. (2010)
	Combined application of 100% RDF + neem cake @ 1 t ha^{-1} resulted in maximum productivity	Sandhya Rani et al. (2017)
	Application of 75% RDN (chemical fertilizer) and 25% RDN (vermicompost) recorded higher growth and grain yield than RDF	Thesiya et al. (2019)
Kodo millet	A combination of 125% RDF + soil application of *Azospirillum* @ 2 kg ha^{-1} + vermicompost @ 2 t ha^{-1} + foliar spray of 1% nutrient supplement increased grain productivity	Prabudoss et al. (2014)

1.5.2 Soil Test Crop Response (STCR)-Based Nutrient Management

Soil test crop response (STCR)-based nutrient management supplies nutrients to the crop based on soil test value and response conditions for a target yield. STCR aims at balanced fertilization by considering the contribution of soil and applied nutrients. STCR approach to nutrient management improves yield and it is environment friendly as well as economical (Das et al. 2015). STCR also improves nutrient-use efficiency (Gangwar et al. 2016; Jemila et al. 2017). As per the STCR equation, for achieving a target yield of 4 t ha^{-1} in finger millet, a combination of fertilizers applied against the recommended dose and a nutrient combination of 200% nitrogen, 100% phosphorus, 100% potassium, 25% zinc, 25% sulphur and 25% boron integrated with 5 t ha^{-1} farmyard manure (FYM) produced satisfactory yield output in the soil with low available N, high P and medium K (Sandhya Rani et al. 2017).

1.5.3 Resource Conserving Technologies

Resource conservation technologies (RCTs) aim at saving resources and improving resource-use efficiency. Conservation agriculture (CA) is a RCT and it has three basic principles, i.e. maintaining crop residues on soil surface, zero tillage and diversified crop rotation. Conservation agriculture improves soil organic matter content, nutrient-use efficiency and soil moisture storage. It also reduces energy use in agriculture. Greenhouse gas (GHG) emission from CA has been found to be lesser as compared to conventional agriculture. As more organic matter is maintained in the field, the microbial activity and overall soil health are also improved. Residue retained on the soil surface improves opportune time for water infiltration and hence helps in situ moisture storage. Soil temperature is also optimized under conservation agriculture because of surface residue retention.

In contrast to conventional tillage where land is ploughed causing a global loss of soil organic carbon (SOC) as much as 60–90 Pg (Lal 1999), in CA, the stored organic matter is not rapidly oxidized as the soil is not disturbed frequently. This helps in long-term carbon storage in the soil. Further, CA improves soil physico-chemical and biological properties (Lal 2004). Finger millet yielded more under substitution of 50% of the recommended N with organic source in Alfisol of Karnataka, India, however, reduced tillage enhanced SOC as recorded by Prasad et al. (2016). Malviya et al. (2019) recommended conservation tillage and crop residue mulching to raise the sole crop of kodo millet in the Rewa region of Madhya Pradesh India. RCTs like conservation agriculture have a large scope in climate-smart agriculture as it reduces the emission of GHG, and improves the soil environment for better resilience to climate change-induced alterations.

In addition to conservation agriculture, other RCTs such as bed planting and laser land levelling may also be applied for improving yield and enhancing climate resilience.

1.5.4 Breeding of Suitable Varieties

Improved varieties of small millets must be bred for their better adaptation to climate change and other biotic and abiotic stresses. Breeding may take a longer time and involve a high initial cost. However, in long run, it can be a very cost-effective strategy for climate change adaptation. Many varieties tolerant against abiotic stresses and biotic stresses have been developed. Developing varieties with high yielding ability, better nutritional bioavailability, tolerance to multiple stresses (both biotic and abiotic), high nutrient efficiency, higher photosynthetic efficiency etc. can help to improve crop productivity and quality. Both conventional breeding and biotechnology approaches may be used for breeding small millets. In this regard, germplasms are the keys to crop improvement as they provide the desired variability. Worldwide, 133,849 cultivated germplasms of small millets are conserved in addition to 30,627 accessions, of which most of them are collected from Asia and Africa (Vetriventhan et al. 2020). There are several small millets germplasms containing promising traits such as nutritional quality and tolerance to biotic and abiotic stresses. The conventional breeding programmes through selection and hybridization have already developed different small millet varieties (Nandini et al. 2019). As a leading producer of small millets, India has developed about 248 varieties of six small millets, namely, finger millet (121), foxtail millet (32), proso millet (24), kodo millet (33), barnyard millet (18) and little millet (20) (AICSMIP 2014). The genome sequence and gene mapping are two advanced methods of crop improvement considered for crop improvement of small millets. The genomes of some small millets have been already sequenced with prior mapping of desired quality traits by following germplasm characterization and marker trait association inclusive of quantitative trait nucleotides (QTNs). Recently, biotechnological tools as well as omics approaches are also included in breeding of small millets. Initiatives have already been taken through transcriptome-based gene expression profiling, proteomics and metabolomics and *Agrobacterium*-mediated system for transformation of small millets for qualitative improvement of these climate-smart crops (Vetriventhan et al. 2020). However, inadequate number of germplasms and insufficient information on genetic diversity are major limitations for crop improvement. Biotechnological processes are involved in high value and major crops and there is a need for future intervention of omics approaches in the improvement of small millets.

1.5.5 Agronomic Practice Adjustment

Sowing time, plant spacing, nutrient application etc. may be manipulated to make the plant more suitable to face different stresses. For example, manipulation of sowing time can help to avoid terminal heat stress to some extent. Selecting a suitable crop can also be an approach to avoid or minimize the effect of stress. In finger millet yield loss due to terminal drought stress is maximum, however, considerable yield loss was noticed in proso millet (34.6%), little millet (80.1%)

and pearl millet (60.1%) (Bidinger et al. 1987; Goron and Raizada 2015; Tadele 2016). Priming of seeds can also be an effective strategy for adapting to moisture stress, especially during the early period of crop growth (Maitra et al. 1997). Further, cropping systems can play a great role in this regard. Intercropping systems with small millets must be considered in this regard (Maitra 2020b). Intercropping small millets with legumes are one of the suitable options for smallholders in the drylands. The multifaceted benefits of intercropping small millets with legumes have been evidenced by researchers in terms of a higher productivity, resource-use efficiency, natural insurance against crop failure under extreme climatic conditions, and food and nutritional security (Maitra et al. 2020).

1.5.6 System of Millet Intensification

Principles of the system of crop intensification (SCI) can also be applied to millet cultivation for improving productivity and resource-use efficiency. Research on the system of finger millet intensification showed that transplanting 10 days old seedlings with square planting of 25 cm yielded more than conventional planting (Bhatta et al. 2017). In some areas of Karnataka such as Dhadwad, Haveri, Kolar and Shimoga, farmers are familiar to raise finger millet with square planting by adopting a traditional method and it is colloquially known as '*guni*' which is nothing but a form of System of Finger Millet Intensification. In the *guni* method, 3-weeks-old seedlings are planted with two seedlings per hill. In between the third and sixth weeks of transplanting, the crop is planked by animal-drawn implement to enhance tillering and growth of adventitious roots. Researchers recorded that guni method yielded more grains of finger millet (Sukanya et al. 2021). The SCI practices may be standardized for more millets and can be an effective strategy for improving productivity.

1.6 Conclusion

Small millets are an excellent source of macro and micronutrients as well as dietary fibre. As millets are low resource consuming crops, it can be grown under resource-scarce conditions, where resources for most other crops seem sub-optimal. As the climate is changing and resource availability is under pressure, agriculture needs to be climate-resilient and resource-efficient for sustainable development. Under such conditions, small millets can be grown to counteract the negative impacts of climate change to a great extent due to their inherent capacity to survive under low moisture, low nutrient demand, C_4 photosynthetic pathway etc. Developing suitable agronomic practices for millets, developing varieties with better stress tolerance and high nutrient bioavailability, identifying suitable microbial strains for improving nutrient cycle or growth-promoting ability etc. need immediate research attention to further improve the productivity and quality of millets. More importantly, millets-centric policies for better storage facilities, good processing platforms and assured market price can further promote millet cultivation.

Further, the present chapter offers the following future scope of research which can also be considered. An integration of multidisciplinary approaches can truly offer possible scope and opportunity for small millets to exploit their real potential as climate-smart crops.

1. Agronomic practices suitable for resource-limited environments need to be standardized. As resource scarcity is one of the prime negative outcomes of climate change; agronomic practices to counteract such environment and resource-scarce conditions need to be standardized.
2. The response of different millets to elevated atmospheric carbon levels may be studied. Alteration in phenological, physiological and biochemical parameters can be monitored. Such knowledge can be utilized for predicting crop response to climate change and developing a more accurate crop model.
3. System of crop intensification knowledge can be applied to small millets and the practice needs to be standardized for different environments.
4. Nutraceutical benefits of millet need to be studied further.
5. Bioavailability of nutrients after processing and value addition needs to be evaluated. Care must be taken to improve the bioavailability of nutrients.
6. Awareness regarding nutraceutical and health benefits of millets and millet products need to be created. It will not only improve millet consumption but also create a good market for millets and its products.

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