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Handbook of Millets – Processing, Quality, and Nutrition Status

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Millets: An Overview

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C. K. Sunil, Ashish Rawson, and C. Anandharamakrishnan

Abstract

There has been an increased interest in millets and its products owing to its nutritional composition, health benefits and ease of cultivation. As a result, the UN declared the year 2023 as the 'International Year of Millets', which would further enhance the public awareness on the health benefits of millets. The present chapter introduces about different types of millets and the countries involved in the production of millets. Also presented here are the information about the composition of different types of millets, the challenges in commercial production and industrial processing of millets.

Keywords

Millet · Production · Composition · Processing

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1.1 Introduction

Millet is a cereal crop belonging to the family *Gramineae* or *Poaceae* and is grown worldwide as a fodder and human food. The term 'millet' is used loosely and refers to a variety of small seeded annual grasses, belonging to species under the five genera, namely, '*Panicum*, *Setaria*, *Echinochloa*, *Pennisetum*, and *Paspalum*' in the tribe 'Paniceae', and one genus '*Eleusine*' in the tribe 'Chlorideae'. The taxonomical classifications of different millets are shown in Table 1.1. Millets are classified as major (sorghum, pearl millet, maize) and minor (foxtail millet, finger millet, kodo millet, proso millet, barnyard millet, brown top millet) millets based on usage and size. They are largely grown in water-deficient 'dry zones' as rainfed crops, under less moisture conditions (drought resistant) as well as soil fertility. Their resistance to diseases and pests, shorter growing period, and higher productivity in drought conditions are other advantages of growing millets (Devi et al. 2011). In order to compare the water requirement, pearl millet and finger millet uses less than 25% of water required for sugarcane and banana production and less than 30% of water required for growing rice.

Asian and African regions offer semi-arid climate favourable for millet production; hence it is grown as staple food to serve as important food ingredient for development of numerous traditional foods and beverages.

Although there are numerous advantages of millet, its contribution to global production is <1% and <3% in the category of cereal and coarse cereals, respectively. Africa accounts for ~59% of total area of millet plantation and contributes for ~55% of total production, whereas Asia holds ~38% share in total plantation and yields ~42% of global production (FAOSTAT 2016). As per the Food and Agriculture organization corporate statistical database (FAOSTAT), the total world production for the year 2017 was 28.45 million tons. India is the major producer of millets with 11.5 million tons followed by Niger (3.79 million tons), China (1.99 million tons), Mali (1.8 million tons), Nigeria (1.5 million tons), and Burkina Faso (0.82 million tons) (Fig. 1.1). Table 1.2 gives the details on the millet general Indian name, common name, vernacular name, scientific name, and major producing countries.

Millets have high nutritive value and nutraceutical benefits which can help the consumer in preventing cardiovascular diseases and cancer, lowering blood pressure, and reducing tumour incidence and various other benefits (Saleh et al. 2013). These could be processed for consumption and preparation to augment their edible, nutritive value and sensory properties. Processing techniques for millets include decorticating, polishing, dehulling, malting, popping, fermentation, roasting, flaking, milling, and parboiling.

1.2 Structure of Millets

Like other cereal grains, millet has a similar structure with three principal components, namely, pericarp (outer covering), endosperm (starchy part), and germ (oily part) (Sharma and Kapoor 1996; Rooney and McDonough 1987; Sullins

Table 1.1 Taxonomical classification of millets from Kingdom 'Plantae' and group 'Monocots'

	Foxtail millet	Sorghum	Pearl millet	Finger millet	Proso millet	Kodo millet	Little millet	Barnyard millet
Order	Poales	Poales	Poales	Cyperales	Poales	Poales	Poales	Poales
Family	Poaceae	Poaceae	Poaceae	Poaceae	Poaceae	Poaceae	Poaceae	Poaceae
Subfamily	Panicoideae	Panicoideae	Panicoideae	Chloridoideae	Panicium	Panicoideae	Panicoideae	Panicoideae
Genus	*Setaria*	*Sorghum*	*Pennisetum*	*Eleusine* Gaertner	*P. miliaceum*	*Paspalum*	*Panicum*	*Echinochloa*
Species	*italica*	*bicolor*	*glaucum*	*coracana*	*Panicum miliaceum* L.	*P. scrobiculatum*	*P. sumatrense*	*E. esculenta*, (Japanese) *E. frumentacea* (Indian)
Botanical name	*Setaria italica* L.	*Sorghum bicolor* (L.) Moench	*Pennisetum glaucum* (L.)R.Br.	*Eleusine coracana* (L.) Gaertn.		*Paspalum scrobiculatum L.*	*Panicum sumatrense*	*Echinochloa esculenta,* (A. Braun) H. Scholz (Japanese) *Echinochloa frumentacea* (Indian)

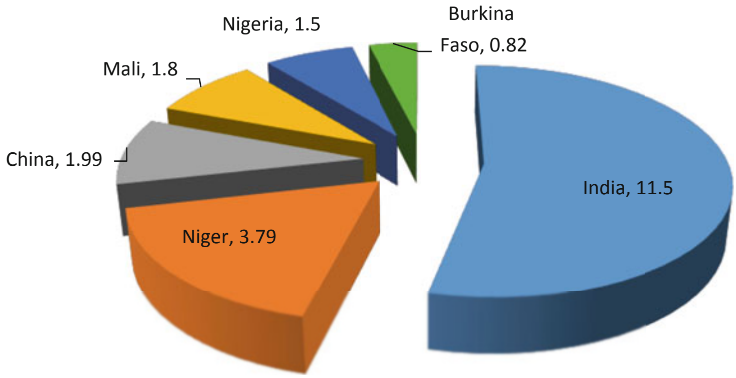

Fig. 1.1 Millet producing countries. (Source: FAOSTAT 2017)

et al. 1971). Figure 1.2 shows the general structure of millet. Botanically, millets are characterized into utricles and caryopses (McDonough (2000). The utricle type has an easily removable pericarp which covers the seed; foxtail, proso, and finger millet grains are and the most common ones in this type. Utricle pericarp provides a sack-like covering to the inner endosperm with a single point attachment and hence is easy to remove. On the other side, sorghum, pearl, fonio, and teff millets fall in the category of caryopses, in which the pericarp is strongly attached to the seed. In this case, higher external energy is required to separate the pericarp from the endosperm. Moreover, the pigmented testa is visible in finger millet and sometimes in pearl millet, whereas fonio and proso millets do not have pigmented testa.

Moreover, the ratio of these three components of the kernel which also varies with the millet type affects the hardness and enzyme susceptibility (Hadimani et al. 2001). In pearl millet, the distribution of endosperm, germ, and pericarp are 7%, 17%, and 8%, respectively (Serna-Saldivar and Rooney 1995). Among all other cereals, pearl millet has a larger portion of germ, with an endosperm-to-germ ratio of 4.5:1, whereas sorghum kernel has an endosperm-to-germ ratio of 8.4:1. On the other hand, finger and proso millets consist of a comparatively smaller germ, and therefore, the endosperm-to-germ ratio ranges from 11:1 to 12:1 (Zarnkow et al. 2007). Except finger millet, others usually have a single-thick seed coat firmly attached to the starchy endosperm and aleurone layer, whereas finger millet has a seed coat of five cell layers with the highest thickness ranging from 10.8 to 24.2 μm (McDonough et al. 1986). The structural features of some millet are shown in Table 1.3.

1.3 Nutritional Composition of Millets

Millets are rich source of nutrients and are comparable to the cereals, but way ahead in terms of nutrient content of wheat and rice. The millets contain 60%–70% carbohydrates, 12%–20% dietary fibre, 6%–19% protein, 1.5%–5% fat, 2%–4%

Table 1.2 Millet—Indian name, common name, vernacular name, scientific name, and major producing countries

Generally used Indian name	Common and other vernacular names	Scientific name	Major producing countries
Sorghum	• Jowar, Cholam (India) • Great millet, milo • Mabele (South Africa) • Mtama (East Africa) • Kaoliang (China)	*Sorghum bicolor L. Moench*	Sudan, Ethiopia, Cameroon, India, Africa, Western Africa (Nigeria, Burkina Faso, Niger, Mali), China, United States, South America (Argentina, Brazil, Bolivia), Australia
Pearl millet	• Bulrush millet • Cattail millet • Babala (Southern Africa) • Bajra (India)	*Pennisetum glaucum (L.) R. Br.*	India, East and Southern Africa (Sudan, Namibia, Botswana), West and Central Africa (Niger, Mali, Burkina Faso, Nigeria), United States, Brazil
Finger millet	• Ragi (India) • Wimbi (East Africa)	*Eleusine coracana (L.) Gaertn.*	Asia—Near East to Far East (India, Nepal, China), Eastern and Southern Africa (Ethiopia, Uganda, Kenya, Zimbabwe)
Foxtail millet	• Italian millet • Foxtail bristle grass • German millet • Hungarian millet	*Setaria italica L.*	Tropical and Subtropical Asia (China, India, Korea), United States, Australia, Eurasia, Eastern and Southern Europe.
Proso millet	• Common millet • Broom millet • Hog millet • Panic millet	*Panicum miliaceum L.*	Eurasia (China, Kazakhstan, Afghanistan, India, Turkey, Romania), United States, Australia
Japanese barnyard millet	• Japanese millet • Siberian millet • White millet • Marsh millet	*Echinochloa esculenta, (A. Braun) H. Scholz*	China, Japan, Korea

(continued)

Table 1.2 (continued)

Generally used Indian name	Common and other vernacular names	Scientific name	Major producing countries
Indian barnyard millet	• Sama/ Shama (India) • Sanwa millet • Billion-dollar grass	*Echinochloa frumentacea Link*	India, China
Kodo millet	• Kodo, Kodra (India)	*Paspalum scrobiculatum L.*	India
Little millet	• Blue panic, Samai (India)	*Panicum sumatrense Roth*	China, India, Nepal, Myanmar, Malaysia, Pakistan, Philippines, Sri Lanka

Source: FAOSTAT data for millet and fonio (Taylor 2019a)

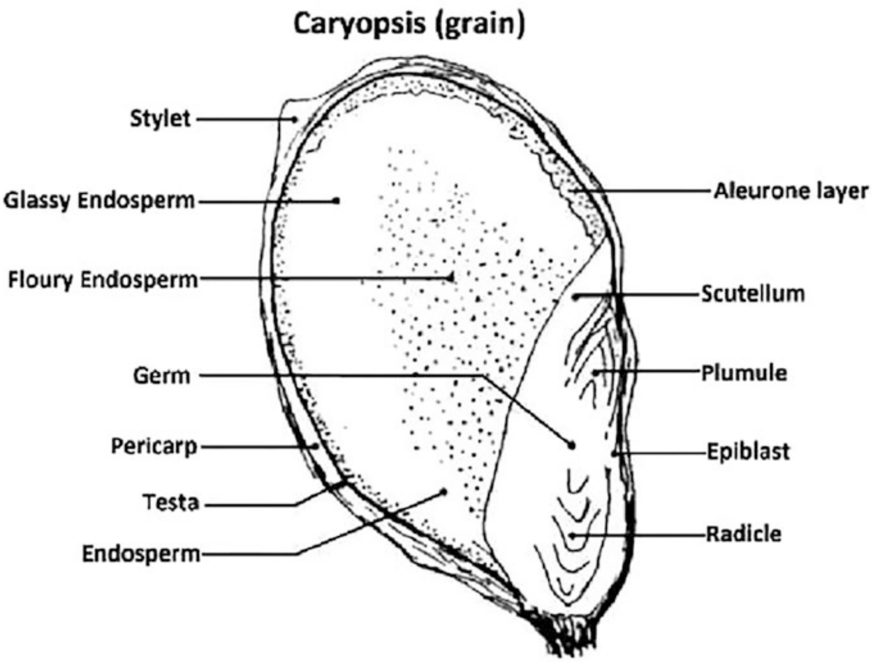

Fig. 1.2 General structure of millet (Dayakar Rao et al. 2017)

minerals, and other phytochemicals (Hadimani et al. 2001). The proximate composition of millets varies with species as they are dependent on environmental and genetic factors. They can also be classified as high protein and low protein based on the protein composition. Barnyard, foxtail, pearl, and proso millets have a higher

Table 1.3 Structural features of some millets

	Sorghum	Pearl millet	Finger millet	Proso millet	Foxtail millet
Seed type	Caryopsis	Caryopsis	Utricle	Utricle	Utricle
Pericarp	Attached	Attached	Unattached	Unattached	Unattached
Seed coat: Pigmented Thickness (μm)	1 layer Sometimes 0.4	1 layer Sometimes 0.4	5 layers Yes 10.8–24.2	1 layer No 0.2–0.4	1 layer
Aleurone Cell size (μm)	1 layer	1 layer 16–30 × 5–15	1 layer 18 × 7.6	1 layer 12 × 6	1 layer
Starch granules					
Diameter (μm)		10–12	3–21	2–10	
Peripheral (μm)	20–30	6.4	8–16.5	3.9	10
Corneous (μm)		6.4	3–19	4.1	
Floury (μm)		7.6	11–21	4.1	
Type	Simple	Simple	Simple/ compound	Simple	–
Protein bodies					
Size (μm)	0.3–3	0.6–0.7	2.0	0.5–1.7	–
Location (μm)	All areas	All areas	Peripheral/ corneous	Peripheral	
Germ					
Size (μm)	–	1420 × 620	980 × 270	1100 × 310	–
Endosperm-to-germ ratio	8.4:1	4.5:1	11:1	12:1	12:1

Source: McDonough 2000

protein content of 14.5%, 11.7%, 11.8%, and 13.4%, respectively. Among all the millets, finger millet has the lowest protein content of 8.0% (McDonough 2000). Moreover, they are rich in vitamin B and also supply the adequate amount of minerals like magnesium, manganese, iron, copper, phosphorous, and zinc. Compared to rice, sorghum, and wheat, millets have higher fat content which comprises of more polyunsaturated fatty acids (PUFA) (Malleshi et al. 1986; Malleshi and Hadimani 1993). Similarly, they have higher crude fibre content than wheat and rice. Millets vary in carbohydrate content, among which finger millet is a good source of carbohydrate. Table 1.4 shows the nutritional availability of various millets, coarse cereals, and fine cereals.

1.3.1 Foxtail Millet (*Setaria italica L.*)

Foxtail millet (*Setaria italica L.*) is an important crop for food and fodder grains in arid and semi-arid Asian and African regions. Being native of China, it is regarded as one of the oldest cultivated crops or annual grasses in the world which can grow as high as 120–200 cm. Foxtail plant ranges from single stemmed to highly tillered with

Table 1.4 Nutritional availability (per 100 g) of various millets, coarse cereals, and fine cereals

Commodity	Sorghum	Pearl millet	Finger millet	Proso millet	Foxtail millet	Kodo millet	Little millet	Barnyard millet	Barley	Maize	Wheat	Rice
Protein (g)	10.4	11.6	7.3	12.5	12.3	8.3	8.7	11.6	11.5	11.5	11.8	6.8
Carbohydrate (g)	72.6	67.5	72.0	70.4	60.9	65.9	75.7	74.3	69.6	66.2	71.2	78.2
Fat (g)	1.9	5.0	1.3	1.1	4.3	1.4	5.3	5.8	1.3	3.6	1.5	0.5
Fibre (g)	1.6	1.2	3.6	2.2	8.0	9.0	8.6	14.7	3.9	2.7	1.2	0.2
Minerals	1.6	2.3	2.7	1.9	3.3	2.6	1.7	4.7	1.2	1.5	1.5	0.6
Calcium (mg)	25.0	42.0	344.0	14.0	31.0	27.0	17.0	14.0	26.0	20.0	41.0	10.0
Phosphorus (mg)	222.0	296.0	283.0	206.0	290.0	188.0	220.0	121.0	215.0	348.0	306.0	160.0

Source: National Institute of Nutrition (NIN), Hyderabad, India a dense seed head, having hairy panicle that is 5–30 cm long. However, the seeds are small (2 to 3 mm in diameter) and light cream in colour, which varies greatly between varieties. The crop can be harvested for hay or silage (65–70 days) and for grains at 75–90 days. Foxtail millets are grown at an altitude of 2000 m (from sea level) and are fairly tolerant to drought. Its adaptability to a wide range of soils and temperature condition has increased its more popularity among farmers. Due to its early maturity, it can be easily cultivated in drought-prone areas and can be grown as a short-term crop.

The '*Setaria*' genus belongs to the 'Paniceae' tribe, the 'Panicoideae' subfamily, and the 'Poaceae' family which are in the grass family. The drought-resistant 125 'Setaria' species are widely distributed in warm and temperate parts of the world (Benabdelmouna et al. 2001). The foxtail millets were initially classified based on the morphology into three races firstly and then into four races (Al-Khayri et al. 2018). The foxtail millet three races are: (1) *moharia* from Afghanistan, Europe, Pakistan, and Southeast Asia; (2) *maxima*, common in China, Japan, Korea, and Northern India; and (3) *indica*, found in India and Sri Lanka (Prasada Rao et al. 1987). In 1995, a new classification system which included the fourth race, *nana* of foxtail millet, was revised (Li et al. 1995).

1.3.2 Sorghum (*Sorghum bicolor* (L.) Moench)

Sorghum is a tropical grass variety in the grass family 'Poaceae', which had been grown primarily in semi-arid parts of the world. Sorghum is intolerant to low temperatures and fairly resistant to pests and disease. It was originally domesticated in Africa and is a major grown crop in Africa and India. Sorghum is taxonomically and genetically considered to be similar to that of maize (*Zea mays* (L.), as both were originated from the 'Andropogoneae' subfamily. Sorghum is grown as cereals for human consumption, fodder, and production of alcoholic beverage and biofuels. Sorghums are classed into four groups based on their colour of pericarp, pericarp thickness, presence or absence of pigmented testa, endosperm colour, and endosperm type: (1) grain sorghum, (2) grass sorghum (3) forage sorghum glum, or (4) Sudan sorghums and broomcorn (Macrae et al. 1993).

1.3.3 Pearl Millet (*Pennisetum glaucum* (L.)R.Br.)

Pearl millet is a major and widely grown millet throughout the world including India, Pakistan, and Africa, which has been mainly used as food and forage. The pearl millet is traced to be originated from the northern parts of Africa such as Sudan to Senegal and are grown in India since prehistoric times (Harlan and de Wet 2012). In the year 1934, Staph classified the genus '*Pennisetum*' into mainly five sections: (1) *Gymnothrix*, (2) *Eupennisetum*, (3) *Penicillaria*, (4) *Heterostachya*, and (5) *Brevivalvula*. From these five sections, the cultivated pearl millet belongs to the section '*Penicillaria*', which are well adapted for cultivation in drought-prone, high-temperature areas and in soil with low fertility. Additionally, soils with high salinity or low pH also favour the growth of pearl millet. It is a summer annual crop which is suited for double cropping and rotations with the cultivation period of 80–100 days. The plant height ranges from 0.5 to 4 m. Grains are ovoid in shape and 3–4 mm long, and usually the colour of grain is yellowish grey or steel grey.

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

Finger millet is a cereal grass widely grown for its grain. It is an annual grass with a height of up to 170 cm and widely grown in arid and semi-arid areas in Africa and Asia. Moreover, it serves as a staple food in many countries of Africa and South Asia. It has a native from early African agriculture (Ethiopian and Ugandan highlands) and was introduced to India around 3000 years ago. Finger millet has characteristics like to withstand cultivation at altitudes 2000 m above sea level, drought tolerance, and longer storage periods of grains. Its inflorescence has a panicle with 4–19 finger-like spikes which bear up to 70 alternate spikelets, carrying 4 to 7 small seeds (Dida and Devos 2006).

In 1759, von Linnaeus firstly founded and documented the finger millet in '*Systema Naturae, Editio Decima II'*. He identified the millet as *Cynosurus coracana*, and hence it was first called as *Cynosurus coracanus* L. Later, Gaertner, in 1788, described the genus of finger millet as *Eleusine* which has been proposed in '*De Fructibus et Seminibus Plantarum',* and thus all the cultivated finger millet are known as '*Eleusine coracana*' (Al-Khayri et al. 2018).

1.3.5 Proso Millet (*Panicum miliaceum* L.)

Proso millet is also known as the common millet that had appeared as a crop in China about 7000 years ago. From there, it had been introduced to Europe around 3000 years ago. Proso millet is an annual grass adapted to temperate parts of the world. It is well suited to dry climates and mainly cultivated in Eastern Asia, Eastern and Central Russia, Northern China, Japan, India, Manchuria, Arabia, Syria, Iran, Iraq, Afghanistan, and United States. Proso millet is considered an annual herbaceous plant in the genera '*Panicum*'. However, the species is subdivided into five races: (1) *contractum*, (2) *compactum*, (3) *miliaceum*, (4) *patentissimum*, and (5) *ovatum*, in which the race *miliaceum* bears a resemblance to the wild *Panicum miliaceum* in panicle characteristics, whereas the other races have unique morphological characteristics (Upadhyaya et al. 2016).

1.3.6 Kodo Millet (*Paspalum scrobiculatum* L.)

Kodo millets are considered to be the native of tropical and subtropical regions of America. In India, it has been domesticated around 3000 years ago, and it was cultivated by tribal people in both southern and western parts of India (de Wet 1986). Kodo millet belongs to the genus *Paspalum* which is a large genus, with over 400 species around the world. The varieties of this millet are found in the western African regions, which are polystachyum and are considered as weed in the rice fields. The variety that is available in China and Japan are *Paspalum scrobiculatum* (Dendy 1995). The millet is resistant to drought and widely distributed in damp habitats across the tropics and subtropics of the world.

1.3.7 Little Millet (*Panicum sumatrense* Roth)

Little millet is a variety of millet (smaller than common millets) that has been domesticated in Eastern Ghats of India by the tribes. It has been diversified into the parts of Sri Lanka, Nepal, and western Burma since it is capable to withstand both drought and water logging. The little millet belongs to the genus of '*Panicum*' and of the species *P. sumatrense*. Moreover, the species of little millet (*Panicum sumatrense*) is further divided into subspecies, 'sumatrense' (cultivated little millet), and '*psilopodium*' (wild progenitor) (Upadhyaya et al. 2016).

1.3.8 Barnyard Millet (*Echinochloa crus-galli* (L.) P. Beauvois)

Barnyard millet (*Echinochloa crus-galli* (L.) P. Beauvois) consists of two different cultivated varieties, Japanese barnyard millet and the Indian barnyard millet. These both belong to the same subfamily 'Panicoideae' and tribe 'Paniceae' (Upadhyaya et al. 2016). The barnyard is said to be domesticated in Asia, mainly in India, Japan, and China (Acheampong et al. 1984).

1.4 Millet Distribution

The distribution of millet crops cultivated globally is shown in Table 1.2. In Asian continent, Nepal, Pakistan, China, Kazakhstan, Myanmar, and India, have the highest availability of some of the major millet crops like sorghum, pearl millet, finger millet, foxtail millet, little millet, and so on. Millets are grown in over 21 states in India and the major millet-growing states include Karnataka, Andhra Pradesh, Kerala, Tamil Nadu, Uttarakhand, Madhya Pradesh, Jharkhand, Rajasthan, and Haryana. Apart from Asian countries, African countries contribute to major millet cultivation and production. The African countries Niger, Nigeria, Burkina Faso, Mali, Sudan, and Senegal are well known for production of millets. Millets are well known to be cultivated in the dry and semi-arid climatic conditions.

1.4.1 Pearl Millet

Pearl millet is the most consumed millet and it accounts for about 50% of total global millet production. Pearl millet is known by different vernacular names like Bajra (India), Dukhon (Sudan), Gero (Nigeria), Hegni (Niger), Mahangu (Namibia), and Sanyo (Mali). Pearl millet cultivation requires lower rainfall (300 to 500 mm per year), and it can also be grown in very high temperature (more than 30 °C). The major producers of pearl millet are India and Western and Central Africa. Pearl millet is also cultivated in Sudan, South Sudan, and Eastern and Southern Africa where there is a band of cultivation from Angola and northern Namibia to Zimbabwe and northern Southern Africa to Mozambique. There is production of pearl millet in Brazil and the United States as well (Taylor 2016).

1.4.2 Finger Millet

Finger millets are also identified as African millet, but it is commonly known as Ragi in India. Finger millet is widely grown in Africa and Southern Asia, mainly in the Nepal and Indian States like Uttar Pradesh, Bihar, Karnataka, Tamil Nadu, and Andhra Pradesh. The eastern side of Africa, Uganda, Kenya, and Tanzania, and up to some extent in Ethiopia, Malawi, Sudan, Rwanda, Zimbabwe, and Zambia are well known for growing finger millet (Dida and Devos 2006).

1.4.3 Foxtail Millet

It is the second most widely grown species of millet and was first domesticated in Eurasia (Taylor 2019b). Foxtail millet is known by different vernacular names like Kangni (India), Awa (Japan), Hirse (German), Kahuno (Nepal), and so on. It is considered as the most important crop in East Asia where it was first domesticated in China. Foxtail millet is the most common millet crop in China, and especially it is common among the poor and dry parts of the country. In India, it is grown and consumed by the people who stay in dry and semi-arid areas of the country. Foxtail millet is considered to be staple diet in the southern part of India. It is also moderately grown in the regions of Europe and North America.

1.4.4 Proso Millet

Proso millet is also called broom corn millet and it is one of the first domesticated cereals of neolithic times, 10,000 years ago. The domestication of proso millet was a single domestication event, and thereby multiple domestication events took place from northern China, Western Asia, and Europe dating back from ca. 10,300 to 7000 BP (Taylor 2019b). Unlike other millets, it is generally cultivated in the cooler parts of Asia, Southern Europe, and Eastern Africa and in the United States. Compared to other crops, it is well adapted to temperate plains and high altitudes. Proso millet is being cultivated in very large quantities in China and Eurasia, especially in Kazakhstan, Afghanistan, India, Turkey, and Romania (Taylor 2019b) (USDA Germplasm Resources Information Network). This crop is more efficient in utilizing top soil moisture, and thus, grain yield directly gets affected by soil moisture content (Kalaisekar et al. 2016).

1.4.5 Little Millet

According to the ICRISAT (1996), little millet was domesticated in the central part of India. It was extended and is grown throughout India, particularly in Madhya Pradesh, Jharkhand, Orissa, Karnataka, Tamil Nadu, Maharashtra, and Uttar Pradesh. It is also cultivated in some of the temperate zones of Asia such as China, Caucasus, and East Asia and also in tropical continents of Indochina, Malaysia, and India. Little millet can be cultivated 2000 m above sea level and can sustain both the condition of drought and water logging.

1.4.6 Kodo Millet

Kodo millet is primarily grown in India, Indonesia, Nepal, Philippines, Thailand, West Africa, and so on. It is found across the humid habitats of the tropical and subtropical areas. In India, it is a minor crop, but people living in the Deccan plateau region have quite high importance of it. Moreover, it is also known as ditch millet, rice grass, cow grass, native *Paspalum*, or Indian crown grass (Deshpande et al. 2015). It is an annual crop; however some of the species are perennial in nature. It is usually grown in semi-arid regions and is generally tolerant to drought.

1.4.7 Challenges in Commercial Production of Millets

Millets can grow in worst environmental conditions like drought, require less water for its cultivation, and is highly nutritious having low glycaemic index as compared to the major crops like rice and wheat. Having all these benefits, still, its cultivation is a problem because of its low popularity. Further crops like wheat and rice have assured the market unlike millets. Moreover, if farmers willingly wish to cultivate millets, they have a point of dilemma or nervousness about its storage (‘Gods Own Crops’ 2008).

Further millet processing facilities are not up to the community level, which has led to increase in cost of millets over other common grains such as rice (Michaelraj and Shanmugam 2013).

Reasons for low production and marketing of millet include the following:

1. Problem is due to lack of adaptation to the environment and to the soil. For example, pearl millet was originated from Western Africa which was adapted to the harsher environment with the number of diseases and pests. But, on the other hand, the local landraces developed the crop by the natural and human selection which gave crops with higher tolerance towards hazard, but yield was significantly very low. People have tried the improved varieties of crops from Asia, Eastern Africa, and the United States which show quite good growth but have failed to show any superiority over local varieties. Thus, with the lack of tolerance to high soil temperature and sandstorms, the sustainability of seedlings becomes a problem and thus adaptation can be concluded as one of the major problems (FAO).
2. Another issue is with experimental conditions during breeding. To stimulate drought conditions for drought-tolerant crops is hard. And in the process of manipulating the crops in order to improve the tolerance against drought stress, it may also happen to increase the sensitivity at one stage.
3. Millets are often cultivated without manure or fertilizers. The non-adaptation of improved varieties and agricultural practices like tillage, weeding, sowing, and inter-culturing has resulted in lower yield.
4. Research on agro-techniques is required. Millet grains are very small in size, and thus threshing is still a problem as for some crops. Still, in some countries, people de-hull the grains manually and making the whole process time consuming and tedious. There is significant production loss due to poor harvesting, grain spilling, and breakage due to lack of availability of proper harvesting, grading, sorting, and other processing equipment. Still, many researchers are being carried out in order to get a high yield.
5. Lack of improved cultivars is another challenge, so there is a need for improved extension and development support to millet farmers (Michaelraj and Shanmugam 2013).

1.5 Processing of Millets

Millet is a highly nutritious crop and compliant to climate change, which can serve as an income crop for farmers and also improve the health of the common people thereby reducing nutrient deficiency. Millet-based products have low sensory acceptance and the presence of anti-nutritional factors is a major limitation for product formation. However, this limitation can be overcome by adopting appropriate processing methods. Reduction in anti-nutritional factors can be achieved through different preprocessing/processing methods such as germination, fermentation, cooking, and roasting. Okpala et al. (2013) reported that using of millet in blend with other cereals, pulses, or legumes improves the overall acceptability of the product. Blend is a convenient option, where mixing of millet fractions with other cereals enhances the nutritional and functional quality and also promotes their utilization in a variety of products, majorly bakery products, because millet grain being gluten-free is difficult to make cookies, bread, and other snack products; thus blending is an easier way.

1.5.1 Different Processing Methods

Processing of millets helps in the conversion of grains into more consumable form of food products. Processing of millet grains retains and enhances their nutritional value and also promotes consumption. There are several processing methods which have been practiced traditionally in rural areas such as soaking, germination, malting, fermentation, cooking, milling, puffing, and roasting. Novel processing methods are required for the production and commercialization of value-added food product from millets. Development of composite flours and extruded products through modern processing methods could increases the availability and awareness of highly nutritious millet-based products in urban areas (Ramashia et al. 2019).

1.5.2 Effect of Different Processing Methods on the Functional Properties of Millets

Different processing methods, which improve the functional property and acceptability of millet grains for various applications, include primary operations such as dehulling and milling, secondary operations such as fermentation, popping, malting, baking, and extrusion. The benefits of some of the processing methods have been briefly described below:

Soaking is a commonly practiced method which helps in the reduction of phytic acid content which is present in the bran and endosperm portion of the millet grain, thereby improving the bioaccessibility of minerals.

Germination is a traditional process with low operational cost and an easily adaptable technology. The kernel structure of the grain is softened by this process, and thus the nutritional composition of the grain is enhanced. Germination is a technique used to prepare nutrient-rich malt which can be further utilized in the development of various nutritional food products, composite flours, and complementary food products. Novel germinators assisted by high-tech control system with germination conditions are used to produce high-quality malt product at industrial scale.

Decortication of millet grains is difficult due to its small size when compared to other cereals; similarly cooking of millet as discrete grain like rice was a challenge. However, when millets are hydrothermally processed, it hardens the endosperm texture and enables decortication. Hama et al. (2011) reported that dehulling reduces the phytic acid content, tannins, polyphenols, and other antinutrients as all these components are majorly present in the peripheral of grain (pericarp and aleurone layer). Also during decortication, nutrients such as minerals, fibres, and phenols are reduced while removing the pericarp which lowers the acceptability of millet as functional food (Lestienne et al. 2005). Still, it is done prior to consumption as it improves the appearance, edibleness, and sensory properties of the grain.

Popping or puffing is a traditional processing method used for the preparation of expanded cereals to make ready-to-eat products. Ushakumari et al. (2007) state that cereal processing methods are applicable to millet grains for the production of ready-to-eat products, and traditional methods such as flaking and popping and contemporary methods like roller drying and extrusion cooking are used. Popped foxtail millet has low crude fibre and crude fat when compared to the raw millet; this is due to the effect of processing, as fat and fibre are present in the outer layer of the grain, and it is more affected when compared to the other nutrients present in the inner layer. Thus, the use of novel technology with optimized conditions enables millet production in large scale (Choudhury et al. 2011). Nutritional and functional variations during different processing are listed in Table 1.5.

1.5.3 Development of Millet-Based Food Products

Application of novel processing technology to produce ready-to-eat products such as puffed or popped, flaked grains, composite flours, and extruded products from millet grains at a commercial scale promotes the utilization of millets. However, there are some losses during industrial millet processing since the existing methods are not as developed as the methods used for processing of wheat and rice (FAO 2012). Due to changing lifestyle, ready-to-eat products are most preferred by consumers, in which children and teenagers especially enjoy having extruded foods like noodles as snack food. Since there is a high demand for both healthy and convenient food, noodles made from millet would be a highly nutritious and consumer-satisfying product. Noodles prepared from blends of millet and legume flour give a nutritionally balanced food which can be consumed as supplementary food (Verma and Patel 2013). Similarly, in recent times, bakery products like biscuit, bread, muffin, and nankhatai are also made from millet flour. About 20% of wheat is substituted by millet in bakery flours. Addition of higher levels of millet flour in products may affect the texture but not its nutritive value (Krishnan et al. 2011). The seed coat is the major by-product of processing units such as decorticating, milling, and malting industries which can be valorized as composite flour in biscuit production (Awadalla 1974), thereby increasing the utilization of millet and millet-based products.

1.5.4 Challenges in Millet Processing

Millet grain processing is difficult because of its small size and variety in raw materials due to diverse varieties that vary by crop, region, cultivation practice, and different climatic conditions in production regions. Designing of millet processing machineries is also difficult due to the above-mentioned factors. Thus, the hulling efficiency and the output quality of the grain are less accepted. The major issue from the consumer is that they find the presence of unhulled fraction of grain in

Table 1.5 Effect of different processing methods on nutritional and functional quality (Elshazali et al. 2011; Chandrasekara et al. 2012)

Processing	Protein	Dietary/ crude fibre	Fat	Vitamins	Iron	Calcium	Phenolic content	Protein digestibility	Starch digestibility	Antinutrients (phytate, tannins)	Mineral bioavailability
Dehulling	↓	↓	↓	↓ Vit. E	↓	↓	↓	↑	↑	↓	↑
Soaking	–	–	–	–	↓	↓	↓	↑	↑	↓	↑
Germination	↑	↑	↑	↑ Vit. C	↑	↑	↑	↑	↑	↓	↑
Milling/sieving	↓	↓	↓	↓ Vit. B, E	↓	↓	↓	↑	↑	↓	–
Cooking	↓ or ↑	↑	↑	–	–	–	↑	↓	↓	↓	–
Fermentation	↑	↓	↓	↑ Vit. B1, B2	↑	↑	↑ or ↓	↑	↑	↓	–
Roasting	↓	↑ or ↓	↓	–	↑	↑ or ↓	↑ or ↓	↑	–	↓	
Parboiling	↑	↓	↓	–	↑	↓	↑	↑	↑	↓	–
Puffing/ popping					↑						
Extrusion	–	–	–	–	–	–	–	↑	–	–	–
Irradiation	–	↓	–	–	–	–	–	–	–	–	–
Microwave cooking	–	–	–	↑ Vit. B1	–	–	–	–	–	–	–
Nixtamalization	–	↑	–	↑ Vit. B12	–	↓	↑	–	–	↓	↑

the millet rice. From the processor aspect, high processing cost for the production of high-quality millet grain fetches high price in the market substantially, thereby hampering the sales volume of the grains. In the supply chain of small millet, processing is a critical link between production and consumption, and thus the constraint in processing is a major limitation in marketing millet products. Therefore, there is a rising need for optimizing the existing processing machineries of small millet which improves the quality and quantity of grain and also its usage.

Millets are difficult to process and cook because of its hard seed coat and a typical grain texture. Lack of appropriate processing technology for the preparation of ready-to-eat products is the major hindrance for its diversified food use and also for its low-economic status when compared with other cereals.

Major limiting factors for production and consumption of millets are lack of production support, postharvest technologies, changes in consumer preference pattern, and lack of marketing support (Renganathan et al. 2020), whereas its coarse fibrous seed coat, astringent flavour, and poor keeping quality of processed products are the constraints in millet utilization.

1.5.5 Needs for Industrial Scale Processing of Millets

Millet is a staple crop which is being commonly consumed at household level with traditional processing. Decortication, sieving, and milling of millet grains are manually done. Lack of postharvest processing techniques is the major challenge for industrial scale operation of millets and commercialization of millet-based food products. Therefore, there is a high demand for motorized processing technologies which are more convenient and can produce a large amount of millet flour for the production of different food products at commercial scale (Saleh et al. 2013).

Further, lack of comprehensive nutritional profile of various cultivars and its mapping to end product characteristics are required. Research endeavour are required for improving the bioavailability of nutrients and proving the efficacy of functional and therapeutic characteristics of millets in curing the chronic diseases. Authenticated clinical data will support claiming the health benefits, labelling, and marketing for commercialization. Novel processing and packing techniques for extending the shelf-life of millets and proper supply chain management are required for the success of commercialization of millet-based products.

1.6 Conclusion and Future Trends

Millet has emerged as a robust and highly nutritional crop in recent years, which has led to its increase in demand. To further highlight its importance globally, the UN adopted the resolution sponsored by India and supported by over 70 nations declaring year 2023 as the International Year of Millets. However, much research is required to make it available in processable form; improving the designs of equipments to handle and process them with improved efficiency is the need of the hour. Further, branding, marketing, and packaging of millet-based food products need to be taken into consideration, highlighting its various health benefits to the prospective consumers. Also, storage aspect of bulk produce needs to be further studied owing to the scope of improvement in agricultural practices and improvement in production.

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Millet Cultivation: An Overview

2

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Abstract

Millets are emerging nutritionally rich crops with hidden abilities to adapt to the varying climatic conditions. Its fibre richness and amino acid compositions make it more preferable in many food processing industries. Although they were once extensively cultivated in the historic periods, its cultivation eventually declined due to the shift towards rice and wheat farming during green revolution. Currently, the progress of the millet cultivation has been facing a leap due to poor cultivational practices and intercultural operations. As these millets are being grown predominantly in the rainfed zones, proper land preparation methods and nutrient supplements have to be forged to exploit their maximum yield potential. Most of the small millets possess the ability to survive on diverse conditions and are known to have seldom crop protection techniques due to their sturdy nature. Only the major millets sorghum, pearl millet, and finger millet have their epidemics towards the viral and bacterial infections which can be overcome by timely management strategies. Thus, this chapter summarizes the overview of the millet cultivation and crop management procedures to attain maximum productivity.

Keywords

Millet technologies · Economics · Disease and pest management

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Abbreviations

DAS	Days After Sowing
DASM	Depletion of Available Soil Moisture
DAT	Days After Transplanting
FYM	Farm Yard Manure
LER	Land Equivalent Ratio
NPK	Nitrogen, Phosphorous, and Potassium
RBC	Red Blood Cell
STCR-IPNS	Soil Test Crop Response Studies-Integrated Plant Nutrient System

2.1 Introduction

Millets are small grained crops, which are hardy and tolerant to drought and other extreme weather conditions. In India, these crops are predominantly grown in arid and semi-arid regions with minimum inputs. These millets have a short growing season with a wider ecological adaptability. They are predominantly cultivated from a lower altitude to the mid hills right from Tamil Nadu in the south to Uttarakhand in the north and Gujarat from the west to Arunachal Pradesh in the northeast. Millets are popularly called as nutricereals as they are nutritionally superior to rice and wheat by providing the essential nutrients necessary for regular functioning of human body. With all these nutritional values, they are also gluten-free and have a low glycaemic index (Nautiyal and Kaechele 2006). Hence, consumption of millets is healthier, and this poses us to adapt to a diverse food habit that prevailed in the earlier days of civilizations (CRIDA n.d.).

In India, millets are grown in states like Andhra Pradesh, Karnataka, Tamil Nadu, Kerala, Telangana, Uttarakhand, Jharkhand, Madhya Pradesh, Haryana, etc. These account for an area of 14.25 m ha with a production of 16.44 m tons. Among all the millets, finger millet occupies 1.19 m ha with a production of 1.98 m. tons and a productivity of 1662 kg ha^{-1} (Ministry of Agriculture and Farmers welfare, Govt. of India (ON 2271) and past issues (2017–18). The decline in area under millets after the era of green revolution was mainly due to the change in consumption pattern and conversion of irrigated area towards rice and wheat (Fig. 2.1). This low production in millets is also attributed by the usage of conventional laborious techniques, poor-quality seeds, and non-adoption of recent technological interventions.

2.1.1 Constraints

- Millets are usually grown under rainfed conditions where the soils are eroded, degraded, or marginal with poor soil fertility.
- Farming depends solely on rainfall.

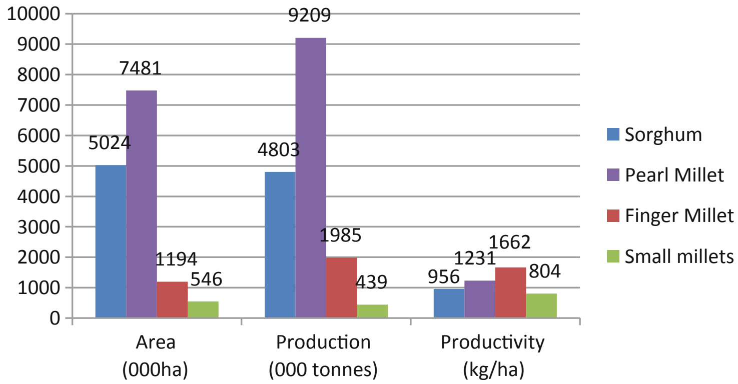

Fig. 2.1 Extent of millet cultivation in India (2017–2018). (Ministry of Agriculture and Farmers Welfare, Govt. of India (ON 2271) and past issues (2017–2018))

- Frequent occurrence of drought and complete crop failure due to erratic distribution of rainfall with long dry spells during rainy season.
- Non-adoption of high-yielding varieties.
- Usually sowing is done by broadcasting which restricts the operation of intercultural implements leading to more water and nutrient uptake by weeds.
- Optimum plant population is not maintained by farmers.
- Improper soil and moisture conservation practices and imbalanced application of manures and fertilizers resulting in widespread occurrence of nutrient deficiencies in soils lead to low productivity.
- Shortage of labour during peak season (Das and Rakshit 2016).

2.1.2 Nutritional Importance of Small Millets

The millets are nutritionally superior to the mainstream crops like rice and wheat. They possess a higher water-soluble fibre with a lowest glycaemic index which is a desirable diet for the diabetics. They consist of a higher protein and other micronutrients to supplement the daily requirements of a balanced diet (Taylor and Duodo 2018). Hence inclusion of these forgotten millets in diets would enable people to overcome the hidden hunger across the world (Table 2.1).

2.2 Production Technologies of Millets

In this section, the popular varieties of millet crops and their production technologies are elaborated for each crops, viz., sorghum, pearl millet, finger millet, foxtail millet, little millet, barnyard millet, kodo millet, and proso millet (TNAU n.d.; agritech n.d.; Vikaspedia n.d.; AICRP n.d.; AICRPSM n.d.).

Table 2.1 Nutritional properties of small millets and other cereals (Dayakar et al. 2017)

Crop	Per 100 g							
	Protein (g)	Fat (g)	Ash (g)	Crude fibre (g)	Carbohydrate (g)	Ca (mg)	Fe (mg)	P (mg)
Sorghum	10.4	1.9	1.6	1.6	72.6	25	4.1	222
Pearl millet	11.4	5.0	2.3	1.2	67.5	42	16.0	296
Finger millet	7.3	1.3	2.7	3.6	72.0	344	3.9	283
Kodo millet	8.3	1.4	2.6	9.0	65.9	27	1.7	188
Little millet	8.7	5.3	1.7	8.6	75.7	17	9.3	220
Foxtail millet	12.3	4.3	3.3	8.0	60.9	31	5.0	290
Proso millet	12.5	1.1	1.9	2.2	70.4	14	10.0	206
Barnyard millet	11.6	5.8	4.7	14.7	74.3	14	15.2	121
Maize	11.5	3.6	1.5	2.7	66.2	20	2.3	348
Wheat	11.8	1.5	1.5	1.2	71.2	41	5.3	306
Rice	6.8	0.5	0.6	0.2	78.2	10	0.7	160

Source: Sumathi et al. (2018)

2.2.1 Sorghum (Great Millet) *Sorghum bicolor* (L.) Moench

Sorghum is a major millet crop native of the tropical and subtropical regions and has the abilities to persist in warm seasons. It is the major forage crop cultivated in the United States during the dry spells when corn does not grow. This is a wholesome millet with each part of its plant being used for several industrial purposes like sugar, syrup, and bagasse and even used in malting for brewing alcoholic beverages (Dillon et al. 2007).

2.2.1.1 Land Preparation

Plough the field with primary tillage implements, viz. disc or mouldboard plough, once after spreading Farm Yard Manure (FYM) or compost at optimum moisture level and expose the field to hot sun which helps in controlling weeds, pests, and pathogens. Deep tillage is essential when the field is dominated with perennial weeds like *Cynodon dactylon* or *Cyperus rotundus*. Secondary tillage implements like cultivator or harrows are used to break the clods and the soil is pulverized with rotovator. The abovementioned operations are repeated for obtaining the desired tilth. Ridges and furrows may be formed using tractor drawn Ridger at 6 m long and 45 cm apart and with irrigation channels across the furrows. Alternatively, based on the availability of water, form beds of size 10 m^2 to 20 m^2. Thus, sorghum can be grown either in ridges and furrows or in beds and channels.

2.2.1.2 Sowing

Sorghum can be grown as a transplanted or direct sown crop. Under irrigated conditions, raise nursery in an area of 7.5 cents by using 7.5 kg of seeds for transplanting in 1 hectare. Seedlings with an age of 15 to 18 days are transplanted in the main field at a depth of 3 to 5 cm by maintaining the spacing of 45 $\times$ 15 cm. In respect of direct sown crop, adopt the seed rate of 10 kg ha^{-1} by maintaining the spacing of 45 × 15 cm. The depth of sowing should not be deeper than 1 cm. Under rainfed conditions, broadcasting can be done by adopting the seed rate of 15 kg ha^{-1}.

2.2.1.3 Nutrient Management

Apply FYM or composted coir pith at 12.5 t ha^{-1}/poultry manure at 5 t ha^{-1} along with 2 kg of *Azospirillum* and 2 kg of phosphobacteria or 4 kg of Azophos on the unploughed field and incorporate the manure in the soil. Application of these organics helps in improving physical, chemical, and biological properties of soil to attain high yield.

For both the transplanted and direct sown crop, mix 12.5 kg ha^{-1} micronutrient mixture with equal sand to make a total quantity of 50 kg, and apply the mixture over the furrows and on top one-third of the ridges or apply the mixture evenly on the beds as basal application. With respect to nitrogen, phosphorous, and potassium (NPK) fertilizers, recommendation for Soil Test Crop Response: Integrated Plant Nutrition System (STCR-IPNS) may be adopted for achieving the desirable yield. Adopt a blanket recommendation of 90:45:45 NPK kg ha^{-1}, if the STCR- IPNS recommendation is not available. Before sowing 50% N, full doses of P and K are applied as basal. Top dressing should be done with 25% N each on 15 days after sowing (DAS) and 30 DAS.

2.2.1.4 Weed Management

Weeds strive with crops for nutrients, moisture, sunlight, and space resulting in lower yields, poor grain quality, and elevated production costs. The yield reduction by weeds in sorghum varies from 15% to 83% (Mishra 1997). For controlling weeds, apply pre-emergence herbicide Atrazine at 0.25 to 0.5 kg ha^{-1}on 3 DAS/days after transplanting (DAT) on the soil using backpack or knapsack sprayer fitted with a flat fan nozzle using 500 litres of water/ha. On 20–25 DAS/DAT, apply post-emergence herbicide 2,4-D at 1 kg ha^{-1} for controlling broadleaved weeds in both the direct sown and transplanted crop. On 10–15 DAS and 30–35 DAS, hand weeding is done if herbicides are not applied. In case of sorghum + pulse intercropping, apply pendimethalin at 0.75 kg ha^{-1} on 3 DAS.

2.2.1.5 Water Management

Sorghum requires 400 mm of water for better growth and development. Generally, irrigation is provided immediately after sowing and life irrigation on the third day followed by once in 7–10 days depending upon climatic and edaphic conditions. Knee height stage, flowering, and grain filling are the most critical stages for water requirement. Irrigation of the crop during these stages will avert reduction in yield by avoiding moisture stress. Under limited water supply, irrigation is given based on 25% DASM (depletion of available soil moisture) during growth phase and 50% DASM during grain filling stage (Sorghum Research n.d.).

2.2.1.6 Crop Protection

2.2.1.6.1 Pest Management

- Spray methyl demeton or dimethoate at 2 mL L^{-1} of water on 7 and 14 DAS to control pests in the nursery.
- Seed treatment with chlorpyrifos or phosalone at 4 mL kg^{-1} or imidacloprid or thiamethoxam at 10 g kg^{-1} to minimize the incidence of pests at an early stage.
- To attract and kill adults of stem borer, grain midge and earhead caterpillars light traps may be set up in the field.

Pest	Management strategies
Shoot fly (*Atherigona soccata*)	After the commencement of monsoon, take up sowing which minimizes the incidence of shoot fly Remove the shoot fly-damaged seedlings while thinning Set up fish meal trap at 12 ha^{-1} till the crop is 30-day-old Carbofuran at 33.3 kg ha^{-1} at the time of sowing or dimethoate at 500 mL ha^{-1} or neem seed kernel extract at 5%
Aphids (*Rhopalosiphum maidis* and *Melanaphis sacchari)*	Dimethoate at 500 mL ha^{-1}
Stem borer (*Chilo partellus* and *Sesamia inferens)*	Sorghum is intercropped with lablab or cowpea (4:1) to minimize the damage of stem borer Application of carbofuran at 17 kg ha^{-1} in leaf whorls

2.2.1.6.2 Disease Management

Treat the seeds with carbendazim or Captan or Thiram at 2 g kg^{-1} of seed or Metalaxyl at 6 g kg^{-1} of seed before sowing to help in preventing seed and soil borne diseases.

Disease	Management strategies
Rust (*Puccinia purpurea*)	Mancozeb at 1 kg ha^{-1}
Ergot or sugary disease (*Sphacelia sorghi* and *Claviceps purpurea*)	Adjust the time of sowing to prevent heading during rainy season or severe winter Spraying of Mancozeb at 1 kg ha^{-1} or propiconazole at 500 mL ha^{-1} during earhead emergence (5–10% flowering) and another spray at 50% flowering stage
Head mould (Fungal complex—*Fusarium*, *Curvularia*, *Alternaria*, *Aspergillus*, and *Phoma* sp.)	Mancozeb or Captan at 1000 g + Aureofungin Sol at 100 g ha^{-1}
Downy mildew (*Peronosclerospora sorghi*)	Metalaxyl + Mancozeb at 500 g or Mancozeb at 1000 g ha^{-1}
Charcoal rot (*Macrophomina phaseolina*)	Seed treatment with *Pseudomonas fluorescens* at 10 g kg^{-1} or *Trichoderma viride* at 4 g kg^{-1} of seed

2.2.1.7 Ratoon Management in Sorghum

- After harvest, allow the stubbles to grow into a new crop, which mature earlier in about 80 to 85 days.
- Short-duration varieties are preferred for ratooning.
- Harvest the plants 10–15 cm above the ground level.
- Remove the first formed two sprouts and allow only the later formed two sprouts to grow thus maintaining two tillers per hill.
- Old leaves and parts of stem are to be collected and burnt for avoiding the spread of pests and diseases.
- Irrigate immediately after harvest.
- Irrigation should be given immediately within 24 h after cutting.
- Irrigate on third or fourth day after cutting.
- After weeding, apply 100 kg N ha^{-1} (I top dressing, 50 kg N on 15th day after cutting (before earthing up), II top dressing, 50 kg N + 50 kg P on 45th day after cutting).
- Subsequent irrigation to be given once in 7 to 10 days.
- No water stress during boot leaf and grain filling stages.

2.2.1.8 Varieties/Hybrids of Sorghum

Varieties/ hybrids	Grain yield (kg ha^{-1})	Duration (days)	Fodder yield (kg ha^{-1})	Special features
CO 32	2900 (Irrigated) 2400 (Rainfed)	105–110	11,000 (Irrigated) 6500 (Rainfed)	Semi-compact earhead Moderately resistant to shoot fly and stem borer
K 12	3000	95	11,500	Resistant to downy mildew and moderately resistant to shoot fly and stem borer Tolerant to drought
CO (S) 28	2493 (rainfed) 4568 (irrigated)	100–105	12,600 (rainfed) 17,700 (irrigated)	Semi-compact White-coloured grains with moderate resistance to shoot fly, earhead bugs, and grain mould
TNAU Sorghum Variety CO 30	2400 (rainfed) 3360 (irrigated)	95–105	7000 (rainfed) 9200 (irrigated)	Dull white, semi-compact High dry matter Digestibility, moderately tolerant to shoot fly, grain mould, and downy mildew
Paiyur 2	2113 (rainfed)	90–95	8789 (rainfed)	Dual-purpose sorghum with red grains. Downy mildew and charcoal rot tolerant
CSV 36	3300	106–110	12,200	High yielding recommended for Tamil Nadu, Telengana, Andhra Pradesh, Rajasthan, and Gujarat

(continued)

Varieties/ hybrids	Grain yield (kg ha^{-1})	Duration (days)	Fodder yield (kg ha^{-1})	Special features
CSV 39	3400	102–110	11,500	High yielding early maturation recommended for Karnataka Rajasthan, Maharashtra, Gujarat, Madhya Pradesh, Tamil Nadu, and Telengana
CSH 41	4700	105	12,400	High yielding early and recommended to MP, Rajasthan, Gujarat, Maharashtra, Karnataka, AP, TS, and TN
CSV 33 MF	–	First cut (60–65 days) Subsequent cuts (45–50 days)	GF—103 t ha^{-1} (Three cuts)	Haryana, Punjab, Uttarakhand, Uttar Pradesh, Gujarat Rajasthan, Tamil Nadu, Karnataka, and Maharashtra
CSV 38F	–	105–115	Green fodder: 46,500 Dry fodder: 14,400	Fodder sorghum with a higher yield and recommended to Maharashtra, Karnataka, and TN

2.2.2 Pearl Millet (*Pennisetum glaucum*)

Pearl millet is highly rich in all the essential minerals and is cultivated in the tropic and subtropics of India and Africa. It is essentially rich in iron, phosphorous, potassium, calcium, magnesium, manganese, zinc, and copper. It is the most preferred millet for making porridges, gruel, doughs, and beverages (Fuller 2003).

2.2.2.1 Land Preparation

Plough the field with disc or mouldboard plough once after spreading FYM or compost at optimum moisture level which results in cloddy condition. Break the clods using cultivator or harrows and the soil is pulverized with rotavator. These operations are repeated for obtaining the fine tilth, to yield better germination and establishment of seedlings. Successively the ridges and furrows are formed by using a tractor drawn Ridger at 6 m long and 45 cm apart and create irrigation channels across the furrows. Alternatively, based on the availability of water, form beds of size 10 m^2 to 20 m^2.

2.2.2.2 Sowing

It can be grown as a transplanted or direct sown crop. Under irrigated conditions, raise nursery in an area of 7.5 cents by using 3.75 kg of seeds for transplanting in 1 hectare. Seedlings with an age of 15 to 18 days are transplanted in the main field at a depth of 3 to 5 cm by maintaining the spacing of 45 × 15 cm. In respect of direct sown crop, adopt the seed rate of 5 kg ha^{-1} with the spacing of 45 × 15 cm. The depth of sowing should not be deeper than 1 cm. Under rainfed conditions, broadcasting can be done by adopting the seed rate of 15 kg ha^{-1}.

2.2.2.3 Nutrient Management

Apply FYM or composted coir pith at 12.5 t ha^{-1} or poultry manure at 5 t ha^{-1} along with 2 kg of Azospirillum and 2 kg of phosphobacteria or 4 kg of Azophos on the unploughed field and incorporate the manure in the soil. The application of these organics helps in improving physical, chemical, and biological properties of soil leading to high yield.

For both the transplanted and direct sown crop, mix 12.5 kg ha^{-1}of micronutrient mixture with enough sand to make a total quantity of 50, and apply the mixture over the furrows and on top one-third of the ridges, or apply the mixture evenly on the beds as basal application. In respect of NPK fertilizers, STCR-IPNS recommendation may be adopted for achieving the desirable yield. Adopt a blanket recommendation of 70:35:35 NPK kg ha^{-1} for varieties and 80:40:40 NPK kg ha^{-1} for hybrids, if the STCR-IPNS recommendation is not available. Before sowing 25% N, the entire P and K are applied as basal. Top dressing should be done with 50% N on 15 DAS and 25% N 30 DAS (Khairwal et al. 2007).

2.2.2.4 Weed Management

Yield loss in pearl millet ranges from 35 to 90% (Umarani et al. 1980). These losses are to be reduced for which pre-emergence herbicide Atrazine at 0.25 kg ha^{-1} on 3 DAS/DAT is applied on the soil. On 20–25 DAS, apply post-emergence herbicide 2,4-D at 0.5 to 0.75 kg ha^{-1} for controlling broadleaved weeds (Ram et al. 2005). If herbicides are not applied, hand weeding is done on 15 DAS and 30 DAS.

2.2.2.5 Water Management

It requires 250 to 350 mm of water for maintaining proper growth and development, thus resulting in high yield. Generally, irrigation is given immediately after sowing and life irrigation on the third day and thereafter once in 7–10 days depending upon soil and climatic conditions. The most critical stages for irrigation are maximum tillering, flowering, and grain filling. Any moisture stress during these stages has a direct impact on yield. Hence, ensure irrigation to critical stages of the crop to avoid yield loss (Khairwal et al. 2007).

2.2.2.6 Crop Protection

2.2.2.6.1 Pest Management

- Spray methyl demeton or dimethoate at 2 mL L^{-1} of water on 7 and 14 DAS to control pests in the nursery.
- Seed treatment with chlorpyriphos or phosalone at 4 mL kg^{-1} or imidacloprid or thiamethoxam at 10 g kg^{-1} to minimize the incidence of pests at an early stage.

- Attract and kill adults of stem borer, grain midge, and earhead caterpillars through light traps.

Pest	Management strategies
Shoot fly (*Atherigona approximata*)	Seed treatment with imidacloprid at 10 g kg^{-1} of seed Set up fish meal trap at 12 ha^{-1} till the crop is 30 days old Methyl demeton or dimethoate at 500 mL ha^{-1} or neem seed kernel extract at 5%
Ear midge (*Geromyia pennisetti*)	Carbaryl at 25 kg ha^{-1} or Malathion at 25 kg ha^{-1} Or dimethoate at 500 mL ha^{-1}

2.2.2.6.2 Disease Management

Seed treatment with Metalaxyl at 6 g/kg of seed before sowing helps in preventing seed and soil-borne diseases.

Disease	Management strategies
Rust (*Puccinia substriata*)	Sowing should be taken during December–May to reduce the incidence Wettable sulphur at 2.5 kg ha^{-1} or mancozeb at 1 kg ha^{-1}
Ergot or sugary disease (*Claviceps fusiformis*)	Spray carbendazim at 500 g ha^{-1} or mancozeb at 1 kg ha^{-1} during 5–10% flowering and another spray at 50% flowering stage
Downy mildew (*Sclerospora graminicola*)	Grow resistant varieties: CO (Cu) 9 and TNAU-Cumbu Hybrid—CO 9 and CO 10 Metalaxyl + mancozeb at 500 g ha^{-1} or mancozeb at 1 kg ha^{-1}

2.2.2.7 Varieties/Hybrids of Pearl Millet

Varieties/ hybrids	Grain yield (kg ha^{-1})	Duration (days)	Special features
X7	2513 (rainfed) 3295 (irrigated)	90	Resistant to downy mildew
CO (Cu) 9	2354 (rainfed) 2865 (irrigated)	80–85	Resistant to downy mildew
ICMV 221	2100	75–80	Resistant to downy mildew, semi-compact panicles
TNAU Cumbu Hybrid CO 9	2707 (rainfed) 3728 (irrigated)	75–80	Short duration and resistant to downy mildew
Composite CO 10	2900 (rainfed) 3450 (irrigated)	85–90	High tillering, bold grains with compact earhead

(continued)

Varieties/ hybrids	Grain yield (kg ha^{-1})	Duration (days)	Special features
PB 1705	3640	79	Resistant to downy mildew, blast, rust, smut, ergot, tolerant to lodging, shoot fly, and stem borer
AHB 1200 Fe	3170	78	Medium maturing, high iron content, long cylindrical panicle with resistance to downy mildew and stem borer
Hybrid Pusa 1201	2810	80	Medium maturating, yellow anthers, stay green trait, resistant to smut and downy mildew
HHB 299	3274	81	Medium maturing purple anther, greyish resisters to pests and diseases
NBH 4903	4444	85	Highly resistant to downy mildew, resistant to smut, ergot, blast, and stem borer
MPMH 21	2469	75	Early maturing, compact earhead, resistant to downy mildew, rust, and smut
PHB 2884	3300	88	Late maturing tall panicle, grey seeds

2.2.3 Finger Millet (*Eleusine coracana*)

Finger millet, well known as Ragi in Tamil, is grown in various regions of India. It is highly nutritious with highest calcium content and ranks sixth in the production after the mainstream cereals across the world (Joel et al. 2005; Taylor and Emmambux 2008).

2.2.3.1 Land Preparation

Plough the field with disc or mouldboard plough once after spreading FYM or compost at optimum moisture level which results in cloddy condition. Break the clods using cultivator or harrows and the soil is pulverized with rotavator. These operations are repeated to obtain the fine tilth, which favours better establishment of seedlings. Then form beds of size 10 m^2 to 20 m^2 based on the availability of water.

2.2.3.2 Sowing

Finger millet can be grown as a transplanted or direct sown crop. Under irrigated conditions, raise nursery in an area of 12.5 cents using 5 kg of seeds for transplanting in 1 hectare. Seedlings with an age of 18 to 20 days are transplanted in the main field at a depth of 3 to 5 cm with the spacing of 30 × 10 cm. In respect of direct sown crop, adopt the seed rate of 10–12.5 kg ha^{-1} by maintaining the spacing of 25 × 10 cm. The depth of sowing should not be deeper than 2.5 cm.

2.2.3.3 Nutrient Management

Apply FYM or composted coir pith at 12.5 t ha^{-1} or poultry manure at 5 t ha^{-1} along with 2 kg of Azospirillum and 2 kg of phosphobacteria or 2 kg of Azophos in the unploughed field, and incorporate the manure in the soil. The application of these organics enhances the physical, chemical, and biological properties of soil leading to high yield (Aranachalam et al. 1995; Basavaraju and Rao 1997).

For both the transplanted or direct sown crop, mix 12.5 kg ha^{-1} of micronutrient mixture with enough sand to make a total quantity of 50 kg, and apply the mixture evenly on the beds as basal application. With respect to NPK fertilizers, STCR-IPNS recommendation may be adopted to achieve the desirable yield. Adopt a blanket recommendation of 60:30:30 NPK kg ha^{-1}, if the STCR-IPNS recommendation is not available. Before sowing 50% N, full doses of P and K are applied as basal. The top dressing should be done with 50% N on 30 DAS. The highest yield of 4166 kg ha^{-1} was obtained with the application of 50:40:25 NPK kg ha^{-1} under a spacing of 60 × 60 cm (Prakasha et al. 2018).

2.2.3.4 Weed Management

Apply pre-emergence herbicide Oxyfluorfen at 0.05 a.i kg ha^{-1} or Oxadiazone at 1 kg ha^{-1} or Butachlor at 0.75 kg ha^{-1} (Prasad et al. 2010) on 3 DAS/DAT on the soil using backpack or knapsack sprayer fitted with a flat fan nozzle using 500 L of water ha^{-1}. On 20–25 DAS/DAT, apply post-emergence herbicide 2,4-D at 0.75 kg ha^{-1} to control broadleaved weeds in both the direct sown and transplanted crop. On 15 DAS and 30 DAS, hand weeding is done if herbicides are not applied.

2.2.3.5 Water Management

Finger millet crop requires 450 to 500 mm of water for better growth and development. Generally, irrigation is provided instantaneously after sowing and life irrigation on the third day and once in the following 7–10 days depending upon the climatic and edaphic conditions. The most critical stages for irrigation are tillering, flowering, and grain filling. Irrigate the crop during these stages to avoid reduction in yield by preventing moisture stress.

2.2.3.6 Crop Protection

2.2.3.6.1 Pest Management

Pest	Management strategies
Aphids (*Schizaphis graminum* and *Rhopalosiphum maidis*)	In nursery, spray Dimethoate at 500 mL ha^{-1}
Stem borer (*Sesamia inferens*)	Application of carbofuran at 50 kg ha^{-1} in leaf whorls
Earhead bug (*Calocoris angustatus*)	Malathion at 25 kg ha^{-1} or neem seed kernel extract at 5% on the third and 18th day after panicle emergence

2.2.3.6.2 Disease Management

Seed treatment with Captan or Thiram at 4 g kg^{-1} of seed or Carbendazim at 2 g/kg of seed or *Pseudomonas fluorescens* at 10 g kg^{-1} of seed before sowing helps in preventing seed and soil borne diseases.

Disease	Management strategies
Blast (*Pyricularia grisea*)	Carbendazim at 500 g ha^{-1} or Iprobenphos at 500 mL ha^{-1} and repeat at flowering stage and 15 days later to manage neck and finger blast Aureofungin sol at 100 ppm at 50% earhead emergence followed by spray with mancozeb at 1 kg ha^{-1} or *Pseudomonas fluorescens* at 0.2% 10 days later Tricyclazole at 500 g ha^{-1} at maximum tillering and heading stages
Virus diseases Mosaic and mottle streak	Remove the infected plants Spray methyl demeton at 500 mL ha^{-1}

2.2.3.7 Recently Released Varieties of Finger Millet

Varietal name	Institute	Duration (days)	Avg yield (q ha^{-1})	Special features
GPU 66	PC unit, Bangalore	110–115	35–40	Medium compact ears with top curved fingers
GPU 67	PC unit, Bangalore	115–120	30–35	Non-lodging (semi-dwarf)
VL-376	ICAR-VPKAS, Almora	103–109	29–31	Fertilizer responsive and moderately resistant to blast
GNN-6	Navsari Agricultural University	120–130	28–30	Moderately resistant to leaf and finger blast
GN-5	Navsari Agricultural University	120–130	25–27	Late maturing, white coloured, with moderate resistance to leaf and finger blast
VL-Mandua-347	ICAR-VPKAS	104–112	20–22	Moderately resistant to neck, finger last, tolerant to lodging and light copper grains
KMR-340	VC Farm, Mandya	90–95	35–40	White grains with resistance to blast, blight, stem borer, and aphids
Dapoli 2	Dapoli	115–120	25–27	Soma clonally derived variety Rich in Fe and Ca, moderately resistant to blast
CO 15	TNAU, Coimbatore	115–120	29–34	Fertilizer responsive, non-lodging, resistant to leaf, neck, finger blast. Bold copper red grains
Chhattisgarh-ragi-2 (BR-36)	Jagdalpur, IGKVV	115–118	34–36	Moderately resistant to neck and finger blast with tolerance to stem borer and aphids
VL-Mandua-379	ICAR-VPKAS, Almora	105–110	31.3	Resistant to neck and finger blast, Medium bold light copper colour grains
ATL 1	TNAU, CEM, Athiyanthal	105–110	31.28	Drought tolerant, Blast resistant and non lodging

2.2.4 Foxtail Millet (*Setaria italica*)

Foxtail millet, i.e. *Setaria italica,* is an annual grass grown as food. It consists of nine chromosomes with a diploid nature and is an important nutricereal with climate resilience ability. (Taylor 2019).

2.2.4.1 Land Preparation

Plough the field with disc or mouldboard plough once after spreading FYM or compost at optimum moisture level which results in cloddy condition. Secondary tillage is done to break the clods using cultivator or harrows and the soil is pulverized with rotavator. These operations are repeated for obtaining the fine tilth, which favours better germination and establishment of seedlings. Then form beds of size 10 m^2 to 20 m^2 based on the availability of water.

2.2.4.2 Sowing

Take up sowing by adopting the seed rate of 10 kg ha^{-1} with the spacing of 25 × 10 cm. The depth of sowing should not be deeper than 2.5 cm. A seed rate of 12.5 kg ha^{-1} is used for sowing by Gorru or seed drill.

2.2.4.3 Nutrient Management

Apply FYM or compost at 12.5 t ha^{-1} on the unploughed field and incorporate the manure in the soil which helps in improving the soil structure, water holding capacity, and fertility status of soil. These conditions favour high productivity. In respect of inorganic fertilizers, adopt a blanket recommendation of 44:22:0 NPK kg ha^{-1}. Before sowing, the entire N, P, and K are applied as basal. The highest grain yield of 1770 kg $ha^{-1}$was recorded with the application of 30:24:15 NPK kg ha^{-1} (Hasan et al. 2013).

2.2.4.4 Weed Management

Weeds compete with crop plants for nutrients, moisture, space, and sunlight, thus reducing the yield of crops. The yield loss varies depending on the type of weed species, intensity, their period of infestation, ability of the crop to compete, and environmental conditions. Apply pre-emergence herbicide Isoproturon at 1.0 kg ha^{-1} on 3 DAS on the soil using backpack or knapsack sprayer fitted with a flat fan nozzle using 500 L of water ha^{-1}. On 20–25 DAS, apply post-emergence herbicide 2,4-D at 1.0 kg ha^{-1} to control weeds (Chapke et al. 2018). On 15 DAS and 40 DAS, hand weeding is done if herbicides are not applied.

2.2.4.5 Water Management

Foxtail millet is raised as a rainfed crop where the crop production solely depends on rainfall. In these regions, when precipitation happens at a higher intensity which exceeds the infiltration rate of the soils leading to runoff of the rainwater. Generally, about 40% of rainfall may be lost as runoff under unchecked conditions. Although optimum moisture conservation strategies are adopted, around 10–15% of rainfall in black soils as well as 20% of rainfall in red soils are lost as runoff. It can be collected and recycled to make the water available to rainfed crops at critical stages.

2.2.4.6 Crop Protection

Generally, spraying of pesticides and fungicides is not required as there is no major problem of pests and diseases.

2.2.4.7 Recently Released Varieties of Foxtail Millet

Variety	Institute	Duration (days)	Avg. yld (kg ha^{-1})	Special features
RAU (Rajendra kauni 1–2)	Rajendra Agricultural University, 2017 PUSA	80–85	2300–2500	Resistant against leaf blast rust, smut, brown spot, blight, and downy mildew
DHFt-109-3	ARS, Hanmanammatti, UAS, Dharward	86–88	Grain: 2900 Fodder: 5230	For contingency planting
Suryanandi (SiA 3088)	RARS, Nadhyal	70–75	2000–2500	Non-lodging, early duration, and suitable for double cropping
ATL 1	TNAU, CEM, Athiyanthal	80–85	Grain: 2117 Fodder: 2780	Non-lodging and high yielding and synchronised maturity

2.2.5 Little Millet (*Panicum sumatrense*)

Little millet is a highly fibrous millet which is comprised of healthy polyunsaturated fatty acids. It also consists of flavonoids that act as an antioxidant to protect the immune defence system. It is cultivated in the temperate and tropical regions of Asia (Goron and Raizada 2015).

2.2.5.1 Land Preparation

Plough the field with disc or mouldboard plough once after spreading FYM or compost at optimum moisture level which results in cloddy condition. Secondary tillage is done to break the clods using cultivator or harrows, and the soil is pulverized with rotavator. These operations are repeated for obtaining the fine tilth, to favour better germination and establishment of seedlings. After that, form beds of size 10 m^2 to 20 m^2 based on the availability of water.

2.2.5.2 Sowing

Take up sowing by adopting the seed rate of 10 kg ha^{-1} with the spacing of 25 × 10 cm. The depth of sowing should not be deeper than 1 cm. A seed rate of 12.5 kg ha^{-1} is used for sowing by Gorru or seed drill. Blackgram, greengram, redgram, and soybean are grown along with little millet as intercrop. The recommended ratio of intercropping for achieving more land equivalent ratio (LER) is as follows: little millet + blackgram (2:1), little millet + greengram (2:1), little millet + redgram (2:1), and little millet + soybean (2:1).

2.2.5.3 Nutrient Management

Apply FYM or compost at 12.5 t ha^{-1} on the unploughed field, and incorporate the manure in the soil to help in improving the soil structure, water holding capacity, fertility status of soil, and yield. In respect of inorganic fertilizers, adopt a blanket recommendation of 44:22:0 NPK kg ha^{-1} (Charate et al. 2018). Before sowing, the entire N, P, and K are applied as basal. Application of N at 40 kg and K at 20 kg ha^{-1} was the optimum dose for achieving higher yield under rainfed condition (Chapke et al. 2018).

2.2.5.4 Weed Management

Weeds compete with crop plants for nutrients, moisture, space, and sunlight, thus reducing the yield of crops. The yield loss varies depending on the type of weed species, intensity and period of infestation, ability of crop to compete, and environmental conditions. Apply pre-emergence herbicide Isoproturon at 1.0 kg ha^{-1} on 3 DAS on the soil using backpack or knapsack sprayer fitted with a flat fan nozzle using 500 L of water ha^{-1}. On 20–25 DAS, apply post-emergence herbicide 2,4-D at 1.0 kg ha^{-1} to control weeds (Chapke et al. 2018). If herbicides are not applied, hand weeding should be done on 15 DAS and 40 DAS.

2.2.5.5 Water Management

Little millet is grown as a rainfed crop which depends on precipitation for growth and development. The productivity of little millet can be increased to a greater extent by adopting proper in situ soil and moisture conservation practices. Through proper water harvesting, the runoff can be recycled and protective irrigation is given at critical stages.

2.2.5.6 Crop Protection

Generally, spraying of pesticides and fungicides is not required as there is no major problem of pests and diseases.

2.2.5.7 Released Varieties of Little Millet

Varieties	Institute	Grain yield (kg ha^{-1})	Duration (days)	Special features
CO (Samai) 4	TNAU, Coimbatore	1567 (rainfed)	75–80	Short duration, suitable for double cropping rainfed situations
Paiyur 2	RRS, TNAU, Paiyur	850 (rainfed)	85	Short duration suitable for little millet-horse gram cropping sequence

(continued)

Varieties	Institute	Grain yield (kg ha^{-1})	Duration (days)	Special features
GNV 3	NAU, Navsari	2800 to 2900	110–115	Bold seeded multi-tillering and non-lodging. High minerals and crude fibre content
BL 6	IGKVV, Raipur	1200–1400	90–95	Suitable for upland cultivation Rich in zinc and calcium
ATL 1	CEM, TNAU, Athiyanthal	1587 (rainfed)	85–90	High yielding strong culm, tolerant to drought and non-lodging
Jawahar Kutki 4 (JK 4)	JNKVV, Jabalpur	1300–1500	75–80	Resistant to drought and shoot fly, non-lodging
Phule Ekadashi	MPKV, Rahuri	1200–1400	120–130	Non-lodging
DHLM 36–3	UAS, Dharwad	1400 to 1600	95–100	Late maturing
DHLM −14-1	UAS, Dharwad	1600	95–100	Tolerant to shoot fly

2.2.6 Kodo Millet (*Paspalum scrobiculatum L.*)

Kodo millet is an important millet crop with higher composition of lecithin and folate which has various beneficial emoluments (folic acid, which is essential for the production of red blood cells [RBCs] in the human body) in achieving the daily nutritional uptake. It is predominantly cultivated in Nepal and eastern Asian countries (Kodo Millet Farming n.d.; Hariprasanna 2016).

2.2.6.1 Land Preparation

Primary tillage is done either with disc or mouldboard plough after the harvest of crops which is followed by secondary tillage with cultivator or harrows. The soil is pulverized with rotavator for obtaining the fine tilth, to enhance the germination and establishment of seedlings. Then beds of size 10 m^2 to 20 m^2 based on the availability of water are formed.

2.2.6.2 Sowing

Take up sowing by adopting the seed rate of 10 kg ha^{-1} with the spacing of 25 × 10 cm. The depth of sowing should be 3–4 cm. A seed rate of 12.5 kg ha^{-1} is used for sowing by Gorru or seed drill. Blackgram and greengram are grown as intercrop in kodo millet (kodo millet + blackgram (2:1) and kodo millet + greengram (2:1)).

2.2.6.3 Nutrient Management

Apply FYM or compost at 12.5 t ha^{-1} on the unploughed field and incorporate the manure in the soil. In respect of inorganic fertilizers, adopt a blanket recommendation of 44:22:0 NPK kg ha^{-1}. Before sowing, the entire N, P and K are applied as basal. The highest grain yield of 3863 kg ha^{-1} was obtained with the application of 125% recommended dose of fertilizers (55:27.5:0 kg NPK ha^{-1}) + soil application of *Azospirillum* at 2 kg ha^{-1}+ vermicompost at 2 t ha^{-1} + foliar application of 1% poly feed at tillering and flowering stages (Prabudoss et al. 2014).

2.2.6.4 Weed Management

Apply pre-emergence herbicide Isoproturon at 1.0 kg ha^{-1} on 3 DAS on the soil using backpack or knapsack sprayer fitted with a flat fan nozzle using 500 L of water ha^{-1}. On 20–25 DAS, apply post-emergence herbicide 2,4-D at 1.0 kg ha^{-1} to control weeds (Chapke et al. 2018). If herbicides are not used, hand weeding is recommended on 15 DAS and 40 DAS which helps to control the weeds thus improving the yield (Prajapati et al. 2007).

2.2.6.5 Water Management

Kodo millet is grown as a rainfed crop and it requires 300 to 400 mm of rainfall for growth and development. Soil and moisture conservation, viz. conservation tillage, contour and graded bunding, compartmental bunding, etc., are adopted to improve the water use efficiency of the crop. To achieve the desirable yield, supplemental irrigation could be given from the farm pond at critical stages through mobile sprinklers.

2.2.6.6 Crop Protection

Generally, spraying of pesticides and fungicides is not required as there is no major problem of pests and diseases.

2.2.6.7 Recently Released Varieties of Kodo Millet

Variety	Institute	Duration (days)	Avg yld (kg ha^{-1})	Special features
Chhattisgharh-kodo-2	Jagdalpur-IGKVV	95–100	2500–2600	Resistant to major pest and diseases, early maturing
JK 98	JNKVV, Jabalpur	100–105	2500–3000	Resistant to shoot fly and MR to head smut
DPS 9–1	JNKVV, Jabalpur	105–110	2700–3000	Tolerant to shoot fly
RK 390–25	Jagdalpur-IGKVV	100–105	2500–2800	Non shattering and non-lodging
Jawahar kodo	Rewa, JNKVV	100–105	2600–2900	Suitable for sole and mixed cropping
CO 3	TNAU	120	1500–1800	Tolerant to smut
TNAU 86	TNAU	105–110	2700–3200	Tolerant to head smut, sheath blight, and brown spot
JK 137	JNKVV, Jabalpur	102–107	2900	Resistant to drought and tolerant to diseases

(continued)

Variety	Institute	Duration (days)	Avg yld (kg ha^{-1})	Special features
ATL 1	TNAU, CEM, Athiyanthal	105–110	2600	Drought tolerant, uniform maturity, Non lodging

2.2.7 Proso Millet (*Panicum miliaceum L.*)

Proso millet is a drought-evading crop with its minimum duration across all the minor millets. It consists of several other names such as hog millet, hershey millet, and broom corn millet. It is widely grown in Japan, Egypt, India, China, and eastern European countries (Lu et al. 2009).

2.2.7.1 Land Preparation

Primary tillage is done either with disc or mouldboard plough after the harvest of crops which is followed by secondary tillage with cultivator or harrows. Then, form beds of size 10 m^2 to 20 m^2 based on the availability of water.

2.2.7.2 Sowing

Take up sowing by adopting the seed rate of 10–12 kg ha^{-1} with the spacing of 25 × 10 cm. The depth of sowing should be 3–4 cm. Broadcasting can also be done.

2.2.7.3 Nutrient Management

Apply FYM or compost at 12.5 t ha^{-1} on the unploughed field, and incorporate the manure in the soil. In respect of inorganic fertilizers, adopt a blanket recommendation of 30:15:10 NPK kg ha^{-1}. Before sowing, the entire N, P, and K are applied as basal. The highest yield of 1887 kg ha^{-1} was recorded with the application of 40:20: 10 NPK kg ha^{-1} in shallow red soils (Basavarajappa and Basavaraj 2003).

2.2.7.4 Weed Management

Apply pre-emergence herbicide Atrazine at 0.28–0.56 kg ha^{-1} on 3 DAS (Anderson and Greb 1987) on the soil using backpack or knapsack sprayer fitted with a flat fan nozzle using 500 L of water ha^{-1} or apply pre-emergence herbicide Isoproturon at 0.5 kg ha^{-1} on 3 DAS, and on 20–25 DAS, apply post-emergence herbicide 2,4-D at 1.0 kg ha^{-1} to control weeds (Chapke et al. 2018). If herbicides are not used, hand weeding is done on 15 DAS and 30 DAS to control weeds.

2.2.7.5 Water Management

It is grown as a rainfed crop and it requires very less rainfall for growth and development. Soil and moisture conservation practices are adopted to improve the yield of crop. During dry spell, protective irrigation is given from the farm pond through mobile sprinklers.

2.2.7.6 Crop Protection

Generally, spraying of pesticides and fungicides is not required as there is no major problem of pests and diseases.

2.2.7.7 Varieties of Proso Millet

Varieties	Institute	Grain yield (kg ha^{-1})	Duration (days)	Special features
PRC 1	GBPUA&T, Pantnagar	Grain: 1000–1200	70–75	Resistant to leaf blight
CO (PV) 5	TNAU, Coimbatore	2400 (rainfed)	70	High tillering, short duration, fits well in double cropping system
TNAU 202	TNAU, Coimbatore	2000 (rainfed)	70–75	Short duration, no incidence of pest and diseases and nutritive grains suitable for value addition
ATL 1 (TN*Pm* 230)	TNAU, CEM, Athiyanthal	2152 (grain yld)	70–75	Tolerant to shoot fly high yielding and drought tolerant with good grain quality
DHP 2769	UAS, Dharwad	Grain: 2450 Fodder: 4100	70–72	Suitable for contingency planting

2.2.8 Barnyard Millet (*Echinochloa frumentacea*)

Barnyard millet is a drought-tolerant millet with compromising hidden potential to withstand the water logging conditions. It is consumed similarly as rice and is used as a cage feed for birds. It also encompasses a good forage ability and is used as a fodder crop (Ugare et al. 2014).

2.2.8.1 Land Preparation

Primary tillage is done either with iron plough or country plough after the harvest of crops which is followed by secondary tillage with cultivator for breaking clods. Then, form beds of size 10 m^2 to 20 m^2 based on the availability of water.

2.2.8.2 Sowing

Take up sowing by adopting the seed rate of 10 kg ha^{-1} at a depth of 3–4 cm. Spacing of 25 × 10 cm is maintained to obtain the desirable yield. Broadcasting can also be done after planting.

2.2.8.3 Nutrient Management

Apply FYM or compost at 12.5 t ha^{-1} on the unploughed field and incorporate the manure in the soil. In respect of inorganic fertilizers, adopt a blanket recommendation of 40:30:50 NPK kg ha^{-1}. Before sowing, the entire N, P, and K are applied as basal. The highest grain yield of 2019 kg ha^{-1} was recorded with the application of 60:20:15 NPK kg ha^{-1} (Vimalan et al. 2019).

2.2.8.4 Weed Management

Apply pre-emergence herbicide Isoproturon at 1.0 kg ha^{-1} on 3 DAS on the soil using backpack or knapsack sprayer fitted with a flat fan nozzle using 500 L of water ha^{-1}. On 20–25 DAS, apply post-emergence herbicide 2,4-D at 1.0 kg ha^{-1} to control weeds (Chapke et al. 2018). Hand weeding is recommended on 15 DAS and 40 DAS, if herbicides are not applied.

2.2.8.5 Water Management

Barnyard millet is grown as a rainfed crop and it requires very less rainfall for growth and development. Soil and moisture conservation practices are adopted to achieve the desirable yield.

2.2.8.6 Crop Protection

Generally, spraying of pesticides and fungicides is not required as there is no major problem of pests and diseases.

2.2.8.7 Recently Released Varieties of Barnyard Millet

Variety	Institute	Duration (days)	Avg. yld (kg ha^{-1})	Special features
DHB-93-2	ARS, Hanumanmatti, UAS Dharward	86–88	Grain yield: 2760 Fodder yield: 6190	Suitable for contingency planting
MDU-1	TNAU, Madurai	95–100	Grain yield: 1500–1700 Fodder: 3000–3300	Non-shattering, suitable for all cropping seasons with high milling percentage (70%)
DHBM-93-3	ARS, Hanumanmatti, UAS, Dharwad	90–95	2200–2400	Responsive to fertilizer application
CO (KV) 2	TNAU, Coimbatore	95	Grain yld: 2650 (irrigated) 1500–1700 (rainfed)	Non-shattering and good grain quality

2.3 Economics of Millet Cultivation

2.3.1 Economics of Millet Cultivation

The economics for each crop was worked out based on the average yield of the crop at normal conditions which may vary with climatic factors. The cost of production was also worked out based on the prices of inputs at this point of time. The cost of production and the net return are variable based on their location among the states (Table 2.2).

Table 2.2 Cost of production and net returns of millet crops (ICAR–Indian Institute of Millets Research 2016)

Crops	Grain yield (kg ha^{-1})	Straw yield (kg ha^{-1})	Gross return—grain yield (Rs. ha^{-1})	Gross return—straw yield (Rs. ha^{-1})	Total gross return (Rs. ha^{-1})	Cost of production (Rs. ha^{-1})	Net return (Rs. ha^{-1})	B:C ratio
Great millet	3400	9200	68,000 (Rs. 20 kg^{-1})	9200 (Rs. 1 kg^{-1})	77,200	38,264	38,936	2.02
Pearl millet	3800	7200	76,000 (Rs. 20 kg^{-1})	7200 (Rs. 1 kg^{-1})	83,200	38,951	44,249	2.14
Finger millet	3500	6698	70,000 (Rs. 20 kg^{-1})	6698 (Rs. 1 kg^{-1})	76,698	38,867	37,831	1.97
Little millet	1700	4300	34,000 (Rs. 20 kg^{-1})	4200 (Rs. 1 kg^{-1})	38,300	19,820	18,480	1.93
Foxtail millet	1900	5100	38,000 (Rs. 20 kg^{-1})	5100 (Rs. 1 kg^{-1})	43,100	21,980	21,120	1.96
Kodo millet	3000	7400	60,000 (Rs. 20 kg^{-1})	7400 (Rs. 1 kg^{-1})	67,400	29,180	38,220	2.31
Proso millet	2400	6000	60,000 (Rs. 25 kg^{-1})	6000 (Rs. 1 kg^{-1})	66,000	28,746	37,254	2.30
Barnyard millet	2700	6800	54,000 (Rs. 20 kg^{-1})	6800 (Rs. 1 kg^{-1})	60,800	30,425	30,375	2.00

2.3.2 Strategies for Enhancing the Productivity

More opportunities are now available for maximizing the productivity of millets to meet the increasing demand of millets owing to the recent changes in consumption pattern towards better nutrition (Bisalaiah and Patil 1987; Badal and Singh 2010).

To overcome the constraints and to improve their productivity, the following strategies should be adopted.

- Replacement of low yielding or conventional varieties with high yielding recently released varieties.
- Public–private partnership for production and delivery of high-quality seed.
- Inclusion of legumes in crop rotation or through intercropping to enrich soil fertility and sustainable productivity.
- Proper soil and moisture conservation measures, viz. agronomic, engineering, and agro-ecological techniques, should be followed to improve the soil moisture storage.
- Adopt mechanization practices for sowing, fertilizer application, weeding, and harvest.
- Organize field demonstrations to evince the yield potential of the high yielding varieties with recent technological interventions.
- Balanced application of manures and fertilizers through integrated nutrient management.
- Promotion of processing industries and value addition.
- Create awareness among the farmers and SHG in respect of production and value addition in millets through trainings.
- Commodity group formation for higher market price.

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Millet Storage and Pest Management

3

R. Meenatchi and M. Loganathan

Abstract

Millets are grown in Asian and African countries, where India is the leading producer. Due to the presence of nutrients, it is capable of preventing micronutrient deficiencies. Majorly grown millets in the world are pearl millet (*Pennisetum glaucum),* finger millet (*Eleusine coracana*), finger foxtail millet (*Setaria italica*), barnyard millet (*Echinochloa frumentacea*, sorghum (*Sorghum bicolor*), kodo millet (*Paspalum scrobiculatum*), and little millet (*Panicum sumatrense*). They are rich in vitamins, minerals, proteins, and essential amino acids such as linoleic and linolenic acids. They are the good source of phytochemicals and micronutrients, hence called as "nutria-cereals." Millets are traditionally stored in traditional storage structures such as clay pots or raised huts. At farm and at household level, millets are stored conventionally in jute gunny bags, clay pots, and airtight containers during surplus and off season. Millets are stored either at farm or household level. During storage, they are infested by several species of insects including *Rhyzopertha dominica, Sitophilus oryzae, Tribolium castaneum, Sitotroga cerealella*, and *Ephestia cautella*, resulting in loss of quantity and nutritional quality. Biotic and abiotic factors affect the insect infestation and quality of the stored millets. Indigenous traditional knowledge (ITK) has tremendous role in insect pest management. Natural products and plant-based insecticides are used from ancient days to protect the crops and commodities from pests and livestock. The scientific knowledge available with the literature on various methods of insect pest management can be used for the storage of millets. It is necessary to consider the storage conditions, environmental factors, and the stage of the insect to protect millets from insect pests and to

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preserve its quality. Stored pests of millets, their damage, and management techniques used for the safe storage millets are discussed in this chapter.

Keywords

Millets · Storage · Infestation · Insect management · Traditional knowledge

3.1 Introduction

Millets are rich in nutrients capable of solving the problem of micronutrient deficiency. They are majorly grown in dry areas of Asian and African countries since they tolerant to drought. India, the leading producer of millets, produced 11.64 MMT (FAOSTAT 2018). It is considered as one of the oldest human food and believed to be the first domestic cereal grain (Michaelraj and Shanmugam 2013).

Majorly grown millets in the world are pearl millet (*Pennisetum glaucum),* finger millet (*Eleusine coracana*), finger foxtail millet (*Setaria italica*), barnyard millet (*Echinochloa frumentacea*, sorghum (*Sorghum bicolor*), kodo millet (*Paspalum scrobiculatum*), and little millet (*Panicum sumatrense*). Finger millet is considered as the most common small millet in the world, and Uganda is the center of its origin. They are rich in vitamins, minerals, proteins, and essential amino acids such as methionine. They are good source of phytochemicals and micronutrients, hence termed as "nutria-cereals" (Sehgal and Kwatra 2003).

Normally, millets are harvested as panicle/heads, dried, and stored intact in storage structures. The heads after harvesting are pounded and winnowed to separate the grains and used for future storage. It is dehulled and ground to flour as and when required. Millets are traditionally stored in traditional storage structures such as clay pots or raised huts. At farm and at household level, millets are stored conventionally in jute gunny bags, clay pots, and airtight containers during surplus and off season.

Storage resumes importance and greater significance since storage losses are huge (Aulakh et al. 2013; Bala et al. 2010; Majumder et al. 2016). About 50–60% of millet storage in developing countries used traditional structures (e.g., Kanaja, Kothi, Sanduka, earthen pots, Gummi and Kacheri) for grain and seed purposes (Grover and Singh 2013). Indigenous structures are made using farm materials such as dried grass, wood, mud, etc., which are not ineffective storage. Costa (2014) estimated losses up to 59.48% in maize grains stored for 90 days in the granary/ polypropylene bags.

Millets are less preferred by insects due to its small size. Also, they are commonly grown in semiarid areas of the world where the relative humidity is typically less than 40%. Millets stored in either at farm or household, rural or trader at commercial level, are infested by several species of insects including *Rhyzopertha dominica, Sitophilus oryzae, Tribolium castaneum, Sitotroga cerealella*, and *Ephestia cautella*, resulting in loss in quantity and also nutritional quality. Rajendran and Chayakumari (2003) reported the insect damage susceptibility, physicochemical changes, and germination of millets.

3.2 Insect Pests of Millets

Common name, scientific name, and family	Host	Stage of insect infest millet	Damage symptoms
Rice weevil: *Sitophilus oryzae, S. zeamais, S. granaries* (Curculionidae; Coleoptera)	Maize and jowar	Grubs and adults	Circular hole in the grains
Lesser grain borer: *Rhyzopertha dominica*, (Bostrychidae; Coleoptera)	Maize, pearl millet	Grubs and adults	Webbing and make the grain and flour into frass
Khapra beetle: *Trogoderma granarium* (Dermestidae; Coleoptera)	Maize and sorghum	Grub	Feed on the germ portion; damage is confined to the top portion
Angoumois grain moth or grain moth: *Sitotroga cerealella,* (Gelechiidae; Lepidoptera)	Maize and sorghum	Larva	Damage upper 30 cm grain
Red flour beetle: *Tribolium castaneum* (Tenebrionidae; Coleoptera	Sorghum, jowar, finger millet, proso millet, etc.	Adults and larva	Prefer milled products and broken grains, produce off odor
Flat grain beetle: *Cryptolestes minutas, Laemophloeus pusillus* (Cucujidae; Coleoptera)	Maize, pearl millet, barnyard millet, and flours	Grubs and adults	Grub feeds on germ portion and heating of grains
Saw-toothed grain beetle: *Oryzaephilus surinamensis* (Silvanidae; Coleoptera)	Maize, sorghum, and foxtail millet	Grubs and adults	Grains with more of broken, dockage results in severe damage
Rice moth: *Corcyra cephalonica* (Galleridae; Lepidoptera)	Jowar, pearl millet, and foxtail millet	Larva	Dense webbing. Kernels turn to lumps up to 2 kg
Fig or almond or warehouse moth: *Ephestia cautella* (Phycitidae; Lepidoptera)	Maize, jowar, and pearl millet	Larva	
Indian meal moth: *Plodia interpunctella* (Phycitidae; Lepidoptera)	Pearl millet	Larva	Grains with excreta, larva construct silken tunnel

3.3 Factors Affecting Millet Storage

Shelf life of the millet during storage depends on the levels of abiotic and biotic factors with the grain ecosystem. The following are considered as important factors responsible for damage to the grains: (1) moisture content, (2) temperature, (3) time or storage period, (4) field infestation/carryover infestation, (5) cracks and crevices, (6) packaging materials/containers/bags used for the storage of millets, and (7) trucks, trolleys, and other transportation methods used for shifting.

3.3.1 Moisture Content

The safe moisture content for most of the grains including millets ranges from 11.00% to 12.00%. When the moisture content of the grain is ranging from 8% to 9%, it will not support insect growth especially rice weevil and granary weevil, and the adults will soon die in dry grains (Cotton 1963). Similarly, high moisture content above 16% does not support insect activity and leads to microbial growth.

3.3.2 Temperature

The stored grain insects are capable of reproducing and functioning only in a certain temperature range, because of their inability to maintain a constant body temperature. The moisture content and temperature of the grains are the most significant factors affecting the survival of stored insects. At high temperatures above 55 °C, stored pests cannot survive and develop (Fields 1992). Storage life of millet is inversely related to temperature and relative humidity during storage. Reducing storage temperature and humidity reduces mold growth.

3.3.3 Duration of Storage

The possibilities of infestation are more in the grains stored for longer duration. When the millets are stored for long time, it leads to reduced quality and free fatty acids are increased.

3.3.4 Field Infestation

Infestation in the field level is one of the important sources of infestations. Pulse beetle, *Callosobruchus chinensis* and *Sitotroga* sp. are good fliers, attracted towards light. They fly from stores to fields and lay eggs upon maturing grains. The eggs laid will hatch out when the environmental conditions are favorable, and it reaches the storage areas/godowns. Carryover pest damages both the field and stores.

3.3.5 Cracks and Crevices

It is important to keep the storage structures clean and hygienic to prevent stored pests. The cracks and crevices in the godown and warehouse attract pests; they hide and feed the fresh stocks and reproduce.

3.3.6 Storage Containers

Gunny bags are commonly used for storage for ease of shifting and transport and cost effectiveness. Reuse and improper uncleaned bags are the inoculum for pests. It is important to properly clean and disinfest the storage containers before use. The grains and powders left in the boot during milling should also be removed. There is a possibility that insect eggs and larvae remain hidden in the seams and mesh of the gunny bags.

3.3.7 Transportation Containers

Pests can remain in the transport containers while transporting from one place to another through trucks, trolleys, and bullock carts. Insects found in the joints or corners of the transport containers migrate to uninfected commodities, which acts as the source of cross infestation.

3.3.8 Sources of Infestation

The following are the main sources of infestation.

1. Field infestation.
2. Infestation empty, already used gunny bags.
3. Infestation from the machineries.
4. Infestation by migration.
5. Infestation through conveyances.
6. Infestation from threshing yards.
7. Infestation through wind current from nearby field.
8. Infestation from already stored infected materials.
9. Infestation from the cracks and cervices of the godown.
10. Infestation from the bird's nest.
11. Infestation from the ant and rodent burrows.

3.4 Management of Storage Insects in Millets

3.4.1 Traditional Storage Knowledge

Indigenous knowledge has tremendous role in insect pest management. It is the wisdom of the particular community based on the culture, experience, and understanding of the nature and natural resources. Natural products and plant-based insecticides are used from ancient days to protect the crops and commodities from pests and livestock (Dunkel and Sears 1998). Indigenous grain storage practices are location specific and are widely used in the rural households. Though there are advanced storage methods available, many farmers still rely on traditional storage methods for fodder and seed purpose.

Farmers were unaware of the source of infestation, carryover pests from field to warehouses, lifecycle of the pest, and the stages of insect to which it is tolerant or susceptible. With the rising health and environmental concerns, indigenous traditional knowledge (ITK) is becoming more important.

3.4.2 Conventional/Traditional Storage Structures

They are made of farm waste, grass, wood, mud, etc. It doesn't guarantee to protect millets against pests for long time. Though they are being relatively simple and inexpensive to construct, it leads to substantial post-harvest losses characterized by increased pest density and microbial and fungal contamination which finally affect the producers as well as consumers (Promila and Binoo 2013). Poor maintenance and improper storage lead to accountable loss of commodities through physical, biochemical, and microbial changes which alter the nutritional quality.

Most of the farmers in India are adopting conventional methods with the use of existing available farm-based raw materials such as paddy and straw, bamboo, mud, bricks, and cow dung (Sundaramari et al. 2011). They vary in design, shape, size, and functions and can be used at indoor or underground level (Nagnur et al. 2006). These structures permit free flow of air, resulting insect and rodent damage (Karthikeyan et al. 2009). Oxygen and temperature fluctuations are more common results in quality deterioration through mold growth (Jonfia-Essien et al. 2010). But, indigenous grain storage practices are still in practice in most of the tribal areas.

Tribal farmers use traditional storage structures for maize. The cobs are tied to overhead ropes, mud pots, bamboo basket, gunny bags, and cloth bags for safe storage. Frequent drying in sunlight is considered as the best practice to prevent multiplication of insects. The use of lime powder, neem leaf, *Vitex negundo*, mixing seeds of *Semecarpus anacardium*, etc. is traditionally practiced to protect millets from various stored grain insects (Naveena et al. 2016). They are not airtight and moisture-, insect-, and rodent-proof.

3.4.3 Storing in Pits

Storage pits are usually dug in soils which are rich in sand or stones and possess less water drainage problem so that it does not collapse the pits. It provides protection from fire, theft, insect pests, and animals. Low investment in pit preparation, and the places where wood for aboveground bin construction is not available, is more feasible. Farmers also believe that grain stored in underground pit is blessed by God and bountiful. Pits are neither lined nor plastered with any material that would reduce moisture migration into the stored grain (Gilman 1968). Grains which are in contact with the inner wall of the pit are more susceptible tomoisture migration results in increased relative humidity and moisture content of millets during storage.

High temperature and water activity are common due to respiration by insect pests, mainly by rice weevil, angoumois grain moth and red floor beetle, microfungi, and other microorganisms (Adams 1977; Neergaard 1977; Bothast 1978; Meronuck 1987; Copeland and McDonald 1995). When stored in pots, mold growth and grain deterioration are common (Sashidhar et al. 1992). Also, often it is mixed with collapsing soil from the walls, thus reducing the quality and affecting its purity and market value. Loss varies based on the location where pit is kept, grain, grain moisture, season, etc. High initial grain moisture content during storage results in direct leakage of rainwater increasing the infestation by mold and insect pests (Dejene et al. 2004b).

Underground pits are used for the storage of millets and are usually covered by gunny bags (Sundaramari et al. 2011). Mashilla Dejene et al. (2004b) reported the reduced germination vigor and nutrient loss in sorghum. Underground pit storage for sorghum is not suitable for long-term storage, and grain deterioration is more common as compared to those in improved grain storage structures (Mashilla Dejene et al. 2006).

A study conducted by Lale and Yusuf (2000) in Nigeria shows that damage to pearl millet stored in the underground pits are significantly high (80.1%) followed by storage in rumbu (39.2%), clay pot (15.8%), and polypropylene sack (14.0%). The damage to pearl millet was primarily due to the presence of *R. dominica* (6.80%) and *S. zeamais* (0.6%) and followed by *T. castaneum*, *C. ferrugineus*, and *L. bostrychophilus* with 47.70%, 27.80%, and 17.0% respectively. The grain loss is positively correlated with the storage period.

Maize is stored in traditional granaries in Western Kenya because of the inability to afford the high cost of improved structures. They are damaged by almost all pests causing 40% grain losses (Charles et al. 2016). Increased moisture content of sorghum stored in pits in eastern Ethiopia resulted in elevated grain moisture occurrence of insect pests and fungi (Dejene et al. 2004a). It is essential to go for modified underground pits and to use airtight bins to maintain the quality and for long-term storage.

Nonscientific storage methods, residues left after fumigation, and non-chemical methods are much preferred to maintain quality and safety of the food and prevent foodborne illnesses. Among the various storage methods, hermetic storage is gaining importance due to its pesticide- and chemical-free nature. Low-cost hermetic storage is the suitable method for food commodities that are zero-tolerant to insects and toxic residues, as well as for organic commodities. It is a promising technique to improve the shelf life and to maintain the quality of the stored products (Murdock et al. 2012).

The availability of oxygen for insects and molds get reduced; thus the modified atmosphere within the hermetically stored environment prevents the exchange of gas and moisture (Navarro et al. 1993). Hermetic storage includes the available methods, viz., hermetic bags, silos, and cocoons. There are mainly three types of hermetic storage based on the way in which modified atmosphere is created inside the stored sample (Villers et al. 2006).

1. *Organic Hermetic Storage*
   The modified low-oxygen environment is created due to metabolic activities of insects, fungi, or microflora present inside the airtight hermetic storage during respiration, which leads to asphyxiation of the living organism. The decrease in oxygen and rise in the carbon dioxide lead to the prevention of multiplication of stored pests and molds. This method has wide adaptability since one can use flexible PVC containers and airtight bins, aluminum tins, multilayered bags, etc. (Villers et al. 2006). Farmers in Sub-Saharan Africa store maize and small millets using hermetic storage.
2. *Vacuum-Hermetic Fumigation*
   It is nothing but creating an artificial mechanism by which purging airtight storages with CO_2 or N_2 by using pumps, generators, and scrubbers after creating vacuum with low pressure.
3. *Gas-Hermetic Fumigation*
   Artificially external carbon dioxide gas is injected by removing oxygen inside to create unfavorable condition for pest growth.
4. *Hermetic Bags*
   Flexible single-lined or triple-layered super grain bags of various capacities ranging from 10 to 100 kg are available for farm level usage. These bags are reasonable with cost and reusable (Villers et al. 2006). It possesses good physical strength and impermeable to gases. Double-layered hermetic bags have inner layer made of high-density polyethylene (HDPE) and are transparent in nature. Grains stored in the grains are not affected by external environmental conditions. Grain Pro bags ™, Pro-harvest™, and Storezo bags are used for small-scale storage and Cocoon™ is used for bulk storage.

3.4.4 Controlled Atmospheric Storage

Controlled atmosphere helps to maintain the quality of the product and also reduces the insect infestation due to the availability of less oxygen for respiration. The effect of combination of atmospheric gases (35% CO_2 + 15% N_2 and 13% O_2) on the mortality of *T. castaneum* in raw polished and parboiled little millet using aluminum pouch and HDP and LDP bags were studied under laboratory conditions (Vachanth et al. 2010). The raw polished little millet stored in aluminum pouch attained 100% mortality of adults stored in aluminum pouch followed by HDP and LDP with 40% and 20% in 15 days storage period. The parboiled little millet achieved cent percent mortality of *T. castaneum* in aluminum pouch on the fifth day itself and achieved 60% and 70% adult mortality in HDP and LDP on the 15th day. Retention of gas is based on the permeability of the packaging materials. Parboiled rice gets less rancidity and insect attack compared to raw millets. This may be due to more attraction of bran in raw rice. Studies on the feeding preference of *T. castaneum* in sorghum, finger millet, pearl millet, and barnyard millet by Gagan et al. (2019) showed that sorghum attracted more 34% of *T. castaneum* followed by finger millet (28%) and pearl millet (18%) of the adults. Barnyard millet was least attracted 12% *T. castaneum* in an olfactometer feeding preference test.

3.4.5 Resistance to Insects in Millets

Millets have the natural resistance to stored product insects to some extent. The phenolic content present in some of the varieties are responsible for resistance to stored product insects. The sorghum varieties in Ethiopia were found significant variations by genotype in soluble phenolic content providing resistance to rice weevil, *Sitophilus oryzae* (Ramputha et al. 1999). The variety, temperature, and time had significant effects on infestation and maize quality parameters. Suleiman et al. (2015) found that orange flint corn and yellow and white popcorn showed resistance to *S. zeamais*. Different varieties (white dent, yellow dent, orange flint, Indian flint, white popcorn, yellow popcorn, and sweet corn) were tested. Among the seven varieties, orange flint corn and yellow and white popcorn were reported as potential maize varieties because of their natural resistance to *S. zeamais* infestation and capability of reducing postharvest loss in tropical countries. The resistance is due to non-preference and mortality of larvae feeding the seeds, which is associated with antibiosis. The developmental period of insect was significantly longer in resistant variety than susceptible cultivars. Positive linear relationship between developmental periods and larval mortality due to antibiosis is reported by Adetunji (1988). Harder kernels with higher endosperm percentage, low ash, increased amylose, and reduced free amino nitrogen in sorghum were resistant to *S. zeamais* (Chuck-Hernández et al. 2013). Also, small sized and immature maize grains were reported as susceptible to the damage by stored pest compared to bigger size and matured grains (De Groote et al. 2017).

3.4.6 Biological Control

Biopesticides for the management of storage pests are limited to lab studies. In Africa, insect pathogenic fungi, *Metarhizium anisopliae, Beauveria bassiana*, and *Nomuraea rileyi*, were tested for the management of *Sitotroga cerealella* in grain sorghum. Treatment for 7 days with *M. anisopliae* at a concentration of 2.6×10^9 conidia/50 g of sorghum showed better results than treatment with pirimiphos-methyl at 10 ppm (Ekesi et al. 2000).

3.5 Integrated Pest Management (IPM) for the Management of Insects in Millet Storage

The following practices can be integrated to manage stored pests of millets (Fig. 3.1).

- Harvest millets at correct maturity stage.
- Millets should be dried to a moisture level of 10–12% for safe storage.
- It has to be thoroughly cleaned and graded before storage.
- Packaging materials and storage containers should be properly cleaned and disinfested before storage.

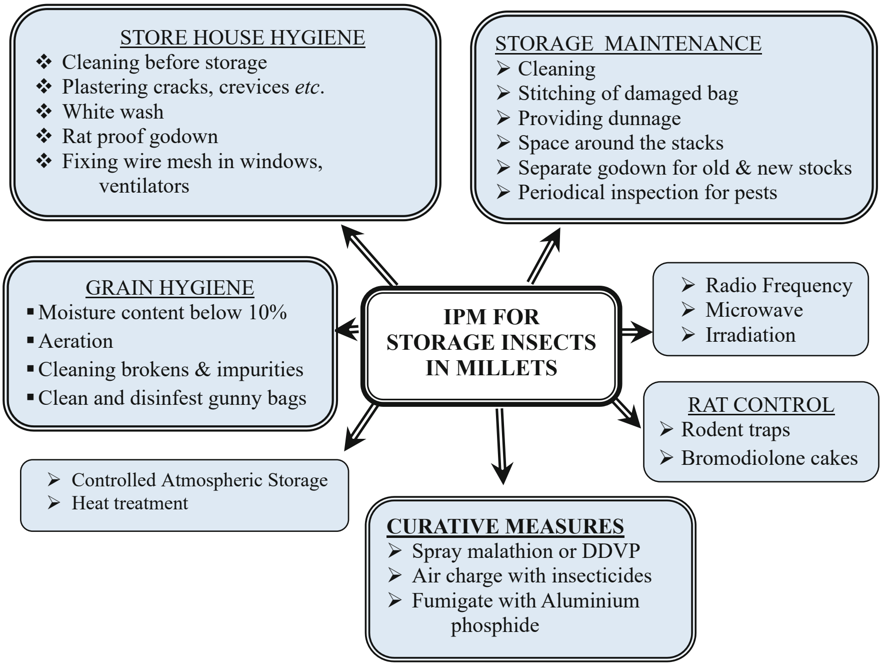

Fig. 3.1 IPM for millet storage

- Storage structures should be kept in the coolest part of the house/farm.
- Monitoring temperature, moisture content, and carbon dioxide concentration inside the storage structure helps us to diagnose early infestation. Insect releases heat as they respire, and at high insect densities, “hot spots” may be created and insects cause significant damage before they are detected. IPM can significantly reduce the population of millet pests as reported by Charles et al. (2016).
- Fixing of wire meshes in the windows and ventilators can prevent the entry of flying insects.

3.6 Conclusion

Storage of millets using scientific safe storage methods and structures are considered as important aspects to preserve their nutritional quality. Though traditional storage structures are used by farmers, it has its own merits and demerits. Further, improved structures and use of ITKs are implemented in the rural and tribal areas to prevent insect infestation. Hermetic storage can be the best method for storing millets at household and at farm level. The millets stored in cocoon retain the nutrients and grain moisture up to 12 months storage periods. There is a need to develop safe storage protocols for millets under Indian conditions since there is a great demand for millets due to its nutrients. It is necessary to increase the knowledge of farmers about the life cycle of stored pests, sources of infestation, and knowledge sharing to create better understanding of stored pests and safe storage protocols. It is evident that the integrated pest management is very effective in the field for managing the insects. Hence, there is a need to address the challenges in the traditional storage structures and also adopting of modern storage and IPM approaches. The scientific knowledge available with the literature on various methods of insect pest management can be used for storage of millet. It is necessary to consider the storage conditions, environmental factors, and the stages of the insect to protect millets from insect pests and to preserve the quality.

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Major Millet Processing

4

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Abstract

In the current global scenario, millets are being widely consumed as "superfood". It is rich in chemical composition, phytochemicals and other nutritional beneficial compounds. It is necessary to understand the structure, composition and engineering properties to develop various postharvest systems and processing and handling equipment. Once the crop attains the desired maturity level, harvesting of millets is carried out manually or using a mechanical harvester-cum-thresher. A series of postharvest unit operations are involved in millet processing such as cleaning, drying, pretreatment, decortication, polishing, grading/sorting and milling. The engineering properties of millets are highly influenced by the moisture level, type of variety, genotype, stage of maturity, geographical location, agricultural practices and many more. Decortication of millet is a challenging process, and a rubber roll sheller and abrasive polisher are commonly used for this purpose. Increase in global demand for consumption of millets has led to the development in production, processing and value addition. Modern processing industries are equipped with sophisticated milling, grading and sorting (colour sorter) facilities to produce high-quality millet products. Still, further research and innovation are required in case of millet processing for the development of the postharvesting system and processing and handling equipment.

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Keywords

Superfood · Engineering properties · Decortication · Grading/sorting · Milling

Abbreviations

CIE	Commission Internationale de l'Eclairage
FAO	Food and Agriculture Organization
hp	Horsepower
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics

4.1 Introduction

The term millet refers to tiny-grained cereal-like species that occur as tropical grass-type plants with edible seed kernels. The major millets sorghum, pearl millet and finger millet are called so due to their larger grain size than the other varieties of millets. They are majorly grown and consumed in Africa (42%) and Eurasia (58%) (Serna-Saldivar and Espinosa-Ramírez 2018). In earlier times, these major millets were very limitedly used for food purposes. It is in recent times that they obtained popularity owing to their superior chemical composition, mineral content and fibre-rich and health benefitting role against diseases like diabetes mellitus and heart ailments (FAO 2017). Millets are semi-arid crops and are mainly grown as subsistence crops. In countries like the United States, these millets are used as livestock feed, whereas in India and African countries, they are used for human consumption, either directly or after processing. These major millets contain good amounts of phytochemicals, phenolics, minerals, vitamin B and tocopherols along with few anti-nutritional factors. They also consist of a few essential antioxidants and exert positive health effects. They have recently been utilized in producing fermented beverages and gluten-free flours for culinary purposes (Serna-Saldivar and Espinosa-Ramírez 2018; Taylor et al. 2018). In developing countries, processing of such locally cultivated foods to produce value-added products can be a good boost to economic growth and can also help in reducing food losses and wastages. Also, processing these crops can add to the value of the product leading to good returns to the growers. The processing included production and postproduction activities along with the production of different products for food and non-food uses from these crops. The non-food uses like the production of bioethanol, extraction of tannins from sorghum, malting and brewing, production of enzymes, starch separation and development of biodegradable polymers (Taylor et al. 2018) can be highly beneficial and can boost the returns to the cultivators.

This chapter elaborates about the major millets, their structure, engineering properties and processing including the unit operations like harvesting, threshing, drying and milling.

4.2 Structure of Millet Grains

Information about the structure of different millets is important to develop postharvest systems and handling and processing equipment. The major millets sorghum and pearl millet are categorized as the caryopsis, which is a single-seeded fruit, in which the pericarp that encompasses the seed adheres tightly to the seed coat, making it difficult to separate, whereas the finger millet belongs to the category utricles, in which the pericarp is loosely attached to the seed coat and is not completely fused (Taylor and Duodu 2017). All the major millets have a similar basic kernel structure, comprising of the pericarp, germ and endosperm, which is the largest component of the kernel structure. The epicarp can be distinguished into three different layers, namely, epicarp, mesocarp and an inner endocarp (Abdelrahman et al. 1984). The epicarp of sorghum is two to three layers thick with rectangular cells and is mostly covered with a thin wax layer called the cuticle, which prevents moisture loss. The mesocarp layer has three or four layers with rectangular-shaped cells and contains small starch granules. The thickness of the endocarp varies from kernel to kernel but generally varies from 8 to 160 μm with tube and cross cells (Earp and Rooney 1982). The tube cells lie on the inner side and conduct water during germination of the seed. The outer lining comprises of cross cells that avoid water transpiration by forming a blockage on tube cells (Serna-Saldivar and Espinosa-Ramírez 2018). In pearl millet, the epicarp is one to four layers of cells with thick walls and the mesocarp does not contain any starch granules (McDonough and Rooney 1989). Unlike sorghum and pearl millet, the pericarp in finger millet is loosely attached and is often detached during harvesting and processing (Mcdonough et al. 1986). Below the endocarp layer, a testa (also called a seed coat) layer occurs in the grain, followed by an endosperm. The thickness of the testa layer differs among different millets and also in different cultivars of the same millet as a varietal property (Siwela et al. 2007). Generally, the testa layer contains the pigmentation compounds of the grain and contains condensed tannins. The finger millet contains five sub-layers in the testa, which contains different proportions of tannins that imparts colour to the grain from red to purple. The sorghum grain is categorized into type II and III based on the level of pigmentation, where type III contains a greater proportion of tannin content (McDonough et al. 1986). The thickness of the sorghum testa usually ranges from 8 to 40 μm and is found to be thickest near the style and thinnest at the side portions of the kernel (Earp and Rooney 1982). The seed coat in pearl millet is very thin and can be disintegrated during maturation according to few reports (Rooney and McDonough 1987).

The endosperm occurs as a peripheral corneous portion and a floury central part. The peripheral portion of the endosperm is layered by a single layer of aleurone that contains protein globules and lipids in the form of spherosomes, apart from enzymes and minor nutrients (Serna-Saldivar 1995; Serna-Saldivar and Espinosa-Ramírez 2018). The peripheral endosperm is rich in protein bodies and contains a small portion of starch molecules in the first one or two layers of cells. The corneous (or vitreous) layer of the endosperm consists of uniform and large starch particles entrenched in a thick protein matrix. The floury endosperm consists of large starch granules that are loosely arranged in a semi-continuous protein matrix. The arrangement of protein bodies and starch granules in the floury endosperm is comparatively loosely packed, as with tight embedding in the corneous portion. The proportion of floury to corneous endosperm is highly varied and depends on the type of millet, cultivar and environment (Rooney and McDonough 1987). The floury endosperm appears to be opaque due to the occurrence of air voids that diffract the incident light (Hoseney et al. 1974). The germ is situated in the endosperm and consists of an embryonic axis and a scutellum. The embryonic axis contains the next generation of the plant and forms the radicle (primary roots) and plumule (shoot part) upon germination. The scutellum contains proteins, enzymes, lipids and minerals as a reserve tissue for further growth. The germ part in pearl millet tends to be higher than that of other grain crops (Zeleznak and Varriano-Marston 1982). In finger millet, a scutellar epithelium separates the scutellum from the floury endosperm.

Starch is one of the most important constituents of millets. The millet starch granules tend to occur as polygonal or angular in the corneous and globular in the floury endosperm. The sorghum grain contains polygonal starch granules with an average size of 15 μm and contains dents on the body due to the protein bodies. The sorghum starches generally comprise of 23%–30% amylose, whereas the waxy cultivars contain way lesser than the average (5%) (Serna-Saldivar 1995). In pearl millet, the starch granules occur as large, round globules of size ranging from 3 to 14 μm that are loosely packed in a discontinuous protein medium. The sorghum cultivars that are rich in lysine contain lesser and smaller protein bodies than the rest of the varieties (Serna-Saldivar and Espinosa-Ramírez 2018). The protein bodies present in sorghum are generally circular, with an average size of 0.5 to 2 μm (Taylor et al. 1984). The major fraction of protein is made up of the prolamine protein that is in the endosperm of almost all millets. The occurrence of a high amount of prolamine fraction makes millets lysine-deficient (Taylor and Schüssler 1986). The pearl millet comprises of superior-quality protein than other major millets, due to its threonine and tryptophan content (Rani et al. 2018). The lipid part of the kernel is largely concentrated near the scutellar portions of the germ and may be lost during milling of grain. The lipid matrix of millets consists of phospholipids, glycolipids, phytosterols, carotenoids and tocopherols. The aleurone and germ portion of millets are rich sources of water-soluble vitamin B. The finger millet germ also contains a substantial amount of calcium than other major millets (Serna-Saldivar 1995).

4.3 Harvesting

The major millets are important grain crops in semi-arid tropics, owing to their disease resistance and lower water consumption. These crops are grown until maturity before harvesting. Determination of grain maturity before harvest is an important criterion to avoid postharvest losses. This can be inspected by three simple tests. Formation of a black layer at the tips of the grain is a very useful direct indicator to determine the maturity of the grain. Also, retention of the shape and rigidity of the kernel when pressed with the thumb and index fingers shows that the grain is mature enough to harvest. Lastly, the grain being able to crack cleanly and show brittleness upon biting is also a good indication for harvesting (Beta and Ndolo 2018). The moisture content of the produce during harvest is a very important factor to consider. Grain with higher moisture content poses a threat of germination, attracts insects and pests and can undergo spoilage by fungi and moulds (Smith and Frederiksen 2000). Such grain tends to be soft and contain more cracked kernels than usual. Moreover, premature harvesting can yield grain of compromised quality and can result in weight loss. Similarly, late harvesting can give overdried grain with too less moisture or loss due to falling of dry grain from the panicles, resulting in loss in produce (Alam 2010; Beta et al. 2016). An ideal moisture content to harvest the grain ranges around 15% to 20%, for good yield and better-quality produce.

Use of appropriate cropping and processing methods can effectively help in obtaining good crop returns with minimal losses. The cultivators adapt the harvesting method best suited for their requirements based on the size of the farm, availability of manpower, etc. However, the most commonly adopted method of harvesting millet crops is traditional manual harvesting, owing to the smaller size of the millet fields and limited economic and agricultural resources with the farmers growing them (Beta et al. 2016). Manual harvesting employs a knife or sickle to cut the produce. Manual harvesting can be carried out in two ways. First, the entire plant is cut and bundled for in-field drying, after which the panicles are separated and threshed for grain. The remaining plant parts are utilized for several purposes like livestock fodder, fuel and biogas production and roofing system in a rural neighbourhood. The alternative approach for this is to manually cut the panicles from the plants, stack them and dry them before threshing to obtain edible grain. The remaining plant straw portions are cut later. However, the farmers generally opt for the first method since it gives them adequate time to prepare the fields for the next cropping season. In the case of mechanical harvesting, most of the cultivars use a combined harvester with sickle bar headers or row crop. Designing of the harvesting equipment must be done considering both short- and long-stalk sorghum varieties for more convenience (Alam 2010). The losses of grain during harvest can be minimized by maintaining a speed of 2.5 to 3.0 miles per hour, which is an acceptable range (McNeill and Montross 2003). While harvesting the long, standing sorghum, the harvesters must be able to cut the stalks as high as possible. In fields with stalks drooping and lodged, harvesters fixed with pickup guards are highly recommended to obtain grain kernels fully without losses (Smith and Frederiksen 2000). In case of fields with mixed stalks, it is recommended to raise the reel of a combined harvester, to ensure collection of all grains without wastage and spillage. In case of highly dense standing stalks, it is advisable to take a partial swath and to adjust speed between 4 and 5 kmph to avoid overloading (Bennett et al. 1990; Beta and Ndolo 2018). Generally, sorghum and pearl millet are harvested in the above-mentioned methods. The finger millet is predominantly harvested manually, mostly using sickle along with panicles. In all millets, after harvesting, the panicles along with stalks are dried in the field for 2 to 12 days based on the environmental conditions. The dried stalks are then bundled and sent to the threshing yard (Beta et al. 2016; Beta and Ndolo 2018).

Threshing is another important post-production unit operation in grain cultivation. It involves the separation of grain from stalks and panicles after drying. Manually, this process is done by laying the panicles on any surface and beating them or inside sacks (Alam 2010; Belton and Taylor 2004). In a few households, threshing is also done by hand pounding using long wooden sticks. In African countries, manual threshing is done by beating grain against any surface in plastic sheets, after which mortar and pestle are used further. In few regions of China and India, farmers (smallholders) spread the grains at 25 to 30 cm thickness on the road for vehicles to pass over them to do the threshing, or by using cattle-driven stone rollers over the grain (Beta et al. 2016). It is advised that manual threshing is done on cement blocks, mats or tarps instead of stones, or ground. Mechanical threshers work on the same principle as manual threshing but lessens the burden on the manpower and have greater output and efficiency. They work based on striking, squeezing or rubbing principles primarily. The efficiency of these mechanical threshers largely depends on moisture content, speed and a concave gap in the equipment (Alam 2010; Belton and Taylor 2004; Beta et al. 2016; Beta and Ndolo 2018). The threshed grain is cleaned to remove any impurities and unwanted material like sand, husk, chaff, small leaves, dust, broken seeds and insects. The traditional settings generally clean the grain by winnowing and washing. The mechanical removal of these unwanted materials is done by using aspirators to remove low-density materials and passing through screens with vibrations to remove stones and other high-density impurities.

4.4 Drying

The millet grains are optimally harvested at a moisture content ranging from 15% to 20%. This can be further brought down during storage up to 10%–12% or lower, by drying at prescribed optimal temperatures of 60 °C (Beta et al. 2016). This practice often helps in good storage of grain without germination, breakages and infestations. Factors like grain moisture content, surrounding temperature, environmental conditions and relative humidity directly affect the storage quality of grains. Improper regulation of temperature and relative humidity can cause absorption or desorption of moisture, leading to grain wastage. The millets usually dry faster than the cereals due to their smaller size. Conventionally, the drying of millets is done on-field as well as using mechanical drying equipment.

4.4.1 On-Farm Drying

On-farm drying involves stacking of the plant panicles into bundles and drying on the ground or a raised platform of about 0.3 m off the ground. The layers in the stacks are arranged perpendicular to the adjacent layer, to ensure uniform drying and to avoid the formation of any cold spots. The dimensions of each stack can be up to 2 to 3 m in height and 0.6 to 2 m in width. This drying is mostly employed by small- and medium-scale farmers with small landholdings and limited resources. The major disadvantages of this method are uneven and uncontrolled drying of grain, greater risk of infestation by pests or microorganisms, higher field losses, unpredictable weather conditions and plant stalk lodging (Alam 2010; Vogel and Graham 1978).

4.4.2 Mechanical Drying

The major challenges faced in on-field drying can be ward off by adapting mechanical drying techniques that are more convenient, efficient and customizable according to requirement. They are generally practised in developed countries and by farmers with large landholdings and higher turnover. Utilization of machine-assisted drying technologies can improve grain quality, minimize infestation and reduce losses and spillage and can be controlled and used during unfavourable weather. Three types of drying systems, namely, (1) unheated drying system, (2) air drying system with supplementary heat generation and (3) heated drying system, are used depending on the requirements (Alam 2010; Beta et al. 2016; Beta and Ndolo 2018). The unheated and supplementary heated drying systems are best suited for deep-bed drying of grain (2–3 m in depth), as low heat is preferred in such cases. However, it is beneficial to use heated bed drying systems in case of thin-layer drying (less than 0.5 m thickness) (Dendy 1995).

The unheated drying systems are the simplest and most economical of all the drying systems. They tend to dry the product by circulating air currents through a bed of the grain on an average speed of 0.02 to 0.04 m^3/s ideally (based on the moisture content of the grain), due to which the moisture gets lifted off from the grain due to desorption. However, this system cannot be used during rainy seasons, when the relative humidity in the atmosphere tends to be higher than 75% that makes drying highly difficult (Alam 2010; Beta et al. 2016; Dendy 1995). The supplementary heating type of drying systems, both direct and indirect type, aid heaters or electric burners to generate heat. The type of heat generation depends on the availability of resources and cost implications. In direct-type heating systems, the heated air comes in direct contact with the grain and eliminates moisture by adsorption. However, in indirect-type systems, a heat exchanger is used to raise the temperature of the grain by using the heat supplemented to it from the heating source. The direct method is rapid and more economical as about 25% heat is lost for the heat exchanger in the indirect method. However, in the direct heating systems, the quality of grain can sometimes be affected by the products of combustion being carried by hot air or the grain acquiring a smoky flavour from the fuel combustion. The heated drying system employs the principle of heating the material by direct contact without any medium of transfer (Beta and Ndolo 2018). Similarly, solar drying can be a very beneficial option for grain moisture adjustment before storage. They can be coupled with either natural circulation or forced convention. Such dryers have quite lesser drying time than unheated and conditionally heated drying systems. These drying systems can be used in both batch and continuous modes to ensure proper drying depending on the requirement. The airflow of air at 60–100 °C can be arranged to blow through the grain bed at a rate of 1.5 to 2.5 m^3/s ideally for continuous systems, whereas it can be up to 0.5 to 1.5 m^3/s for the batch type of drying systems for millets (Dendy 1995).

4.5 Engineering Properties of Major Millets

Engineering properties are also termed physical properties, which can be defined as the characteristics exhibited by foods and biological materials under certain form and state of energy. The engineering properties of millets play an immense role in characterization, quality determination and/or monitoring, handling and processing unit operations. These properties are also associated with the changes in physical and chemical composition at the micro (molecules) and macro (polymer) levels on processing and over storage. Besides, the study of engineering properties plays a significant role in designing various processing and handling equipment, development of sensors (colour sorter and grader) and process design. The major categories of engineering properties are mass, size (length, thickness, width), shape, true density, bulk density, tapped density, porosity, volume, colour, angle of repose, terminal velocity, coefficient of friction, thermal conductivity, specific heat, etc. These properties also change with the stage of maturity, moisture content, variety/genotype, geographical location and agricultural practices. Various methods and standard protocol have been available for measuring these properties. Food engineers and food scientists have developed various mathematical models that elucidate the relationships of the different properties with processing parameters and food quality indicators (Barbosa-Cánovas et al. 2012). The engineering properties of major millets (includes pearl millet, sorghum, finger millet, foxtail millets, kodo millet, barnyard millet) are summarized (Table 4.1) in detail as below.

4.5.1 Shape and Size

The shape and size of grains play an important role in heat and mass transfer calculations, separation (screening), grading and quality evaluation, which is also indicated as the “coarse and fine” size of particles. The shape of grains is usually expressed in terms of sphericity or shape factor. Factors like length, width and thickness correspond to the size of the grains, which is generally measured using micrometres or a vernier calliper. The sphericity (∅) can be expressed as follows (Mohsenin 1986):

$$\text{Sphericity }(\varnothing) = \left(\frac{LWT}{L}\right)^{1/3} \tag{4.1}$$

where L is the length of the grain, W is the width of the grain and T is the thickness of the grain.

Table 4.1 Engineering properties of major millets (Pramodgouda et al. 2019; Sunil et al. 2016; Kulamarva et al. 2009; Swami and Swami 2010)

Properties	Major millets					
	Finger millet	Foxtail millet	Sorghum	Pearl millet	Barnyard millet	Kodo millet
Size (mm)						
L	1.41	2.12	4.33	3.85	2.43	2.74
W	1.38	1.20	3.82	2.40	1.94	2.23
T	1.27	1.06	2.32	2.31	1.26	1.45
Shape	Spherical	Spheroid	Oval	Ovoid	Pyramidal	Spheroid
Sphericity	0.96	0.659	0.74	0.94	0.89	0.76
True density (kg/m^3)	1515.00	1204.82	1471.90	1531.00	1225.50	1176.00
Bulk density (kg/m^3)	1146	734.83	666.37	354	696.02	653.00
Angle of repose	23.40	26.78	15.10	23–25	24.47	18.34
Porosity	24.31	40.08	55.00	76.83	43.00	40.00
Coefficient of friction	0.70 (glass)	0.35 (glass)	0.41 (steel)	0.26 (steel)	0.45 (glass)	0.78 (glass)
Colour						
*L**	19.23	61.38	49.40	95.69	76.33	40.50
*a**	9.28	3.91	07.53	−0.10	1.90	4.00
*b**	5.25	16.2	18.14	2.22	15.96	7.93
1000 kernel weight (g)	2.5	2.36	34.29	8.0	4.17	6.7
Terminal velocity (m/s)	2.94	2.70	9.17	–	4.22	5.66
Specific heat (kJ/kg/K)	1.50–2.40	1.59–2.48	3.22–3.56	–	1.43–2.20	1.42–2.08
Thermal conductivity (W/m/K)	0.14–0.15	0.15–0.21	0.16–0.18	–	0.11–0.15	0.13–0.19

The shape of millets varies from a spheroid or ovoid to pyramidal structure; similarly, the length, width and thickness vary from 1.41 to 4.33 mm, 1.20 to 3.82 mm and 1.06 to 2.32 mm, respectively. The sphericity of millets can be in the range of 0.65–0.96.

4.5.2 Weight of 1000 Kernels

The weight of 1000 kernels is determined by counting and weighing 1000 kernels. The drawn samples should be free from broken and other foreign impurities. The weight of 1000 kernels of major millets were in the range of 2.5–34.29 g.

4.5.3 Bulk Density, True Density and Porosity

The density of agricultural and food materials plays an important role in various food processing unit operations like centrifugation, separation and cleaning. Density can be defined as the space occupied by a unit mass of material and is measured in kilogram per cubic meter (kg/m^3). Generally, the bulk density of grains or flours is measured by calculating the approximate volume using a measuring cylinder which includes bulk and interior porosities. The bulk density of millets can be expressed using the formula given by (Balsubramanian and Viswanathan 2010).

$$\text{Bulk density} = \frac{\text{Weight of millets filled in 100 mL glass beaker (kg)}}{\text{Volume of 100 mL glass beaker } (\text{m}^3)} \tag{4.2}$$

True density is defined as the ratio of the mass of the grain sample to the solid volume occupied by the sample. The water displacement or toluene displacement method is commonly used to measure the true density of the samples. The true density of millets can be expressed using the formula given by (Balsubramanian and Viswanathan 2010).

$$\text{True density} = \frac{\text{Weight of millets (kg)}}{\text{Change in volume of toluene 100 mL glass beaker } (\text{m}^3)} \tag{4.3}$$

where

$$\text{Change in volume of toluene in 100 mL glass beaker} = \frac{\pi}{4} \times D^2 \times H \tag{4.4}$$

D = diameter of the 100-mL glass beaker (mm).
H = height of the 100-mL glass beaker (mm).

The porosity of grains indicates the void space occupied by air in the solid food matrix, which gives the relationship between the bulk density and true density of materials. The porosity of millets can be expressed using the formula given by (Balsubramanian and Viswanathan 2010).

$$\text{Porosity } (\%) = \frac{\text{True density} - \text{Bulk density}}{\text{True density}} \tag{4.5}$$

The bulk density, true density and porosities of major millets vary from 354 to 1146 kg/m^3, 1176 to 1531 kg/m^3 and 24.31 to 76.83%, respectively.

4.5.4 Angle of Repose

Determination of the angle of repose of agricultural materials plays a very important role in designing the hopper, storage silos, conveyors, transportation and packaging systems. The angle of repose can be defined as the angle between the base and slope of the cone formed on a free vertical fall of millets on the horizontal plane (Al-Hashemi et al. 2018). The angle of repose is also associated with the free followability characteristics of particulate materials in bulk forms, which also depends on the surface characteristics of materials. The angle of repose of major millets varies from 15.10° to 26.78°, which indicates that material has free flowable characteristics. Al-Hashemi et al. (2018) reported that millets with an angle of repose $<30°$ are known as free flowable, whereas those with an angle of repose $>55°$ are cohesive or sticky or cracky and non-flowable. The angle of repose of millets can be expressed as

$$\text{Angle of repose}\,(\theta) = \tan^{-1} \times \frac{2H}{r} \tag{4.6}$$

where

θ = angle of repose (degrees).
H = height of heap (mm).
r = radius of heap (mm).

4.5.5 Colour

Colour is the very important optical property of the materials. The Judd-Hunter system is commonly used to describe the colour characteristics of materials in terms of the L^*, a^* and b^* values, also called the $L^*a^*b^*$ system, which are all between 0 and 100. The Commission Internationale de l'Eclairage (CIE) defines these values as lightness for $+L$, darkness for $-L^*$; red for $+a^*$, green for $-a^*$; yellow for $+b^*$ and blue for $-b^*$. The colour value of foods in terms of the $L^*a^*b^*$ system is more commonly used for characterization and system control. The L^*, a^* and b^* values of millets were in the range of 1.41 to 4.33, 1.38 to 3.82 and 1.06 to 2.32, respectively. Nowadays, a colourimeter is commonly used to measure the colour value of the samples.

4.5.6 Coefficient of Friction

Determination of the coefficient of friction of agricultural and food materials is useful in designing storage bins, hoppers, chutes, conveyors, milling, packing, processing, handling and transportation equipment. The coefficient of friction is a measure of the amount of friction existing between two surfaces. A low value of the coefficient of friction indicates that the force required for sliding to occur is less than the force required when the coefficient of friction is high (Bird and Chivers 2014). The coefficient of friction is categorized as internal and external coefficient of friction. The friction exerted between the grain mass of the kernel against each other is termed as the internal coefficient of friction, whereas the sliding friction between the grain and horizontal plane against the wall is called the external coefficient of friction, which can be measured using the test surface of a glass, wood, galvanized iron sheet and cardboard. The coefficient of friction of major millets was in the range of 0.26 to 0.70. The coefficient of friction of millets can be expressed as follows (Shivabasappa et al. 2012):

$$\text{Coefficient of friction } (\mu_e) = \frac{W_2 - W_1}{W} \tag{4.7}$$

where

W_2 = weight to cause sliding of the empty box (g).
W_1 = weight to cause sliding of the filled box (g).
W = weight of grains inside the box (g).

4.5.7 Terminal Velocity

Terminal velocity is a very important aerodynamic property of the agricultural materials and important for the design of the air conveying system and threshing and separation devices. The terminal velocity of the grains is the velocity that results from the action of accelerating and drag forces. It can be measured using an air column method as described by (Shivabasappa et al. 2012). In brief, 100 g of millet is filled from the top of the plexiglass tube ($L = 1.0$ m, $\varnothing = 0.075$ m). The air is blown upward in the tube until the major fraction of millet remains suspended in the stream of air and air velocity can be measured using a calibrated anemometer.

The difference in terminal velocity of the millets is found in Table 4.1, which is due to the difference in size, shape and mass of the grains. The terminal velocity of the major millets was in the range of 2.70 to 9.17 m/s.

4.5.8 Specific Heat

The specific heat of wet agricultural material is the sum of specific heat of bone-dry materials and its moisture content. Specific heat can be defined as the amount of heat required to increase the temperature of a unit mass of material by a unit degree. The specific heat of grains greatly depends on the moisture content and its composition (Sahay and Singh 2004). It can be measured using a differential scanning calorimeter. The specific heat of major millets was in the range of 1.42–2.08 to 3.22–3.56 kJ/kg/K. Variations in the specific heat of the millets are due to changes in moisture content and its composition. The specific heat of grains (bone-dry weight) can be expressed as follows (above 8% moisture content):

$$C = \left[\frac{m}{100}\right] \times C_{\mathrm{w}} + \left[\frac{100 - m}{100}\right] \times C_{\mathrm{d}} \tag{4.8}$$

where

C_{d} = specific heat of bone dry material.
C_{w} = specific heat of water.
m = moisture content (w.b.)
C = specific heat of the grains (kJ/kg/K)

4.5.9 Thermal Conductivity

The thermal conductivity of agricultural materials mainly depends on the moisture content and its composition, like specific heat. It is a measure of the ability of the material to conduct heat (Sahay and Singh 2004). The thermal conductivity of the major millets was in the range from 0.11–0.15 to 0.15–0.21. It can be expressed as

$$Q = K \times A \times \Delta T \tag{4.9}$$

where

Q = amount of heat flow, kcal.
A = area, m^2
ΔT = temperature difference in the direction of heat flow, °C

4.6 Machinery

Processing of millets includes a series of various primary and secondary unit operations. Millets are being used as a staple food and as an ingredient in various food formulations. At household, cottage and industrial levels, various types of processing equipment are being used for decortication, milling and grading/sorting. Recent trend and increase in the consumption of millets as "superfood" have led to the development of various types of modern millet processing equipment.

4.6.1 Thresher

Threshing is one of the most important postharvest unit operations in millet processing. A thresher is generally used to separate the grains from stalks and ears. Traditionally, the bunches of panicles are beaten by hand against a

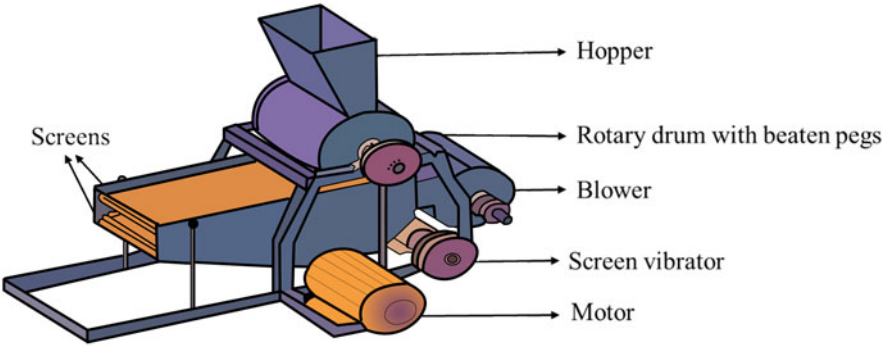

Fig. 4.1 Millet thresher. (Reproduced from Gbabo et al. 2013)

hard-wooded bar log, stone and bamboo table. In some parts of the world, threshing is being practised by trodden underfoot by animals and humans. This method results in higher losses due to grain being broken or buried in the earth (ICRISAT 1996).

Ideally, a mechanical thresher consists of a hopper, threshing chamber or threshing drum, blower house, separating and cleaning chamber, drive, gear assembly and electric motor. Gbabo et al. (2013) developed a thresher for pearl millet. The device (Fig. 4.1) consists of a 0.3-m-height hopper made of a galvanized iron sheet, rotary drum ($L = 0.352$ m and $\emptyset = 0.302$ m) with beater pegs and a stationary concave grid and a separating chamber with length of 0.80 m and diameter of 0.337 m. The cleaning chamber is made up of two sieves with vibratory motion and centrifugal fan to blow the air. The screen is concave in shape and perforated to separate the husk, broken grains and sound grains. The drive and gear assembly is operated with a 5.0-Hp electrical motor with a shaft and pulley unit connected by a V-type belt.

The millet panicles are being fed into the hopper and the grains are beaten out of the panicle and separated from the stalk, where the cylinder is fitted with beater pegs that rotate above the stationary grid called concave. The beaten bulk grains fall through the concave grid into the cleaning section. In the cleaning section, the top sieve retains the chaff and allows the grain into the bottom sieve. On the other hand, a stream of air is blown over the surface of the grain to separate the lighter materials. The developed millet thresher has the highest threshing and cleaning efficiency of 63.20% and 62.70%, respectively, at 13% grain moisture and 800-rpm threshing cylinder speed.

4.6.2 Destoner-Cum-Grader-Cum-Aspirator

Cleaning is the very basic and essential unit operation in millet processing. Prior cleaning is mandatory before dehulling or decortication of millets. A destoner-cum-grader-cum-aspirator (Fig. 4.2) consists of a hopper/feeder, vibratory perforated

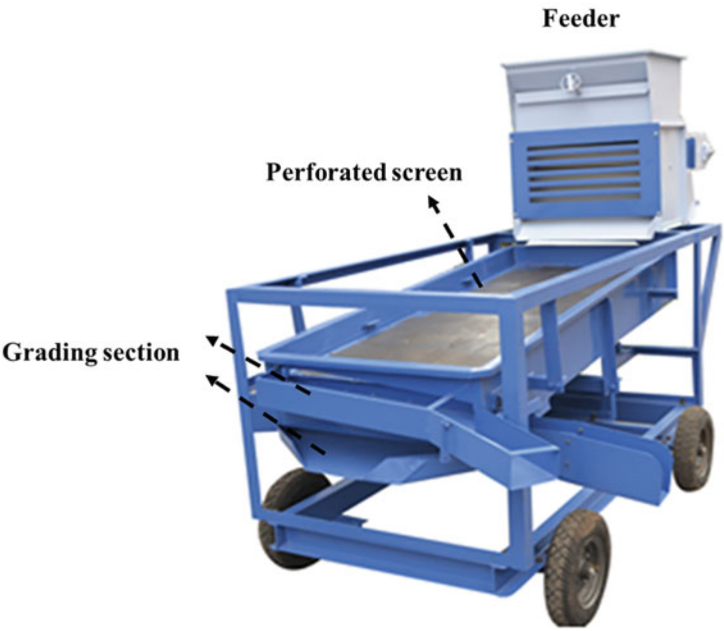

Fig. 4.2 Destoner-cum-grader-cum-aspirator. (Reproduced from https://perfura.in/wp-content/uploads/2019/03/Destoner.jpg)

metal screens operated by an electric motor, blower and collection unit, in which unwanted foreign particulates like stone, sand, dust, dried stalk/stem, chaff seeds and other substandard materials are removed using various sets of vibratory perforated metal screens. Grading of millets is usually done according to the size such as whole grain, broken grains and powders. The aspirator is used as a grain preclearing device where the product passes across the air stream to separate the lightweight materials.

4.6.3 Decorticator

Traditionally, decortication of millets was usually carried out by hand pounding or beating by a stick. Before decortication, the millets are subjected to conditioning and steaming followed by drying. This pretreatment hardens the endosperm of the grain and facilitates easy removal of the outer husk by polishing. The various types of millet decorticators are available in the cottage and industrial level. The milling efficiency of decorticators varies with the type of design. However, the paramount role is to separate the outer husk from the endosperm. Various studies have reported the use of rubber roll hullers (Fig. 4.3) and polishers, wire brush-type mill, peelers and abrasive mills for decortication of various types of millets. Most of the decorticators work on the principle of abrasion and shear force to separate the outermost layer.

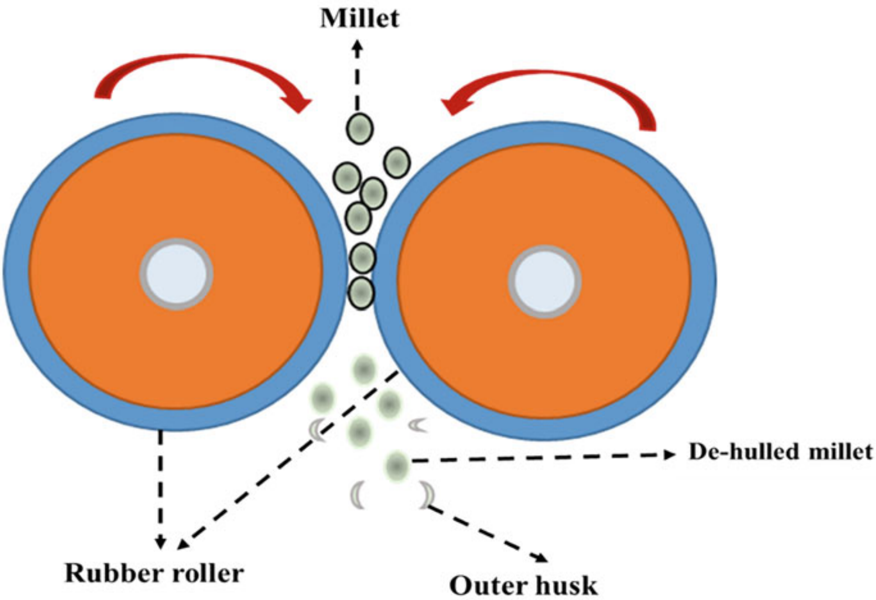

Fig. 4.3 Rubber roll huller

Generally, a decorticator consists of the following components:

(a) *Feeding section*: It consists of a hopper and conveyor. It helps control the flow rate of materials and is usually made of galvanized iron.

(b) *Decortication section*: It consists of two sets of cylindrical rollers with rubber padding to separate the outer husk. The rollers are often driven by gear assembly which is operated by an electrical motor. The grains are usually passed between the rubber rollers and adjusted to the desired clearance between two rollers lesser than the thickness of grains. One of the rollers is fixed, while the other is adjustable to obtain the desired clearance. The difference in roller surface speed develops a shearing force on the grain surface, which results in easy separation of the outer layer. A decreased roller gap develops excess pressure which causes degradation of the colour and quality of the product (Sahay and Singh 2004).

(c) *Cleaning section*: It consists of an air blower and a set of vibratory screens. Separation of admixture of husk and decorticated grain is usually done by blowing a stream of air. Sound grains and broken seeds are separated by a vibratory mesh. According to the type of grains used for decortication, the vibratory mesh can be easily replaced.

4.6.4 Colour Sorter

Nowadays, in modern flour milling industries, optical sorting or colour sorting devices are used for cleaning, grading and separation processes, in which defected, discoloured, chaffy, insect-damaged and immature grains and other unwanted materials (stone, metals, stalk, dried leaves, insects, etc.) are usually removed. The device consists of a feeding system, inspection system and ejection system (data processor). A thin layer of grains is fed on a feed vibrator and gravity chute. The grains are passed through an inspection system, which consists of digital cameras (foreground and background lighting). The device accepts or rejects the material by selectively comparing the magnitude of reflected light from the product surface. The reflectivity response of the materials is continuously processed by a data processor. The defected grains and location of these defects are identified in the data processing section. Colour grain sorting is extremely accurate and versatile when operated properly. However, it has some disadvantages like relatively higher cost and the need for special training for operating and maintenance Inamdar and Suresh 2014).

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Minor Millet Processing and Its Impacts on Composition

5

Anoma Chandrasekara and Fereidoon Shahidi

Abstract

Millets are underutilized cereal grains in some countries and serve to ensure the food security of thousands of people living in African and Asian countries. They are rich sources of nutrients, similarly to other major cereals in the world and are composed of a plethora of phytochemicals. Before preparation as foods, millets undergo several unit processing operations which affect the composition of the grain. This chapter will focus on the compositional changes of millet nutrient and non-nutrient compounds as affected by different millet processing operations. Millet grains are processed following traditional methods as well as modern machineries. Mechanical processing, hydrothermal treatments, soaking, fermentation and malting affect the composition, functionality and health effects imparted upon consumption of millet grains.

Keywords

Fermentation · Glycemic response · Hydrothermal · Mechanical · Malting · Phenolics · Phytates · Soaking

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5.1 Introduction

Millets are considered the oldest domesticated cereals, at the beginning of the human civilization thousands of years ago. According to archaeobotanical evidences, foxtail millet and proso millet were cultivated in Northern China before 8000 cal. BP (Liu et al. 2012). A recent study proved that foxtail and proso millet had been cultivated with rice in Neolithic Southeast coastal China during the period 4000–3500 cal. BP. In addition, dehusking and sieving had been conducted in the site demonstrating the local production of these millet crops (Deng et al. 2018). Furthermore, proso and foxtail millet noodles were found 4000 years ago in Northern China demonstrating the food use of millets among ancient people (Lu et al. 2005).

Millet is a common name called for a group of several small-seeded cereals which are fitted into to the family Poaceae. Botany of plants shows that they do not belong to one species or genus of the family. Generally, the cereal grains with small kernels are categorized into millets. The French word "mille," which means thousands, derives the word millet, implying one handful of millets is counted for thousands of grains (Tylor and Emmambux 2008).

Due to their major contribution to the supply of calories and proteins of economically disadvantaged populations in continents of Africa and Asia, millets are known as the poor man's crop. Today, millets are at the sixth place based on the production among cereals in the world. Millets can be cultivated with minimum inputs in arid areas in South Asia and sub-Saharan Africa and grow well. They are resistant to pests and diseases and are able to thrive in less fertile soils. Furthermore, short growing season and high productivity under heat and drought conditions give popularity for millets among other major cereals (FAO 1995). In addition, millet grains are pest tolerant and thus can be stored with minimum pest attack (FAO 1995). Millets are valuable climatic-resilient crops to cop up the negative influences of climate changes on agriculture productivity and to assure the food security of underprivileged populations. However, millets are underutilized even in food systems where they are produced and are not popular due to poor use in the commercial food industry and novel product developments. Furthermore, lack of adequate agronomic research and advanced millet grain processing technology and exclusion from government price support schemes which aimed to encourage production and consumption led to its poor utilization as human food.

This chapter will focus on minor millet processing and its effect on nutrients and phytochemical composition of grains. Millet types and millet production globally are reviewed first, followed by a discussion of the nutritional and health benefits of millet grains as food and current processing technologies. Finally, the influence of processing on the composition of millets is presented.

5.2 Millet Production

Global millet production is about 31 million tons in 2018 and more than 97% is produced in Asia and Africa (FAOSTAT 2018). During the last decade, the world millet production has been increased only by approximately three million tons due to the subsistence nature of the crop in the cultivated areas. About 66% of millets grains are used for human consumption, while the rest is used for planting materials and beer production and as animal and bird feed (FAO 1995). According to world production statistics, the major millet is pearl millet (*Pennisetum glaucum*), which accounts for 46% of production. Among the other millet grains, foxtail, proso and finger millets have taken a leading role based on the production and utilization. The other minor millets include kodo, little millet, Japanese barnyard, fonio and teff. These millets are cultivated in several regions in the world. Plate 5.1 shows selected minor millet species and pearl millet cultivated and consumed as staple foods in some parts of the world. Table 5.1 depicts the common names used for millet grains and their taxonomy.

5.3 Millet Grain Structure and Types

Millet grain is composed of major anatomical parts of pericarp, germ and endosperm. However, there is a variation in the colour of the pericarp and the shape and size of the grain. The bran is composed of a sub-aleuron layer, aleuron layer, testa and pericarp. Two types of kernel structures, namely, utricles and caryopses, are identified from millet grains (Serrna-Saldivar and Rooney 1995). Botanically, finger, foxtail and proso millet grains are utricles and the seed is loosely covered by the pericarp. In addition, pearl millet, which is a caryopsis, shows fused seed and pericarp (Serrna-Saldivar and Rooney 1995). Table 5.2 presents the weight of 1000 grains and other selected morphological characteristics of millet grains that are helpful for identification.

5.4 Nutritional Value of Millets

Cereal and cereal products are important sources of some nutrients and provide more than 56% and 50% of energy and protein, respectively (BNF 2004). According to food composition data, millets are similar in nutrient content to major cereal grains (FAO 1995). Apart from finger millet, other grains contain a considerable level of fat ranging from 3.5% to 5.2%. Millets are rich in iron and phosphorus. Furthermore, finger millet is a prominent source of calcium among others and contain 350 mg/100 g. All millet grains are rich sources of dietary fibre (FAO 1995). Millets contain total starch ranging from 64% to 79% (Krishnakumari and Thayumanavan 1995; Geervani and Eggum 1989). Amylose and amylopectin contents in millets range from 26% to 30% and 69% to 74%, respectively (Krishnakumari and Thayumanavan 1995).

Pearl millet (*Pennisetum glaucum*)

Proso millet (*Panicum miliaceum*)

Kodo millet (*Paspalum scrobiculatum*)

Foxtail millet (*Setaria italica*)

Finger millet (*Eleusine coracana*)

Little millet (*Panicum sumatrense*)

Plate 5.1 Types of millets

Barnyard millet has been reported to contain the highest protein content of 15.07%, whereas proso millet had the lowest (8.5%). The protein contents of little, kodo and foxtail millet in average were 9.5%, 8.8% and 11.07%, respectively (Veena et al. 2005; Kumar and Parameshwaran 1998; Hadimani and Malleshi 1993; Monteiro et al. 1988; Malleshi and Desikachar 1985). Millets generally contain methionine and cysteine (sulphur containing amino acids) but lack lysine and tryptophan (Amadou et al. 2013). The proteins in finger millets are comparatively better balanced than other millets and contains more amino acids, namely,

Table 5.1 Scientific and common names of different millet species in the world

Scientific name	Taxonomy (Tribe)	Common name
Pennisetum glaucum	*Paniceae*	Pearl, Bajra, Cattail, Bulrush, Candlestick, Sanyo, Munga, Seno, Bajira, Babala
Elusine coracana	*Eragrostideae*	Finger, Ragi, African bird's foot, Rapoko, Hunsa, Wimbi, Bulo, Telebun, Koracan, Kurakkan
Setaria italica	*Paniceae*	Foxtail, Italian, German, Hungarian, Siberian, Kangani, Navane, Thanahal
Panicum milliaceum	*Paniceae*	Proso, Common millet, Hog, Broom, Samai, Russian, Panivarigu, Panic, Maha Meneri
Panicum sumatrense	*Paniceae*	Little millet, Blue panic, Heen Meneri
Paspalum scrobiculatum	*Paniceae*	Kodo, Varagu, Bastard, Ditch, Naraka, Water couch, Indian paspalum, Creeping paspalum, Amu
Echinochola crus-galli	*Paniceae*	Japanese millet, Japanese Barnyard, Sanwa, Sawan, Korean,
Eragrostis tef	*Eragrostideae*	Teff, Abyssinian lovegrass
Digitaria exilis	*Paniceae*	Fonio, Fundi, Hungry rice, Acha, Crabgrass, Raishan
Echinochola colona (L.)	*Paniceae*	Sawa millet, Shama millet, Corn panic grass, Deccan grass, Jungle rice grass, Jungle rice
Coix Lacryma-jobi L.	*Andropogoneae*	Job's tears, Adlay, Adlay millet

Source: Germplasm Resource Information Network (2007), Shahidi and Chandrasekara (2013) and Ramashia et al. (2019)

Table 5.2 Characteristics of grains of some millet types

Millet type	Weight of 1000 grains (g)	Shape of grain	Colour of grains
Kodo millet	5.2	Elliptical to oval	Dark brown to black
Finger millet	2.1	Spherical	White to brown
Foxtail millet	3.1	Spherical to oval	White cream, red, yellow, brown to black
Proso millet	5.7	Spherical to oval	White cream, yellow, orange, red, brown to black
Little millet	0.4	Oval	Gray to straw white
Pearl millet	10.6	Tear shaped to ovoid	Creamy white to gray and purple
Teff millet	2.0	Oval	White to red and brown
Fonio millet	0.5	Oval	White to black
Japanese banyard millet	3.3	Spherical	Dull white to gray and straw white

Table 5.3 Nutrient composition of major cereals and millets (per 100 g of edible portion at 12% moisture)

Cereal	Energy (kcal)	CHO (g)	Protein (g)	Fat (g)	CF (g)	Calcium (mg)	Iron (mg)	Niacin (mg)
Rice (brown)	362	76.0	7.9	2.7	1.0	33.0	1.8	4.3
Wheat	348	71.0	11.6	2.0	2.0	30.0	3.5	5.1
Maize	358	73.0	9.2	4.6	2.8	26.0	2.7	3.6
Sorghum	329	70.7	10.4	3.1	2.0	25.0	5.4	4.3
Pearl millet	363	67.0	11.8	4.8	2.3	42.0	11.0	2.8
Finger millet	336	72.6	7.7	1.5	3.6	350	3.9	1.1
Foxtail millet	351	63.2	11.2	4.0	6.7	31.0	2.8	3.2
Proso millet	364	63.8	12.5	3.5	5.2	8.0	2.9	4.5
Little millet	329	60.9	9.7	5.2	7.6	17.0	9.3	3.2
Kodo millet	353	66.6	9.8	3.6	5.2	35.0	1.7	2.0

CHO carbohydrates, *CF* crude fibre
(Source: Data adapted from FAO 1995)

threonine and valine. Finger millet also contains methionine, an essential amino acid which is lacking in most of starchy roots (Apoorva et al. 2010; Ravindran 1991). The proteins present in foxtail millets are generally deficient of amino acid and lysine and high in leucine and methionine. Millets do not contain the protein gluten. They are suitable for the preparation of flat breads, and leavened breads are prepared by mixing adequate proportions of gluten-containing flour or glutens. Millet can be used as an alternative cereal for people suffering from celiac diseases in place of wheat and other more common cereal grains (Table 5.3).

The total lipid content of foxtail, proso, finger, little, kodo and barnyard millets varied from 5.1% to 11.0% (dry basis) (Saldivar 2003). According to Ibrahima et al. (2004), millet lipid contains high levels of linoleic, oleic and palmitic acids and trace amounts of behenic, arachidonic and erucic acids. Millet grain oils lack palmitoleic, stearic and linolenic acids. Lipids of minor millets, namely, little, kodo and barnyard millets, exist mainly as free lipids (65%–71%), whereas 21% to 26.5% are bound lipids (Sridhar and Lakshminarayana 1994). The total lipid contents of little, kodo and barnyard millets are 8.3%, 5.1% and 88%, respectively (Sridhar and Lakshminarayana 1994).

Millets are composed of both soluble and insoluble dietary fibres considerably and are comparable to other major cereals (Bagdi et al. 2011; Premavalli et al. 2004). In addition, millets contain considerable quantities of minerals, namely, calcium, magnesium and phosphorus (Amadou et al. 2013).

5.5 Millet Grain Health

Millets provide a number of phenolic compounds demonstrating several health benefits including antioxidant properties (Chandrasekara and Shahidi 2010, 2011a, b, c, d, 2012a, b; Chandrasekara et al. 2012). There are recent evidences that demonstrate the beneficial trends to improve health by consumption of millet grain in reducing the risk of diet-related diseases (Kumari et al. 2019). According to Lakshmi Kumari and Sumathi (2002), finger millet-based diets had significantly reduced plasma glucose levels in individuals with non-insulin-dependent diabetes mellitus. In addition, whole grain meal feeding of finger and kodo millets showed a protective effect by reducing the blood glucose level and oxidative stress in Wistar rats (Hegde et al. 2005). The finger millet feed positively affected the progress of dermal wound healing of alloxan-induced diabetic rats (Rajasekaran et al. 2004). According to their results, finger millet feeding for 4 weeks controlled the blood glucose levels and improved the antioxidant status of the diabetic animals while improving the wound healing process. The topical application of the aqueous paste of kodo millet and finger millet flour was effective in rat dermal wound healing (Hegde et al. 2005). Furthermore, feeding of foxtail and proso millet grains reduced the level of triacylglycerol and C-reactive proteins in hyperlipidaemic rats, demonstrating their potential therapeutic use (Lee et al. 2010). The feeding of 20% finger millet seed coat to streptozotocin-induced diabetic rats showed several beneficial health effects such as hypoglycaemic, nephroprotective, hypocholesterolaemic and anti-cataractogenic properties (Shobana et al. 2009). In a recent study, Kumari et al. (2020) reported that compared to baseline, the plasma antioxidant capacity of healthy adults measured using the ferric ion reducing antioxidant power (FRAP) and trolox equivalent antioxidant capacity (TEAC) increased after an 8-week consumption of finger millet porridge.

Millets are mainstay in the diet of coeliac patients as gluten-free cereal grains which can be tolerated. Coeliac disease is a condition characterized by damage to the mucosa of the small intestine caused by ingestion of certain proteins in wheat, rye and barley. The gliadins and glutenins of wheat gluten have been shown to cause the problem which can be prevented only by consuming gluten-free cereals. Thus, millets are potential candidate cereals for patients with coeliac disease and add variety to their diet.

5.6 Food Use of Millet Grains

As cereals grains of millets are important subsistence crops in tropical as well as semi-arid regions in Asian and African continents, the main uses of millet grains in the North American region are for animal feed. In the USA, pearl millet is used for grazing and hay, whereas proso millet is grown especially in the Great Plains in Dakotas, Colorado and Nebraska for grains (Lyon et al. 2008). Millets are utilized as different types of foods using flour/meal and malt of the grains in Africa, East-Asia and Indian subcontinents. Millet are prepared as boiled rice-like products, thin and thick porridges, fermented and unfermented breads and steam-cooked products at the homestead. At the commercial level, millets are utilized for the production of alcoholic and non-alcoholic beverages, as ingredients in multigrain bakery products and as ingredients in composite flours and snacks (Murty and Kumar 1995). However, consumer-friendly, ready-to-serve millet products with added variety are not available like major cereals such as wheat and rice in markets.

Traditionally, millet is subjected to malting or fermentation and the resultant flour or slurry derived is used in the preparation of weaning foods, infant foods, supplementary food formulations and beverages such as beer. In African countries and the Indian subcontinent, millets play an integral role as a major part of many meals. Millets are consumed as “couscous” (steam-cooked, agglomerated product), “*To*” (stiff porridges) and “*Ogi*” (thin porridges). *Ogi* is also used as a complementary food for infants and young children.

There are region-specific snack foods such as “*Halepe*” prepared in Sri Lanka using finger millet flour, grated coconut, rice flour and treacle. The dough is flattened and wrapped with *Macaranga peltata* leaves before steaming. This leaf brings special flavour to the product. Furthermore, finger millet flour is used to make unfermented flatbread (*roti*) mixed with grated coconut and rice flour and thin porridges mixed with coconut milk. Similar to corns and rice, finger millet grains are also popped especially in India and are consumed as a snack or further processed by milling (Malleshi and Hadimani 1994). Furthermore, whole grain finger millets are boiled to produce a rice-like product (*kichadi*) (Subramanian and Jambunathan 1980).

In some countries, pancake-like flatbreads made from millets serve as staples. The flour used for these flatbread is subjected to a mixed lactic acid and yeast fermentation which entrusts the product with leavened texture and an acidic flavour (Gashe et al. 1987). Injera and Kisra are common in Ethiopia and Sudan, respectively, and they are made from teff or finger millets.

5.7 Millet Processing

Millet grains are small seeds and are protected by glume encasement leading to processing operations which are labour-intensive and time-consuming. Millets are considered low-price commodities due to the poor quality of grains even within the territories where they are cultivated. Inadequate cleaning of millet grains and grading and drying before they are brought to the markets reduce the profit margin of farmers. In addition, poor quality of the grains causes storage problems and prevents consumption and acceptance as an ingredient for food preparations (NAAS 2012). Minor millet processing can be categorized into two stages: primary and secondary millet processing. Primary millet processing comprises of unit operations taking place at the farm/producer levels such as threshing, cleaning (de-stoning), sorting, grading, drying and dehulling, which are essentially needed to ensure the good quality of the millet commodity. Secondary processing includes unit operations carried out after primary processing to transform millet grains into product for direct

Table 5.4 Processing operations and machineries used for minor millets

Process	Machineries	Function
Dehullig	A double chamber centrifugal dehuller	Remove the husk and major portion of bran and endosperm is retained. High kernel recovery with less brokens (4–5%)
	Abrasive roller type dehuller	Remove the husk, bran and small portion of endosperm. The dehulled grains contain about 20% of brokens
	Traditional wooden pestle and motar, stone hand mill	Remove husk but need to add water to moisten leading to reduced shelf life of grains
Cleaning/ de-stoning	De-stoner	Remove immature grains and stones, mud balls
Polishing	Polisher	Remove bran and germ
Grading	Grader	Removes impurities
Colour sorting	Sorter	Remove other seeds
Grinding/ size reduction	Pulverizer	Make flour and flakes
Flour shifting	Shifter	Separate flour based on particle size

consumption, such as pulverizing, flaking, sifting, popping, malting, fermentation, baking, roasting, toasting and boiling.

In African, East-Asian and Indian regions, where millets are traditionally grown, they are prepared for consumption in a number of methods using the grains such as millet rice or flour/meal and malt in a variety of food and beverage choices. Millets after harvesting are subjected to different processing steps to improve the palatability, other organoleptic characters and digestibility and add variety. In the process, grains may undergo a variety of compositional changes of nutrients and non-nutrient phytochemical constituents affecting nutritional and health benefits exerted by millet grains (Table 5.4).

The processing conditions millet grains are usually subjected to include soaking, decortications, flaking, grinding, malting, fermentation and heat treatments (cooking, roasting, popping) using either traditional or advanced technologies (Hemalatha et al. 2007; Saleh et al. 2013; Dutta et al. 2015). Millet grains undergo substantial changes in the composition during initial postharvest practices such as threshing (separation of grains from stalks) and milling as well as other different processing operations at later stages of food preparation. The convenience of food products prepared using millet grains and flours should be made available to promote their consumption (Gunashree et al. 2014). It is noteworthy that much work is on progress on millet food for the introduction of composite flours such as multi-millet mix, millet-pulse blends and extruded products (Patel and Verma 2015).

5.8 Primary Processing Operations

5.8.1 Threshing

Threshing involves the removal of grains from the harvested plants or millet heads. Generally, threshing is done manually by beating with a stick or a club until all grains detach from the heads. Beating is done after placing the heads on a mat or bare ground or after stuffing into bags for easy collection of grains.

5.8.2 Drying

Drying of millet grains is done traditionally under the sunlight and mechanical drying is applied when it is essential and economical. Uniform drying to a moisture content of 14%–16% is important for proper storage and long shelf-life of millet grains (Kajuna 2001).

5.8.3 Cleaning

Cleaning is necessary to remove contaminated foreign matters in the grains during harvesting, threshing and drying. Millet grains are contaminated with stones, soil particles, weed seeds, off-type seeds, leaves, broken seeds, insects and glumes among others. Cleaning is traditionally done by winnowing and aspiration (Odogola and Henrikson 1991).

5.8.4 Decortication/Dehulling

Decortication manually or using abrasive dehullers is done to remove the inedible outermost fibrous husk layer of millet grains. The decortication of millet kernels reduces fibre, ash and fat contents (Hulse et al. 1980). Decortication is essentially required for minor millet grains such as foxtail, proso, kodo, little millet, fonio, teff and Japanese barnyard millets to remove the fibrous husk layer. Dehulling of millet grains reduces the total mineral contents, but increases the bioavailability of calcium, iron and zinc by 15%, 26% and 24%, respectively (Singh and Raghuvanshi 2012; Krishnan et al. 2012).

5.9 Secondary Processing Operations

5.9.1 Polishing

Polishing removes the outer layers of the seed coat of the millet grains. Polishing is useful to increase the digestibility and popularity of grains among consumers especially when the seed coat is black or dark brown in colour. However, polishing removes nutrients and non-nutrient phytochemicals helpful in retaining the nutritious quality of minor millet grains.

5.9.2 Pulverizing

A pulverizer is used to produce semolina and flour from grains. Unless millet grains are boiled and consumed as rice-like food or flakes, size reduction is essential to prepare other different foods such as stiff and soft porridges, flatbreads and pancakes among others.

5.9.3 Soaking

The soaking of grains is done in excessive water for different time periods until the grains get steeped completely at an ambient temperature. Water used for soaking is generally discarded with impurities and foreign materials. The soaked grains are thoroughly cleaned washing with clean water followed by drying in an oven at 60 °C or under the sun before subjected to pulverizing (Banusha and Vasantharuba 2013). Soaking reduces the content of anti-nutrient factors such as phytates and phenolic compounds leading to improvement of the mineral bioavailability (Saleh et al. 2013).

5.9.4 Germination

Germination is a customarily used method of processing cereal grains. This process modifies the composition of the grain increasing the nutritional quality while enhancing the digestibility, variety and palatability of foods prepared (Pradeep and Yadahally 2015). In the germination process, whole unhusked grains are soaked for 2–24 h and are naturally germinated by spreading on a wet cloth for up to 24–48 h or using an incubator at 30 °C for 48 h (Shimray et al. 2012). Germination grains soften the kernel structure and improve the nutritional value by increasing readily available carbohydrates, minerals, vitamins and essential amino acids (Chove and Mamiro 2010; Pushparaj and Urooj 2011).

5.9.5 Malting

Malting is a process combining several unit operations of steeping, germination, drying, toasting, grinding and sieving. Malting improves the bioavailability of some nutrients such as minerals and vitamins and reduces compounds such as phytic acid, tannins and other polyphenolic compounds which act as anti-nutrient compounds. Malting of millet grains produce a product with enhanced nutritional quality which can be used in a wide variety of conventional and novel food formulations including brewing of beverages.

5.9.6 Fermentation

In the fermentation process, grains become the substrate for the growth of several microorganisms. The fermentation process is traditionally used from the ancient time for food processing and is useful in the production of commercial fermented foods and beverages at present. Generally, millets are fermented at room temperature for 24 to 72 h depending on the food product or beverage to be produced. There are several popular indigenous finger millet-fermented food and beverages in Africa (Ranasalva and Visvanathan 2014).

During fermentation, microbial action results in a number of by-products such as organic acids or antibiotics as they utilized starch of the grain. Antibiotics and the acidic medium created inhibit the growth of spoilage and pathogenic microorganisms and improve amino acid balance and the organoleptic qualities and nutritional value of the resulting products (Ranasalva and Visvanathan 2014). Furthermore, fermentation reduces anti-nutritional compounds such as trypsin and amylase inhibitors and phytic acid and tannins in cereal product (Rasane et al. 2015).

5.10 Effect of Processing on Millet Grains

In cereals, non-nutrient compounds and nutrients are not distributed evenly within the grain. Outer layers are rich source of nutrients and non-nutrient antioxidant compounds, whereas the endosperm mainly consists of starch. The processing of millet grains may exert a noted effect on the bioactivities of their constitutional contents.

5.11 Effect of Processing on Nutrient Content

The germination of millet grains such as proso millets increased the contents of free amino acids, namely, lysine and tryptophan, and total sugars of millets (Parameswaran and Sadasivam 1994). Malting enhances the contents of nutrients such as crude fat, vitamins B and C, minerals and their bioavailability (Kumari and Srivastava 2000). Malting improves the bioavailability of nutrients and digestibility

(Platel et al. 2010). Further, they showed that malting is an appropriate strategy to improve the bioavailability of iron and other minerals from food grains.

Suma and Urooj (2014) showed that germination of finger and pearl millet grains increased the bioaccessibility of iron and calcium and their in vitro extractability. Furthermore, germination of pearl millet doubled the solubility of iron in vitro, while finger millet germination for 48 h at 30 °C improved the in vitro protein digestibility by 17% (Eyzaguirre et al. 2006). Krishnan et al. (2012) showed that malted finger millet increased the bioaccessibility and the content of minerals such as calcium, zinc and iron by 20, 29 and 65 g/100 g, respectively, with a reduction of compounds like phytic acid (84 g/100 g), polyphenols (78 g/100 g) and dietary fibre (81 g/100 g).

5.12 Effect of Processing on Phenolics and Bioactivities

Several studies showed that the bran of the grains is a rich source of phenolics and demonstrates effective antioxidant properties (Chandrasekara and Shahidi 2011c; Chandrasekara et al. 2012; Shahidi and Chandrasekara 2014). Different processing conditions applied during food preparation may exert varying effects on the antioxidant activities of millet grains.

There was reduction in tannins and polyphenols after subjecting the grains to germination, soaking, de-branning and dry heating of millets (Hassan et al. 2006). Malting changed the proportion of free and bound phenolic acids in finger millet. Malting of finger millet for 96 h decreased bound phenolic acid content, while that of free phenolic acid increased (Rao and Muralikrishna 2002). Ferulic, coumaric and caffeic acids were major bound phenolic acids in native finger millet, and upon malting for 96 h, the contents were decreased by one- to twofold (Rao and Muralikrishna 2002). Furthermore, malting of finger millets decreased the content of some free phenolic acids. The protocatechuic acid content decreased from 45 to 16 mg/100 g, and *p*-coumaric, gallic and ferulic acid contents increased by two-, four- and tenfold, respectively (Rao and Muralikrishna 2002).

Cooking is a commonly used hydrothermal treatment for the preparation of millet foods. N'Dri et al. (2012) showed that cooking of millets may increase the total content of phenolic compounds, whereas some specific phenolic acids disappear. Fonio millets showed a significant decrease in almost all soluble phenolic acids along with an increase in bound phenolic compounds (N'Dri et al. 2012). According to Chandrasekara et al. (2012), the total phenolic content (TPC) of cooked millet grains did not differ significantly from their uncooked counterparts except for finger millets. Cooked finger millets showed an 11% to 36% reduction in TPC. Degradation of phenolics upon cooking or leaching of phenolics into the endosperm, thus making them less extractable, could be the reason for the apparent deduction (Chandrasekara et al. 2012). Furthermore, they showed that the antioxidant activities vary depending on the type of millet.

According to Pradeep and Guha (2011), germination, steaming and roasting of little millets increased the TPC compared to the unprocessed counterparts. The TPC of native, germinated, steamed and roasted millets were 430, 453, 486 and 521 mg of gallic acid equivalents (GAE)/100 g of sample (dry basis), respectively. It is noteworthy that there was an increase in the content of total flavonoids and tannins. The release of insoluble bound phenolics by thermal degradation of cellular constituents may increase the TPC during roasting of little millet grains (Pushparaj and Urooj 2014).

Dehulling and removal of the outer layers by polishing of the grain decreased the TPC of whole grain millets (Chandrasekara et al. 2012). Hulls showed a higher TPC than those of the counterpart grain fractions of kodo, foxtail, proso, pearl, little and finger millets. Furthermore, the TPC of dehulled raw and counterpart cooked grains of millets did not differ significantly except for finger millets (Chandrasekara et al. 2012). High content of phenolic acids was reported in the hulls of millets (Chandrasekara and Shahidi 2011c). Kodo millet hulls showed a 34-fold more ferulic acid, compared to the dehulled counterpart grain. Furthermore, *p*-coumaric acid content in hulls of kodo millet grains was seven times higher than the corresponding dehulled grains (Chandrasekara and Shahidi 2011c). Demonstrating a similar trend of reduction on the TPC, dehulled grains showed less inhibition of low-density lipoprotein (LDL) cholesterol, DNA strand scission induced by peroxyl radicals and liposome oxidation.

Fermentation decreases the levels of phenolic compounds in food grains and increases the in vitro protein digestibility (IVPD) and nutritive value of millets (Hassan et al. 2006). Fermentation of pearl millet changed its chemical composition (Ahmed et al. 2009). Mamiro et al. (2001) reported a smaller or insignificant effect on the in vitro extractability of minerals after fermentation of finger millet grains. Khetarpaul and Chauhan (1991) utilized mixed-culture fermentation of pearl millet flour using *Lactobacillus fermentum*, *Lactobacillus brevis*, *Saccharomyces diastaticus and Saccharomyces cerevisiae.* Fermentation improved the bioavailability, apparent protein digestibility, protein efficiency and feed efficiency ratio, net protein utilization and retention, true protein digestibility, protein retention efficiency and utilizable protein values in pure-culture-fermented pearl millet flour (Khetarpaul and Chauhan (1991). It was also noted that fermentation released the phenolics bound to the insoluble fibre in the grain (Khetarpaul and Chauhan 1991).

Hag et al. (2002) demonstrated that fermentation and dehulling of pearl millet are effective methods to reduce their TPC and dehulling reduced the total phenolic content by 22% from its original value (Hag et al. 2002).

Changing the degree of decortication from 0% to 50% and cooking reduced the concentration of *C*-glycosylflavones (vitexin and orientin) of pearl millets (Akingbala 1991). In addition, conversion of pearl millet (*Pennisetum americanum*) into Ogi, a thin porridge which is a traditional Nigerian fermented food, reduced the flavanol content of the native grain by 38% (Akingbala et al. 2002).

Matuschek et al. (2001) showed that soaking, cooking and germination reduced the TPC of finger millet and sorghum udo. Fermentation and germination of finger millets decreased their 2,2-diphenyl-1-pcryllhydrazyl (DPPH) radical scavenging ability compared to their raw counterparts (Sripriya et al. 1996). According to Shobana and Malleshi (2004), two processing methods, namely, hydrothermal treatment and decortication of finger millets, reduced phenolic content by 14% and 74%, respectively. Hydrothermal treatment of finger millet reduced the TPC by 1.7 times than that of raw grain (Towo et al. 2003). Oghbaei and Jamuna Prakash (2012) demonstrated that sieving decreased the content of polyphenols and flavonoids in whole finger millet flour. However, sieved finger millet flour showed increased in vitro bioaccessibility. Sieving of whole finger millet flour removes the outer coating of the grain which prevents fine grinding. However, the outer coating is rich in phenolic compounds and tannin. Wafers and vermicelli are basically prepared by mixing the flour with water, heating the slurry, extruding or pressing the hot paste and finally sun drying (Oghbaei and Jamuna Prakash 2012). The sieving of finger millet flour before preparation of different food products significantly reduced the TPC.

Pradeep and Guha (2011) showed that germination of little millet (*Pannicum sumatrense*) grains increased the tannin content by 17% compared to the native grain, the reason for which remaining unclear. Tannins bind to proteins, carbohydrates and minerals and reduce the digestibility and absorption of these nutrients.

A variety of food processing methods such as boiling, pressure cooking, roasting and germination could affect the available tannin content of foods prepared with pearl millets (Pushparaj and Urooj 2011). Semi-refining of pearl millet flour lowered the constitutional tannin levels. Furthermore, bran-rich millet flour had high tannin content due to the high level of tannins in the outer layer of the grain. Tannin contents were reduced upon wet and dry heat treatments due to their possible loss upon leaching into water. In addition, during heat processing, tannins may bind to proteins, carbohydrates or minerals, thus making their extraction difficult (Pushparaj and Urooj 2011).

5.13 Effect of Processing on Phytic Acid Content

The content of phytates in the millet grain reduced after submitting to different processing conditions. According to Lestienne et al. (2007), 4% and 8% of the phytates of pearl millet grains was removed from Gampela and IKMP-5 cultivars, respectively, at 12% decortication. This study further showed that phytates are mainly distributed in the starchy endosperm and the germ of pearl millet grains (Lestienne et al. 2007). Suma and Urooj (2014) showed that germination of finger and pearl millet grains decreased the phytic acid content.

Eyzaguirre et al. (2006) demonstrated that cooking alone did not reduce the phytate content of whole meal flour of pearl millet (IKMP-5 variety). Cooking in kanwa slightly reduced the level of phytates, possibly due to the formation of complexes with the minerals during cooking. Kanwa is an alkaline rock salt, containing sesquicarbonates (Na_2CO_3, $NaHCO_3.xH_2O$) and various other elements such as Cl, Si, P, K, Ca, Fe, Al and S (Eyzaguirre et al. 2006). In West and Central Africa, kanwa is used as a tenderizer and to reduce the cooking time of beans and other tough foods.

Wet grinding and cooking reduced phytic acid to IP5 (inositol pentaphosphate) and IP4 (inositol tetraphosphate) configurations after soaking of pearl millet (*Pennisetum glaucum*) grains (Eyzaguirre et al. 2006). Soaking grains in water can result in the passive diffusion of water-soluble phytate, which will be removed by decanting the water.

Germination and lactic acid fermentation can partially decompose phytic acid. However, phytate reduction by the action of endogenous phytases is inhibited at low pH during fermentation due to the production of low-molecular-weight organic acids such as citric, malic and lactic acids. The phytate content of whole grain of pearl millet was reduced by soaking for 24 h in water from 419 to 250 mg/100 g on a dry weight basis (Eyzaguirre et al. 2006). Furthermore, soaking for 24 h and germination for 4 d decreased the phytate content by 39% of the original value of the whole grains of pearl millets (Eyzaguirre et al. 2006).

5.14 Effect of Processing on Plasma Glycaemic Response

According to Shobana and Malleshi (2007), finger millet phenolic compounds had the ability to inhibit the intestinal α-glucosidase and pancreatic α-amylase to lower the postprandial blood glucose response. According to some studies, different processing conditions and preparation methods of finger millet foods changed the glycaemic response (Jayasinghe et al. 2013; Shobana et al. 2013; Shobana and Malleshi 2007; Lakshmi Kumari and Sumathi 2002). Foods prepared using ground millet grains and roasted millet flour showed different glycaemic responses (Roopa and Premavalli 2008). The glycaemic index (GI) is the incremental area under the curve (AUC) for blood glucose response after ingestion of a food relative to that produced by a reference food (white bread or glucose) given in an equivalent carbohydrate content (50 or 25 g) taken by the same subject over a specified period of time (Jenkins et al. 1981). Foods prepared with finger millet flour with larger particle size showed low GI (Jayasinghe et al. 2013). Barnyard millet grains were processed using heat treatment (60 °C) and intermittent cooling cycles for 1 h before making the meal (Ugare et al. 2014). They showed that the GI of *Uppma* prepared with the processed barnyard millet meal was low compared to that of the unprocessed grain meal. Recently, Kumari et al. (2020) showed that finger millet porridges exhibited low GI values (<55) except that prepared with the raw roasted flour. The raw roasted flour showed a high GI value (>70) for large particle size and medium GI value (56–69) for small particle size of the flour.

5.15 Summary

Millets are important cereal grains that add variety to the diet and allow healthy food choices in African and Indian regions in the world for millions of people. Millets remain underutilized grains even in countries they grow. However, they are comparatively nutritious, similar with other cereal grains, and consist of a myriad of beneficial bioactive compounds including phenolics and phytates.

Primary and secondary processing of millet grains affect the content of nutrients and non-nutrient compounds. This review showed that content of nutrients as well as non-nutrient compounds varies with the processing condition cereals undergo and affect the functionality of food.

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Chemistry of Millets: Major and Minor Constituents

6

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Abstract

Millets are small grains that are considered hardy and nutritious. In addition to providing basic nutrition with carbohydrates, proteins, and lipids, millet grains have an abundance of phytochemicals, particularly phenolic compounds, and useful minerals such as iron and zinc. The chemistry of millets is dependent on the variety, cultivars, growing practices, postharvest handling, processing, and storage conditions. With their favorable nutritional content and phytochemical-associated health benefits, millets have a good potential for increased consumption as healthy ingredients in food product development.

Keywords

Composition · Processing · Proteins · Lipids · Dietary fiber · Minerals · Phytochemicals

6.1 Introduction

Millets are widely variable and different small-seeded annual grasses, which are increasingly grown worldwide as cereal crops and as fodder for animal (Tariq et al. 2011). Millets are classified as cereals, belonging to the genus *Panicum* and Pennisetum, family Poaceae, and subfamily Panicoideae (Bagdi et al. 2011). Depending on the size of the seed, millets are classified as either minor or major millets (Table 6.1). In the category of minor millets, there are some 14 species often categorized as lesser known, neglected, and underutilized crops (Rengalakshmi

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Table 6.1 List of commonly available major and minor millet varieties (FAO 1995, 1996)

Major millet	Biological name
Finger millet	*Eleusine coracana*
Proso millet	*Panicum miliaceum*
Pearl millet (Bajra)	*Pennisetum glaucum*; *P. typhoides; P. tyhpideum; P. americanum*
Foxtail millet (Italian millet)	*Setaria italica*
Minor millet	**Biological name**
Adlay millet (Job's tears)	*Coix lacryma-jobi*
Polish millet (Fonio)	*Digitaria sanguinalis*
Barnyard millet (Indian and Japanese)	*Echinochloa esculenta*
Little millet	*Panicum sumatrense*
Kodo millet	*Paspalum scrobiculatum*
Browntop millet	*Urochloa ramose*

2005). Although different types of millets exist, only a few are used for consumption and are processed in the food industry. Approximately 30 million tons of millets are produced worldwide on an annual basis (Obilana 2003; FAOSTAT 2021). Millets are produced for both human and animal feed, and the millets used for human consumption are pearl millet (*Pennisetum glaucum*), finger millet (*Eleusine coracana*), proso millet (*Panicum miliaceum*), foxtail millet (*Setaria italica*), kodo millet (*Paspalum scrobiculatum*), little millet (*Panicum sumatrense*), and barnyard millet (*Echinochloa crus-galli*). The term millet refers to a variety of small grains, some of which do not belong to the same genus. For example, fonio (*Digitaria*) and tef (*Eragrostis tef*) are considered as millet grains, while they have significant differences in their agronomical practices and chemical composition due to actually being different species (FAO 1996). They are placed in the subfamily of Panicoideae cereals, the Chloridoideae (Belton and Taylor 2002).

Even though millets are highly nutritional, they have not received much attention compared to the available major cereals. The production practices and quantities produced for millets have not changed significantly in the past 50 years when compared to the mainstream wheat and rice. This is mainly due to the substantial investment (over the past decades) in research and development that has been dedicated for the production of rice and wheat and their effective postharvest processing. Millets have long been at a disadvantage, since millets have most of the times been considered as a poor person's food, and this has created an inequity in the promotion of millet consumption (Fuller 2005, 2006; Morrison 2006; Smith 2006).

This fact is changing slowly with the gradual increase of millet production and consumption, in different parts of the world, due to their climate resilience (Saxena et al. 2018). Since millet is a gluten-free cereal, with hypoglycemic property, it is gaining importance in Europe and North America. Pearl millet, also known as bajra, has gained an increasing importance, and various studies are going on to improve its quality, quantity, and processing techniques (Eyzaguirre et al. 2006; Gupta and Nagar 2010; Eltayeb et al. 2010; Tiwari et al. 2014). On the other hand, minor millets have not received as much attention thus far. The present review is focused on the nutritional value of many of the major and minor millets.

6.2 Nutritional Comparison of Millet with Other Major Cereals

Several studies can be found reporting on the nutritional properties of millet (Dayakar et al. 2017; Devi et al. 2011). Millets have different nutritive components depending on their species. In their overall nutritional quality, millets are equivalent to many other major cereals (FAO 1995).

From a detailed survey of the literature, it can be stated that millets are highly nutritious when compared with rice and wheat (Parameswaran and Sadasivam 1994; Saleh et al. 2013; Singh et al. 2012), which are considered the two major crops in terms of economic and global production. Millets are unique as a cereal crop with their particularly higher content of calcium, dietary fiber, polyphenols, and protein (Devi et al. 2011; Mal et al. 2010; Ravindran 1991).

A comparative study of the nutrient profile of different cereals was reported by Devi et al. (2011), which is presented in Table 6.2. The contents of minerals present in different cereals were compared by Hongxing and Rui (2012) (Table 6.3). It is observed that the mineral composition is ranked from K > Mg > Ca > Fe > Zn > Mn > Cu > Mo > Li, and that the food grains can be arranged in the order from high to low levels of mineral elements from soybean > millet > wheat > corn (Hongxing and Rui 2012). It has been widely recognized that

Table 6.2 Macronutrient composition of cereal grains and millets (Devi et al. 2011)

Cereal/grain	Protein (%)	Fat (%)	Crude fiber (%)	Ash (%)	Starch (%)	Total dietary fiber (%)	Total phenol (mg/100 g)
Wheat	14.4	2.3	2.9	1.9	64.0	12.1	20.5
Rice	7.5	2.4	10.2	4.7	77.2	3.7	2.51
Maize	12.1	4.6	2.3	1.8	62.3	12.8	2.91
Sorghum	11	3.2	2.7	1.8	73.8	11.8	43.1
Barley	11.5	2.2	5.6	2.9	58.5	15.4	16.4
Oats	17.1	6.4	11.3	3.2	52.8	12.5	1.2
Rye	13.4	1.8	2.1	2.0	68.3	16.1	13.2
Finger millet	7.3	1.3	3.6	3.0	59.0	19.1	102
Pearl millet	14.5	5.1	2.0	2.0	60.5	7.0	51.4
Proso millet	11	3.5	9.0	3.6	56.1	8.5	–
Foxtail millet	11.7	3.9	7.0	3.0	59.1	19.11	106
Kodo millet	8.3	1.4	9.0	3.6	72.0	37.8	368

Table 6.3 Mineral composition of corn, soybean, wheat, and millet (Hongxing and Rui 2012)

Elements	Corn (μg/g)	Soybean (μg/g)	Wheat (μg/g)	Millet (μg/g)
Li	0.014	0.065	0.020	0.012
Ca	47.96	699.53	200.63	154.20
Mg	313.09	1184.51	321.11	1129.71
Fe	16.99	108.44	19.02	34.13
Mn	1.42	15.11	6.69	11.16
Cu	0.647	6.698	2.896	6.119
Zn	6.11	31.70	8.01	26.89
Mo	0.248	2.403	0.175	0.261
K	1688.87	9611.04	1569.34	2285.54
Se	–	0.352	0.067	–

millets can be considered a nutritional equivalent to the major cereals that are consumed on a regular basis.

The Indian Institute of Millets Research within the Council of Agricultural Research of India (Dayakar et al. 2017) summarized well the average nutrient composition of some millet grains and other cereal grains (presented in Table 6.4).

6.3 Composition of Millets

The major nutrients such as carbohydrate, protein, fat, crude fibers, minerals, etc. are present in adequate amounts in millets, and hence, millets can be considered as a complete food or food ingredient. Millets contain on average 60–72% carbohydrate, 7–13% protein, 1.5–5% fat, and 2–7% crude fiber. They have an excellent nutritional profile with relatively high concentrations of vitamin and in particular B vitamins, niacin, folic acid, pro-vitamin A, and micronutrients particularly calcium, iron, potassium, magnesium, and zinc (Lebiedzinska and Szefer 2006; Malleshi and Hadimani 1993). Millets also possess high levels of methionine, cystine, and other essential amino acids in similar amounts to other cereal grains (Obilana 2003). The seed husk of millets is an edible component of the grain kernel and is a major source of phytochemicals (such as polyphenols) and dietary fiber (Malleshi and Hadimani 1993; Ramachandra et al. 1977), which can serve as a useful food ingredient.

6.3.1 Carbohydrates

The total percentage of carbohydrates present in different types of millets ranges from 55 to 85% (Tables 6.4 and 6.5). Structural and non-structural carbohydrates are the two types of carbohydrate present in millets. Among the non-structural carbohydrates, starch and fructosans are predominant. The structural carbohydrates are cellulose and hemicellulose.

Table 6.4 Comparison of the proximate analysis on common millets and cereals (Dayakar et al. 2017)

Millets and cereals		Moisture (g)	Protein (g)	Ash (g)	Total fat (g)	Dietary fibre (g)			Carbohydrates (g)	Energy (KJ)
						Total	Insoluble	Soluble		
Bajra (*Pennisetum typhoideum*)		08.97 ± 0.60	10.96 ± 0.28	1.38 ± 0.17	5.43 ± 0.64	11.49 ± 0.62	9.14 ± 0.58	2.34 ± 0.42	61.78 ± 0.85	1456 ± 18
Sorghum (*Sorghum vulgare*)		09.01 ± 0.77	09.97 ± 0.43	1.39 ± 0.34	1.73 ± 0.31	10.22 ± 0.49	8.49 ± 0.40	1.73 ± 0.40	67.68 ± 1.03	1398 ± 13
Ragi (*Eleusine coracana*)		10.89 ± 0.61	07.16 ± 0.63	2.04 ± 0.34	1.92 ± 0.14	11.18 ± 1.14	9.51 ± 0.65	1.67 ± 0.55	66.82 ± 0.73	1342. ± 10
Little millet (*Panicum millare*)		14.29 ± 0.45	08.92 ± 1.09	1.72 ± 0.27	2.55 ± 0.13	06.39 ± 0.60	5.45 ± 0.48	2.27 ± 0.52	65.55 ± 1.29	1449 ± 19
Foxtail millet (*Setaria italica*)		14.23 ± 0.45	08.92 ± 1.09	1.72 ± 0.27	2.55 ± 01.3	06.39 ± 0.60	4.29 ± 0.82	2.11 ± 0.34	66.19 ± 1.19	1388 ± 10
Foxtail millet[a]		–	12.30	–	4.30	–	–	–	60.90	331
Barnyard millet[a]		–	6.20	–	2.20	–	–	–	65.55	307
Wheat	Whole	10.58 ± 1.11	10.59 ± 0.60	1 42 ± 0.19	1.47 ± 0.05	11.23 ± 0.77	9.63 ± 0.19	1 60 ± 0.75	84.72 ± 1.74	1347 ± 23
	Refined flour	11.34 ± 0.93	10.36 ± 0.29	0.51 ± 0.07	0.76 ± 0.07	02.76 ± 0.29	2.14 ± 0.30	0.62 ± 0.14	74.27 ± 0.92	1472 ± 16
	Atta	11.10 ± 0.35	10.57 ± 0.37	1.28 ± 0.19	1.53 ± 0.12	11.36 ± 0.29	9.73 ± 0.47	1.63 ± 0.64	64.17 ± 0.32	1340 ± 07
	Semolina	08.94 ± 0.68	11.38 ± 0.37	0.80 ± 0.17	0.74 ± 0.10	09.72 ± 0.74	8.16 ± 0.58	1.55 ± 0.18	68.43 ± 0.99	1396 ± 18
Rice	Raw Brown	9.33 ± 0.39	09.16 ± 0.75	1.04 ± 0.18	1.24 ± 0.08	04.43 ± 0.54	3.60 ± 0.55	0.82 ± 0.15	74.80 ± 0.85	1480 ± 10
	Raw milled	9.93 ± 0.39	09.16 ± 0.75	1.04 ± 0.18	1.24 ± 0.08	04.43 ± 0.54	3.60 ± 0.55	0.82 ± 0.15	74.80 ± 0.85	1480 ± 10
	Parboiled	10.09 ± 0.43	07.89 ± 0.63	0.65 ± 0.8	0.55 ± 0.08	03.74 ± 0.36	2.98 ± 0.35	0.76 ± 0.09	77.18 ± 0.76	1471 ± 8
Quinoa (*Cheno podium quinoa*)		10.43	13.11	2.65	5.50	14.66	10.21	4.46	53.65	1374
Amaranth seed	Black	9.89	14.59	2.78	5.74	7.02	5.75	1.26	59.98	1490
	Pale Brown	09 ± 0.40	13.27 ± 0.34	3.05 ± 0.30	5.56 ± 0.3	07.47 ± 0.09	5.83 ± 0.17	16.7 ± 0.21	64.46 ± 0.60	1489 ± 10
Maize	Dry	09.26 ± 0.55	8.80 ± 0.49	1.17 ± 0.16	3.77 ± 0.48	12.24 ± 0.93	11.29 ± 0.85	0.94 ± 0.18	64.77 ± 1.58	1398 ± 25

[a]Fragmented data from additional cultivars

Table 6.5 Proximate analysis of various millets (% dwb) (Gomez and Gupta 2003)

Millet type	Protein		Lipid		Fiber		Ash		Carbohydrate	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
Little	10.7	7.5–13.8	6	5.3–6.8	7	3.7–7.6	5.9	4.6–10.1	66.3	62.6–71.0
Foxtail	11.8	10–15.8	4.1	2.5–6.8	7.1	6.3–8.1	3.3	1.4–5.7	66.9	63.0–72.4
Barnyard	11.3	10.2–11.6	4	3.0–5.1	13.9		4.6		55.7	
Finger	8.7	6.0–10.9	1.8	1.0–4.6	3.4	3.0–7.5	2.8	2.3–3.9	82.3	73.5–87.5
Kodo	10.2	6.6–12.1	3.9	1.5–6.6	8.4	6.2–10.5	3.6	2.9–4.1	73.5	72.5–74.0
Proso	13.5	10.9–18.6	3.7	2.3–4.9	5.5	0.7–9.0	3.3	2.8–3.7	68.9	60.6–80.1
Pearl	11.6	8.6–17.4	4.8	1.5–6.8	2.3	1.4–7.3	2.2	1.6–3.6	75.6	61.5–89.1

Starch represents between 50 and 75% of the total grain weight and represents the main source of energy utilized by the grain during germination. Total starch content in millet ranges from 55 to 66% (Krishnakumari and Thayumanavan 1995; Geervani and Eggum 1989b).

The starch molecules are composed of amylose and amylopectin, and their respective concentrations may affect the functionality of millet starch since the amylose and amylopectin of the starch are held together by hydrogen bonds. Millet endosperm is composed of about 23 to 30% of amylose (Cagampang and Kierleis 1985). The pasting behavior and thermal property show that the millet starch pastes are cohesive, while the water-binding capacity in millet starch is considered less than for corn starch. Millet starches are considered less soluble than corn starch.

Millets contain between 1 and 2% of free sugars composed of variations of glucose, fructose, and sucrose. The sucrose is predominant among them with 0.3%–1.2% (Malleshi et al. 1986b). In minor millets, the total free sugars range from 0.5 to 2% with proso millet having the highest free sugar content. Mature millet grains will have higher free sugars, containing between 2.2 and 3.8% of soluble sugars, 0.9 and 2.5% free reducing sugars, and 1.3 and 1.4% non-reducing sugars (Bhatia et al. 1972). Glucose and fructose contents range, respectively, between 0.6% and 1.8% and 0.3% and 0.7% (Bhatia et al. 1972).

6.3.2 Dietary Fibers

The compositions in dietary fibers in various millets are presented in Tables 6.4, 6.5 and 6.6. Millets are rich in both soluble dietary (SDF) and insoluble dietary fibers (IDF) (Nakarani et al. 2021). The dietary fibers are principally present in the outer layers of the grain; hence, the traditional decortication that takes place for most millets reduces the percentage of total dietary fiber in the millets that are available for human consumption (Geervani and Eggum 1989b). Significant differences are reported as a function of the level of dehusking, dehulling, and polishing done on the grain. When assessing whole grain millets, little millet has been found to have higher levels of insoluble dietary fiber (29.48%), soluble dietary fiber (1.33%), and total dietary fiber (30.81%) followed by barnyard millet. Kodo, proso, and foxtail millets were found to have similar total dietary fiber (Murugesan 2015). All

Table 6.6 Dietary fiber in whole versus dehusked millet grains, % (Geervani and Eggum 1989b)

	Insoluble dietary fiber		Soluble dietary fiber		Total dietary fiber	
Millet type	Whole grain	Dehusked grain	Whole grain	Dehusked grain	Whole grain	Dehusked grain
Little	29.48	1.83	1.33	0.7	30.81	2.53
Foxtail	17.8	1.53	1.31	0.87	19.11	2.4
Barnyard	26.04	1.98	0.59	0	26.63	1.98
Kodo	19.05	2.17	1.94	0.3	20.99	2.47
Proso	17.83	2.91	2.21	0.73	20.04	3.64

dehusked millet grains will have a significantly lower amount of total dietary fiber than their whole grain counterpart. This is expected from the removal of the bran layers during the dehusking process, which contain the largest proportion of fiber (Geervani and Eggum 1989b).

6.3.3 Protein

Protein content in millet grain varies as a function of the agronomic conditions that prevailed during growth (such as availability of water, soil fertility, temperature, and other environmental factors during both plant and grain development) and genotype (Tables 6.4 and 6.5). In a report by the FAO, the average protein content of minor millets was reported to range between 7.7 and 12.5%. In particular, the protein contents were reported as 11.8%, 7.7%, 11.2%, 12.5%, 9.7%, and 9.8% for pearl, finger, foxtail, proso, and kodo millets, respectively (FAO 1995).

The protein in millet is located mainly (80%) in the endosperm, germ (16%), and pericarp (3%) (Taylor et al. 2006). The quality of millet protein, in terms of amino acid profile, is considered fair when compared to major cereals. The protein from the endosperm contains kafirins and glutenins, while the protein in the germ is rich in albumins and globulins. The millet proteins have been divided into six protein fractions: fraction I, albumin+globulin; fraction II, prolamin; fraction III, prolamin; fraction IV, glutelin like; fraction V, true glutelin; and fraction, VI residual protein (Parameswaran and Thayumanavan 1995). The combined globulin and albumin fraction represents 8.5–16.26%, prolamin 15–30%, and glutelin 45–55%, of the total millet protein. Foxtail millet is an exception with higher prolamin (60%) and lower glutelin (15–23%) (Parameswaran and Thayumanavan 1995). Pearl millets have 33–49.5% prolamins and 30–45% glutelins, while globulins and albumins make up the balance with 18–26% (Chandna and Matta 1990). The amino acid profiles are different in different types of millets (Table 6.7). As with most cereals, lysine is the limiting essential amino acid in millets. Glutamic acid (16–23%) and leucine (12–22%) are the major amino acids in the prolamin fraction for most millets, while barnyard millet has been reported to have a higher content of alanine (18%), than leucine (Parameswaran and Thayumanavan 1995; Kumar and Parameswaran 1998).

6.3.4 Lipids

Millets are known to deteriorate quickly during storage with the common oxidation of their lipids (Osagie and Kates 1984). Indeed, millets are found to have a higher amount of lipids when compared to wheat (Tables 6.4 and 6.5). As a comparison, the spring wheat cultivated in Canada contains 1.3 to 2.75% (dwb) of free lipids (Bekes et al. 1986), and Hungarian wheat contains 1.7 to 3% (dwb) (Karpati et al. 1990), while most millets contain between 1.5 and 7.2% lipids (Osagie and Kates 1984). Sridhar and Lakshminarayana (1994) studied and compared the lipid content and

Table 6.7 Amino acid profile of most common millets and major cereals (Dayakar et al. 2017)

Millets and cereals		Histidine	Isoleucine	Leucine	Lysine	Methionine	Cystine	Phenylalanine	Threonine	Tryptophan	Valine
Bajra (*Pennisetum typhoideum*)		2.15 ± 0.37	3.45 ± 0.74	08.52 ± 0.88	3.19 ± 0.49	2.11 ± 0.50	1.23 ± 0.33	4.82 ± 1.18	3.55 ± 0.40	1.33 ± 0.030	4.79 ± 1.04
Sorghum (*Sorghum vulgare*)		2.07 ± 0.20	3.45 ± 0.83	12.03 ± 1.51	2.31 ± 0.40	1.52 ± 0.50	1.06 ± 0.30	5.10 ± 0.50	2.96 ± 0.17	1.03 ± 21	4.51 ± 0.71
Ragi (*Eleusine coracana*)		2.37 ± 0.46	3.70 ± 0.44	08.86 ± 0.54	2.83 ± 0.34	2.74 ± 0.27	1.48 ± 0.23	5.70 ± 1.27	3.84 ± 0.45	0.91 ± 0.30	5.65 ± 0.44
Little millet (*Panicum millare*)		2.35 ± 0.18	4.14 ± 0.08	08.08 ± 0.06	2.42 ± 0.10	2.21 ± 0.10	1.85 ± 0.14	6.14 ± 0.10	4.24 ± 012	1.35 ± 010	5.31 ± 0.18
Foxtail millet (*Setaria italica*)		2.14 ± 0.07	4.55 ± 0.22	11.96 ± 1.65	1.42 ± 0.17	2.69 ± 0.16	1.92 ± 0.05	6.27 ± 0.34	3.89 ± 0.16	1.32 ± 0.19	5.49 ± 0.23
Wheat	Whole	2.85 ± 0.31	3.83 ± 0.20	06.81 ± 0.33	3.13 ± 0.26	1.75 ± 0.21	2.35 ± 0.23	4.75 ± 0.38	3.01 ± 0.17	1.40 ± 1.10	8.11 ± 0.05
	Refined flour	1.96 ± 0.23	3.19 ± 0.27	06.22 ± 0.46	2.05 ± 0.18	1.64 ± 0.20	2.03 ± 0.27	4.29 ± 0.28	2.34 ± 0.08	1.04 ± 0.16	4.01 ± 0.44
	Atta	2.56 ± 0.25	3.78 ± 0.21	06.13 ± 0.48	2.42 ± 0.22	1.77 ± 19.4	2.24 ± 0.18	5.03 ± 0.14	2.58 ± 0.14	0.99 ± 0.16	5.12 ± 0.48
	Semolina	2.38 ± 4.28	3.43 ± 0.26	06.71 ± 0.59	2.54 ± 0.13	1.57 ± 0.23	1.79 ± 0.03	4.77 ± 0.32	2.71 ± 0.15	1.04 ± 0.12	4.47 ± 0.39
Rice	Raw brown	2.36 ± 0.18	4.08 ± 0.05	08.40 ± 0.55	3.63 ± 0.29	2.39 ± 0.26	2.02 ± 0.12	5.50 ± 0.49	3.38 ± 0.25	1.00 ± 0.17	6.72 ± 0.38
	Raw milled	2.45 ± 0.30	4.29 ± 0.23	08.09 ± 0.40	3.70 ± 0.39	2.60 ± 0.24	1.84 ± 0.18	5.36 ± 0.43	3.28 ± 0.27	1.27 ± 0.14	6.06 ± 02
	Parboiled	2.35 ± 0.18	4.14 ± 0.08	08.08 ± 0.06	3.42 ± 0.10	2.48 ± 0.24	2.15 ± 0.08	5.14 ± 0.10	3.24 ± 0.12	1.15 ± 0.08	6.26 ± 0.13
Quinoa (*Cheno podium quinoa*)		2.98	3.75	6.08	5.58	2.24	1.85	4.35	3.01	1.25	4.55
Amaranth seed	Black	1.86	2.82	4.83	5.45	1.86	1.60	3.98	3.02	1.06	4.34
	Pale brown	1.98 ± 0.50	2.85 ± 0.04	04.94 ± 0.17	5.50 ± 0.35	1.95 ± 0.12	1.51 ± 0.15	4.75 ± 0.41	2.99 ± 0.21	1.69 ± 0.10	4.30 ± 0.27
Maize	Dry	2.70 ± 0.21	3.67 ± 0.22	12.24 ± 0.57	2.64 ± 0.18	2.10 ± 0.17	1.55 ± 0.14	5.14 ± 0.29	3.23 ± 0.29	0.57 ± 0.12	5.41 ± 0.71

composition of foxtail millet (*S. italica*), proso millet (*P. miliaceum*), and finger millet (*E. coracana*) grains. They found that the total lipid content (dwb) varied significantly between different cultivars, as high as 11% in foxtail, 9% in proso, and 5.2% in finger millets. Triacylglycerol in finger millet accounted for 80% of the total lipid, whereas phospholipids and glycolipids accounted for 14% and 6% of the total lipid (Sridhar and Lakshminarayana 1994). Bagdi et al. (2011) studied the free and bound lipid composition for proso millet, and they found that hydrocarbons, sterol esters, triacylglycerols, diacylglycerols, and free fatty acids were present in the free lipid fraction, while linoleic, oleic, and palmitic acids were the main free fatty acids present. In the bound lipid fraction, phosphatidylserine, phosphatidylcholine, monogalactosyl diacylglycerols, digalactosyl diacylglycerols, and phosphatidylethanolamine were identified (Osagie and Kates 1984; Bagdi et al. 2011; Murugesan 2015). Liang et al. (2010) studied the chemical characteristics and the fatty acid profile of foxtail millet and found that foxtail millet oil is rich in unsaturated linoleic acid (66.5%) and oleic acid (13.0%), while the saturated fatty acids included palmitic acid (6.4%) and stearic acid (6.3%) (Liang et al. 2010).

The FAO reported lipid values of 4.8%, 1.5%, 4.0%, 3.5%, 5.2%, and 3.6% for pearl millet, finger millet, foxtail millet, proso millet, little millet, and kodo millet, respectively (FAO 1995). The majority of the lipid fraction is present in the pericarp and germ of the millet grain (Liang et al. 2010). Thus, the amount of lipid can be considerably decreased with decortication of the grain. The majority of the lipids present in millet are considered to be non-polar lipids (Sridhar and Lakshminarayana 1992). The non-polar lipids of millets are mainly composed of triglycerides (85%), sterols (4.1%), and diglycerides (4.0%) (Osagie and Kates 1984). For seed germination, the triglycerides serve as an energy reserve. The polar lipids such as glycolipids and phospholipids are also present in millets (Table 6.8). The ranges of glycolipids vary from 2.5% to 6.2% and phospholipids range from 17% to 25% of total lipids (Sridhar and Lakshminarayana 1994). These less abundant polar lipids have important biochemical functions with oil-soluble vitamins. The non-saponifiable compounds including carotenoids, phytosterols, and tocopherols are present in the range of micrograms.

6.4 Minerals and Phytochemicals

Vitamins and minerals are present in varied amounts in millets (Tables 6.9 and 6.10). Of all the available millets, pearl millet has been found to have the highest amount of carotene (132 mg/100 g) when compared with other millets (Murugesan 2015). All millets have been found to have similar thiamine and riboflavin contents. Barnyard millet, little millet, and foxtail millet were found to have a higher amount of niacin when compared with other millets or other grains (Lebiedzinska and Szefer 2006; Shobana et al. 2012).

The minerals in millets (Table 6.9), such as iron and calcium, are generally present in concentrations comparable to other grains such as rice and wheat. The amount of calcium present in finger millet is significantly high in comparison to the

Table 6.8 Classes of lipids for most common millets (Sridhar and Lakshminarayana 1992, 1994)

Lipid subclasses	Little millet	Foxtail millet	Barnyard millet	Finger millet	Proso millet	Kodo millet
Nonpolar lipid subclasses						
Triacylglycerols	86.3	83.2	84.2	84.8	81.2	90.8
Diacylglycerols	2.3	2.2	0.8	2.9	2.9	2.0
Monoacylglycerols	0.7	Trace	0.2	1.7	1.1	0.8
Free fatty acids	1.5	3.5	1.8	3.6	4.0	1.8
Free sterols	5.9	6.0	10.2	5.8	7.8	3.8
Steryl esters	3.3	4.8	2.8	1.2	3.0	0.8
Glycolipid subclasses						
Steryl glycosides	7.6	8.5	20.2	6.9	12.5	16.3
Esterified steryl glycosides	24.1	23.4	18.6	13.2	29.5	21.4
Cerebrosides	1.2	1.5	9.1	8.3	2.0	5.0
Digalactosyldiglycerides	9.0	15.7	21.4	30.7	11.5	28.0
Digalactosylmonoglycerides	1.8	2.0				Trace
Monogalactosyldiglycerides	55.3	47.6	30.7	40.9	40.4	29.2
Monogalactosylmonoglycerides	0.9	1.3	Trace		4.1	
Phospholipid subclasses						
Phosphatidic acid	5.5	5.5	1.8	2.5	1.5	9.0
Phosphatidylglycerol	8.0	8.0	3.8	9.2	Trace	18.0
Phosphatidylethanolamine	21.0	21.0	24.0	23.0	30.0	30.2
Phosphatidylcholine	36.5	36.5	30.7	26.5	36.8	21.2
Lysophosphatidylcholine	28.0	28.0	24.8	30.0	22.0	20.1
Phosphatidylserine	Trace	Trace	8.3	Trace	8.5	Trace
Phosphatidylinositol	Trace	Trace	6.6	8.0	Trace	Trace

Table 6.9 Minerals and minor trace elements in millets (per 100 g) (Geervani and Eggum 1989b; Gopalan et al. 1976)

	Calcium (mg)	Phosphorus (mg)	Iron (mg)	Magnesium (mg)	Sodium (mg)	Potassium (mg)	Copper (mg)	Manganese (mg)	Molybdenum (mg)	Zinc (mg)	Chromium (mg)	Sulfur (mg)	Chlorine (mg)
Little	17	220	9.3	133	8.1	129	1.00	0.68	0.016	3.7	0.180	149	13
Foxtail	31	290	2.8	81	4.6	250	1.40	0.60	0.70	2.4	0.030	171	37
Barnyard	20	280	5.0	82	–	–	0.60	0.96	–	3.0	0.090	–	–
Finger	344	283	3.9	137	11	408	0.47	5.49	0.102	2.3	0.028	160	44
Kodo	27	188	0.5	147	4.6	144	1.60	1.10	–	0.7	0.020	136	11
Proso	14	206	0.8	153	8.2	113	1.60	0.60	–	1.4	0.020	157	19
Pearl	42	296	8.0	137	10.9	307	1.06	1.15	0.069	3.1	0.023	147	39

Table 6.10 Common vitamins present in millets (per 100 g) (Shobana et al. 2012)

Millets	Carotene (mg)	Thiamine (mg)	Riboflavin (mg)	Niacin (mg)	Choline (mg)
Little millet	0	0.30	0.09	3.2	–
Foxtail millet	32	0.59	0.11	3.2	–
Barnyard millet	0	0.33	0.10	4.2	–
Finger millet	42	0.42	0.19	1.1	–
Kodo millet	0	0.33	0.09	2.0	–
Proso millet	0	0.20	0.18	2.3	748
Pearl millet	132	0.33	0.25	2.3	–

Table 6.11 Polyphenolic composition of finger, pearl, and foxtail millets (μg/mg samples) (Dykes and Rooney 2006)

Compound	Finger millet	Pearl millet	Foxtail millet
Protocatechuic	23.1	11.8	–
Gentisic	61.5	96.3	21.5
p-Hydroxybenzoic	8.9	22	14.6
Vanillic	15.2	16.3	87.1
Caffeic	16.6	21.3	10.6
Syringic	7.7	17.3	93.6
Coumaric	56.9	268.2	2133.7
Ferulic	387	679.7	765.8
Cinnamic	35.1	345.3	781.7

other millets with 344 mg of calcium in 100 g of millets. Pearl, foxtail, proso, little, and kodo millets have 42, 31, 8, 17, and 35 mg of calcium in 100 g of edible millet, respectively (Geervani and Eggum 1989b; Gopalan et al. 1976).

The iron contents in pearl and little millets are the highest at 8 and 9.3 mg per 100 g of edible millet. Finger millet follows next with 3.9 mg/100 g. Foxtail, proso, and kodo millets possess 2.8, 0.8 and 1.7 mg of iron in 100 g of millet, respectively (Gopalan et al. 1976).

Millets are known to contain high amounts of phenolic acids (Li et al. 2021), when compared to rice and wheat (Table 6.2), and the major phenolic acids present in finger, foxtail, and pearl millets are listed in Table 6.11 (Dykes and Rooney 2006). Millets are also important sources of tannins, anthocyanins, and phytosterols.

Certain parts of millet seeds, particularly the seed coat, contain antinutritional compounds such as phytates (0.48%), polyphenols, tannins (0.61%), trypsin inhibitory factors, hydrochloric acid, and dietary fibers (Shobana and Malleshi 2007). These components are considered as antinutrients due to their metal-chelating and enzyme inhibitory activities (Thompson 1993). The phenolic compounds found in millets are a complex mixture and derivatives of benzoic acid and cinnamic acid, and they may exhibit enzyme inhibitory activities. The antinutritional compounds are usually concentrated in the bran layers such as the aleurone, testa, and pericarp;

hence, most millets usually lose the bulk of their phenolic compounds during the dehulling and milling processes. Histochemical examinations have demonstrated that the majority (60%) of polyphenols in millet are located in the seed coat. Millets contain mainly free, soluble form and conjugated forms of phenolic acids, i.e., hydroxybenzoic and hydroxycinnamic acid (Li et al. 2021). The different types of hydroxybenzoic acids present are gallic, protocatechuic, p-hydroxybenzoic, gentisic, vanillic, and syringic acids. The various types of hydroxycinnamic acids present are chlorogenic, caffeic, trans-cinnamic, p-coumaric, sinapic, trans-ferulic, and cis-ferulic acids. In finger millet, ferulic acid (64–96%) and p-coumaric acid (50–99%) are the principal bound phenolics. Several flavonoids are also present in millet, namely, orientin, isoorientin, vitexin, isovitexin, saponarin, violathin, lucenin-1, and tricin (Shahidi and Chandrashekhara 2013).

The characteristics phenolics found in millets are thermo resistant, pH sensitive, and largely unstable under alkaline conditions (Chethan and Malleshi 2007). Rao and Muralikrishna (2002) have reported that ferulic acid represents the most important bound phenolic acid (18.60 mg/100 g), while protocatechuic acid is known as the most important free phenolic acid (45.0 mg/100 g) contained in finger millet.

Finger millet varieties are also reported to contain proanthocyanidins, also known as condensed tannins with metal-chelating activities (Dykes and Rooney 2006; Sharma and Gujral 2019). Tannins are biologically active and, when present in sufficient quantities, may lower the nutritional value and biological availability of proteins and minerals (Sharma and Gujral 2019). Condensed tannins are generally considered to have high antioxidant activity. Chandrasekara and Shahidi (2010) have shown that finger millet had the highest content of tannins (311.28 μmol of catechin equivalent/g) followed by foxtail, little, pearl, and proso millets. The values reported for millets were higher than those reported for barley (Chandrasekara and Shahidi 2010) and for wheat (Sharma and Gujral 2019). The different proanthocyanins found in the available varieties of millets are apigeninidin, apigeninidine 5-glucoside, luteolinidin, 5-methoxyluteolinidin, 5-methoxyluteolinidin 7-glucoside, 7-methoxyapigeninidine, 7-methoxyapigeninidine 5-glucoside, and luteolinidin 5-glucoside (Sharma and Gujral 2019). For the flavones present, the compounds identified are apigenin and luteolins, whereas for the flavanones present, the compounds have been identified as eriodictyol and eriodictyol 5-glucoside (Li et al. 2021).

Using spectrometric analysis, Watanabe (1999) studied the phenolic compounds present in barnyard millet, and the data compiled recognized the different phenolic structures to be N-(*p*-coumaroyl) serotonin, luteolin, and tricin. Luteolin was found to have a lower antioxidant activity when compared with N-(*p*-coumaroyl) serotonin, while it was found to be equivalent to quercetin, known as the reference standard. In the case of tricin, its antioxidant activity was determined to be even lower when compared with luteolin and quercetin (Watanabe 1999).

Hegde and Chandra (2005) studied the free radical quenching 1,1, diphenyl-2-picrylhydrazyl (DPPH) by electron spin resonance of six different millets, in particular, little millet (*Panicum sumatrense*), kodo millet (*Paspalum scrobiculatum*), barnyard millet (*Echinochloa utilis*), finger millet (*Eleusine coracana*), foxtail millet

(*Setaria italica*), and sorghum (*Sorghum bicolor*). Kodo millet flour quenched DPPH by 70%, which was higher than all the other millets with DPPH quenching ranging between 15 and 53% (Hegde and Chandra 2005). The colored and darker-colored millets exhibited higher quenching when compared with their respective pale or white varieties indicating that the seed coat is principally responsible for the higher antioxidant activity (Hegde and Chandra 2005; Li et al. 2021).

Suma and Urooj (2012) studied the antioxidant activity of foxtail millet whole flours and their bran-rich fractions. They found that the millet flours contain alkaloids, phenolics, reducing sugars, and flavonoids, all with significantly high radical scavenging activity and reducing power. The bran layer was found to contribute the most antioxidant compounds since it is the bran-rich fraction that exhibited the highest antioxidant activity (Suma and Urooj 2012).

As of today, and thanks to modern identification techniques using HPLC and HPLC coupled with combinations of mass spectrometry, more than 50 phenolic compounds, belonging to several classes, have been identified in millet grains such as barnyard, finger, foxtail, kodo, proso, little, and pearl millets (Saleh et al. 2013; Sharma et al. 2017). The presence in significant amounts and the diversity of these phenolic compounds make millets a valuable nutritional grain with nutraceutical and functional characteristics that can be used in the production of health-promoting foods (Li et al. 2021).

6.5 Changes in Composition Due to Processing and Storage

Millets are traditional grains consumed worldwide that undergo a variety of processing steps to reach the palatable state desired by the consumer. These processing steps consist of dehusking/decortication, drying, polishing, etc. During processing, the grains will experience various physicochemical changes that may affect the nutritional value, the bioavailability, digestibility, and overall quality of the final grain products.

6.5.1 Decortication/Dehulling of Millets

Decortication/dehusking or dehulling is a mechanical process of removing the seed coat/protective layer from the endosperm of the grain (Dharmaraj et al. 2013). Coarse grains such as wheat, sorghum, or millet are usually dehusked/dehulled in order to remove the fibrous outer layer to make them suitable for adequate cooking or roasting in order to improve the texture and the sensory profile of the grains (Liu et al. 2012). Decortication/dehulling of minor millets is considered difficult because of the small size and round shape of millets, making the process more difficult to handle than with any other cereal grains (Vetriventhan et al. 2021). The success of the dehulling process and the yield of decortication depend largely on the forces applied and on the moisture conditioning and moisture content of the grains underlining the fact that successful decortication is a delicate process (Vetriventhan et al. 2021). The whole success of the decortication process will depend on the overall quality of the grains, stemming from the harvesting conditions, drying parameters, preprocessing consideration, removal of cracked grains, and the quality and efficiency of the milling machinery (Bhattacharya 1980). As a pre-processing step, hydrothermal processing, such as steaming, has been reported to improve yield and quality of decorticated millet grains with controlled steaming conditions (Dharmaraj et al. 2013; Onyango et al. 2020).

Depending on the hardness of the seed coat, dehulling or decortication of millets can be performed by shearing at the grain surface by hand pounding, with rotating emery boards or by mechanical dehulling (Hama et al. 2011). To clean the dehulled grains, the bran and chaff are separated from the decorticated grains by movement of air in a process known as winnowing. Since the process of decortication of millets removes the bran and outer layer of the grains, the intensity of the process may affect their nutrient content (Lestienne et al. 2007). This stems from the variable distribution of the nutritional components throughout the different parts of a grain. Indeed, the endosperm of a grain, which represents between 75 and more than 80% of the kernel mass, is principally rich in starch. While on the other hand, the pericarp is composed principally of fiber and phenolic compounds, while the germ is principally rich in lipids, minerals, and phytates. Inevitably, the decortication process of millets results in some nutritional losses such as fiber, minerals, phenols, and antioxidant activity. This reduction in nutritional value is attributed to the extent of the removal of both the pericarp and aleurone layers of the grain where most of the minerals, fibers, antioxidants, phytates, and tannins are effectively located (Hama et al. 2011; Dharmaraj et al. 2013). Similar events of loss in nutrient content, as compared to whole grains, due to the decortication process were found by other researchers (Chandrasekara et al. 2012; Krishnan et al. 2012). Although decortication has been demonstrated to reduce the overall nutrient content of finger millet, decortication was also found to increase the bioavailability and digestibility of certain nutrients with the decrease in antinutritional compounds such as polyphenols and phytates that are removed with the fiber (Dharmaraj et al. 2013).

6.5.2 Milling/Grinding

Milling or grinding is a very important step in grain processing. While decortication may serve to treat the raw whole grain in order to be made available into a ready-to-cook/ready-to-eat product that can be consumed like rice, milling/grinding is the process necessary to transform the grains into a flour, which can then be used in a variety of bakery and pasta formulations (Mannuramath and Yenagi 2015; Verma et al. 2015). The milling process for millet grains can affect the nutritional content and quality of the produced flour, and these changes have only been explored by only a few researchers (Chowdhury and Punia 1997; Sharma et al. 2021; Sruthi and Rao 2021; Yousaf et al. 2021). Chowdhury and Punia (1997) studied pearl millet milling of flours in baking applications. They determined the effect of milling and baking parameters on both nutritional and antinutritional compositions. The study confirmed that the milling process changed the chemical composition of the millet flour. In addition, the milling of the flour and the baking heat treatment during the production of chapattis, an Indian unleavened bread, increased the digestibility of both the protein and starch, while it minimized the antinutritional effects of the polyphenols and phytate contents (Chowdhury and Punia 1997). Suma and Urooj (2014b) studied two separate varieties of pearl millets to assess the impact of milling on their nutrients, antinutrients, and in vitro mineral bioaccessibility. The two pearl millet varieties were processed and ground into three different flours, as whole grain flour, semi-refined grain flour, and a bran-rich flour. The study confirmed that semi-refined flour had the best mineral bioavailability along with the lowest concentration of antinutritional compounds. These results are supported by the fact that the semi-refined millet grains are polished during milling, removing part of the bran/seed coat (Suma and Urooj 2014b).

It is clear that changes in the nutritional function of milled flours are principally attributed to the removal of the bran/seed coat, with significant differences between whole versus polished millet grains. Removal of the bran/seed coat, by either dehulling, milling, or polishing, decreases the overall nutritional value of the product, while it reduces the concentration of antinutritional compounds. In the study by Oghbaei and Prakash (2012), whole or sieved finger millet flours were evaluated to assess their chemical composition, the bioavailability of their minerals, and the in vitro digestibility of their starch and proteins. Evidently, the two flours were different in composition with the whole grain flour richer in certain nutrients found in the seed coat, while the sieved flour had higher protein digestibility and mineral bioavailability (Oghbaei and Prakash 2012). Similar changes to the nutritional profiles during milling were also noted in barnyard millet flour by Lohani et al. (2012), in finger millet flour by Onyango et al. (2020), in kodo millet flour by Sharma et al. (2021), and in little millet by Guha et al. (2015).

6.6 Hydrothermal Treatments

Treating with heat and moisture is the traditional process for the preparation of millet grains for ready-to-eat consumption (like hot steamed rice) (Verma et al. 2015). Depending on the hardness of the millet seed, hydrothermal treatments may involve first the soaking of grains, followed by steaming or wet cooking/boiling. Soaking grains is one of the most popular and traditional method used by households to reduce the antinutritional compounds (such as phytates) via leaching into the soaking water (Saleh et al. 2013), thus improving their overall digestibility.

Sharma and Sharma (2022) studied the soaking of foxtail millet seeds. Their results showed similar degradation and leaching of phytates as reported by Lestienne et al. (2005) after soaking of whole and dehulled pearl millet varieties, where dehulling and milling prior to soaking improved the leaching of antinutritional compounds. Similar results were reported for the soaking of foxtail millet in a study conducted by Pawar and Machewad (2006) and for little millets by

Mannuramath and Yenagi (2015) where improved protein digestibility was also demonstrated.

The effects of hydrothermal treatments on finger millet's carbohydrates, proteins, and lipids were evaluated by Dharmaraj and Malleshi (2011), while the effects on the physical and textural properties were assessed by Dharmaraj et al. (2013), indicating an increase in hardness in the kernels. Moisture conditioning of finger millets, enhanced by ultrasound, was investigated by Yadav et al. (2021). Their findings highlighted the benefit of using ultrasound during the hydration process to increase the water-binding capacity while reducing both phytate and tannin contents. The applied ultrasounds at high amplitude and extended time disrupted the cell wall leading to a greater water uptake during soaking (Yadav et al. 2021). Parboiling (hydrothermal treatments) can also be considered as a useful pre-treatment to help with seed coat removal. In a study conducted by Bora et al. (2018), parboiling resulted in a significant increase in the yield of the decorticated millets when compared with non-parboiled millets, and proso millets showed a 28% improvement in decortication yield from the increase in hardness of the kernel and a lifting of the hull from the seed's endosperm. Hydrothermal treatments also serve to improve the palatability of grains, which was the case when proso millet grains were subjected to steam at 97 °C for 12 min. Their flavor score during sensory evaluation was higher in the case of processed versus unprocessed proso millet flours (Bookwalter et al. 1987). In the study by Geervani and Eggum (1989a), the effects of thermal treatments on protein quality and improved digestibility were evaluated for a variety of millets, namely, foxtail (*Setaria italica*), proso millet (*Panicum miliaceum*), barnyard millet (*Echinochloa colona*), kodo millet (*Paspalum scrobiculatum*), and little millet (*Panicum sumatrense*) (Geervani and Eggum 1989a).

6.7 Malting/Germinating

Malting/germinating of grains and seeds is a traditional food preparation technique requiring soaking of the seeds followed by a resting period allowing seed germination. The germination process generally improves the nutritional quality of the seeds/ grains through a series of biochemical processes taking place during the degradation/ consumption of the reserve materials for the development of the embryo from the seed. Hemalatha et al. (2006) studied finger millet and showed that after 48 h of germination, the availability of iron increased from 24.8% to 29.5%. Physicochemical changes in the raw versus germinated finger millet was studied by Malleshi et al. (1986a). They found that following 48 h of germination, the finger millet starch was slightly less vulnerable to amylolysis, when compared to raw pearl millet and foxtail millet starches (Malleshi et al. 1986b).

Parameswaran and Sadasivam (1994) studied the effect of germination on carbohydrates and nitrogenous components in proso millet. The study established that germination increased the availability of free amino acids, tryptophan, and non-protein nitrogen, while there was a decrease in the starch content (Parameswaran and Sadasivam 1994). Improvements in the in vitro protein digestibility in germinated seeds were demonstrated by Archana et al. (2001) for pearl millet (*Pennisetum gluacum* L.), while significant reductions in polyphenols (28%) and phytic acids (38%) were noted. Similar conclusions were reported by numerous researchers, with different millets, stating that germination increased extractability, solubility, and bioaccessibility of proteins and minerals, while it decreased the detrimental effects of antinutritional elements (Coulibaly and Chen 2011; Eyzaguirre et al. 2006; Hassan et al. 2006; Krishnan et al. 2012; Mamiro et al. 2001; Sharma et al. 2021; Suma and Urooj 2014a; Theodoro et al. 2021). In their study on the impact of germination on barnyard millet, Sharma et al. (2016) established that the germination process improved its health-promoting quality by enhancing its GABA content.

The germination process can significantly improve the digestibility and nutrient availability in foods especially in grains such as millets. Germinated seeds can then be processed into a powder/flour that can serve to produce malt-rich products that are nutritious and easily digestible for infants and small children (Najdi Hejazi and Orsat 2017; Syeunda et al. 2021).

6.8 Fermentation

Fermentation is an age-old process to ensure food preservation (Motarjemi 2002), while it can also improve the nutritional and sensory properties of fermented foods. Through a fermentation process, the chemical composition of millets can change, reducing the levels of antinutrients while improving digestibility (Elyas et al. 2002; Gowthamraj et al. 2021; Saleh et al. 2013; Sripriya et al. 1997).

A study on the fermentation of pearl millet (*Pennisetum typhoideum*) and finger millet (*Eleusine coracana*) found that fermentation significantly increased the bioavailability and digestibility of their protein and thiamin and riboflavin contents (Aliya and Geervani 1981). The fermentation of foxtail millet was studied by Antony et al. (1996), which found that fermentation significantly increased the availability of soluble sugars and reducing sugars, while it decreased the starch and resistant starch contents as is also experienced with malting of millets (Najdi Hejazi and Orsat 2017).

Improvements in protein digestibility during fermentation are attributed to the partial protein denaturation and degradation (Chavan et al. 1988) and to proteolytic activity, which is enhanced during fermentation, breaking down the proteins into their peptides and amino acid building blocks (El Hag et al. 2002). Protein digestibility improvements are also subsequent to the degradation of some of the antinutrients in millets such as tannins and phytates by the fermentative microbes and their enzymes (Gowthamraj et al. 2021; Hassan et al. 2006). Fermentation inevitably leads to changes in the starch content and its digestibility with the strong enzymatic action of the fermentative microorganisms present (Antony et al. 1996; Arora et al. 2011). The fermentation processes for a variety of millets including foxtail, little, finger, kodo, proso, and pearl millets were studied by Chandrasekara and Shahidi (2012) to assess the impacts on their phenolic contents. The phenolic compounds of fermented millets were found to be more bioaccessible (Chandrasekara and Shahidi 2012).

The process of food fermentation is widely accepted as favoring digestibility, the development of diverse flavor profiles, and the bioavailability of functional compounds. It holds true for the processing of millets and millet-based ingredients to reduce their antinutritional compounds and optimize their functional quality (Gowthamraj et al. 2021).

6.9 Health Functionality of Millets

With the diversity of millets available and their diverse composition with precious phytochemicals, millets are being recognized worldwide for their nutri-health benefits especially for their positive impact on hyperglycemia and blood sugar modulation (Pradeep and Sreerama 2015). Other reported health benefits include the potential prevention of certain cancers and cardiovascular disease. In addition, millets are gluten-free grains with increasing adoption with celiac or gluten-sensitive consumers (Murugesan 2015; Taylor and Emmambux 2008). A study by Pradeep and Sreerama (2015) showed that germinated millets (foxtail, barnyard, and proso), compared with ungerminated millets, showed the highest phenolic content and superior antioxidant and enzyme inhibitory activities against hyperglycemia. Similar functionality of germinated millets was confirmed by a study from Theodoro et al. (2021), where germinated millet flour presented high antioxidant activity, while it increased anti-inflammatory cytokine and reduced inflammatory markers in rats fed a high fat and high fructose diet. Finger and proso millets have been shown to help reduce plasma triglycerides, which, in turn, can help in the prevention of cardiovascular diseases (Lee et al. 2010). It is the presence of the phenolic compounds and their antioxidant capacity (Bravo 1998; Rice-Evans et al. 1997) that helps prevent the normal metabolic and biological oxidation that could lead to cardiovascular diseases and certain cancers (Kaur and Kapoor 2001; Shan et al. 2014).

The antinutritional compounds found in millets, such as the phenolic acids, tannins, and phytates, have been demonstrated to reduce the risk of cancers in animals (Graf and Eaton 1990). The inhibitory activities of phenolics extracted from varieties of millet grains such as pearl, kodo, finger, proso, foxtail, and little millets were studied by Chandrasekara and Shahidi (2011) and were found effective in suppressing cell growth, especially the growth of malignant cells (Chandrasekara and Shahidi 2011).

The radical quenching potential of finger millets (*Eleusine coracana*) was determined using spectroscopic techniques by Sripriya et al. (1996) and compared with sorghum, foxtail, and pearl millets. The results indicated the strong antioxidant capacity of the phytochemicals contained in millets (Sripriya et al. 1996). The free radical quenching capacity and reducing capability of the tannins found in millets were further confirmed in finger millet by Siwela et al. (2007), in pearl millet by Odusola et al. (2013), in proso millet by Li et al. (2021), and in foxtail millet by Suma and Urooj (2012), who found that foxtail millet whole flour and its bran-rich fraction exhibited a significantly high radical scavenging activity (Suma and Urooj 2012).

The polyphenols contained in millets have demonstrated their antimicrobial activity (Saleh et al. 2013; Viswanath et al. 2009). Millet extracts obtained from pearl, sorghum, foxtail, barnyard, finger, and proso millets were tested by Radhajeyalakshmi et al. (2003) to assess their capacity to inhibit growth from different fungal species, namely, *Rhizoctonia solani*, *Macrophomina phaseolina*, and *Fusarium oxysporum*. It was concluded that the extracts obtained from pearl millet and sorghum were effective growth inhibitors for the three phytopathogenic fungi tested (Radhajeyalakshmi et al. 2003). Further studies were conducted by Xu et al. (2011) with the extraction of antifungal peptides from foxtail millet. The foxtail millet peptides inhibited mycelial growth in *Alternaria* and expressed antifungal activity against *Trichoderma viride*, *Botrytis cinerea*, and *Fusarium oxysporum* (Xu et al. 2011).

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7 Nutritional Properties of Millets: Nutricereals with Health Benefits to Reduce Lifestyle Diseases and Malnutrition

C. V. Ratnavathi and V. A. Tonapi

Abstract

Millets are nutricereals embedded with lot of nutrients, minerals, and antioxidants grown the semiarid tropics of the world used for both human food, feed, fuel, and fodder. Nutricereals include sorghum (*Sorghum bicolor* [L.] Moench), pearl millet (*Pennisetum glaucum* [L.] R. Br), finger millet (*Eleusine coracana* [L.] Gaertn.), foxtail millet (*Setaria italica* [L.] Beauv.), kodo millet (*Paspalum scrobiculatum* L.), little millet (*Panicum sumatrense*), proso millet (*Panicum miliaceum* L.), and barnyard millet (*Echinochloa colona* [L.] Link and *Echinochloa crus-galli* [L.] P.B.). Database on nutritional and phytochemical constituents of nutricereals is not adequate, and research studies are required to create awareness among urban population. Millet grains were found promising for nutritive value and potential health benefits compared to major cereals such as wheat, rice, and maize. To increase consumption of millets, awareness about the availability of millet-processed food needs to be strengthened. Awareness about processing technologies which will improve nutrition as well as consumer acceptability is crucial to popularize millets. Food products like breakfast cereals, pasta, vermicelli, and bakery products such as cakes and cookies, which are consumer friendly, are ideal foods to popularize in urban areas. To convince the consumer, nutrient information of millets is also important for popularization of novel food products.

Keywords

Minerals · Antioxidants · Fermentation · Soaking · Malting · Fortification

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7.1 Nutritional Importance of Millets

To maintain human health, nutritious food is important. Food should have functional uses and health benefits to support disease-free life. Quality components of food in terms of nutrition play a major role in the maintenance of human health and fitness, thereby reducing malnutrition. Diversified millet food production is an important priority to increase consumption of millets and thereby millet yields to achieve nutritional security. Coarse cereal commodities like millets are not being used as human staple food due to lack of awareness among urban population. Presently, millets are often used for feeding livestock and birds. Nutritional and health-based functional qualities were reported in millets. These crops are less utilized because of the reasons like availability of grains in public distribution system, lower digestibility, taste, etc. Millets are improved with new recipes and awareness created for their increased nutrition to make them feasible in public distribution system and as a source of livelihood for resource-poor farmers.

Millets are important nutricereal crops being drought resistant, climate resilient, and pest and disease resistant grown in 4 months unlike rice and wheat, which are grown for 6 months. Due to these merit characters, millet grains are grown abundantly in countries like India, China, and some African countries to use as human food. In some countries, millets are also used for non-food uses like bioethanol and biofilms. Millets are enriched with major and minor nutrients. Millets are considered as high-energy nutritious cereals to combat malnutrition, feeding the rural population. Millet consumption can prevent and cure the diseases like obesity, diabetes, CVD, etc. Nutricereals are good alternative to celiac patients as a gluten-free food (Saleh et al. 2013).

7.2 Nuticereal Production

Nutricereals are major crops grown in Asian and African countries like India, Nigeria, and Niger, with 97% of the world's production. Millets are considered as important food staples in the human history. Nutricereals are cultivated since 10,000 years ago in East Asia. The world's largest production of nutricereals is from India. Though the annual production of millets increased in India, the consumption of nutricereals has fallen down from 50 to 75%. In India during 2005, a major portion of nutricereals produced are utilized as raw material for ethanol production and livestock feed. However, efforts are made by the Indian organizations to increase millet utilization toward human food and also increase consumer acceptability to achieve higher production.

7.3 Millet Utilization in India

Utilization of millets was higher for pearl millet and maize in Gujarat, finger millet in Karnataka, and jowar in Maharashtra and very low in Kerala, Orissa, West Bengal, and Tamil Nadu. Reports by the National Nutrition Monitoring Bureau (NNMB) showed that rice is the major cereal consumed. Major cereals are being consumed as staple by majority of the population, which comprises of 70–80% of the calories. The study on dietary profile of urban Indians (from the Chennai Urban Rural Epidemiology Study [CURES]) by the NNMB showed that millets contributed only 2% of the total calories (6.7 g/day).

7.4 Types of Millet

Nutricereals are different from each other physically and chemically. They also differ in plant, grain type, maturity, morphological features, etc. Millets are grouped as major millets and minor millets. Major millets are sorghum (*Sorghum bicolor* L. Moench), pearl millet (*Pennisetum glaucum*), and finger millet (*Eleusine coracana*), which are most widely used for human consumption. Minor millets include foxtail millet (*Setaria italica*), proso millet or white millet (*Panicum miliaceum*), barnyard millet (*Echinochloa* spp.), kodo millet (*Paspalum scrobiculatum*), little millet (*Panicum sumatrense*), guinea millet (*Brachiaria deflexa*), browntop millet *(Urochloa ramose*), teff (*Eragrostis tef*), fonio *(Digitaria exilis*), and Job's tears (*Coix lacryma-jobi*).

7.4.1 Sorghum

Sorghum (*Sorghum bicolor* [L.] Moench) is usually referred as jowar (great millet) and has the potential to grow in three seasons, kharif, rabi, and summer seasons. The crop is cold temperature sensitive but able to resist pests and pathogens. It is grown as a staple food crop in West Africa, Asia, and parts of Middle East. Sorghum is also produced in North and Central America, South America, and Oceania, which is used for livestock as per FAO (1995) reports (Fig. 7.1).

In 1981, the sorghum growing area in India earlier is approximately above 16 Mha but slowly reduced to 7.8 Mha in 2007–2008 (equal to 20% of the world's sorghum acreage). Of this, 3.5 million ha was grown in *kharif* season and 4.3 Mha in *rabi* season. Jowar production increased from 9 MT in the early 1970s to 12 MT in the early 1980s, and this for over a period of 10 years until the early 1990s declines to 7.3 MT. At present, average sorghum grain yields in India is 1170 kg/ha in the kharif season and 880 kg/ha in the rabi season.

7.4.1.1 Nutritional Composition

Whole sorghum's nutritional and biochemical quality is superior to rice, corn, and wheat. Sorghum grains have an energy value ranging 296.1 to 356.0 kcal. The

Fig. 7.1 Sorghum panicles and its grain

important biochemical components of sorghum are starch and non-starch carbohydrates apart from total proteins and fats.

7.4.1.1.1 Sorghum Starch

Starch, the major carbohydrate of sorghum, content and composition are affected by the genetic variability and growing environment of the grain. The variability for starch ranges from 32.1 to 72.5%. Starch is composed of amylose (3.5–19.0%) and amylopectin (81.0–96.5%).The amylose and amylopectin in sorghum influence the gelatinization, retrogradation, gelling, and digestibility.

As the association of starch with proteins and tannins is strong in sorghum, sorghum has the lowest starch digestibility among cereals. Sorghum starch can be classified into slowly digestible, which accounts for 30.0–66.2%; rapidly digestible, which accounts for 15.3–26.6%; and non-digestible, which accounts for 16.7–43.2%. Non-starch polysaccharides (6.0 to 15.0 g/100 g) comprise arabinoxylans, which include both soluble (10.0–25.0%) and insoluble fiber (75.0–90.0%).

7.4.1.1.2 Sorghum Proteins

Proteins in sorghum are two types. Major proteins are prolamins, which are contributing to 79% with a range of 77–82% out of the total proteins (7 to 15 g/100 g). The other proteins present include albumins, globulins, and glutelins. Prolamins are more popular as kafirins stored in the endoplasmic reticulum as spherical protein bodies, which include α-kafirins with a range of 66–84%, β-Kafirins with a range of 8–13%, and γ-kafirins with a range of 9–21%. The β- and γ-kafirins are present in the peripheral region of protein bodies, while α- and δ-kafirins are located inside. This structure determines the digestibility of sorghum proteins.

The amino acids present in the sorghum proteins include glutamic acid (highest) followed by proline, leucine, and alanine. Usually, kafirins contains less lysine, and it is the main limiting amino acid. The other 5 amino acids such as methionine, cysteine, isoleucine, valine, and threonine are also essential and are limiting in kafirins. With higher content of proteins other than kafirins, amino acid lysine also will increase in the grain endosperm.

Sorghum proteins express low protein digestibility after cooking compared to wheat and maize. Kafirins become resistant to peptidase because of intramolecular disulfide bonds formed, which makes them low digestible. Varieties rich in tannins express reduced protein digestibility up to 50%. Interaction of proteins with starch, non-starch polysaccharides, phytic acid, and lipids and arrangement of proteins inside the grain also cause low digestibility.

7.4.1.1.3 Lipids

As a coarse cereal, sorghum has low lipid content ranging from 1.24 to 3.07%. A major portion of lipids are unsaturated fatty acids (83–88%), while polyunsaturated fatty acids (PUFA) are higher than monounsaturated fatty acids (MUFA) in sorghum. Four major fatty acids are present in many genotypes, the highest content being linoleic (45.6–51.1%), followed with oleic (32.2–42.0%), and palmitic (12.4–16.0%) acid and the lowest fatty acid present being linolenic acid (1.4–2.8%).

7.4.1.1.4 Micronutrients

The micronutrients play a very important role in human nutrition. Micronutrients include minerals and vitamins. Phosphorus, potassium, and zinc are the major minerals present in sorghum. Little variability exists in mineral content as per place of cultivation. The available zinc ranges from 9.7 to 17.1%, while available iron content ranges from 6.6 to 15.7%. Saleh et al. (2013) reported that sorghum is a rich source of some B-complex vitamins (thiamine, riboflavin, and pyridoxine) and fat-soluble vitamins (D, E, and K).

7.4.1.1.5 Phenolic Group of Compounds and Their Bioavailability

The main phytochemical compounds are phenolic compounds, which are biologically active and present in all genotypes. All types of phenolic compounds are present in sorghum, the major being phenolic acids, tannins, and flavonoids (Aruna et al. 2020).

Phenolic Acids

In sorghum, mostly phenolic acids exist as hydroxybenzoic and hydroxycinnamic acid derivatives, which express high scavenging activity and are beneficial to promote health. In sorghum genotypes, which expressed high antioxidant activity, total phenolic acids range from 135.5 to 479.40 μg/g. Among them, protocatechuic acid ranged from 150.3 to 178.2 μg/g and ferulic acid ranged from 120.5 to 173.5 μg/g. Low amounts of the other phenolic acids are included like p-coumaric (41.9 to

71.9 μg/g), followed by syringic (15.7 to 17.5 μg/g), vanillic (15.4 to 23.4 μg/g), gallic (14.8 to 21.5 μg/g), caffeic (13.6 to 20.8 μg/g), cinnamic (9.8 to 15.0 μg/g), and *p*-hydroxybenzoic (6.1 to 16.4 μg/g) acids. They also may contribute to the health benefits of sorghum (Ranga et al. 2020).

Proanthocyanidins (Tannins)

In sorghum genotypes with pigmented testa, like any other plant species, tannins are present as secondary metabolites, which are being produced in abundance against pests and diseases. Tannins are present in sorghum, while they are absent in other cereals such as rice, wheat, and maize. Tannins usually are either extracted with methanol or acidic methanol. Sorghum tannins are mostly in condensed form and usually formed by polymerization of catechins or flavan-3-ols and/or flavan-3,4-diols with a higher molecular weight and polymerization (Awika and Rooney 2004).

Flavonoids

A larger part of flavonoids in sorghum are located in the grain pericarp. Depending on the amount of flavonoids present, pericarp color varies. The three categories of flavonoids are anthocyanins, flavones, and flavanones, which are present abundantly in sorghum. In sorghum, 79% of the flavonoids are 3-deoxyanthocyanidins, which are more stable. The other major flavonoids present in higher quantity in yellow pericarp sorghums are aglycone forms of eriodictyol, luteolin, apigenin, and naringenin ranging from 474 to 1780 μg/g. White sorghums contain the lowest amount of flavanones ranging from 0 to 386 μg/g.

Other Phenolic Compounds

Other phenolic compounds are stilbenes having beneficial effects on plant defense and human health, which are produced from the phenol metabolic pathway. In red sorghum, stilbenes are present in the form of trans-resveratrol and in white genotypes in the form of trans-piceid (0.1 mg/kg) in smaller quantity.

Policosanols and Phytosterols

Sorghum lipid fractions largely comprised of policosanols and phytosterols, which contribute to 33.4–44%. Policosanols that have physiological benefits are long-chained lipids extracted from the sorghum grain. Total policosanol content located in the pericarp of the grain in unpolished sorghum grain was 74.5 mg/100 g, while the content in the polished grain was reduced to 9.8 mg/100 g.

Compared to fruits, vegetables, and other cereal grains, sorghum grains are rich source of phytosterols ranging from 4.13 to 24.45 μg/g, and these are also influenced by growing conditions. Three sterols, namely, sitosterol (44.8 to 48.2%), campesterol (26.1 to 38.0%), and stigmasterol (17.3% to 25.6%), are found in vegetables present in sorghum.

Phytochemicals with Antinutritional Activity

The phytochemicals that have antinutritional activity identified in sorghum largely are phytates, protease inhibitors (trypsin, chymotrypsin, and amylase), and lectins.

The digestibility of proteins and carbohydrates and mineral bioavailability also are decreased with these phytochemicals.

7.4.1.2 Health Benefits

7.4.1.2.1 Oxidative Stress

Chronic and excessive production of free radicals and further development of noncommunicable diseases is prevented by sorghum isolates extracted. Usually phenolic compounds rich in the extracts from black or red sorghum express the functional benefits.

Sorghum phenolic compounds modulate the defense system against oxidative stress through regulation of phase II enzymes and convert them into non-toxic and excretable metabolites. Phase II enzymes are mostly sorghum 3-deoxyanthocyanidins and their profile.

7.4.1.2.2 Cancer

Sorghum phenolics like 3-deoxyanthocyanidins react with carcinogenic cells and increase the apoptosis and inhibit growth and metastasis of affected cancer cells. Sorghum 3-deoxyanthocyanidins exhibit increased cytotoxicity to cancer cells than the respective analogous anthocyanidins such as cyanidin and pelargonidin present in other foods. Sorghum flavones exhibit the estrogenic activity showing apoptosis of the colon cancer cells. Generally, cancers occur due to DNA damage through carcinogens that form reactive intermediates, reactive oxygen species (ROS), and reactive nitrogen species (RNS). The enzyme activity of the phase I (cytochrome P-450) and II removes carcinogens that are endogenous and environmental, thus showing prevention of cancer.

Studies have confirmed that tannins extracted from other foods affect regulatory enzymes, inducing apoptosis. Sorghum tannins also have anticancer activity, and they are known for cancer treatment. Bran extract rich in tannins isolated from sumac sorghum inhibited human aromatase (CYP19) activity in vitro. The inhibition is stronger than black sorghum bran extract rich in 3-deoxyanthocyanidins. This confirmed that the tannins observed in sumac sorghum are having higher inhibitory potential than the 3-deoxyanthocyanidins of black sorghum. Tannins showed inhibition and precipitation of aromatase, which is a key enzyme to the synthesis of estrogen. It is an important target for chemotherapy of breast cancer dependent on this hormone.

7.4.1.2.3 Obesity and Inflammation

Obesity is a lifestyle disorder that leads to many problems. Studies on sorghum rich in tannins showed reduction in weight gain in animals (rats, pigs, rabbits, and poultry). Studies showed that tannins from sorghum can naturally modify starch by interacting strongly with amylose, and a more resistant starch is produced, which is hard to be digested by the small intestine and thus reaches the large intestine, thus showing the functional food benefits of dietary fiber.

Sorghum tannins bind proteins having high proline compared to other proteins. Protein containing more proline units will attract more tannin than the one with lesser units of proline. The increased consumption of sorghum having high tannin may reduce the bioavailability of iron and zinc. Obesity is considered as a chronic low-grade inflammation. The role of fat leading to the development of obesity and its effects was assumed to be a passive one, and adipocytes were assumed to be little more than storage cells for fat. But the new concept derived is that adipocytes and obesity play an important role on inflammatory mediators that initiate this process.

7.4.1.2.4 Dyslipidemia

Dyslipidemia may lead to the risk of cardiovascular disease, and earlier studies (in vitro) observed that sorghum lipid and phenolic fractions influence to reduce parameters related to dyslipidemia. The presence of phytosterols, policosanols, and phenolic compounds and their action may modulate absorption, excretion, and synthesis of cholesterol.

Studies have shown that diet added with sorghum lipids reduced the hepatic and plasma cholesterol of normolipidemic hamsters. The phytosterols of sorghum lipids have the potential to inhibit the cholesterol absorption. It is also shown that phytosterols from other foods inhibited cholesterol absorption in humans, showing increased fecal excretion and reduction of plasma low-density lipoprotein (LDL) concentration. Sorghum lipids having bioactive compounds also reduce the amount of cholesterol present in the gut enterocytes leading to inhibition of its incorporation into micelles, thereby reducing cholesterol absorption.

7.4.1.2.5 Diabetes

Recent studies showed that extracts from sorghum regulate the glucose levels in animals due to the presence of the phenolic compounds. It is known from a clinical study conducted by IIMR in collaboration with the National Institute of Nutrition, Hyderabad, with diabetic patients for 90 days that sorghum consumption in the form of roti supplemented in lunch has decreased the glycosylated hemoglobin HbA_1c and also affected the glucose metabolism positively. Research experiments with mice also, with the intake of extracts of sorghum phenolic compounds, showed hypoglycemic effect and effect on plasma glucose and insulin. Animal studies have shown that sorghum phenolic extracts expressed a hypoglycemic effect similar to glibenclamida, an antidiabetic medication used in the control group.

Sorghum phenolic compounds affect metabolic pathways before and after absorption of carbohydrates and help in the prevention and treatment of glycemic disorders in humans. It was also indicated that phenolic extracts of sorghum express inhibition to the in vitro activity of the enzymes *Bacillus stearothermophilus* α-glucosidase and human pancreatic and salivary α-amylase. The first action mechanism of sorghum on human metabolism is through a decrease in the rate of glucose digestion through inhibition of enzymes.

7.4.1.2.6 Hypertension

In the literature, it is reported that sorghum can reduce blood pressure with the protein isolates of α-kafirins, which inhibit the activity of angiotensin I–converting enzyme.

7.4.1.2.7 Gut Microbiota

The human gut is populated by an array of bacterial species, which perform important metabolic and immune functions, with influence on the nutritional and health status of the host. The uses of sorghum phenolic compounds on human health may result in the action of the absorbed bioactive compounds and their metabolites that affect the microbiota environment.

A lot of investigations reported on health-promoting activities of dietary phenolic compounds; research efforts should be continued in relation to their effect on modulation of gut microbiota. Earlier research studies showed positive effects of phenolic compounds (tannins and anthocyanins) present in foods on gut microbiota increasing the probiotic species such as *Bifidobacterium* spp. and *Lactobacillus* spp. and lowering the harmful microbiota such as *Bacteroides* spp., *Clostridium* spp., *Propionibacterium* spp., *Salmonella typhimurium*, *Streptococcus mutans*, and *Escherichia coli*.

7.4.2 Bajra (Pearl Millet)

Bajra (pearl millet [*Pennisetum glaucum* (L.) R. Br.]) (Fig. 7.2) initially grown in the tropics of Asia, Africa, Central Africa, and India. It is known as bajra in Hindi and sajjalu in Telugu. For a long time, pearl millet has been an important cereal food grain and also as a fodder for livestock and stover crop in the arid and semiarid regions of many countries.

Fig. 7.2 Pearl millet panicles and its grain

7.4.2.1 Nutritive Value of Pearl Millet

In most Asian and African countries, pearl millet is recognized as an important cereal food crop and often supports with shortages of cereal food grains and the nutritional needs of consumers in rural and urban areas. It is a principal source of energy through carbohydrates and other nutrients in the everyday food of a major portion of low-income group consumers.

Bajra contains a fairly good amount of resistant starch, total dietary fiber including soluble and insoluble dietary fiber, minerals, and antioxidants. The chemical composition includes dry matter (92.5%), insoluble ash (2.1%), crude fiber (2.8%), fat (7.8%), protein (13.6%), and total carbohydrates (63.2%) (Patni and Agrawal 2017).

7.4.2.1.1 Calories

Bajra contains a fair amount of calories (361 Kcal/100 g) and is also equal to other staple commodities (wheat, rice, maize). Pearl millet starches have amylose content ranging 20–21.5% and have a higher swelling power and solubility than other millet starches. In this cereal varieties, the percent starch varies from 62.8 to 70.5%, and free soluble sugars such as glucose, fructose, sucrose and raffinose range from 1.2 to 2.6%.

7.4.2.1.2 Proteins

Like other millets, pearl millet grain is gluten free. Protein usually ranges from 9 to 13%. The essential amino acid profile in pearl millet protein is more than sorghum and maize. It contains more lysine (1.9–3.9 g/100 g), threonine, methionine, tryptophan, and cystine. This fair balance of amino acids includes essential amino acids. It has good protein digestibility showing that bajra is a superior cereal as human food. In bajra, essential amino acids (arginine, threonine, valine, isoleucine, and lysine) also had higher digestibility, and bajra is superior to other millet grains.

7.4.2.1.3 Lipids

The average total fat content in bajra grain varied from 1.5 to 6.8%, and it is the highest of all millets. About 75% of the fatty acids in bajra are unsaturated, and the fatty acids present in pearl millet are palmitic, stearic, linoleic, oleic, and linolenic acids, while the first three acids are in higher content and the latter two acids are in lower content. Due to the higher fat content, energy density of pearl millet grain is relatively high and linoleic acid is particularly high (46.3%).

7.4.2.2 Micronutrients

7.4.2.2.1 Minerals

The mineral content of pearl millet grain is determined by the environmental factors like composition and nature of soil. Like other millets, bajra is a rich source of minerals, containing fair amounts of calcium, phosphorus, magnesium, and iron, which are found in the pericarp, aleurone layer, and germ. Polishing grain lowers the important nutrients that are located in the pericarp.

7.4.2.2.2 Other Bioactive Compounds

Pearl millet has antinutrient components such as polyphenols, tannin, phytic acid and phytate, goitrogens, and oxalic acid. Polyphenols and tannin compounds are concentrated in the pericarp. Tannin levels and in vitro protein digestibility are negatively correlated. Polishing and removal of the pericarp decrease the amount of tannins in the grain with a corresponding increase in protein digestibility. Pearl millet contains phenolic compounds (glucosylvitexin, glucosyl, orientin, vitexin) because of which color changes from grey to yellow green at alkaline pH and grey to creamy white under acidic conditions.

7.4.3 Potential Health Benefits in Pearl Millet

Pearl millet is rich in nutritional composition and, hence, has several health-promoting abilities.

7.4.3.1 Malnutrition

Bajra has a high amount of iron approximately 8 mg/100 g and zinc 3.1 mg/100 g, which will contribute to increase the Hb levels. The presence of phytates and polyphenols may affect the iron availability. The use of domestic processes such as popping, germination, and fermentation may decrease phytates and polyphenols, and thus, the availability of iron and zinc may enhance.

7.4.3.2 Constipation

The high fiber content (12 g/100 g) of pearl millet is helpful in obesity and dealing with problem of constipation and can be extensively used to prepare healthy foods with high fiber diet for people.

7.4.3.3 Cancer

Pearl millet contains a higher content of phenolic compounds, which exhibit antioxidant activity, which has anticancer property. Pearl millet has phenols in the grain of 608.1 mg/100 g, while flour contains 761 mg/ 100 g. Phenolic compounds particularly flavonoids have been reported to inhibit tumor development. Phenols are concentrated in the pericarp and testa, and hence, products prepared from whole grain would provide the beneficial effects of the flavonoids and phenols.

7.4.3.4 Diabetes

Diet is considered as an important keypoint in the management of diabetes and other lifestyle disorders, more so in the case of type II diabetes in which the major reason is of glucose absorption, with additional complications of lipid and protein absorptions. Bajra has a very high amylase activity, tenfold higher to wheat. Maltose and D-ribose are being the predominant sugars in whole grain, while fructose and glucose levels are low. Bajra has the lowest glycemic index (GI) (55) as compared to varagu alone, diabetic medicine, and combined with whole and dehulled green gram, owar and ragi. Dietary management of diabetes involves the decrease of post-lunch blood sugar levels and good glycemic control by taking low glycemic foods. The glycemic index (GI) emerged as a dietary basis for designating starchy foods according to the blood glucose response they produce on ingestion. Foods with a low glycemic index are useful to maturity-onset diabetes, by improving metabolic control of blood pressure and plasma low-density lipoprotein cholesterol levels due to less pronounced insulin response.

7.4.3.5 Other Noncommunicable Diseases

Bajra has omega-3 fatty acids showing its potential in prevention and treatment of cardiovascular diseases, diabetes, arthritis, and certain types of cancer. Studies showed that certain omega-3 and omega-6 fatty acids are also converted into eicosanoids, which exhibit anti-inflammatory properties; however eicosanoids made from $n - 6$ fats are more anti-inflammatory. These are known to lower triglycerides in the blood and improve immune response and brain and eye function. They also help in infant development. Omega-3 fatty acids are not synthesized in mammals but have a limited ability to form the long-chain EPA (20-carbon atoms) and DHA (22-carbon atoms) with short-chain 18-carbon $n - 3$ fatty acid ALA. Pennisetins, the class of prolamins in pearl millet, differ from prolamin, zeins of maize and sorghum, respectively.

Chandrasekhara and Shahidi (2011) reported arika (kodo millet) phenolics had higher inhibition activities against oxidation of LDL cholesterol and liposome than that of bajra. They also reported that dehulled grains and hulls inhibited DNA scission, LDL cholesterol, liposome oxidation, and proliferation of HT-29 adeno-carcinoma cells. Bound phenolic extracts showed bioactivity and release of these compounds in the colon upon microbial fermentation showed health benefits locally.

7.4.3.6 Allergies

Bajra is gluten free like other millets, and it is the only grain that retains its alkaline properties after being cooked. This is ideal for people with wheat allergies. Gluten-intolerant persons (celiac) are allergic to gliadin, a prolamin specific to wheat and some other common grains.

7.4.4 Finger Millet

Finger millet (*Eleusine coracana* [L.] Gaertn) also called as ragi is known as a calcium capsule. This is a small brown-colored grain looking similar to rai seeds. It is a major food crop in parts of Africa and Asia and Indian subcontinent. Ragi is like any other millets, a robust, tufted, tillering annual grass, nearly 170 cm high. Finger millets are like earhead with approximately 20 nos that resembles a fist when mature and, hence, are called as finger millet. It is known by a variety of names such as mandua in Hindi and ragulu in Telugu (Fig. 7.3).

Finger millet contains a good amount of protein (5–10.6%), starch (65–75%), dietary fiber (15–20%), and minerals (2.5–3.5%). It is rich in calcium among all cereals (344 mg/100 g). However, ragi also contains phytic acid (0.48%), phenolics

Fig. 7.3 Finger millet panicles and its grain

(0.07–0.15), tannins (0.61%), which are protease inhibitors, earlier considered as "antinutrients" because of metal binding and protease inhibition properties, but with the latest research studies and in view of health benefits with these nutrients, they are termed as neutraceuticals. The studies at IIMR reported that antioxidant activity or free radical scavenging capacity is 3.7–14.7%, while IC_{50} is in the range 83–97%. Finger millet genotypes are significantly rich in calcium (0.91 mg/g), phosphorous (5.46 mg/g), sodium (0.62 mg/g), potassium (9.82 mg/g), and magnesium (3.14 mg/g). Trace elements include Fe (547 mg/g), copper (12 mg/g), zinc (63 μg/g), manganese (μg/g), chromium (18 μg/g), molybdenum (10 μg/g), and selenium (1.5 μg/g) (Pasha et al. 2018).

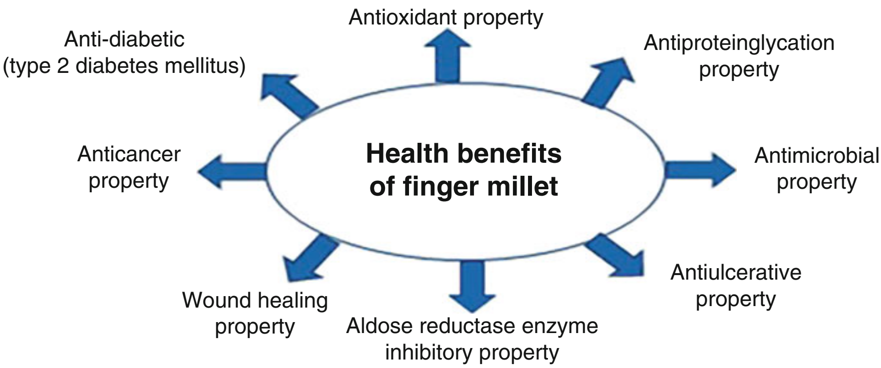
7.4.4.1 Phenolic Compounds

Finger millet is rich in bound and free phenolics. The major bound phenolic acids include ferulic acid and p-coumaric acid, accounting for 64–96% ferulic and 50–99% *p*-coumaric of millet grains, respectively. High-performance liquid chromatography (HPLC) fractionation studies of the polyphenols showed that they were derivatives of benzoic acid (gallic acid, protocatechuic acid, and *p*-hydroxybenzoic acid), cinnamic acid (*p*-coumaric acid, syringic acid, ferulic acid, and trans-cinnamic acid), and a flavonoid compound (quercetin). Benzoic acid derivatives accounted for about 85% of the total phenolic compounds. In addition to these phenolic compounds, direct infusion electrospray ionization mass spectrometry of the seed coat extract showed the presence of naringenin, kaempferol, luteolin glycoside, phloroglucinol, apigenin, (+)catechin/(−)-epicatechin, trans-feruloyl-malic acid, dimer of prodelphinidin (epigallocatechins, 2GC), daidzein, catechin gallates, and trimers and tetramers of catechin (Shobana et al. 2009).

Finger millet genotypes are also known to have proanthocyanidins, i.e., condensed tannins. Procyanidins are high-molecular-weight polyphenols that consist of polymerized flavan-3-ol and/or flavan-3,4-diol units. They are biologically active and, when present in sufficient quantities, may lower the nutritional value and biological availability of proteins and minerals. Among the millet varieties studied, finger (local) millet had the highest content (311.28 $\pm$ 3.0 μmol of catechin equivalent/g of defatted meal) followed by finger (ravi), foxtail, little, pearl, and proso millets.

7.4.4.2 Health Benefits

Polyphenols offer several health beneficial and antifungal activities, and the beneficial properties of phenols present in finger millets are outlined below (Devi et al. 2014):



7.4.4.2.1 Losing Weight

Tryptophan, an amino acid present in ragi, reduces appetite and helps to check obesity. *Ragi* also has slow digestibility and has a check on intake of calorie load. The total dietary fiber present in *ragi* gives a high satiety feeling, thus controlling excessive food consumption.

7.4.4.2.2 Bone Health

Calcium-rich *ragi* helps for the bone's strengthening as it is the natural source having the highest calcium for pregnant mothers, children, and geriatric population. Its intake supports for healthy growth of bones in pregnant mothers, children, and geriatric population. It reduces the problems related to the bones preventing fractures.

7.4.4.2.3 Antimicrobial Properties

Plant phenolics specially originated from millets are known to minimize the severity of many lifestyle disorders and prevent the spread of a wide spectrum of fungal pathogens. Grain phenolic compounds, tannins, of finger millet exhibit defense against fungal organisms. Polyphenols and tannins located in the pericarp offer resistance and create an obstacle to the fungal infection. The methanol (acidified) extracts prepared with grain pericarp exhibited high resistance to bacterial and fungal infections in comparison to the extract made from whole grain as the pericarp is rich in high polyphenols.

The major biochemical benefits of polyphenols include prevention of oxidation and cell components by the free radicals formed and irreversible complexation with nucleophilic amino acids, leading to inactivation of enzymes. Some of the mechanisms involved in the inhibitory effect of phenolic compounds include loss of their functionality and the interaction of phenolic compounds and formation of complexes with metals especially tannins with proteins and polysaccharides. During the entire process, they were made unavailable to microorganisms.

7.4.4.2.4 Glycemic Response

Diabetes is a lifestyle metabolic disease shown with hyperglycemia, due to insufficient release of insulin with metabolic changes in starch, protein, and fats. Research studies showed that hyperglycemia leads to glycosylation of proteins (non-enzymatic), resulting in increased problems in diabetes. Hence, regulating the increase in post-lunch blood glucose is critical for treatment of diabetes. The intake of diets with high fiber and complex slow digestible starches lowers acute cardiovascular problems. The finger millet diet is known as an example for this with high sustaining power and is usually recommended for diabetics. The phenolics are associated in partial inhibition of amylase and α-glucosidase during enzymatic hydrolysis of complex carbohydrates, which delay the absorption of glucose, thereby controlling the post-lunch blood glucose levels. Beneficial effect of dietary fiber is usually attributed to either slower gastric emptying or formation of unabsorbable complexes with available carbohydrates in the gut lumen, and these two properties might result in the delayed absorption of carbohydrates and in the reduction of absolute quantity absorbed.

7.4.4.2.5 Inhibition of Collagen Glycation and Crosslinking

Finger millet could have a potent therapeutic role as dietary supplements for the prevention of glycation-induced complications, which occur in diabetes or aging. The non-enzymatic glycosylation, which is referred as a chemical reaction between the aldehyde group of reducing sugars and the amino group of proteins, is a major factor for the complications of diabetes and aging. Increased oxidative stress and hyperglycemia contribute significantly to the accelerated accumulation of advanced glycation end products and the crosslinking of collagen in diabetic patients. Free radicals play a major role in non-enzymatic glycosylation of collagen and crosslinking whereas antioxidative conditions and free radical scavengers inhibit these reactions.

7.4.4.2.6 Wound Healing Process

Antioxidants in terms of phenolics present in all nutricereals prevent tissue damage and initiate healing of the wounds. The injured cells at the wound site show inflammation, which is a reaction to the wound and protective response toward healing process and process of tissue repair is initiated. The wound healing process is disturbed in diseased situations like hyperglycemia and age-related problems due to sudden shooting up of free radicals. This leads to cell damage, and the wound becomes a deeper wound. The antioxidants from millets intervene here and reduce the wound and allow it to heal.

The perfect wound healing process is interrupted in diseased conditions like diabetes and age-associated biochemical phenomenon due to an increased level of free radicals. Eventually, cell damage leads to necrosis and conversion of superficial wound into a deeper wound.

7.4.4.2.7 Earlier Research on Millets for Inhibition of Malt Amylases, Pancreatic Amylase, and Intestinal α-Glucosidase

Phenols and phenolic group of compounds are considered as inhibitors of digestive enzymes (amylase, glucosidase, pepsin, trypsin, and lipases) reported in literature extensively. These compounds inhibit amylase and glucosidase and reduce post-prandial glucose. Also association between phenolics and dietary fiber may lead to amylase inhibition and thereby have the potential to control type II diabetes mellitus. Phenolic acid such as trans-cinnamic acid showed more inhibitory activity up to 79.2%, while syringic acid exhibited lower inhibitory activity up to 56%. The phenolic compounds also modify proteins/enzymes and affect characters like molecular weight, solubility, and in vitro digestibility of biopolymers depending on the structure. The concentration and the number and position of hydroxyl groups of the phenolics affect the decrease in enzyme activity.

7.4.4.2.8 Inhibition of Aldose Reductase (AR)

Cataract occurs through the polyol pathway. Aldose reductase (AR) enzyme is very important in genesis of cataract. Cataract caused by diabetes is indicated by sorbitol accumulation with the action of aldose reductase (AR). AR-mediated sugar-induced cataract during diabetes is caused by the glycation (non-enzymatic), i.e., binding of glucose to protein molecule (Chethan et al. 2008).

The biochemical action of polyphenol inhibition on aldose reductase is assumed to be by replenishing the depletion of NADPH levels, inhibiting conversion of glyceraldehyde to glycerol and glucose to sorbitol in enzymatic mode. Specific phytochemicals such as phenolic acids in finger millet (gallic, protocatechuic, *p*-hydroxybenzoic, *p*-coumaric, vanillic, syringic, ferulic, and trans-cinnamic acids and the quercetin) were found to reduce cataract substantially.

7.4.5 Foxtail Millet

Foxtail millet (*Setaria italica* L.) is one of the world's oldest grown cereal, which is mostly grown in China, Japan, and India (Fig. 7.4). Foxtail millet is also popular as Italian or German or Siberian or Hungarian millet. It is known as kangni in Hindi and korralu in Telugu. This cereal stands the second producing 6 MT among the overall

Fig. 7.4 Foxtail millet panicle and its grain

world's total millet production feeding millions of people, grown on poor or marginal soils in continents of southern Europe and temperate, subtropical, and tropical Asia.

7.4.5.1 Nutritional Composition

The major nutritional constituents of this cereal are total carbohydrates, which include starch, total protein, total dietary fiber, fat, vitamins, and minerals. The biochemical composition of korralu (foxtail millet) imparts to its nutritional and sensory qualities like aroma and flavor.

The mean protein content varied from 113 to 129 mg/g, starch is in the range of 466–521 mg/g, amylose is 111–165 mg/g, and fat range is 36–39 mg/g. The total dietary fiber content is in the range of 173–208 mg/g, total phenols are 0.74–0.88 mg/g, and free radical scavenging activity is 13.3–20.6%. Mineral profile includes calcium (0.19–0.23 mg/g), phosphorous (4.1–7.15 mg/g), sodium (0.54–0.61 mg/g), potassium (5.43–9.2 mg/g), and magnesium (2–3.5 mg/g). Trace elements include iron (208–386 mg/g), copper (11–21 mg/g), zinc (70–80 mg/g), manganese (24–39 mg/g), chromium (12–18 mg/g), molybdenum (1–2.9 mg/g), and selenium (0.9–1.0 mg/g) (Longvah et al. 2017).

7.4.6 Kodo Millet

Kodo millet (*Paspalum scrobiculatum* L.) is also a traditionally cultivated millet mostly grown in Tamil Nadu, state in India. It is largely cultivated in damp habitats of tropical and subtropical places of the world (Fig. 7.5). This cereal is also known as kodon in Hindi and arikelu in Telugu. It is grown today in Uttar Pradesh in the North and Kerala and Tamil Nadu in the South in the Indian subcontinent.

Fig. 7.5 Kodo millet panicles and its grain

7.4.6.1 Nutritional Composition

The mean protein content varied from 78 to 103 mg/g, starch is in the range of 476–603 mg/g, amylose is 153–167 mg/g, and fat range is 25–32 mg/g. The total dietary fiber content is in the range of 318–331 mg/g, total phenols are 1.85–2.0 mg/g, and free radical scavenging activity is 6.6–7.4%. Mineral profile includes calcium (0.22–0.25 mg/g), phosphorous (3.45–4.73 mg/g), sodium (0.61–0.65 mg/g), potassium (4.23–6.40 mg/g), and magnesium (2.1–3.01 mg/g). Trace elements include iron (1082–1413 mg/g), copper (17–20 mg/g), zinc (59–76 mg/g), manganese (47–89 mg/g), chromium (20–42 mg/g), molybdenum (0.6–1.2 mg/g), and selenium (1.2 mg/g).

7.4.7 Proso Millet

Proso millet (*Panicum miliaceum* L.), also known as common millet, hog millet, broom corn, Russian corn, and brown corn, is an annual grass, growing from seed each year (Fig. 7.6). It is grown since 2000 BC in the central regions of Europe and also known as barre in Hindi and varigalu in Telugu.

7.4.7.1 Nutritional Value

The mean protein content varied from 106 to 122 mg/g, starch is in the range of 501–527 mg/g, amylose is 100–175 mg/g, and fat range is 33–35 mg/g. The total dietary fiber content is in the range of 219–243 mg/g, total phenols are 0.66–0.77 mg/g, and free radical scavenging activity is 19.9–21.5%. Mineral profile includes calcium (0.15–0.22 mg/g), phosphorous (4.26–5.54 mg/g), sodium (0.57–0.60 mg/g), potassium (4.41–5.32 mg/g), and magnesium (1.97–2.97 mg/g). Trace elements include iron (423–550 mg/ kg $^{-1}$), copper (14–18 mg/g), zinc (74–91 mg/g), manganese (21–45 mg/g), chromium (13–19 mg/g), molybdenum (1–1.4 mg/g), and selenium (1.1–1.2 mg/g).

Fig. 7.6 Proso millet panicles and its grain

Fig. 7.7 Barnyard millet panicles and its grain

7.4.8 Japanese Barnyard Millet

Japanese barnyard millet (*Echinochloa crus-galli* [L.] P. Beauvois) is a crop that can be used for various uses. This millet is also cultivated for human food and livestock fodder (Fig. 7.7). This cereal is also known as barnyard millet in English, jhangon in Hindi and udalu in Telugu. It is a rich source of protein and dietary fiber. The protein is highly digestible and fibre also is good in soluble and insoluble fractions.

7.4.8.1 Nutritional Value

The mean protein content varied from 101 to 126 mg/g, starch is in the range of 482–542 mg/g, amylose is 89–119 mg/g, and fat range is 36–39 mg/g. The total dietary fiber content is in the range of 242–261 mg/g, total phenols are 1–1.16 mg/g, and free radical scavenging activity is 13.2–16.2%. Mineral profile includes calcium (0.20–0.22 mg/g), phosphorous (5.33–6.17 mg/g), sodium (0.68–0.69 mg/g), potassium (7.34–7.92 mg/g), and magnesium (2.40–3.08 mg/g). Trace elements include iron (301–381 mg/g), copper (10–11 mg/g), zinc (76–103 mg/g), manganese

Fig. 7.8 Little millet panicles and its grain

(36–42 mg/g), chromium (19–22 mg/g), molybdenum (0.7–1.3 mg/g), and selenium (1.1–1.2 mg/g).

7.4.9 Little Millet

Little millet (*Panicum sumatrense*) is a traditional millet grown and consumed as rice at a larger scale in India (Fig. 7.8). It is also grown to some extent in altitudes of 2100 m. This cereal is also known as kutki in Hindi and samalu in telugu. The grains are of smaller size than those of other small millets.

7.4.9.1 Nutritional Composition

The mean protein content varied from 102 to 134 mg/g, starch is in the range of 420–521 mg/g, amylose is 119–125 mg/g, and fat range is 37–41 mg/g. The total dietary fiber content is in the range of 210–272 mg/g, total phenols are 0.95–1.18 mg/g, and free radical scavenging activity is 6–14%. Mineral profile includes calcium (0.19–0.24 mg/g), phosphorous (4.82–6.98 mg/g), sodium (0.50–0.72 mg/g), potassium (3.74–5.04 mg/g), and magnesium (2.33–3.44 mg/g). Trace elements include iron (457–515 mg/g), copper (9–12 mg/g), zinc (88–161 mg/g), manganese (26–33 mg/g), chromium (21–28 mg/g), molybdenum (1.3–1.9 mg/g), and selenium (1–1.3 mg/g).

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Post-harvest Treatments and Storage of Millets

8

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Abstract

Prior to storage, millets undergo different pretreatments such as drying, threshing and winnowing and other post-harvest processing methods for the effective storage of the grains. Various storage methods have been explored to feasibly store the millet grains. Bin/silo storage, hermetic storage and modified atmospheric (MA) storage have been identified to be the novel techniques for efficient storage, providing protection in terms of overall quality. This chapter discusses about the various storage techniques and the changes in compositional quality of millets during storage, as well as conventional and novel post-harvest treatment methods such as thermal treatment, irradiation, microwave treatment and biological treatments such as fermentation to enrich nutrient value and bioavailability and to enhance storage stability of millets and millet products.

Keywords

Bin/silo storage · Hermetic storage · Modified atmospheric storage · Irradiation · Microwave · Fermentation

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8.1 Introduction

Millets are defined as small seeded plants which are cultivated as grasses. When compared to other cereals, millets are resistant to pests and diseases and are able to show productivity under drought conditions. Therefore, it is an important food crop for people in semi-arid tropics of Africa, Asia and Latin America where the environment is too harsh. They are regarded as a subsistence product and generally looked up as a famine crop for the poor. Millets play a major role in food security and economy of many South Asian and African countries. Millets have excellent nutritional qualities comparable to commonly used cereals such as wheat, rice and maize. Millet proteins are excellent source of essential amino acids except lysine and threonine. Millets are gluten-free; therefore, they serve as a wheat alternative to patients with coeliac disease. Kodo millet and little millet are reported to have the highest dietary fibre content among all cereals (Saleh et al. 2013). Millet lipids are also good source of polyunsaturated fatty acids. Apart from this, millets possess many health benefits due to the presence of several compounds such as phenolics, flavonoids and tannins (Kaur et al. 2019). Some studies have reported anti-diabetic activity and reduction in blood glucose levels (Taylor et al. 2014). Owing to all these attractive features, there has been an increase in development of several millet-based products for healthy lifestyle (Kaur et al. 2019).

Prior to processing, millets undergo post-harvest unit operations such as drying, threshing, cleaning, winnowing, decortication, etc. The harvesting can be performed either by cutting whole plant or by cutting the head only. This is followed by separation of grains which is done by drying, threshing and cleaning. The objective of drying is to bring down moisture for safe storage, and threshing is done to loosen and separate grains from panicle. The separated grains can undergo storage. Milling or decortication is one of the operations in which hull and bran are removed to prepare grains for consumption. However, it has to be noted that the milling brings down the natural defence of the grain making it more susceptible for deterioration. Therefore, it is indispensable to conduct all these operations with careful concern.

The objective of this work is to provide a concise summary of different traditional and novel methods used for the storage of millets along with their advantages and limitations. Some of the novel techniques have achieved excellent results; however, they need to be commercialized. This chapter also focuses on different pre-treatments for maintaining the quality of millet and millet products and extending the shelf life of processed products.

8.2 Storage of Millets

Storage is an important interim and repeated post-harvest operation in the supply chain of food grains. The primary objectives of storage include availing food for future needs, saving seeds for next growing season and allowing farmers to sell in future for better prices. Millet grains are usually harvested at 15–20% moisture content and are dried to 10–12% moisture for optimum storage. Temperature, relative humidity and moisture content are important parameters in maintaining quality through storage period. Clean and dry environment during storage protects the grain from pest infestation, foreign material contamination and unintended grain germination. Hot and humid environment is responsible for moisture uptake and growth of insect pests and fungi.

The present section focuses on several conventional and novel approaches for the storage of millets. Conventional methods include temporary methods such as aerial storage, open platform and long-term methods that include cribs, thatched and mud bins, earthenware pots, and underground pits. Apart from these, some novel techniques such as modified atmosphere and hermetic storage are also discussed along with advantages and limitations.

8.2.1 Traditional Storage Systems

In the context of storage, farmers in arid and semi-arid countries where millets are grown have achieved quite impressive performance using relatively simple traditional methods (Kajuna 2001). The most primitive form of storage is aerial storage in which sorghum and millet panicles are tied in bundles and suspended from tree branches, posts or tight lines or inside homes in India and some African countries (Nukenine 2010; Mobolade et al. 2019). This acts as a temporary method of storage during which the grain gets dried in air. The major disadvantage possessed by this method is that the grains are exposed to the rainfall and pests (Mobolade et al. 2019). Other temporary storage methods include storage on open timber platform, on ground or on drying floor. Open timber platform is constructed using split bamboo, bamboo or straw mats supported on 1 m high hard-forked sticks (Mobolade et al. 2019). This structure provides excellent ventilation and protection from developing larvae due to direct solar radiations. The raised platform provides protection from rodents. However, this storage structure possesses similar disadvantage, and therefore, its use is discontinued in rainy season (Mobolade et al. 2019).

Apart from these temporary storage structures, several structures are used for long-term storage of millets. These include different types of storage baskets (crib, mud straw bins), earthenware pots, bins, underground storage, etc. Crib is an improved version of timber platform in which a rectangular structure is elevated to 0.5–1 m height, supported on columns, and the sides are made up of straw, palm leaves, bamboo or wire netting. Cribs can be placed inside dwelling place to provide protection against rain. Cribs offer a simple, rodent-free, economical storage approach; however, it provides very less protection against insect pests (Mobolade et al. 2019). Granaries constructed from sorghum stems, reeds, bamboos and other flexible long sticks are also used for storage of millets. Some granaries are constructed using reeds and mud walls (Kajuna 2001). A similar structure named *Doke* is used for storage of millets along with other grains in northern part of India (Negi and Solanki 2015). Earthen pots made of burnt clay with or without straw as binding material for strength are used for storage of threshed millet grains along with other grains (Mobolade et al. 2019). These structures differ in shape depending upon locality, and the capacity ranges from 5 to 1500 kg for short to longer duration. The mouth of pot is covered with earthen lid and sealed with mud. The objective of storage of grains in this structure is to maintain viability of seeds for planting purpose (Mobolade et al. 2019). Another structures called thatched rhombus and mud rhombus are commonly used for storage of sorghum and millets along with maize and cowpea in Sudan Savanna zone of Nigeria (Naveena et al. 2017). Mud rhombus is a cylindrical, spherical or circular shaped storage structure built from a mixture of dried straw and mud or clay. The whole structure is supported on large stones and is covered with thatched roof. The grains can be stored for the duration of 2–5 years or more. The loading of the grains is done manually by opening the thatched roof, and unthreshed sorghum and millets are stacked into the rhombus. A part of bin can be broken in order to create an opening for unloading of grains which can be sealed after complete evacuation (Mobolade et al. 2019). Underground grain storage pit is a versatile low-cost structure mainly used for storage for millets. These storage structures are more suitable in agro-ecological zone with low water table for long duration of storage (Mobolade et al. 2019). The dimensions and shape of the pit varies according to the locality and requirement. Most common shapes are bell shaped with narrow entrance, rectangular or cylindrical shape. Before loading the pits, the bottom is spread with chaffy earheads, straw, bran, husk and other crop wastes. The sides are lined with dried stalks of sorghum or pearl millet. Paddy straw can also be coiled into rope and used for lining in concentric circles. Once loaded, the pit is sealed with rectangular stone blocks, iron or polyethylene sheet or gunny clothes. This is followed by concealing with husk or dry sand (Sundaramari et al. 2011). Proper sealing provides oxygen-deficient atmosphere which provides protection against insect infestation. The grains can be stored for few months to 5 years based on the durability of structure.

8.2.2 Bin/Silo Storage

Several bin-like traditional structures made from straw, bamboo, mud, etc. are widely used for storage of millets. However, these structures are not airtight and unable to provide protection against moisture and rodents (Mobolade et al. 2019). Different structures have been developed to overcome these shortcomings. Pusa bin is an improved storage structure developed by Indian Agricultural Research Institute (IARI) which has been employed for the storage of pearl millet (Yadav 2012). It is a structure made up of bricks and mud which is rendered moisture proof with the application of a plastic film. The construction of a bin consists of a brick platform covered with 700 gauge plastic. The walls and roof are made from bricks and lined from inside with plastic sheet. A wooden or steel pipe is fixed for the discharge of grains.

Apart from this, advanced versions of bins constructed from metals and concrete are developed for long-term storage of millets. These silos are huge structures used for centralized storage with very high capacity up to thousands of tonnes. Based on the relative dimensions, silos are broadly classified as deep and shallow bin. Several criteria for classification are described by Sahay and Singh (1996). Flat and hopper bottom silos are also common. Hopper bottom silos are expensive than flat bottom but are proved to be useful in continuous throughput situations.

Silos can be made from reinforced concrete, plain or corrugated galvanized sheet, mild steel black sheet, aluminium sheet, fibre glass, ferro cement, asbestos sheet, etc. (Sahay and Singh 1996). Out of these, concrete, bricks and metal are the most common. Considering the materials, the durability and air tightness is of prime importance. Metal silos are more flexible in construction and operation but need to be protected from corrosion by galvanization or applying paint. Concrete silos are low in maintenance and are waterproof and fireproof; however, development of cracks leads to moisture migration and loss of fumigants. Another disadvantage is carbonation, i.e. reaction between carbon dioxide and calcium hydroxide in concrete, which leads to the corrosion of reinforcing steel. Metal silos are valid for storing of large quantities of grains and often are regarded as costly for small-scale storage. Nevertheless, several metal bins have been developed for scientific storage in rural areas (Yadav 2012).

8.2.3 Modified Atmospheric (MA) Storage

MA storage or MA packaging is an interesting technique which can extend the shelf life of food by modifying the atmosphere surrounding it along with preservation of natural qualities. In the context of grain storage, MA causes alterations of the composition of natural atmospheric gases such as CO_2, O_2 and N_2 surrounding the grains to render lethal atmosphere to pests which results in disinfestation. However, it does not involve addition of toxic gases such as phosphine or methyl bromide (Jayas and Jeyamkondan 2002). For the application of MA, the storage container essentially needs to be airtight. The MA can be achieved in several ways, namely, by adding gaseous or solid CO_2 (high CO_2) and by adding gas with low O_2 content (low O_2). Another approach uses metabolic activities inside an airtight storage to create low O_2 and high CO_2 environment (Jayas and Jeyamkondan 2002). This is termed as hermetic storage which is discussed in detail in the next section. Creation of such anoxic environment is lethal to moulds and insects which are anaerobic in nature and thereby increasing the storage life considerably.

Vachanth et al. 2010 employed CA packaging and studied its effect on red flour beetle (*Tribolium castaneum*) in raw and parboiled polished little millet. The samples were filled in low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP) and aluminium pouches followed by release of adult red flour beetle and flushing with gas combination (35% CO_2, 52% N_2 and 13% O_2). Aluminium pouches gives better retention of the gas concentration and was reported to have maximum insect mortality. Among both the samples, parboiled polished millet was reported to have better mortality owing to the parboiling process which makes feeding of insects difficult.

8.2.4 Hermetic Storage

Hermetic storage is a form of modified atmospheric storage in which the atmosphere is modified by sealing the container hermetically to obtain low oxygen and high carbon dioxide gas concentration (Caliboso and Sabio 2010). The development of such atmosphere is a result of respiration of living organisms in sealed storage ecosystem (Villers et al. 2006). Hermetic storage has become an excellent replacement to several storage structures and methods especially in hot and humid conditions, because of its chemical-free nature, control of moisture content, avoidance of pesticides and need of refrigeration (Villers and Navarro 2010). Though hermetic storage technology has emerged as a novel approach, the similar principle is being used for grain storage in traditional grain storage structures such as underground pits (Caliboso and Sabio 2010). Hermetic conditions can be created using several approaches such as plastic or metal bins, flexible bags, bunker, etc. Bins constructed from plastic, metal or concrete that have been sealed and made airtight for the purging of carbon dioxide or nitrogen mixtures can be used as hermetic structure. SuperGrainbag™ is a flexible bag made from coextrusion of polyethylene as outer layer, and the proprietary middle barrier layer acts as a liner inside a polypropylene or gunny bag providing hermetic conditions. These bags are available in the capacity from 15 to 69 kg (https://www.grainpro.com/). Cocoon™ is a hermetic storage made up of flexible UV-resistant polyvinyl chloride which consists of two halves which are joined together with an airtight zipper once it is loaded with sacks of commodity to be stored. The capacity of cocoon ranges from 5 to 300 tonnes. The same material is used for making Bunkers™ having a capacity of more than 20,000 tonnes (Villers and Navarro 2010). Another approach is Purdue Improved Crop Storage (PICS) bags originally developed for hermetic storage of cowpea which have gained popularity for storage of other crops such as maize and sorghum (Williams et al. 2017). Hermetic storage has been a successful technique for storage of cereals, pulses and millets and other high-value products such as coffee and cocoa.

In the context of millet storage, hermetic storage has been very effective. Preethi et al. in 2016 evaluated the effectiveness of hermetic storage of sorghum and pearl millet for control of rice weevils (*Sitophilus oryzae*). The hermetic conditions were created using two approaches, namely, PVC bin and SuperGrainbag™, for a period of 90 days. PVC bin was able to create more severe hermetic conditions. Considering insect mortality, oxygen depletion to 7% from initial value was found to be an important factor causing lethal effect. Waongo et al. in 2019 conducted a study on hermetic storage of sorghum using PICS bags and woven polypropylene bag as control. Naturally infested sorghum grains were stored for 12 months, and the stored grains were assessed for insect infestation, grain viability and O_2 and CO_2 variations. PICS bags were able to create hermetic conditions with O_2 concentration to 8% and CO_2 concentration to 6% in 8 months. Among the four insect species present naturally at the beginning of storage, only two species were observed in PICS bags at the end of 12 months, while PP bag showed the presence of all four species. In case of post storage emergence, PICS bags showed emergence of only one species with population 15 times lesser as compared to PP bags. PICS bags were reported to have considerably lower grain damage and better retention of germination capability than PP bags.

8.2.5 Storage Pest Management

Insects are the most serious pests for stored grains and are responsible for major post-harvest loss in both quantitative and qualitative ways. Understanding the types of insects and their behaviour is indispensable for effective control. The storage pests can be primary and secondary. Primary pests feed on whole grains, while secondary feeds prefer cracked, damaged grains or flour. Hot and humid environment favours the growth of insects. In the context of millets, insects do not cause major loss as the produce is being stored unthreshed for shorter duration of time. However, losses have been reported in the storage of threshed millet grains due to insects (Tanzubil and Yakubu 1997). The major insect pests found in stored sorghum and millets include grain weevils (*Sitophilus oryzae*) and large grain borers (*Prostephanus truncatus*), small grain borer (*Rhyzopertha dominica*) and Angoumois grain moth (*Sitotroga cerealella*). Grain weevils (*Sitophilus oryzae*) and Angoumois grain moth (*Sitotroga cerealella*) begin their infestation in field itself, while others are commonly found in stored grains (Beta and Ndolo 2018; Gahukar 1989). Both of them are primary pests and internal feeders. In the case of the former, both adult and larvae are responsible for the damage. The adult bore a hole and lays eggs inside the kernel and seal it with gelatinous material. On the other hand, only larvae of Angoumois grain moth cause damage. *R. dominica* is also an internal feeder and both grub and adult are responsible for the damage.

Effective pest management requires an integrated approach in which multiple measures are taken in a planned manner. The basic approach is proper drying of grains and storing under hygienic conditions which was found effective in pest control. The preventive measures include removal of old grains from storage structure and thorough cleaning of transport carriers, bags and storage structures. Frequent monitoring and inspecting is crucial for early detection of infestation. Traditional methods for pest control involve use of ash, cow dung or plant leaves which are supposed to have insecticidal or repellent properties. Insecticides and fumigants for control of insect pests have gained popularity. Aluminium phosphide (Phosphine) is the most commonly used fumigant for pest control in commercial silos and warehouses. However, the structure has to be sealed for effective fumigation. Fumigation is responsible for instant mortality of pests, but it does not provide residual protection. Though application of insecticides and fumigants is an easier and effective way of pest control, repeated use leads to the development of resistance in insects which renders subsequent treatments ineffective.

Hazardous nature of insecticides and fumigants and development of resistance in pests leads to the search of novel, less hazardous and effective methods for control of insect pests. Therefore, the research focus has been shifted to the application of botanicals, i.e. plant-derived materials for pest control. Lale and Yusuf in 2000 used

Piper guineense seed oil to control the infestation of *Tribolium castaneum* in pearl millet seeds and products. *T. castaneum* mortality showed increasing trend with an increase in dosage, with the highest mortality recorded at a dosage of 80 mg/10 g seeds. At all dosage levels, mortality was higher in whole grains as compared to broken and flour. A study on the development of adult *T. castaneum* revealed that the development significantly decreased with an increase in dosage. Infestation of treated grains was also found to reduce with increased dosage. Using the same feed and pest, Babarinde and Adeyemo in 2010 studied the toxic and repellent properties of *Xylopia aethiopica* seed extract. Increase in concentration of seed extract and days after treatment caused significant increase in mortality in a filter paper assay. In the case of application of the extract to pearl millet seeds at the rate of 0.2 mL extract for 5 g seeds, mortality at 5–7 days after treatment was significantly higher than mortality in control sample. Filter paper assay of repellency revealed insignificant results which suggest that *Xylopia aethiopica* can cause effective disinfestation; nevertheless it cannot prevent cross infestation via repellency.

8.3 Changes During Storage of Millets

Grain storage is a complex ecosystem in which several biotic and abiotic factors interact with others, leading to both desirable and detrimental changes. Important storage parameters such as temperature, relative humidity, moisture content of grains, availability of oxygen and air tightness are responsible for several physical and biochemical changes. Millets have slightly different composition than cereals, especially in the case of lipid content. Storage of decorticated or ground millet is a challenge owing to the lipid content. The present section focuses on the changes occurring in whole and powdered millet and the effect of different storage parameters and packaging materials on it.

8.3.1 Protein

Millets appear to be an excellent source of protein for people with coeliac disease as it lacks gluten. Pearl millet has the highest protein content among all millets. It is also reported to contain the highest amount of free lipids and acts as a good source of unsaturated fatty acids (Bora et al. 2019). The presence of these fatty acids makes it highly susceptible to oxidative rancidity and may further interfere with the quality of protein.

Boora and Kapoor in 1985 studied about the protein quality of pearl millet flour stored in cans for 8 days at the prevailing room temperature (25 ± 5 °C). The values of protein efficiency ratio, true digestibility, biological value, net protein retention and protein utilization fell markedly during storage. The protein quality of the cultivar with the higher amount of oil content was more prone to deterioration during storage. This decrease in values of these parameters on storage may be due to cross-link formation between protein and other nutrients such as sugars and oxidative products of lipids and aldehydes, which lowers the digestibility and nutritional quality of food protein (Cheftel 1977). This cross-link formation not only lowers the protein quality but also sometimes causes toxicity in the millets (Saio 1980).

Varsha in 2017 reported in their study on storage stability of pearl millet flour that there is a significant reduction in the protein content over a storage period of 60 days in double HDPE covers. The reduction can be attributed to the interaction between reducing sugars and amino acids (Maillard reaction).

8.3.2 Lipids

As compared to other cereals, millets contain higher levels of lipids, and studies have reported that they could be rich source of unsaturated fatty acids. These fatty acids are highly susceptible to hydrolytic and oxidative rancidity, which results in quality deterioration. Whole grains of millets are quite stable during storage; however, when grains are ground to meal, the quality deteriorates at faster rate, resulting in development of off flavour and odour.

The lipase activity is a major cause of spoilage of pearl millet meal; therefore its inactivation before milling is essential. Lipase located in the germ and surface layers of the millets gets mixed throughout during milling and decomposes the lipids into free fatty acids during storage (Hoseney et al. 1983). This is evidenced by a rapid increase in fat acidity of the stored millets meal and acid value or % free fatty acids (FFA) of the meal oil (Boora and Kapoor 1985).

A study by Kadlag et al. in 1995 showed a rapid hydrolytic decomposition during storage in pearl millet meal. The magnitude of such degradation was influenced significantly by the nature of the storage container used, the temperature and heat treatments given to the pearl millet seeds. The hydrolytic breakdown of lipids was significantly low in the meals stored in polyethylene bags, plastic boxes and under refrigerated (5 ± 2 °C) conditions. Similar results were reported by Varsha in 2017 showing that free fatty acid increase was least in refrigerated samples. The presence of high level of activity of peroxidase enzyme also causes development of rancid odours. Higher levels of preoxidase activity were linked with quality deterioration (Suzuki et al. 2010). A study by Goyal et al. in 2017 showed a decrease in peroxide activity over 8 days of storage time. Along with this, fat acidity and free fatty acid content also increased over the same storage duration which is attributed to lipase activity.

In a study on storage of pearl millet for 60 days (Varsha 2017), peroxide value did not increase till 45 days; however, after 45 days, a rise in peroxide value was reported. The increase in peroxide value is concurrent with the increase in moisture content which could have triggered the hydrolytic rancidity. Contradictory to this, some studies have reported an increase in early storage, reaching a maximum and followed by a decline (Lai and Varriano-Marston 1980). Malondialdehyde is a product of lipid peroxidation of polyunsaturated fatty acids and is used for the study of extent of lipid peroxidation. A study has reported an increase in malondialdehyde level during storage of pearl millet flour, and it is dependent on temperature and method of storage. A rise in malondialdehyde levels was less at lower temperature and packaging materials providing excellent barrier such as HDPE and tin container (Bhatt et al. 2017). Application of several pretreatments prior to milling and storage has achieved success in the prevention of rancidity and off flavours in millet products.

8.3.3 Fungi and Mycotoxins

Despite being non-perishable foods, cereals and millets are susceptible to growth of fungi and development of mycotoxins in the field as well as during storage, which is one of the major problems. Growth of fungi is dependent on several factors such as temperature, relative humidity, moisture content of grains, initial condition of grains, insect infestation, grain maturity, etc. Jurjevic et al. in 2007 conducted three experiments that observe changes in fungi and mycotoxins due to relative humidity, oxygen availability and moisture content of grains. Fungi isolated included *Fusarium chlamydosporum* (19% of grain), *Curvularia* spp. (14%), *F. semitectum* (16%), *Alternaria* spp. (9%), *Aspergillus flavus* (8%), "*Helminthosporium*"-type spp. (6%) and *F. moniliforme sensu lato* (3%). Results revealed that the growing environment and initial grain moisture content have significant effect on storage moulds. Shehu and Bello in 2011 studied the effect of several environmental factors such as light, relative humidity and temperature on growth of *Aspergillus* species. *A. niger* is the most commonly occurring fungal species. It was observed that the light had no positive effect on the vegetative growth and condition of *Aspergillus* species. An increase in relative humidity has caused significant growth in a linear trend. The optimum temperature for the growth of *Aspergillus* species was found to be 30 and 35 °C. Only *A. fumigatus* appeared to have been influenced by incubation temperature of 40 °C.

Another study was conducted by Raghavender et al. in 2007 on aflatoxin contamination in five varieties of pearl millet and the effect of field and storage conditions, maturity and insect damage on it. Considering the harvesting, the contamination was more frequent in the seed sample collected during rainy season than winter season. Similar trend was reported in storage of millet grains harvested in rainy and winter season and stored at 38 °C and relative humidity of 80%. In the case of stored grains harvested from the rainy season, 33 out of total 100 screened samples were found positive for one or more aflatoxins, whereas only 24 samples were found positive in grains harvested in the winter season. This can be attributed to favourable conditions for growth of fungi during the rainy season. Insect damage in grains also has a significant effect on the occurrence of aflatoxins. Greater aflatoxin production with high percentage of *A. flavus* contamination was observed in sample with insect damage of 16–40% as compared to two samples with insect damage of 0–15% and 41–67%.

In order to achieve effective control of fungi and mycotoxins, meticulous control of the above-mentioned factors is essential. Apart from these preventive measures, some novel approaches can be used to protect millets. *Gaultheria fragrantissima*

(Wall) essential oil (EO) and its major component methyl salicylate (MS) as plant-based preservative can provide safeguard to millets during storage from against fungal, aflatoxin B1 (AFB1) contamination and lipid peroxidation during storage (Kumar et al. 2017). The EO significantly inhibited growth and AFB1 production by toxigenic strain of *A. flavus* LHP (B)-7 at 1.0 and 0.7 μl ml^{-1}, respectively. In addition, the EO exhibited remarkable antioxidant activity (IC50 7.5 μml^{-1}). The EO and MS showed non-phytotoxic nature on germination of millets. Kumar et al. in 2019 recommended *Artemisia nilagirica* (Clarke) Pamp. essential oil (ANEO) as plant-based shelf life enhancer of millets against fungal, aflatoxin B1 (AFB1) contamination and lipid peroxidation during storage. The mycoflora analysis of millet samples showed *Aspergillus flavus* strain [LHP(R)-5] as the most AFB1 secreting strain. The ANEO inhibited growth and AFB1 production by the toxigenic strain at 1.4 mL/L and 1.0 mL/L, respectively. More than 70.78% protection of Ragi samples from fungal contamination was observed during an in situ trial. The ANEO showed favourable safety profile with high LD_{50} value (7528.10 mL/kg) for male mice and also exhibited non-phytotoxicity for Ragi seed germination.

8.3.4 Other Changes During Storage

Moisture is an important parameter in storing of grains and reactions are dependent on it. The moisture content usually increases or decreases depending on the storage conditions and packaging material. Availability of moisture in storage environment, i.e. relative humidity, is a major contributing factor. Grains absorb or desorb the moisture, bringing them closer to the equilibrium moisture content (Sahay and Singh 1996). Studies have reported an increase in moisture content with an increase in storage duration. The moisture take-up during storage is highly dependent on the barrier properties of packaging material (Bhatt et al. 2017; Varsha 2017).

Hedimbi et al. in 2012 studied on the effects of storage conditions on viability, germination and sugar content of pearl millet stored in different containers stored at 4 °C in the dark. In cement containers, the germination and viability of the pearl millet were reported to decrease in a range of 64–50% after 8–16 months post-harvest compared to 83–74% in plastic container and 30–12% in wooden container after a similar period of storage. Viability was higher than germination in all storage facilities, and this might be an indication of low correlation between viability and germination, which means not all viable grains are capable of germination. It is possible that the low germination observed in this study might be attributed to the artificial growth medium (vermiculate) used. The rapid loss of viability and germination in cement can be attributed to pest degradation due to the high pest infestation associated with this storage facility.

Pearl millet grains were found to contain high amounts of starch and sucrose for the first 4 months, and it decreases as storage time increases. As the duration time of storing the pearl millet grain increased, the amount of starch and sucrose decreased. This happened in all storage containers, but there was a rapid loss in starch and sucrose content in cement storage than in other storage facilities. Starch and sucrose content remained better in plastic facility with medium amount after 16 months of storage compared to other storage facilities which had low to no presence after the same period of storage. This study has shown that pearl millets are rich in starch and sucrose. In a similar study by Hulse et al. in 1980, high amounts of starch were found in sorghum and millets grains.

Therefore, plastic storage facility was the best in preserving the millet grain qualities according to studies, but it is likely to be good at absorbing heat which will cause proteins to change from one form to another (Boora and Kapoor 1985).

8.4 Post-harvest Treatments of Millets

Post-harvest processing of millets is essential to improve the nutritive value, to enhance the bioavailability of nutrients as well as to ensure the storage stability. These treatments are also reported to reduce the concentration of anti-nutrients.

Post-harvest treatments often include heat treatments, drying, biological and chemical methods. Several physical chemical and biological treatments are done on the millets to reduce the concentration of phytic acid and free fatty acids that are produced due to the presence of active lipase enzymes in the millets. It reduces the stability of millets and processed products by becoming rancid over the storage period. Due to this high fat content and lipase activity, the shelf life of millets and their products are often limited. Several treatments such as mechanical treatments, heat treatments and irradiation are done to reduce the lipase activity and thus reduce FFA content. Lipase enzyme present in pericarp, aleurone layer and germ hydrolyzes the triglycerides in millet grains and produces off odour and taste in millet grains and its products. Wet, dry heat treatments are often done to reduce the activity of lipase enzymes. Other than conventional heating methods, several novel techniques such as dielectric heating and irradiation are also done.

In harvested millet grains, field pests, parasites and moulds are the common problems that damage the grains during storage. In order to attain effective disinfestation, several pretreatments are performed on millet grains prior to storage.

In this section, different post-harvest treatments done on the millet grains and millet products in order to achieve improved storage stability, nutrient bioavailability, digestibility, nutritive value and yield during milling and other treatments, have been discussed.

8.4.1 Thermal Treatments on Millets and Their Effect on Quality

Millets and their products develops rancidity and bitterness during storage which reduces their storage shelf life. This is due to the increased lipase activity that causes increase in FFA profile by the breakdown of glycerides. Heat treatments can reduce the lipase activity and thus can improve the storage life by the decomposition of lipids in millet grains.

Heat treatments done in millets and their products can be classified into two types.

- Hydrothermal treatment/wet heat treatment
- Dry heat treatment

Thermal treatments also have significant effects on the phenolic content, and their antioxidant activities, depending on several factors including heat treatment intensity, time of exposure and type of grain.

8.4.1.1 Hydrothermal Treatment of Millets

Hydrothermal treatment or parboiling is performed to improve their milling efficiency in different millet varieties. Hydrothermal treatment on millets enhances the hardness and ensures decortication and production of grits (Dharmaraj and Malleshi 2011). Hydrothermal treatment often involves hydration by soaking of grains in water at ambient temperature for about 8 h, steaming at atmospheric pressure for 20 min and then drying.

For little millet species, the treatment conditions were optimized to be 70 °C for 3 h and steaming at 110 °C for 20 min for improving the milling and cooking quality characteristics (Mannuramath and Yenagi 2015).

Hydrothermal treatment on millet grains have been reported to improve the decortication efficiency. During steaming, gelatinization of starch and swelling of starch granules take place, and denaturation of proteins takes place because the protein structure integrity reduces. These changes lead to the textural modification of millet endosperm with a minimum of no visible cracks on the kernel. Further drying of steamed kernel improves the decortication yield of millet grains (Shobana and Malleshi 2007).

Several studies also report that heat processing methods improve the storage stability of ground millet products. During hydrothermal processing of pearl millet flour, lipase activity reported to be decreasing, which led to a significant decrease in the rate of increase in FFA content, which is attributed to the minimized hydrolysis of fat. This indicates that the development of rancid odour is significantly reduced during hydrothermal treatment and, thus, storage stability was reported to be improved (Yadav et al. 2012b).

In millet-based products such as millet starch, hydrothermal treatments improve the functional and pasting properties, without abolishing the granular structure. Hydrothermal modification of millet starch alters the physical structure of starch without causing damage to starch granules and gelatinization. During hydrothermal treatment, water binding capacity of proso millet starch increases. This is due to the increased hydrophilicity that reduced the amount of crystalline regions and increases accessible water binding sites. HTM-treated starch have shown higher pasting temperature, which is due to the requirement of additional heat for the formation of paste (Singh and Adedeji 2017). An increased paste stability and gelatinization temperature of heat moisture-treated millet starch have been observed (Adebowale et al. 2005).

Hydrothermal treatments done on millets also cause several changes in the nutrient profile of the grains. These treatments result in a significant reduction of polyphenols and anti-nutrients, thus improving the bioavailability of nutrients.

However, temperature and time of exposure also may lead to reduction in nutrient levels in grain (Chandrasekara et al. 2012). Hydrothermal treatment increases the carbohydrate and protein digestibility. This might be due to the presence of partially gelatinized starch in treated millet. A significant decrease in polyphenols result in improved protein digestibility (Dharmaraj and Malleshi 2011).

Hydrothermal treatment on millets has been reported to cause thermal degradation of several nutrients such as dietary fibres and minerals. However, it is an efficient treatment done on millet grains to enhance storage stability while improving their nutrient bioavailability and digestibility.

8.4.1.2 Dry Heat Treatment

Millet flours when stored developed bitterness and rancidity, leading to limited shelf life in storage. Inactivation of lipase enzymes that caused the rancidity before milling is essential. Dry heat treatment significantly reduces the lipase activity and thus reduces the lipid decomposition during storage (Rai et al. 2008). Dry heating is generally done in hot air oven. Grains are heated to a temperature of 100 ± 2 °C for 60–120 min, followed by rapid cooling prior to milling (Kadlag et al. 1995).

Pearl millet samples subjected to dry heat treatment in hot air oven for 120 min have shown a significant reduction in FFA profile and acid value during 30 days of storage (Kadlag et al. 1995).

Nithya et al. in 2007 have reported that dry heat treatment (110 °C for 1 h) has shown reduction in anti-nutritional compounds such as polyphenols (from 3.00 to 2.27 g/100 g) and tannin (from 1.52 to 1.30 g/100 g). This might be attributed to the loss of compounds due to high heat treatment of the grains. Due to the decrease in lipase activity, reduction of free fatty acid content (from 1.85 to 1.50 g/100 g) has also been observed. A significant reduction in phytic acid content in pearl millet flour was also observed (Yadav et al. 2011).

During heat treatment, polyphenol content decreases and the total phenol content increases. This is due to the release of bound phenolic during the breakdown of cellular constituents during heating. There is also an increase in antioxidant activity attributed to the formation of non-enzymatic browning products especially melanoids at high temperatures (Table 8.1) (Siroha and Sandhu 2017).

8.4.2 Irradiation of Millets and Their Products

Insect and pest infestation and mouldiness in millets cultivated cause a large decline in quantity, quality and germination potential of grains in storage. Food irradiation is a method of physical processing in which the pre-packed bulk food stuffs are exposed to gamma rays, electron beams or X-rays. Irradiation of foods with a particular dosage helps in reduction of spoilage microbes, pests and insects. Gamma irradiation generally practiced on millet grains prior to storage causes significant reduction in microbial growth and improves their storage stability. In addition, irradiation application also causes several effects on nutritional and functional properties of millets.

Table 8.1 Effect of dry heat treatment on millets and millet products

Millet variety	Treatment conditions	Results	References
Proso millet flour	130 °C for 2 or 4 h	Increased pasting viscosity of millet flour	Sun et al. (2014)
		Increased onset of gelatinization and peak temperatures	
Pearl millet	121 °C at 1.05 kg/cm^2 pressure for 10 min	Reduction in phytic acid content (808.2–761.2 mg/100 g), polyphenol content (608.1–542.5 mg/100 g) and amylase inhibitor activity (387.5–220.0 AIU)	Sharma and Kapoor (1996)
Pearl millet flour	100 ± 2 °C for 120 min	Reduction in fat acidity (123.7–50.5 mg KOH/100 g), FFA content (1115.0–84.0 mg/100 g of fat) and lipase activity (14.6–1.1) of flour stored at room temperature for 28 days	Arora et al. (2002)
Foxtail millet flour	100 °C for 16 h	Decrease in crude protein content	Amadou et al. (2014)
		Increase in the total starch levels (from 15.78% to 40.13%)	
Pearl millet	Toasting at 115 ± 5 °C in an oven for 180 min	Increase in total phenol content (4.3–22.1%) and total flavonoids content (3.4–62.6%) with increase in antioxidant activity (6.5–23.5%)	Siroha and Sandhu (2017)
White proso millet	98.9 °C for 4–12 min	Reduced fat acidity (268–68 mg KOH/kg sample) values and peroxidase acidity (17–13 meq/kg fat) after 2 months of storage	Bookwalter et al. (1987)

The effects of irradiation on bacterial and fungal growth of millet grains have been reported by several researchers. Since the radiation causes direct and indirect damage to DNA, fungi and mould have higher sensitivity to radiation. Mahmoud et al. in 2016 have observed a significant reduction in fungal growth when grains are irradiated with a dose level of more than 0.5 kGy. Fungal growth percentage was observed to be decreasing to 21.3% at 0.75 kGy of applied dose. When the dose is 2.0 kGy, the fungal incidence was observed to be 5.3%. Dikkala et al. in 2018 have studied the effect of gamma irradiation on total bacterial count of millet grains and have observed a significant reduction in fungal and total bacterial count at an applied dose of 2.5 kGy. Mustapha et al. in 2014 observed that D_{10} values for yeasts and moulds in total plate count of Tunisian millet are 1.5 kGy and 3.7 kGy, respectively.

Nutritional and functional properties of millets during irradiation treatment have been reported in several studies. Mustapha et al. in 2014 have studied the effect of Cobalt-60 irradiation on physicochemical, microbial and antioxidant properties of Tunisian millet. Reduction in ochratoxin A (10 kGy) and an increase in peroxide value (with 3 kGy) on the millet flour were observed. Inhibition of fungal growth during irradiation results in significant reduction of mycotoxins produced by fungi. An increase in peroxide value is due to the lipid peroxidation and peroxide formation enhanced by applied irradiation dose.

The application of irradiation also leads to a significant loss of nutrients. Mustapha et al. in 2014 have observed about 88.6% loss of vitamin A. This may be due to the higher radiosensitivity of vitamin A. Several amino acids such as leucine, glutamic acid and phenylalanine were found to be decreasing, which is due to selective modification of amino acids during irradiation that causes decarboxylation and hydroxylation for the formation of free amine (Cataldo et al. 2011). Mohamed et al. in 2010 have reported a slight decrease in concentration of phenylalanine, glutamic acid and leucine on irradiated (2 kGy) pearl millet flour during 60 days of storage. Partial triglyceride degradation during irradiation releases some fatty acids, and thus, irradiation treatment increases the concentration of FFA. The free radicals OH^- and H^+ fit to the glycerol and free fatty acid linkage, which leads to the rupture of the linkage and formation of FFA.

Gamma irradiation treatment conducted on 1 kg pre-packed millet grains using Cobalt-60 source with 2–4 kGy was found to bring minimum significant change in colour and functional properties while reducing the microbe and pest concentration (Falade and Kolawole 2013).

Gamma irradiation has also reported to be an efficient mutagen for mutation breeding in plants. Ambavane et al. in 2015 have studied the mutagenic efficiency of the gamma irradiation on finger millets. And it was observed that 500 and 600 Gy doses of gamma irradiation treatment have given possibilities to isolate the early maturing mutants from high yield mutants.

Millet variety	Irradiation source	Irradiation dosage	Result	References
Tunisian millet	Gamma irradiation (Co-60 shelf shielded gamma chamber)	1 kGy	Dose-dependent decrease in amino acid concentration and phenolic content	Mustapha et al. (2014)
			Reduction in ochratoxin A concentration by 44% (at 3 kGy), 74% (at 10 kGy)	
Finger millet flour		1 kGy dose rate	Increase in bioactive compounds such as calcium and iron and slight decrease in crude fibre on treated flour during storage	Manjula et al. (2015)
Pearl millet		2–4 kGy	Bringing minimum significant change in colour and functional properties while reducing the microbe and pest concentration	Falade and Kolawole (2013)
Finger millet		2–15 kGy	Reduced moisture content	Reddy and Viswanath (2019)
			Increased protein content	
			Lipoxygenase activity and malondialdehyde content decreased	

8.4.3 Microwave Treatment of Millets and Products

Microwave-based thermal treatment has been widely used to inactivate lipase enzyme in several agricultural commodities. The efficacy of microwave treatment depends on duration of microwave exposure, moisture content of grains and final temperature of grains after microwave exposure (Tao et al. 1993). Microwave treatment of millet grains (900 W at 2450 MHz) for 80 s result in reduced lipase activity in flour. Also, microwave-treated flour was acceptable up to 30 days at ambient conditions (15–35 °C) packed in LDPE pouches (Yadav et al. 2012a, b).

Microwave treatment is also done in millets for drying. Microwave energy penetrate through inner layers leading to quick energy absorption and thus rapid evaporation of moisture.

8.4.4 Fermentation of Millets and Products

Several millet varieties such as pearl millet have lower bioavailability due to the presence of several anti-nutritional factors such as phytic acid, polyphenols and tannins. Fermentation is a process that reduces the anti-nutrients, thus improving the bioavailability of several nutrients. Fermentation of millets is often done in mixed cultures of yeast and lactobacilli. Studies have been reporting the significant reduction in concentration of anti-nutritional factors. Elyas et al. in 2002 reported that natural millet fermentation at room temperature has reduced the concentration of polyphenols, condensed tannins and phytates present in pearl millet. A significant decrease in polyphenols from 319 to 196 mg/100 g after 24 h and from 294 to 199 mg/100 g after 20 h was reported by Elyas et al. (2002). This is due to the activation of polyphenol oxidase enzyme (DHANKHER and Chauhan 1987). Phytic acid contents decreased from 786 to 393 mg/100 g and from 618 to 309 mg/100 g which may be attributed to hydrolysis of phytic acid by microbial phytase present in several microorganisms (Mahajan and Chauhan 1987).

During fermentation process, the starch and soluble sugars are degraded by enzymes present in grains and media.

During fermentation, the nutritional value of the millet grains also significantly changes. Sripriya et al. (1997) has observed a significant reduction in carbohydrate content of millets, which is due to the hydrolysis of polysaccharides by fermenting microbes which possesses alpha and beta amylases. This hydrolysis also causes an increase in organic acids during fermentation. In finger millet fermentation, lactic acid concentration was reported to be increased by heterofermentative organisms (Antony and Chandra 1997).

It also improves the flavour, protein availability and in-vitro protein digestibility (IVPD). Ali et al. in 2003 reported that the - IVPD of pearl millet increases during fermentation for 14 h at ambient conditions. IVPD was found to be increasing from 69% to 77.5%. Microflora may produce proteolytic enzymes which may cause partial degradation of complex proteins to simple and soluble products (El Hag et al. 2002). Also, the elimination of phytic acid results in improved IVPD.

Fermentation of millet grains and millet flour are often done in different parts of the world for the production of different traditional foods and beverages such as instant Fura from pearl millet (in Nigeria), kodo ko jaanr beverage from finger millet (in Eastern Himalayas), Rabadi from pearl millet (India), probiotic koko from pearl millet (in Africa), etc. (DHANKHER and Chauhan 1987; Inyang and Zakari 2008; Lei and Jakobsen 2004; Thapa and Tamang 2004).

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Millet Milling Technologies

9

A. Srinivas

Abstract

Millets, also known as “Nutricereals” in India, is gaining importance due to the various health benefits it offers. Millets can be broadly classified into grains having husk layers and those with only seed coat. Processing of these millets into grains either for consumption or development of value added products is of importance. The millet grains with husk are cleaned, destoned, dehusked and the separated husk is blown off. The mixture of dehusked and unhusked grains are separated using a separator. The unhusked grains are sent back for dehusking. Dehusked grains (without husk) are polished, normally in stages in order to reduce breakage, and polished grains are passed through a sifter to remove any brokens. The intact or complete grains (also known as “head grains”) are then colour sorted (optional) prior to weighing and bagging. Grains with only seed coat, with the exception of finger millet (ragi), are conditioned with water to soften the seed coat. These grains are then polished to remove the seed coat. Aspiration of the mixture removes the lighter seed coat material and the grains are then graded to remove brokens. These whole grains are either used as is, or pulverized into flour and converted into products. In a technology developed by CSIR – CFTRI, the endosperm portion of finger millet grains are hardened by appropriate processing. Then, the outer layers are removed using abrasive principle. The grains are then further processed by the consumer in value added products. In order to empower farmers and marginal growers, CSIR – CFTRI has developed a pedal-operated millet dehuller. The drawing of this machine has been put up on the Institute’s website as a free technology. Interested

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entrepreneurs can download the drawing, fabricate and market the same. All the components of the machine are available indigenously.

Keywords

Millets · Cleaning · Dehusking · Gravity separation · Polishing · Grading · Colour sorting · Pedal-operated millet dehuller

Grain milling operations are performed primarily due to the following reasons:

1. For better product quality
2. To meet target-specific product characteristics
3. To increase scale of operation
4. To market more products with the same machinery

Obviously, grain milling facilities include a certain degree of automation or mechanization which allows process monitoring and control. Nowadays, online quality monitoring is more commonplace owing to the development of economic electronic gadgets/systems. Internet of Things (IOT), Machine Learning (ML), Big Data and Artificial Intelligence (AI) systems are being adopted in grain processing by a few progressive manufacturers.

There are many grain-based processed food products available in the market. Milling protocols are different depending on the type of food products being manufactured. The agronomical and physico-chemical properties of the grain have to be considered by the miller before choosing the milling protocols. Each grain is unique in its composition and changes it undergoes due to processing, thus a common processing facility cannot be used for a very wide range of product manufacture.

9.1 Introduction

Millets are crops with a shorter growing season compared to other cereals. Some developed countries are also giving due attention to the developing countries in terms of millets' utilization as food. They are also considered as a good alternative in the manufacture of bioethanol and biofilms. Maharashtra, Rajasthan and Karnataka top the list of millet producing states of India. Recognizing the nutritious advantages of consuming millets they are now called "nutricereals" in India, by Government of India. Millets are classified as major and minor millets. Major millets include foxtail, sorghum, pearl, proso and finger millet. Minor millets include barnyard, kodo, little, guinea, browntop millet, teff, fonio and Job's tears. Millets can also be classified according to their morphological features viz., naked millets and millets with husk. Sorghum, pearl millet and finger millet fall under the first category and the rest under the latter. Millets play an important role in the economy of many less developed countries since farmers and others consume it daily as food, after suitable small-scale processing.

9.2 Milling/Processing of Millets

Since the morphology of the grains are different, in some cases, processing machines/principles are common. In general, the post-harvest treatment is unique or specific depending on the type of grain involved; and more often than not the number of processing steps are many. Owing to the nature of grains and its composition, grains undergo a number of processing stages between farm and fork. This chain of processes is often referred to as the total post-harvest system, which can be split into three distinct areas: primary processing (first step) is preparing the grains after harvest for storage. The second, referred to as secondary processing, involves further treatment of the grain to clean it, remove the husk or reduce the size. The products from secondary processing are still not in consumable form. The third stage transforms the grains into edible and/or value added products. This chapter is restricted to primary and secondary processing of millets.

9.3 Milling of Covered Millet Grains

The millet grains having a husk and/or bran layers are Proso Millet, Kodo Millet, Little Millet, Barnyard Millet and Brown Top Millet. Thus, milling of these grains encompasses removal of husk layer and optionally, bran layers (to varying degree) depending on the market demand. The general flow diagram of milling of these grains is as given below (Fig. 9.1):

The raw material (millets) are passed through a cleaner to clean the grains off impurities. The impurities which are bigger than, lighter than and smaller than millet grains are removed. However, impurities having the same size of millets like stones and glass pieces are not removed. Although these impurities are of the same size of millets they are heavier than the grains. Such impurities are removed in the destoner. The grains are then passed through a magnetic separator which would remove all ferrous impurities. Cleaning (including destoning) is done not only to enable producing grains which do not contain inedible material but to protect the subsequent machinery from damage. The cleaned grains are then subject to dehusking, i.e., removal of husk layers. Generally, centrifugal sheller or rubber roll shellers are used. After dehusking, the grains are then subjected to aspiration to remove husk layers which have a lower terminal velocity than grains. However, due to variation in size and weight, it is not possible to achieve 100% dehusking in a single stage. In addition, adjusting the dehusking parameters to achieve cent percent dehusking would also result in breakage of sound grains, which is generally avoided in order to reduce processing losses. The mixture of dehusked and unhusked grains are then subjected to separation. The dehusked grains (grains stripped off husk layers) are taken for polishing or removal of bran layers. The unhusked grains are sent back for

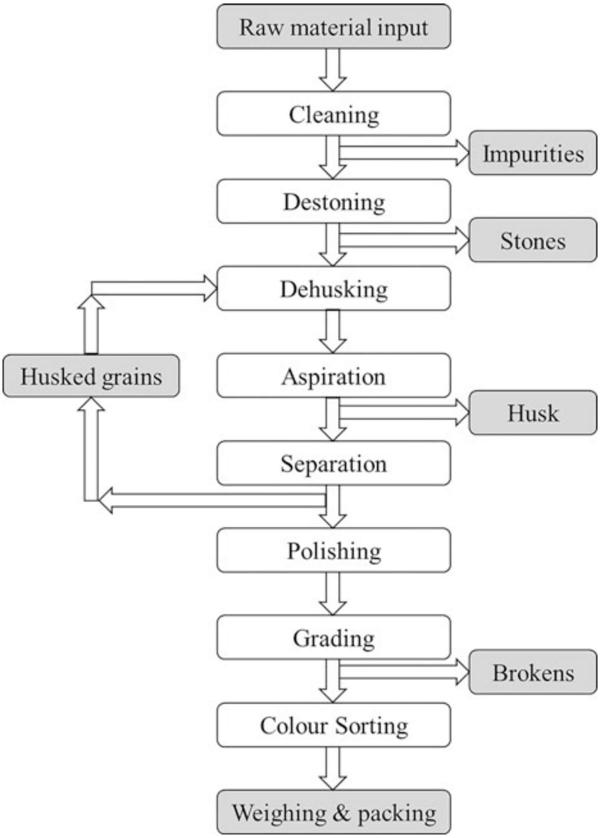


Fig. 9.1 Flow diagram of milling of millets with husk

dehusking with a different setting of the dehusker, since the grains were either smaller or lighter than the other grains in the stock even though they are of the same variety. Normally, such grains are stored in a bin and passed through the same dehusker with a different setting. In case the capacity of the plant is higher, then a second dehusker is employed. Polishing or debranning or pearling is the process of removal of bran layers to improve cooking quality, palatability and appearance. Of course, stripping the grain off bran layers leads to loss of nutrition. Presence of bran layers reduces shelf life due to oxidative rancidity. Polishing is generally done in stages to avoid breakage of grain. More the number of stages of polishing, better is the milling yield of sound and whole grains. But not only would this increase the initial cost in setting up of the plant but the running cost (electricity charges) also increases. Hence the number of stages of polishing is a trade-off between the above indicated parameters. After polishing, the grains are then subjected to size separation to remove brokens and head millets (complete or whole, polished millets). The head millets are then subjected to colour sorting where the grains are compared with set standard of colour, and grains not conforming to this colour are rejected from the lot.

Colour sorted grains are then collected in a bin and packed according to market demand in packets ranging from 1 to 50 kg in a packing machine.

9.3.1 Bucket Elevator

This is a material moving machine which is used to vertically transport grains facilitating continuous feeding of machines. It consists of an endless flat belt between two pulleys. On the belt, “buckets” or cups are fastened. These buckets scoop the material from the boot of the elevator and discharge them at a greater height. These machines are built in “segments” and their height are generally based on “on-site” requirements. Their capacities range from a few kg/h to tonnes/h, based on the capacity of the plant. These machines come in two variants: single- or double trunk elevators. In the double trunk elevator, two elevators are placed side by side, the input and output of which feed two separate machines. Feed to these machines should be regulated to the rated capacity or else input material would get filled up in the boot space of the elevator and stop the pulleys from rotating. The buckets were made out of mild steel earlier, and nowadays plastic buckets are being employed. These have inherent advantages like lesser weight (and hence lower power requirement), cause lesser damage to grains during scooping up of material and offer longer life compared to metal buckets, especially when handling the abrasive material like paddy. Normally, bucket elevators are used for vertical transport of material; however, they can also be used to transport material at an angle also. Nowadays, bucket elevators come with a safety feature which prevents the buckets moving in the reverse direction. This is a very useful feature since it protects the mill worker from getting hurt when removing excess material at the boot due to erroneous input feed to the elevator. Provision to maintain proper belt tension by moving the bottom pulley is also provided (Fig. 9.2).

9.3.2 Cleaning Section

In this section, the input grains are cleaned off impurities. Impurities also known as material other than grain, may be in the form of dust, sticks, straw, sand, stones, ferrous and non-ferrous impurities. Separation is achieved by virtue of differences in their size, shape, terminal velocity and magnetic properties.

9.3.3 Cleaner

There are many different types of cleaners available for the grain processing industry which vary with the manufacturer and the grain being cleaned. Since the amount of impurities and mog (material other than grain) varies, a cleaner should be selected only after the representative samples have been tested by the manufacturer. Impurities come in various shapes, sizes and weight and differ in these attributes from that of the grain.

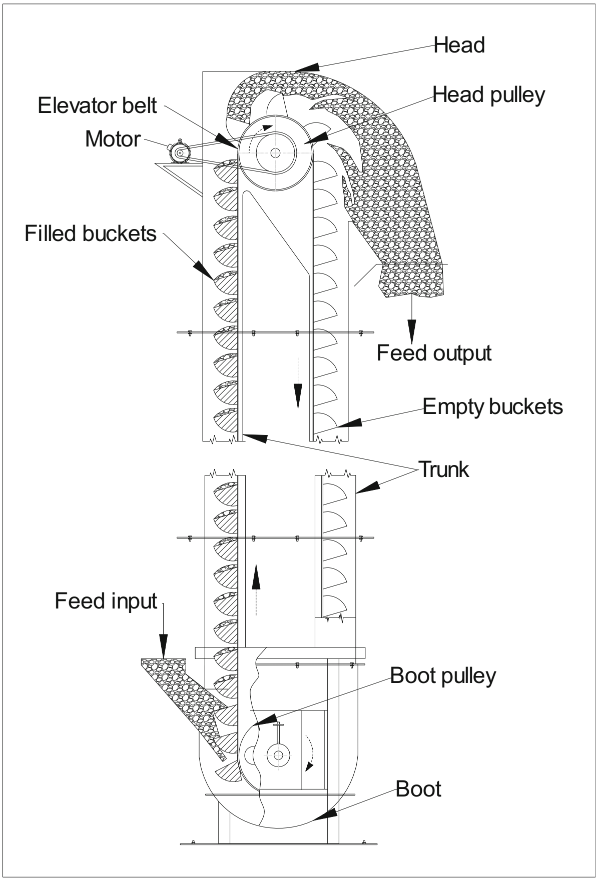


Fig. 9.2 Schematic diagram of bucket elevator

Even within the same variety or lot of millet, variation in the physical properties are present. Since the same facility is used across many millets, cleaners should be able to handle the vide variation in size, shape and weight of grains. A "typical" cleaner is as shown in Fig. 9.3. Grains are fed into this machine through the opening provided at the top. A suction fan draws air through the moving grain bed and separates all light impurities which are collected and discharged separately. Millets subsequently fall onto a vibrating sieve with large perforations to remove large impurities like straw, sticks and mud balls. Millets and remaining small impurities fall onto the bottom vibrating sieve with small perforations and smaller impurities are separated. The output of this sieve (grains) is subjected to an aspiration again, which removes any remaining light impurities and dust. When procuring cleaner for processing of millets, the manufacturer should be informed to supply sets of screens to handle the different types of millets, so that efficient cleaning of the grains can be performed. These screens are easily replaceable to suit the size of grain being handled. In addition, the amount of air passing through the grain stream can be adjusted so as to remove only the lighter impurities.

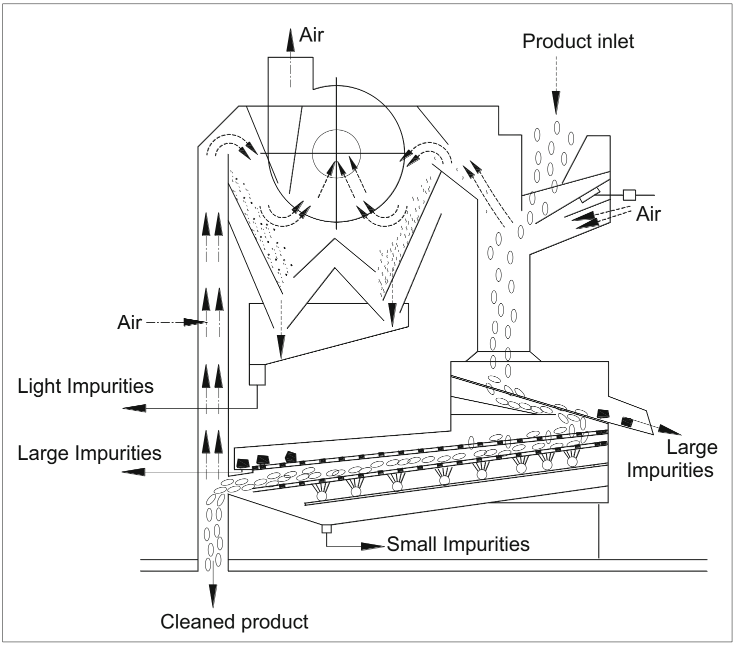


Fig. 9.3 Schematic diagram of a cleaner

9.3.4 Destoner

This machine separates grains and stones based on the differences in their respective density. A cushion of air, either blown from below the reciprocating screen or sucked from the top. If air is blown from the bottom they are known as pressure type destoners and if air is sucked from the top they are vacuum destoners. Usually destoners up to 1 tonne/h are available as pressure type models. Higher capacities are generally vacuum type. Pressure type destoners are compact in construction. Since the vacuum destoners "suck" the air through the grain mass, some fugitive dust particles are also caught in the air stream. Hence, these systems come with a cyclone separation system to discharge the trapped dust particles, outside the milling premises. Hence vacuum type destoners have a dust-free operation. In both the destoners, the air cushion through the vibrating deck is so adjusted that only the grains float and the heavier impurities like stones, glass, brick pieces, non-ferrous impurities would settle on the deck and with the inertia of the deck, these impurities are discharged at the higher end of the deck. Floating grains are discharged at the lower end of the deck. Separation can be obtained by adjusting feed rate, air volume and sieve inclination (Fig. 9.4).

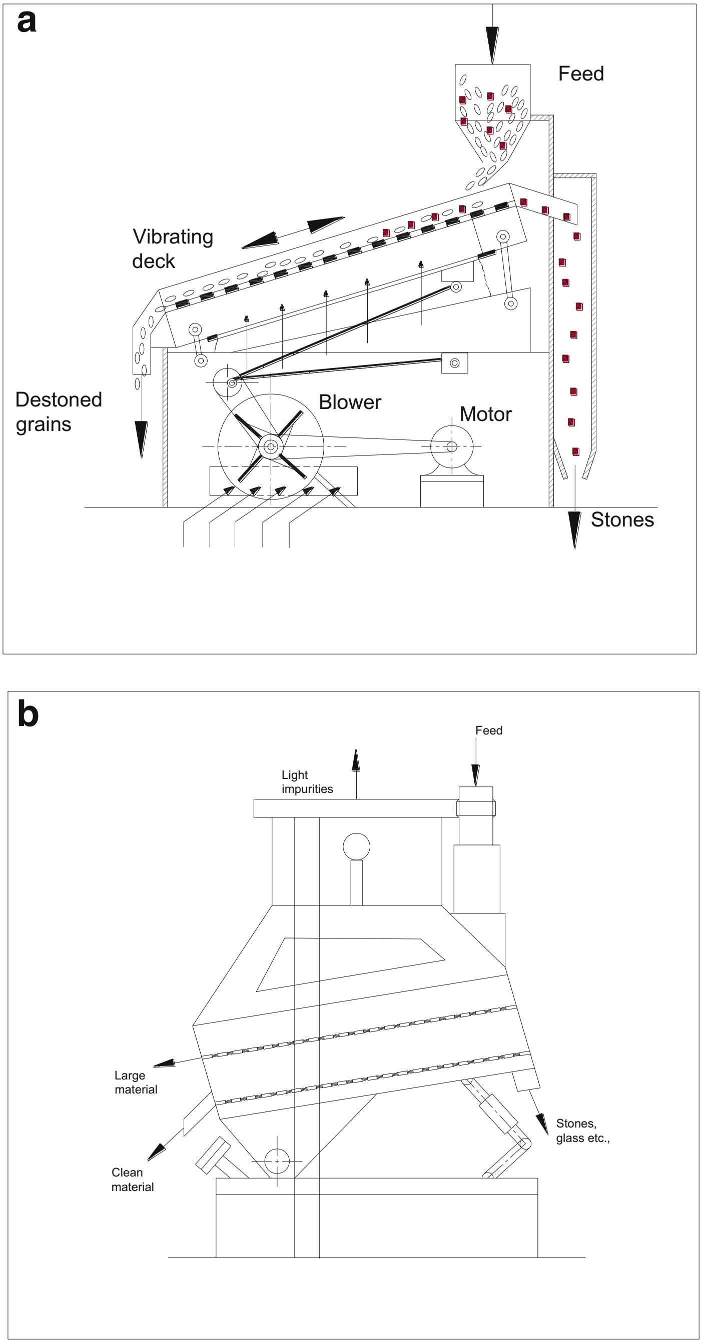


Fig. 9.4 (**a**) Pressure destoner. (**b**) Vacuum destoner

9.3.5 Magnetic Separator

Magnetic (ferrous) impurities are separated from the grain stock using magnetic separators. Type A is a permanent magnet which comes in contact with grains having magnetic impurities. The ferrous impurities are attracted to the plate above the magnet and these should be cleared regularly. However, after a certain period of time since magnetic impurities are stuck in the path of the grains, this would cause obstruction to free flow of grains subsequently. The magnetic impurities have to be cleaned manually which leads to stoppage of the entire plant and requires periodic inspection. This is true of "draw type" magnetic cleaners also. In order to overcome this situation, magnetic separators as shown in Fig. 9.5 (Type B) are preferred. In this system, a semi-circular magnet is enclosed by a rotating cylinder (made of non-ferrous material). When the mixture of grains and ferrous impurities are fed to the machine, grains flow past the magnet due to gravity. However, magnetic impurities are held against the non-ferrous drum due to the action of the stationary magnet and automatically discharged when they come across a non-magnetic zone. Thus, such a system is cleaned automatically and requires practically no inspection. As a safety feature, after cleaning of grains, in-hopper magnets are placed in the subsequent machines to trap magnetic impurities like nuts, bolts and washers that may have accidently entered the grain stream.

9.3.6 Dehusking Section

In this section, the cleaned grains are stripped off the husk layers in order to make the grains palatable. Since the millet grains differ from each other in their husk content and number of layers, the milling protocols and machine used for dehusking has to be done judiciously. There are two types of dehuskers employed for millets viz.,

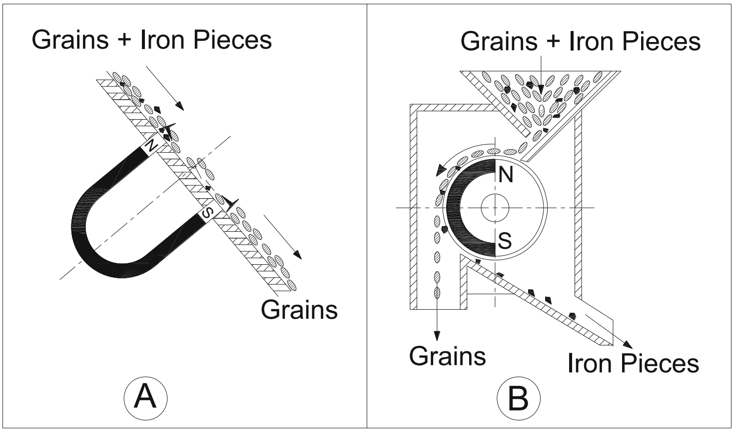


Fig. 9.5 Magnetic separator

centrifugal sheller and rubber roll sheller. The former type is employed for smaller capacities, say up to 1 TPH and the latter is used across the spectrum of milling capacities. Centrifugal shellers are easy to operate, maintain and require lesser operator skill and attention. Since the centrifugal sheller operates on the principal of friction and predominantly impact, chances of breaking the inner cotyledon is higher. Rubber roll sheller employs compression and shear forces to dehusk the grain and are preferred by millers who are conscious on maximizing head grain recovery. However, this sheller needs constant attention during processing and also a skilled operator.

9.3.7 Centrifugal Sheller

The centrifugal sheller dehusks millets by rotating it with impellers or rotating blades, accelerating it radially by adding centrifugal force, and dehulling the husk with the aid of pressure such as Coriolis force, frictional force from the blades, or impact force at collision with the blades and the peripheral surface. Due to the inertial (centrifugal) force in the radial direction, the grains are thrown outward. It also receives impact due to collision with the surfaces of the blades and their periphery and is dehulled. In other words, the dehulling system employed by the impeller husker depends on impact and friction forces. Normally, radial or curved vanes are employed in these shellers. Studies have been made by researchers on the configuration of vanes to reduce the speed of impeller while achieving maximum exit velocity of the grains. Centrifugal shellers come in two variants viz., vertical and horizontal which is based on the positioning of the main shaft carrying the impeller. For the same vane configuration and speed, there is no difference in the dehusking efficiency between the two types of shellers. The horizontal centrifugal sheller requires a feed screw to push the grains to the centre of the impeller, whereas in the vertical configuration, gravitational forces are made use of for the same purpose. After dehusking, the husking fan acts as a thrower and blows the husked material to the port of the husk separator. Owing to differences in size and weight, it is not possible to achieve 100% dehusking in one pass. In addition, increasing the impeller speed would bring about 100% dehusking but would also increase the percentage of broken grains which is normally avoided. The mixture of husk, dehusked and unhusked grains are then passed through the aspiration system to remove the husk (Fig. 9.6).

9.3.8 Rubber Roll Sheller

This sheller employs two rubber rolls rotating in opposite direction so that at the point of contact with grains the direction of motion is downwards. Dehusking is achieved due to compression and shear forces. Compressive forces are achieved by reducing the gap between the two rubber rolls. To achieve this, one rubber roll is fixed and the other is moved laterally—towards or away from the fixed roll. The

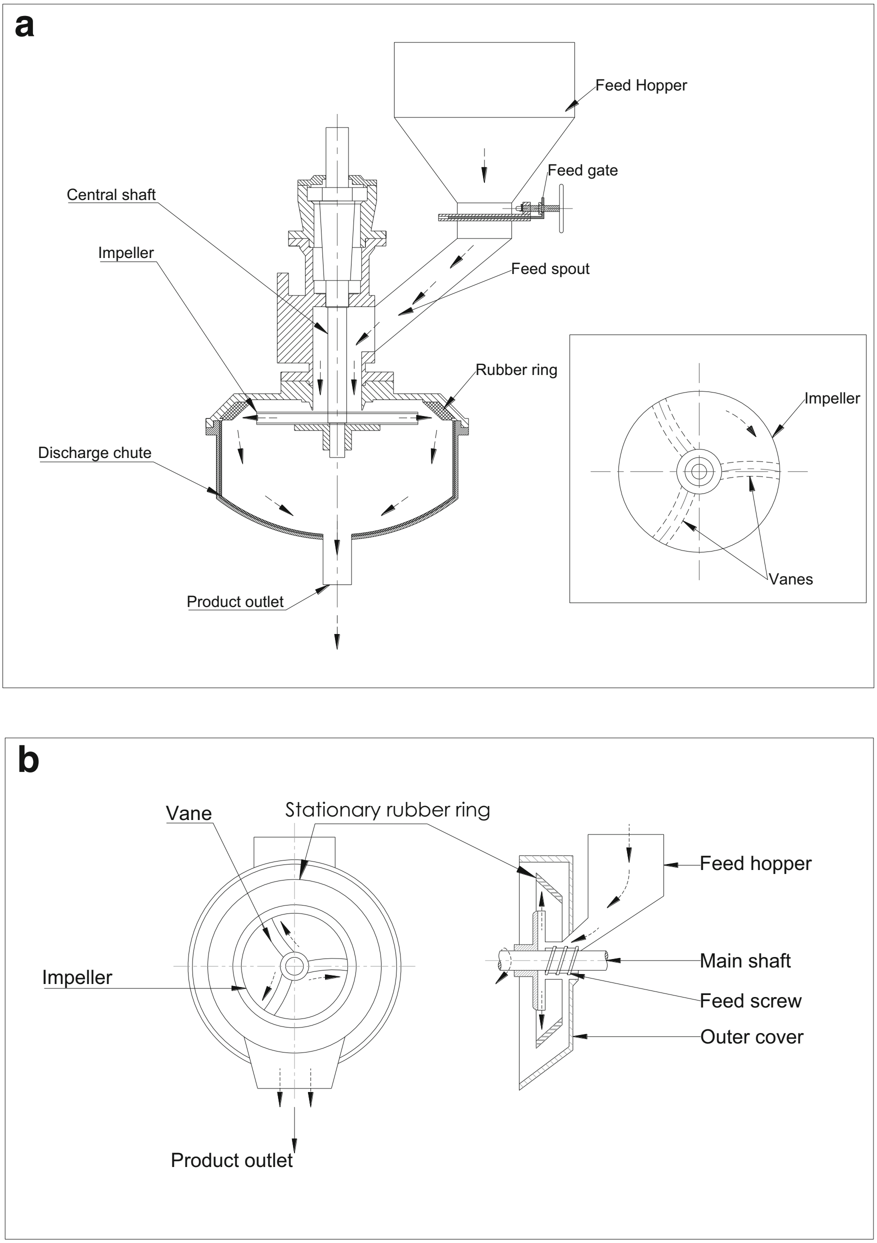


Fig. 9.6 (**a**) Vertical centrifugal sheller. (**b**) Horizontal centrifugal sheller

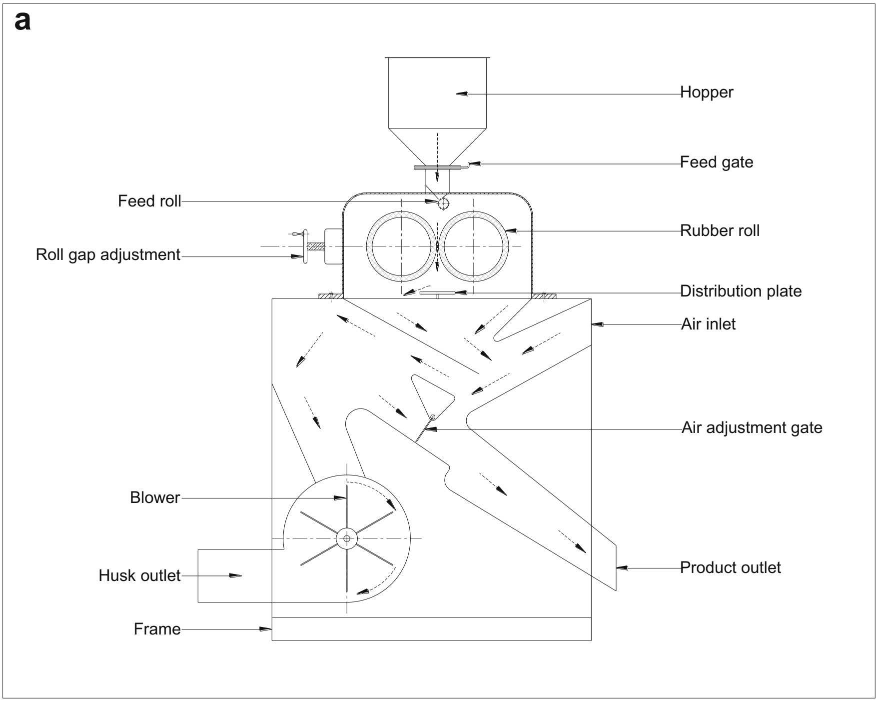
fixed roll rotates faster than the movable roll by about 20–25%. The two rubber rolls are either spring loaded or inter-roll pressure is controlled pneumatically. The difference in peripheral speed along with the inter-roll pressure subjects the grains falling in to the nip of the rollers to compression and shear forces which strips off the husk. Figure 9.7b shows that the portion of husk in contact move in accordance with the roll speeds. In other words, the portion of husk in contact with the faster roll moves faster than the other half of the husk thus bringing about dehusking. Since frictional forces are also present, it leads to generation of heat which is detrimental to the hardness of rubber. The rubber roll becomes soft due to heat and would thus wear out faster reducing its optimal life of use. During continuous operation, the temperature of rubber rolls would increase and hence they are cooled by blowing air on the surface of rolls. The hardness of rubber rolls is normally in the range of 85–90 Shore A. Care should be taken to see that the rolls do not come in contact with each other. In addition, feed should be uniform across the full length of the rubber roll. Due to difference in the speed of the two rolls, the wear of rolls is not uniform. The faster roll wears out faster than the other roll due to which there would be no difference in the circumferential speed (or linear speed) between the rolls. In this condition, the shear forces required to strip off the husk layers would be zero and the grains would be compressed and discharged. In order to overcome this condition, the rolls should be interchanged after about 6–8 h of operation. Figure 9.7a shows a schematic diagram of a rubber roll sheller with a built in aspirator. Sometimes the husk separator is not an integral part of the rubber roll sheller and would be installed separately.

9.3.9 Husk Separator

Many different types of husk separators are available in the market today and their designs vary with the manufacturer. Basically, the difference in the terminal velocity of husk and grains is made use of to separate the husk from the mixture. Either suction or positive pressure (blowing) methods are employed to separate husk. In the blowing system, the husk separated cannot be carried too far away from the system and would require additional blowers. In the suction system, the husk particles pass through the blower vanes and may, sometimes, lead to wear and tear of the blower blades. A few husk separators also have the option of separating the brokens, if any, obtained after dehusking. A typical closed circuit husk separator is shown in Fig. 9.8.

9.3.10 Separation Section

Normally cent percent dehusking is not achieved during dehusking due to differences in size, weight and also to avoid production of brokens during this process. After husk separation a mixture of dehusked and undehusked (grains with husk—raw material) grains are obtained. Separation of this mixture is essential for the following reasons. Grains with husk (undehusked grains) are not preferred either



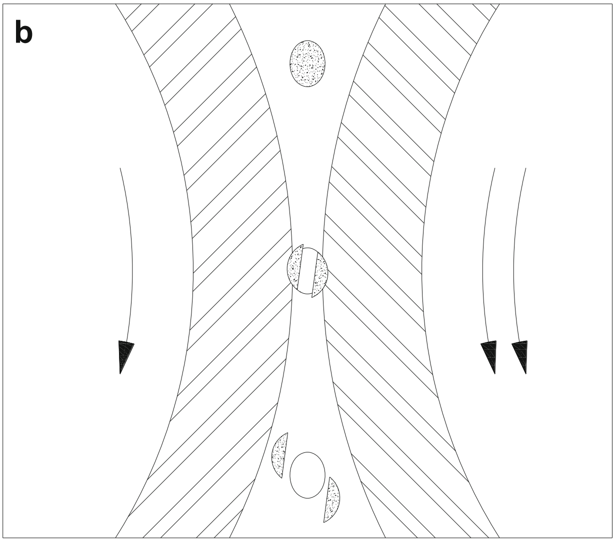


Fig. 9.7 (**a**) Rubber roll sheller. (**b**) Close up of dehusking zone

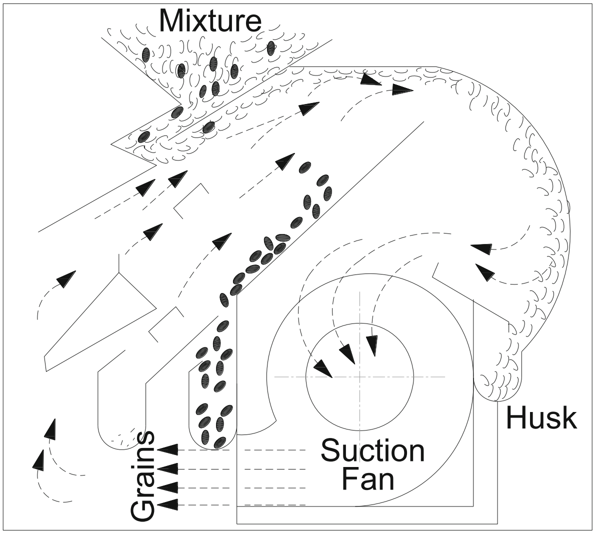


Fig. 9.8 Husk separator

for consumption or for further processing into value added products. In addition, during the stages of polishing, the polishing pressure can be increased to convert these undehusked grains into dehusked grains. This would require additional polishing pressure which would lead to production of higher content of broken grains. It is therefore preferred to polish only dehusked grains thereby reducing milling pressures and increasing the outturn of head millets. Separation of dehusked and undehusked grains is brought about employing the differences in frictional, coefficient of restitution properties and specific gravity between them. Commonly, compartment and tray separators are employed for the purpose. The principle of operation of these machinery are described below.

9.3.11 Compartment Separator

This separator makes use of the fact that frictional properties of unhusked and dehusked millet grains are different. The dehusked millets are smooth and have a lower coefficient of friction. In addition, the coefficient of restitution (a measure of the bouncing property) is also different. If, for instance, dehusked and undehusked millet grains are dropped from the same height at the same time on a smooth, flat surface, the dehusked grain would bounce more than the undehusked one. When apparently similar bodies (dehusked and undehusked grains) are moving over an inclined plane surface, there is a difference in their behaviour. The speed at which these grains gravitate downward are a function of their specific gravity, shape, contact area and coefficient of friction between the inclined surface and grain. Smoother and rounder grains (dehusked grains) slide down faster than the undehusked grains. Thus, in this machine, the grains are fed into compartments

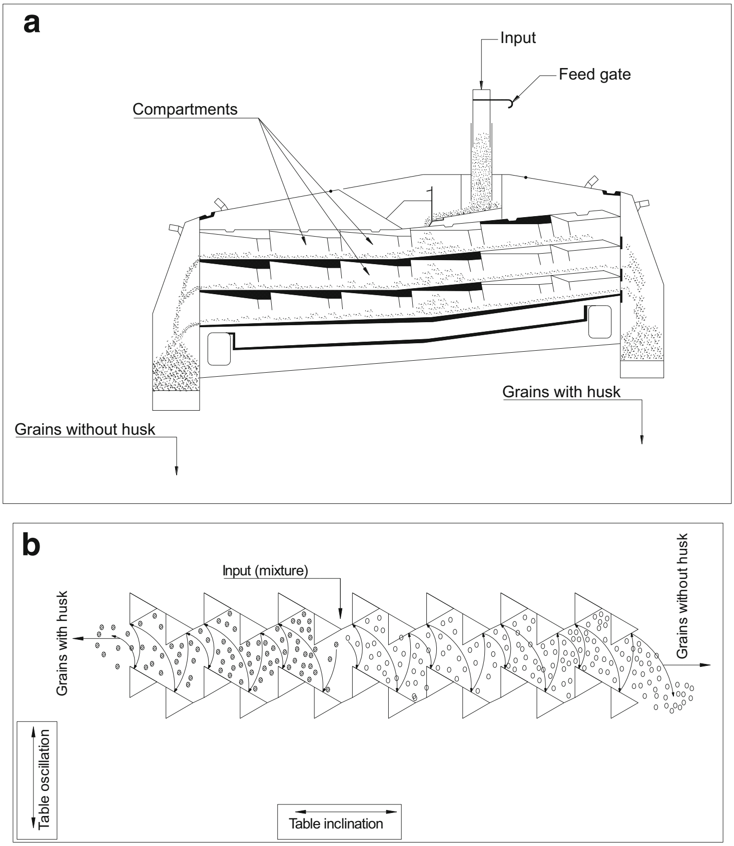


Fig. 9.9 (**a**) Compartment separator. (**b**) Working principle of Compartment separator

equally, at a point which is slightly off-centre to the entire machine deck; more towards the higher edge of the inclined smooth surface. The inclined surface (made of smooth steel) also known as table reciprocates in a direction perpendicular to the motion of the grains (see Fig. 9.9b). Each grain is imparted an oblique upward thrust. In order to increase the length of contact in a smaller distance, zig-zag walls are provided in each compartment. The dehusked grains, in spite of this thrust, move down albeit slowly due to their specific gravity and smoothness. The undehusked grains, with a higher coefficient of friction, move upwards and are discharged at the higher end of the table or inclined surface. Feed rate of the mixture to the compartment separator, speed, stroke and table inclination can be adjusted to bring about separation as desired. Number of compartments are placed side by side and the entire row of compartments are placed one above the other based on plant capacity. It is important that the feed rate to all the compartments should be equal in order to achieve complete and efficient separation. The speed of the table refers to the number of strokes the table makes in a minute. Stroke is the stroke length in mm or the distance to which the table moves. The reciprocating movement of the table should be steady and it must be free from jerks or rolling. The acceleration must be identical in both directions. The inclination of the table with the horizontal can be varied to suit the millet grains being subject to separation. The capacity of each individual compartment ranges between 30 and 50 kg/h. The output of the system is greatly affected by grain moisture content and on the percentage of dehusked and undehusked grains in the mixture. The drive system to the compartment separator is generally fitted with a flywheel which minimizes variation in the table movement. This separator offers the advantage of lower power consumption. The operating and running costs are also low since there are no sieves that need to be changed. The same system can be used across different varieties. However, due to its dimensions, reciprocating motion of the table and weight, a strong foundation is required. Moreover, the machine requires constant attention and experienced operators since at the dehusking section there could be variation in the proportion of dehusked and undehusked grains.

9.3.12 Tray Separator

This machine consists of many rectangular trays, one above the other, with a compound inclination i.e., the tray surface being inclined to the horizontal in two directions. The inclination on the long axis is about 4–9° and about 6–11° on the short axis and these values change across manufacturers and design. The trays have indentations or dimples or depressions in them. All the decks are attached to a common oscillating frame which makes a slight jumping movement. Mixture of dehusked and undehusked grains is fed to the top corner (highest point of the tray) from an inlet hopper. The dehusked grains, which are smaller and have a greater bulk density compared to undehusked grains, move to the top part of the tray and discharged from there to be conveyed to polishers. The undehusked grains move to the lower part of the tray from where it is discharged and taken back to the dehusking section. The middle portion of the tray discharges a mixture of dehusked and undehusked grains which is returned to the hopper of the tray separator for recirculation. In this machine, the inclination of the tray is adjusted to meet different grain sizes and conditions. These machines are made completely from steel, have low power requirements and simple in its operation. Of late, one set of trays are placed opposing the other set of trays and are called "butterfly" layout to save space requirements (Fig. 9.10).

9.3.13 Specific Gravity Separator

The basic principle of operation of the specific gravity separator takes advantage of the differences in size, shape and specific gravity of grains which need to be separated. In this machine, the porous table (wire mesh fitted on a reciprocating/ vibrating sieve) and air blown through the table are the main parts responsible for

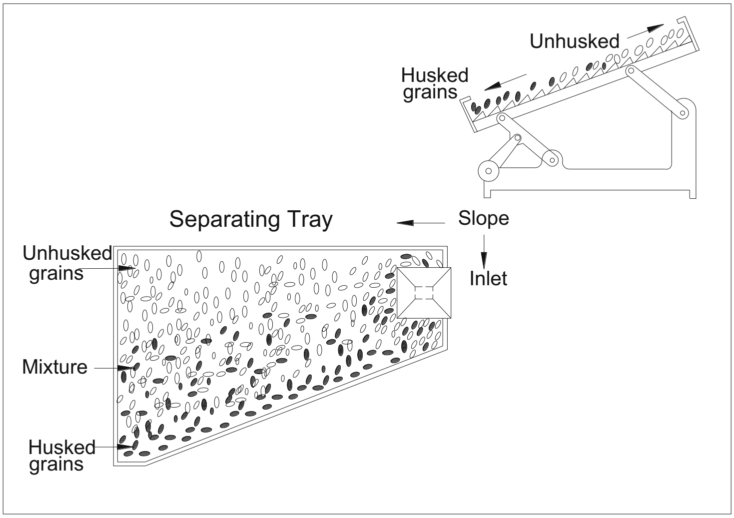


Fig. 9.10 Tray separator

separation, which takes place in two steps. The first is in the vertical direction in which stratification of grains due to air takes place and the second is in the horizontal direction caused by motion of the table and gravity. If the grains are not stratified first, then separation just due to the motion of the table will not take place. An example of this is to take a mixture of straw and sand of the same size and put them in a glass of water. The straw would float on top of water and sand would sink below. The table has a compound inclination i.e., sloping downwards in the *X* and *Y* directions. Feed of the mixture of grains is at the highest point of the table. In other words, the table of the machine is slanted in two directions; from the feeding point to discharge point of heavy grains and also from the feeding point to discharge point of light grains. This slanting of table allows lighter grains to float in air and flow downhill by gravity, while the heavy materials, in contact with the table, are discharged slightly uphill. Care should be taken to see that the fluidization of the material with air is the key to efficient separation. The design of the specific gravity separator is such that all points on the table do not have the same amount of air. This is because the depth of bed and weight of grains vary across the table. The greatest amount of air is given to the feed zone since the grain depth is maximum there. The least amount of air is at the light grain discharge point not only because the material is light but also the grain depth is the lowest in this zone. In addition, the area that requires a lot of air (not as much as in the feeding zone) is at the heavy grain discharge area. The parameters that can be adjusted in a specific gravity separator are feed rate, air flow rate through the table and inclination of the table in *X* and *Y* directions. The operation of the specific gravity separator is largely dependent on the operator's skill to bring about efficient separation (Fig. 9.11).

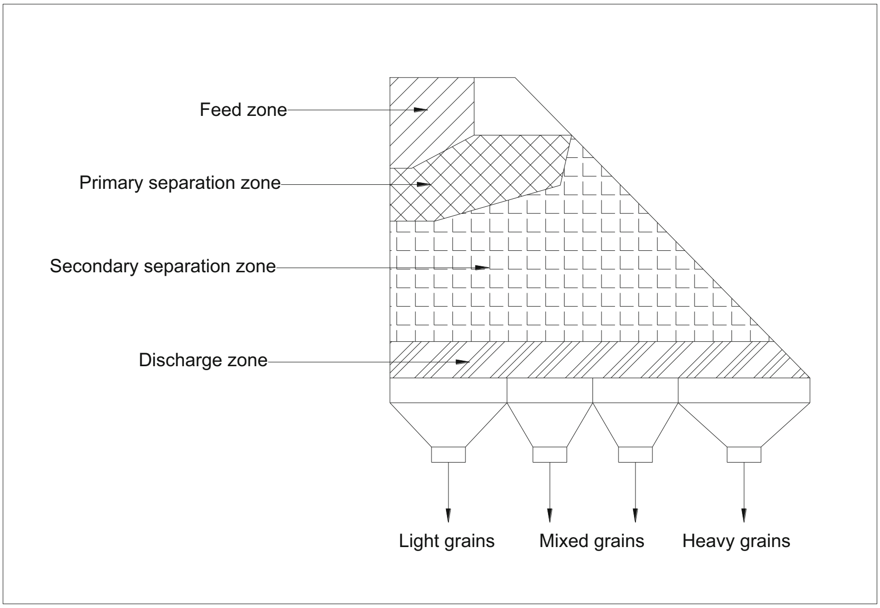


Fig. 9.11 Specific gravity separator

9.3.14 Dehusking of Undehusked Grains After Separation

The undehusked grains obtained after the separation process are conveyed to the dehusking section for removal of husk. It must be remembered here that these grains were not dehusked in the first place since they were either thinner (in case of rubber roll sheller) or lighter (in case of centrifugal sheller). Hence it is preferred to collect these grains in a bin and dehusk them later with changed settings of the dehusker. Alternately, these grains can be fed to another smaller capacity dehusker, which would increase plant capacity. If the "separated" grains are sent to the same dehusker it would lead to endless recirculation thus lowering the capacity of the mill.

9.3.15 Polishing Section

The process of removing the bran layers is known by many terms viz., whitening, debranning, polishing, milling and pearling. There are two basic processes used to remove the bran layers from the grain. They are (a) by abrasion, and (b) by friction, shown schematically in Fig. 9.12. In the abrasion process the grains are made to rub against a rough surface, which is an abrasive stone, to scratch and remove the bran layers. In friction process, friction between grains themselves is used to peel off the bran. Normally, polishing process is a multi-stage operation since the milling

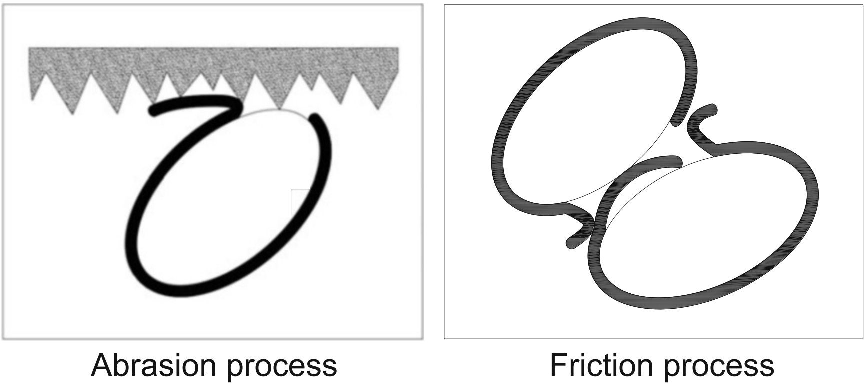


Fig. 9.12 Principle of polishing

engineer would like to keep the polishing pressures low in order to maximize the yield of intact grains which are also known as head grains. Additionally, the milling pressures during the friction method is about four times that of abrasive method. In the abrasive method, the bran layers are scratched off the surface of the cotyledon in successive stages. Even though the bran layers have been removed, they still stick to the cotyledon surface possibly due to electrostatic forces. To remove these bran specks, the friction method is employed which imparts a better look to the grains. Hence, abrasive polishers are used first and then the grains are passed through a friction polisher. There are many types of polishers used widely in the industry: cone polisher, horizontal abrasive polisher, vertical abrasive polisher and horizontal friction polisher. The principles of operation of these machines are described below.

9.3.16 Cone Polisher

A typical cone polisher also known as vertical abrasive whitener is as shown in Fig. 9.13a. This has been used extensively in the rice milling industry for many decades. It is available with the cone directed either up or down, with no difference in the performance or capacity.

The whitening cone consists of an inverted truncated cast iron conical rotor covered with an abrasive material like emery. The cone rotates inside a stationary crib or cage. This is lined with steel wire cloth or perforated metal sheets. A number of vertical rubber brakes are equally spaced across the periphery of the abrasive cone. These rubber brakes protrude into the milling zone to ensure good mixing during polishing and are placed equidistant from the abrasive cone. Vertical movement of the rotor allows for gap adjustment between rotor (cone) and crib (cage) to adjust the required degree of polish per pass of grains. Dehusked millets fed at top of rotor (cone) move outwards towards the edge. Dehusked millets enter the annular space and are rubbed along by the rough surface of the cone (Fig. 9.13b). The rubber

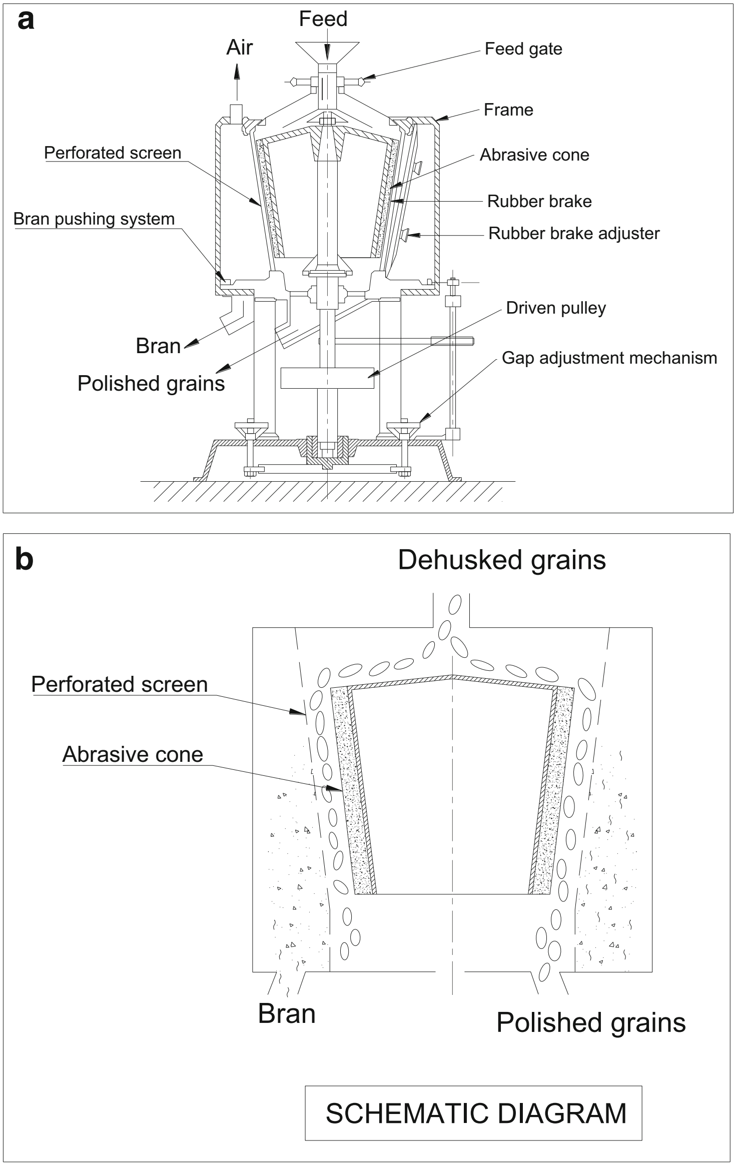


Fig. 9.13 (**a**) Cone polisher. (**b**) Schematic diagram of cone polisher

brakes ensure proper mixing of the grains so that all grain surfaces have a chance to rub against the abrasive cone to ensure equal bran removal. Grains are scoured by the abrasive surface of the cone and also due to the friction as grains are rubbed against the surrounding ones as well as against the rough lining of the crib. The grains revolve around the cone in the gap and move downward due to gravity and selfweight. Finally, the polished grains come out at the bottom of the cone. The bran layers pass through the openings in the crib (cage). Bran, because of its high oil content “lubricates” the grains making scouring and rubbing less effective. Therefore, bran is to be removed from the polishing zone, as soon as it is produced. The peripheral speed at the centre of the cone should be about 13 m s^{-1} for best performance. The abrasive surface wears out eventually and can be replaced locally by the mill mechanic. Nowadays, segmented abrasive discs are available in the market making the process of replacement of cone easier and quicker. Any vibration in the machine must be avoided to prevent excessive grain breakage. Air aspiration through the whitener reduces breakage caused by heating and not only cools the grain but also removes the bran layers from the polishing zone.

9.3.17 Horizontal Abrasive Polisher

This consists of a cylinder with abrasive coating or abrasive rings attached to a steel shaft rotating in a perforated cylindrical, metallic screen horizontally mounted. These polishers are also called initial (primary) polishers. Dehusked millets fed into the system pass through the clearance between abrasive roller and the perforated steel cylinder. A screw element at the inlet ensures movement of grain towards the outlet. As the grain goes through the space between the roll and the perforated screen, bran layers are scraped off from the grain. Bran, being smaller in size than the screen opening passes out and polished rice is discharged at the outlet. The pressure on the grain is controlled by hanging weights on the discharge gate. The more the weight on the discharge gate, more is the pressure inside the milling chamber and leads to more bran removal. Resistance pieces are attached to the perforated steel cylinder which helps to mix the grains during polishing, alter the flow rate and the grain density inside the milling chamber. Angle of these resistance pieces is adjustable from outside even when the machine is in operation. The angle of resistance pieces against the abrasive rotor can be adjusted from 0° to 90°. By changing the angle, grain movement in the milling chamber and milling pressure can be altered. By optimal adjustment of resistance pieces, the breakage can be reduced, processing capacity can be increased and the temperature rise during the whitening process can be minimized. In the newer versions of this polisher, an airstream is blown through the hollow shaft and then through the many openings in the abrasive roller. Air passes through the grains and pass out through the perforated screen and helps in pushing the bran layers away from the milling zone. This keeps the grain temperature lower and not only reduces breakage but also helps in removal of bran sticking to the grains or machine parts. The only disadvantage is that the clearance between the abrasive roll and screen cannot be varied. With the wear down of abrasive roll segments, it cannot be resurfaced and must be replaced with a new ones (Fig. 9.14).

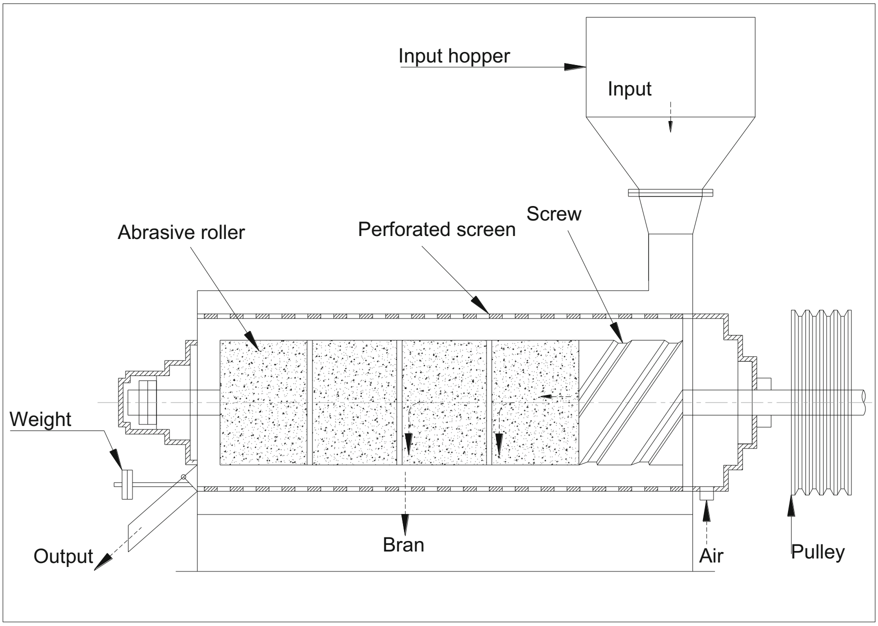


Fig. 9.14 Horizontal abrasive polisher

9.3.18 Vertical Abrasive Polisher

Vertical polishers are divided into two groups according to the direction of flow. The first has grains moving downward. The second has grains being pushed upward. The milling characteristics fall between the abrasive and friction types. Recently, a combination of both abrasive and friction mills in series have been developed. They eliminate the use of intermediate elevator and surge bins and are more compact in structure. In general, vertical polishers receive rice grains under uniform pressure. Incidentally, the mechanism makes it difficult to control the pressure in the milling chamber and to discharge the rice grains uniformly from the circumference of the milling chamber. In the polisher that pushes the grains up, the grains are conveyed by a horizontal conveying screw and then pushed up with a screw roll which is a part of the abrasive rolls. They are then polished by a cylindrical emery grindstones. The grindstones (abrasive cylinder) is formed in the same way as for the horizontal abrasive mill. In the friction section, the rice grains are moved by a side conveying screw and then pushed upward by a screw roll. They are then polished by the friction forces between the milling roll and the screen. An air jet is also used in the vertical abrasive polisher. Although there are large differences in their structures, the basic polishing method is the same as that used in the horizontal mill (Fig. 9.15).

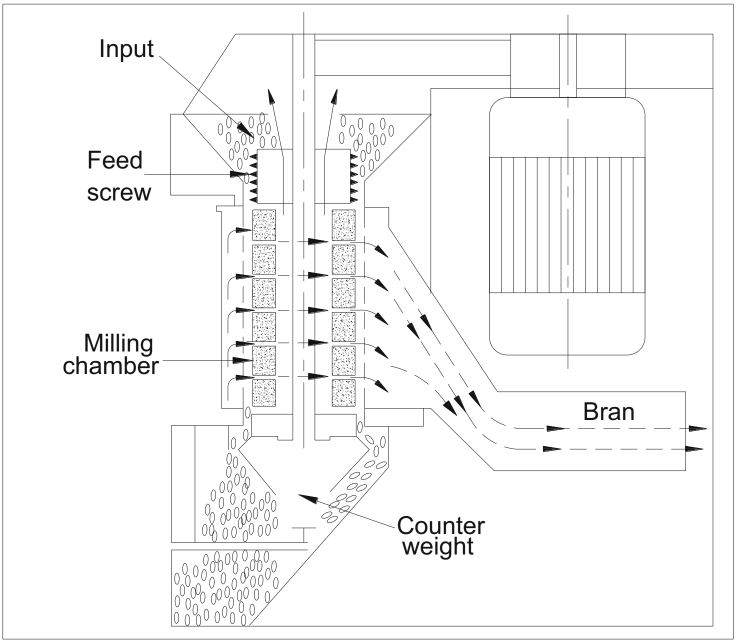


Fig. 9.15 Vertical abrasive polisher

9.3.19 Horizontal Friction Polisher

The unit consists of a steel rotor rotating inside a perforated screen (hexagonal shape). The cylinder has a thin, rectangular opening along its length and hollow shaft for conveying air through the grains. The milling pressure on grain is controlled by hanging weights on discharge gate. The clearance between the screen and cylinder is adjustable by opening or closing the screen. A strong stream of air is blown through the hollow shaft and long slit of the cylinder. The air helps in separating the bran and removing the heat generated due to friction between grains. Generally, the abrasive polishers are used as primary polishers and the friction polishers as the final polishers. The percentage of bran removed in the primary polishers is the greatest. Adhering bran particles are removed in the friction polishers and hence used in the final stage prior to grading brokens from polished millets (Fig. 9.16).

9.3.20 Water Jet Polisher

This is an advanced (or modified) version of friction polisher. Instead of using ambient air to pass through the hollow shaft and subsequently through the grain mass, the air is humidified with a spray of water. This not only assists in cooling the

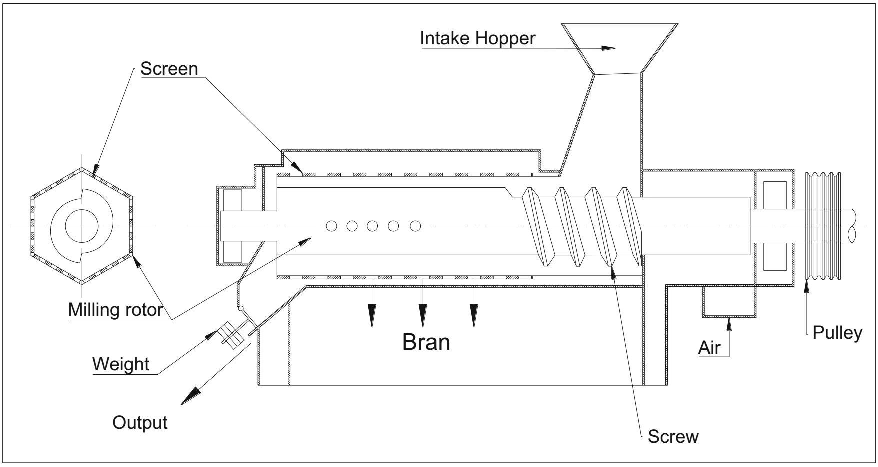


Fig. 9.16 Horizontal friction polisher

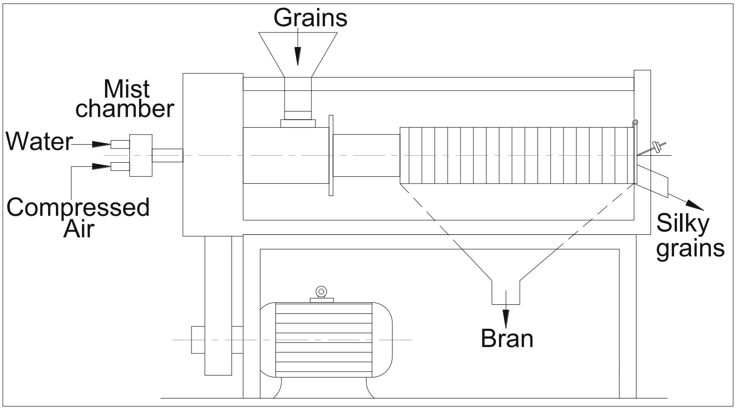


Fig. 9.17 Water jet polisher

grains due to evaporative cooling but also moistens the adhering bran layers, thus affecting their easier removal. This method of polishing also improves the shelf life of millets, since it ensures complete removal of bran layers. The polisher consists of a water tank, air compressor, water spraying nozzles and bran collection system (Fig. 9.17).

9.3.21 Grading Section

After polishing the milled grains, in addition to whole grains, broken grains of different sizes are also present in the product. Separation of broken grains from intact, complete millet grains is termed "grading". Broken grains are separated using a plansifter. Nowadays, sorting grains based on colour has come of age. Colour sorting is the final step in the milling process prior to weighing and packing.

9.3.22 Plansifter

This machine derives its name from planetary motion and is a short form of "Planetary sifter". Depending on the number of fractions to be separated, the sifter may have one or many sieves. The entire deck of sieves is given a rotary, swinging motion that is produced by an eccentric mechanism. It consists of two or more sheets of different perforations (first small and then large) to separate two or more grades of brokens from the polished millet grains. The grain moves across the swinging sieve in a continuous spiral path. A plansifter being of sieve type, cannot separate all broken grains from complete millet grains using a single sieve. Hence, a number of sieves are used to separate brokens successively, starting from small brokens to big brokens. The openings of the sieves of the grader should be kept free from any material closing the holes for maximum efficiency of grading. In some sifters, chains across the breadth of the screens or rubber balls in compartments below the screens are used to declog the screens automatically with little or no human intervention. Screens with round holes are used to separate brokens based on the differences in breadth and screens with oblong (rectangular) holes are used to separate brokens based on thickness (Fig. 9.18).

9.3.23 Colour Sorter

The colour sorter is a photoelectric particle separator. The chute-type colour sorter that is now in wide usage was first developed in the United Kingdom. Towards the end of the 1880s, it was discovered that the electrical conductivity of selenium oxide varies with the amount of light present. This fact provided the basis for the colour sorter. A solenoid air valve (ejector) is connected electrically to a sensor that distinguishes, on the basis of reflected light, the background from the rice grains falling from a conduit-shaped chute; the ejector discharges any grains that are discoloured. Although the development and use of colour sorters in Japan began only 15 years ago, sorter efficiency and accuracy have been significantly improved by taking advantage of the progress in the electronic circuits from transistors to integrated circuits (ICs) and large-scale integrated circuits (LSIs). Grains are fed in a channel to fall one grain at a time. Each grain is then compared with the set standard. Should there be any deviation in the colour of the rice grain from the set colour, then the ejector blows a jet of air thus pushing the discoloured rice grain from the mass. It is possible to set the colour to any desired shade, thus making it possible to colour

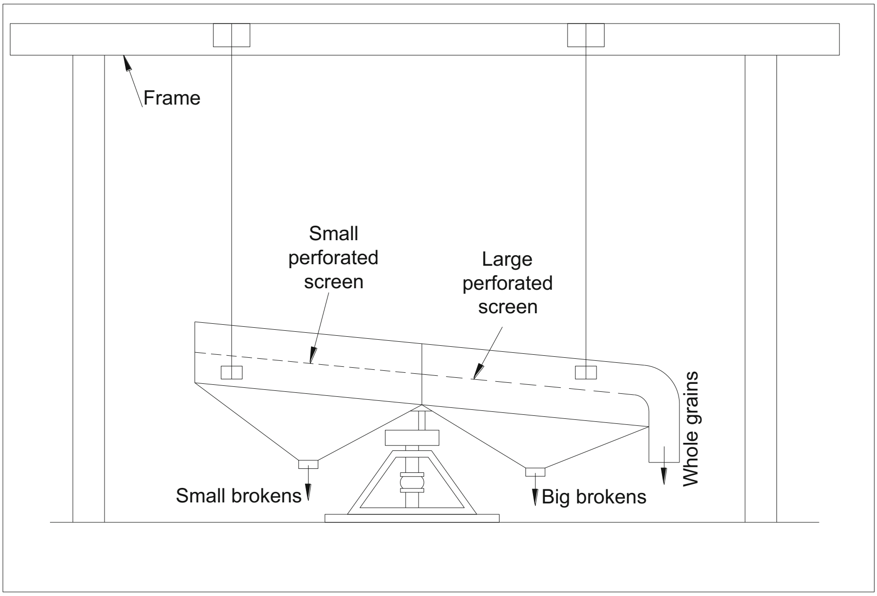


Fig. 9.18 Plansifter

sort the rice grain to a uniform hue. Presently, colour sorters using CCD cameras are in vogue. The selected material is put into the machine hopper. A vibratory feeder ensures uniform feed across the channels or feed distribution channel. Individual grains pass through the observation cabinet between the monitor (camera) and background plate. With the right choice of light, the optoelectronic sensor receives the light from the material which makes the system produce an output signal to the ejectors. The ejectors are basically nozzles connected to an air compressor actuated by solenoid valves to blow off the "rejected" grain into the waste cavity of the receptacle and collected separately. The "accepted" grain continues to fall into the "good" product cavity and is taken for weighing and packing (Fig. 9.19).

9.3.24 Weighing and Bagging Section

The final section in the mill is the weighing and bagging section. Here, the finished product, i.e., polished millets are packed in unit packs ranging from a few hundred grams to kilograms. The normal packing size depends on the market demand being catered to by the manufacturer. A few manufacturers pack the polished millets in 500 g, 1 kg, 5 kg, 10 kg and 25 kg quantities or more. The type of weighing and bagging system employed depends on the miller and consideration of investment either in the form of automatic machinery or manpower decides the level of technology adopted for the purpose. For example, if a mill owner decides to employ women/men for the purpose, a digital weighing balance along with manual/semi-

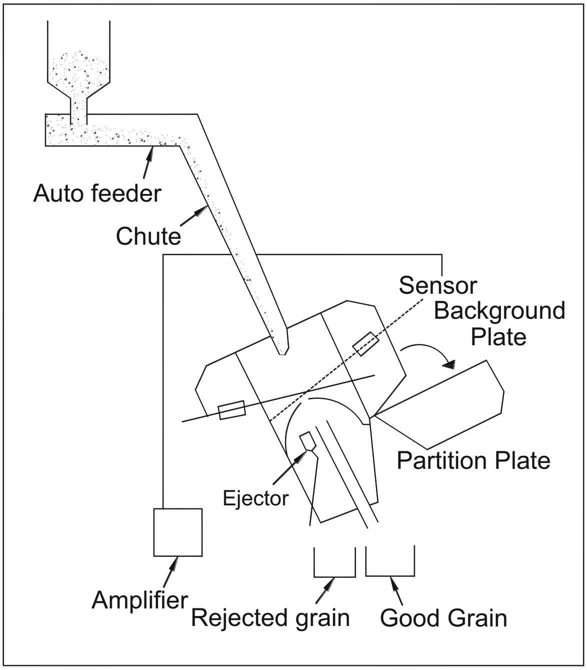


Fig. 9.19 Colour sorter

automatic/automatic sealing machines would be employed. If automatic weighing and bagging systems are commissioned, then there is a wide range of machine systems to choose from depending on the unit pack size. In such systems, the polished millets are filled in an overhead bin which feeds the material to the feed hopper of the packing machine. In the control panel, the user enters the weight of the material to be packed. The weighing system then discharges the selected quantity into the bag placed below. After filling the bag, the bag is then moved on a belt conveyor to the stitching station, where the open end of the bag is stitched (single line or double line of stitches, depending on the weight of the material). The stitched bag is then discharged from the machine, which is then stacked in the finished product warehouse of the manufacturer (Fig. 9.20).

9.3.25 Form Fill Seal System

These are employed for unit packs up to about 1000 g. In this system, the packaging material is fed to the machine in rolls. The sheet is then folded and sealed on the vertical edge either as a fin or overlapping joint. Two edges of the film overlap each other, which is then heat-sealed to form a joint. This is generally preferred since it is aesthetically more appealing and uses lesser material than a fin seal. As this tube passes downwards, a set of heated horizontal jaws seal the tube at the bottom into which pre-weighed material is filled. Present-day technology involves “cold sealing”

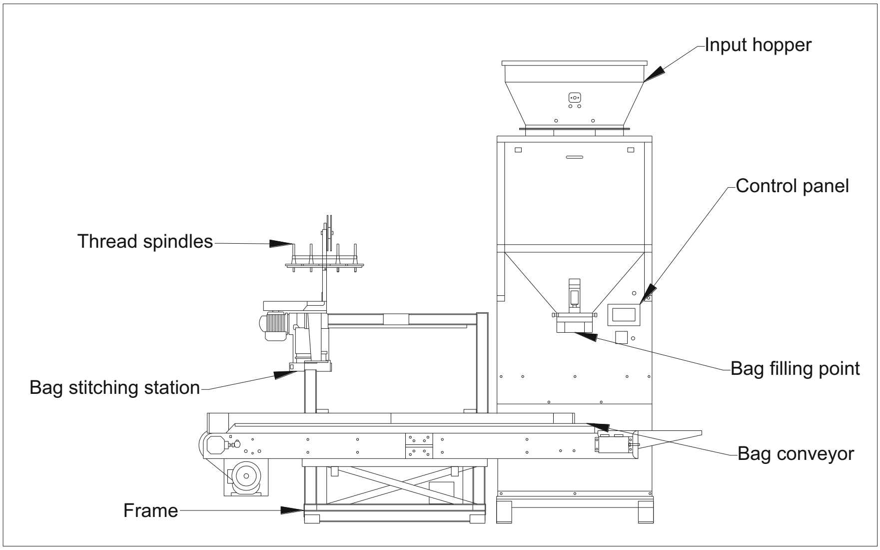


Fig. 9.20 Bag weighing and stitching machine

which uses ultrasonics technology. Such systems are used for products which are heat-sensitive.

Ultrasonic sealing uses vibrations of a certain frequency to induce friction at a molecular level that generates heat only in the area between film layers. Then the top portion of the packet is sealed along with the bottom portion of the next packet on the vertical tube. For moisture-sensitive products, an option is also available to fill the packet with nitrogen. A cutter then cuts the packet at the centre of the sealed zone and the packaged product then falls to the discharge chute. The cycle is then repeated for subsequent packets. The finished packet can be discharged into a collector or onto a conveyor and transported to subsequent equipment like check weighers, quality control machines like X-ray machines, case packing or carton packing equipment, depending on the level of automation involved (Fig. 9.21).

9.3.26 Milling of Millets Without Husk

Millets like sorghum (jowar) and pearl millet (bajra) do not have husk layers but are covered with a seed coat. Removal of seed coat layers is preferred by a few processors prior to grinding into flour or for subsequent product development. Jowar and bajra are cleaned off impurities and destoned to remove stones. They are also made to pass through a magnetic cleaner to remove ferrous impurities. The grains are then, preferably, incipient conditioned with water to soften the seed coat layers. Usually about 3–5% water is added to the grain and allowed to temper for a period ranging from a few minutes to 30 min. The amount of water added and

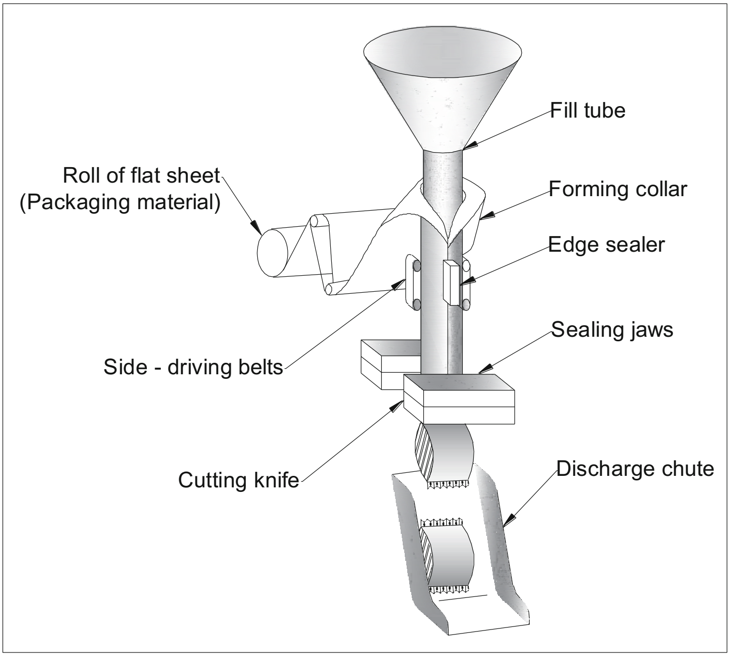


Fig. 9.21 Form fill and seal machine

tempering period is such that moisture content of only the seed coat layers are increased. By doing so, the seed coat layers become tough and leathery and ensure easy removal and separation.

9.3.27 Screw Conveyor Cum Water Mixer

This machine is a modified screw conveyor usually employed to move material horizontally between two points in the plant. A set of nozzles connected with water and compressed air lines ensure a fine spray of water on the grains in the trough of the screw conveyor. The grains and water get mixed well by the time grains move from the inlet to outlet point of the screw conveyor. Many different types of screw flights are employed depending on the usage. Paddle or single flight configuration is used to mix and convey the grains. If required, the grains are then allowed to rest in overhead tempering bins for the duration desired. The tempered grains are then polished in either horizontal abrasive or vertical polishers to the desired degree of seed coat removal. These polished grains are either pulverized into flour or taken for further processing into value added products like flakes and puffed products. Jowar and bajra grains are also milled in a roller mill to get grits and semolina of different sizes and used in the preparation of many traditional and bakery products (Fig. 9.22).

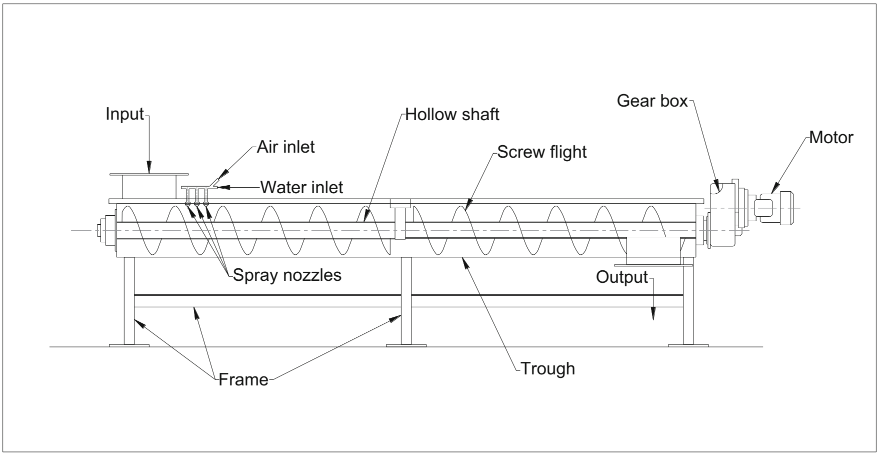


Fig. 9.22 Screw conveyor cum water mixer

9.3.28 Milling of Finger Millet

Since finger millet (ragi) is a bare grain with a seed coat which is tightly adhering to a floury endosperm, milling of ragi is largely restricted to converting it into flour using the many different types of pulverizers available in the market. A technology developed by CSIR—CFTRI, Mysuru, has modified the texture of ragi grains so that it can be polished to remove the seed coat layers alone. These polished ragi grains (also called ragi rice) can then be used to make different products like ragi flakes and puffed ragi grains. It is also used in the preparation of traditional foods like *Upma* wherein ragi rice is cooked and to which cooked vegetables and seasoning material are added.

Many different products can be made from millets and the interested reader is requested to check out the photographs and videos on the website https://www.cftri.com → millet focus. Among the free technologies listed therein, the design drawings of a machine for small-scale dehusking of millets is included. Entrepreneurs are encouraged to download the drawings, fabricate and market these machines in the rural sector.

9.3.29 Pedal-Operated Millet Dehusker

This is a simple machine used to dehusk millets at the rural sector for own use. It is also aimed at marginal fabricators to augment their income. The system has been designed by a team of engineers from CSIR—Central Food Technological Research Institute, Mysuru, of which the author is also a member. It consists a blower that is normally used to blow air through coal manually for applying tin to cooking vessels. The fan configuration has been changed to suit dehusking millets. A 6-gear system

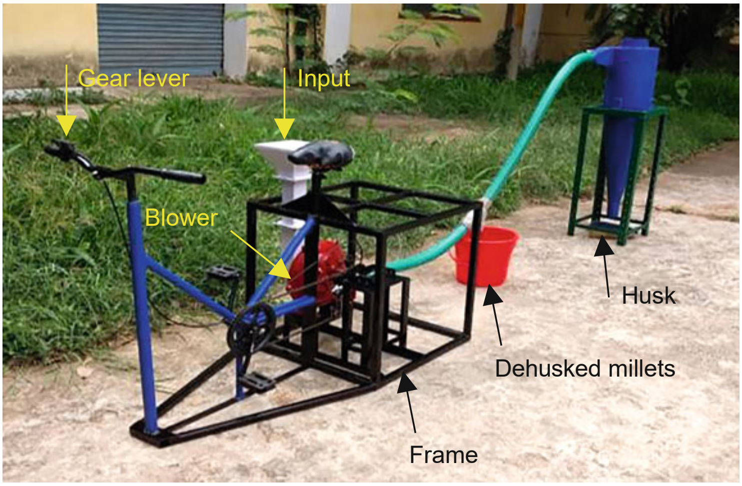


Fig. 9.23 Pedal-operated millet dehuller

normally used in cycles is fitted with a chain drive coupled to the fan shaft. As the user pedals on the input sprocket, the chain drives the fan shaft speed at a higher speed owing to the gear ratio between driving and driven sprockets. The gears can be changed to facilitate the effort put in during cycling. To the air suction inlet of the blower, a feed hopper with feed gate is attached through which millets to be dehusked are fed. To the outlet of the blower a flexible pipe is attached. At about one-third distance of this flexible pipe, a "Y" bend pipe is fitted that discharges dehusked grains. To the tail end of this "Y" bend, the flexible pipe carries the husk to a cyclone separator which discharges the husk. As in the case of the motorized centrifugal sheller, here also 100% dehusking is not obtained in a single pass. The machine gave a dehusking percent between 75% and 85% during performance trials. The dehusked and unhusked grains can be separated manually by winnowing. The dehusked grains are taken for further processing and the unhusked grains are passed through the dehuller once again for dehusking. This system can process about 10–15 kg of millets per hour. To measure the speed of the fan, a non-contact speedometer that is used in cycles is also fitted. The speed of the fan shaft is different for the four different types of millets that can be dehusked in this system. Little, Foxtail, Kodo and Proso can be dehusked. The speed of the fan shaft is 12.8 km/h, 11.3 km/h, 14.5 km/h and 11.3 km/h respectively. The system is designed for manual operation intentionally to keep down the cost of the machine and its operation. Solar-powered or motor-driven systems can be retrofitted by enterprising manufacturers. The cost of manufacturing the unit is estimated at Rs. 18,000 to Rs. 20,000/per system. All the components of the machine are available indigenously. The step-through frame allows for operation even by women. The system is versatile and can be used for dehusking paddy, certain oil seeds, musk melon and pumpkin seeds also (Fig. 9.23).

Effect of Processing on Functional Characteristics, Physiochemical Properties, and Nutritional Accessibility of Millets

10

Anila Wilson, Arunkumar Elumalai, J. A. Moses, and C. Anandharamakrishnan

Abstract

Millets are nutritious minor food crops that can adapt to different agro-climatic conditions and are usually cultivated in drought region. Millet grains are rich in carbohydrates, dietary fiber, and micronutrients like calcium, iron, phosphorous, and magnesium. Researches are undergoing on improving the edible application of millet grains, thus improving the nutritive values and goodness upon consumption. Before consumption it has been refined by different approaches such as malting, milling/grinding, fermentation, roasting, popping, decortication, cooking, and extrusion to convert it into edible forms. These different processing techniques are employed to enhance the nutritional quality, digestibility, and bioavailability of micro- and macroelements and reduce the anti-nutritional factors like phytates, tannins, and oxalates present in millets. This chapter provides an insight into the effect of different processing techniques on the nutritional, anti-nutritional, functional, and physiochemical properties of millets.

Keywords

Millets · Processing · Nutrients · Anti-nutritional factors · Functional properties · Physicochemical properties

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10.1 Introduction

In the twenty-first century, growing population, water paucity, rising food prices, and socioeconomic factors are menaces to the agricultural field and worldwide food security. Interest in the cultivation of drought-resistant crops is growing up in Asian countries like India, West African countries, and China due to high drought area and rising population. Millets are cereal crops with climate-resilient features, low nutrient input requirements, minimum irrigational needs, and resistance to environmental stresses (Bandyopadhyay et al. 2017). Millets are defiant to pest and diseases, have a short growth period, and have yielded even under drought conditions. Millets are nutritionally high compared to regularly consumed cereals like rice and wheat as they contain ample dietary fiber, proteins, essential amino acids, phytochemicals, and micronutrients and hence these are reported as functional foods (Rathore et al. 2016). They are rich in flavonoids, phenolic compounds, and carotenoids hence these millets can be useful in the prevention and/or management of diabetes. Further, there are several advantages such as lower risk of cancer and cardiovascular diseases, reduced cholesterol, slowdown of gastric emptying, and improved gastrointestinal bulkiness (Saleh et al. 2013).

Despite its excellent nutritive aspects, millets contain some anti-nutritional factors whose existence reduces the availability of the nutrients to our system. This includes phytates, protease inhibitors, non-starch polysaccharides-glucans, tannins, and oxalates. The presence of these factors either directly or indirectly influences the digestibility of the nutrients. The anti-nutritional factors reduce the bioaccessibility and bioavailability of minerals, as they have the ability to chelate the micronutrients in the gastrointestinal tract. Moreover, the availability of these factors may also cause off taste and unpleasant color in the final products. Also, some enzymes present in grains, such as lipase enzyme can cause off-odor and taste (Rani et al. 2018). Therefore, to improve the shelf-life and quality of products, these factors are to be minimized and this is accomplished by the processing of millets. Before consumption, it should be subjected to various processing methods like malting, decortication, fermentation, roasting, popping, milling/grinding, cooking, and extrusion to convert it into edible forms. Processing produces significant changes in the proximate composition, anti-nutritional factors, functional, and physiochemical properties of millets. This chapter discusses the effect of processing on the various nutritional, anti-nutritional, functional, and physiochemical properties of millets.

10.2 Effect of Processing on the Properties of Millets

10.2.1 Indigenous and Conventional Methods

10.2.1.1 Germination

Germination involves sprouting of cereal grains in humid atmosphere and under controlled conditions. It results in biological and chemical modifications of grain and enhances dietetic quality and functional characteristics (Table 10.1). This process

Table 10.1 Effect of germination on the nutritional and anti-nutritional factors of millets

Millet	Objective	Results	References
Foxtail millet	Effect of germination	No significant change in the protein content; reduction in the levels of carbohydrates, fats, and free fatty acids; increase in vitamins and minerals: increase in total soluble solids, titrable acidity, and DPPH-scavenging activity	Coulibaly and Chen (2011)
Foxtail millet	Process optimization	Soaking for 15.84 h followed by germination at 25 °C for 40 h increased protein, dietary fiber, antioxidant activity, total flavonoid content, minerals such as calcium, magnesium, iron, sodium, and decrease in the anti-nutrients	Sharma et al. (2015)
Barnyard millet and foxtail millet	Effect of germination on nutritional, anti-nutritional, and functional properties	Significant reduction in protein and total carbohydrates; increase in total fat, amylose content, and titrable acidity; significant decrease in bulk density, swelling power and solid loss and WAC; significant increase in solubility index and OAC	Nazni and Devi (2016)
Barnyard millet	Optimization of germination conditions to enhance the activity of bioactive compounds	Soaking time of 11.78 h, germination temperature and time of 33 °C and 36.48 h caused significant rise in the antioxidant activity (AoxA) and total phenolic and flavonoid content (TP & FC); Phenolic extract of germinated flour contained more amount of hexadecanoic acid, octadecadienoic acid, lupeol, and campesterol; a significant increase in dietary fiber and mineral content; better yield and purity of γ-aminobutyric acid	Sharma et al. (2016)
Finger millet	Effect on bioactive compounds and anti-nutrients	Significant decrease in total phenolic content (TPC) and tannins; a significant increase in the antioxidant activity and flavonoid content; reduction in the amount of anti-nutritional factors	Abioye et al. (2018)
Pearl millet	Germination as a pre-milling process and its effect on iron availability	Enhancement of in vitro iron availability	Bhati et al. (2016)

causes the breakdown of major nutrient elements like starch, protein, and fiber, and also initiates hydrolytic action of enzymes such as proteases and amylases (Li et al. 2017). Moreover, studies have also reported that germination has a significant effect on the starch digestibility and in vitro protein digestibility which results in the better availability of free amino acids. However, there will be a drastic reduction in the crude protein and fat content upon germination. This may be due to the deprivation of low molecular weight nitrogen compounds during soaking and fatty acid hydrolysis followed by fat oxidation respectively on germination. The consumption of nutrients by the sprouts could also be another reason for this reduction. Germination has significant role in producing water-soluble protein with the ability to inhibit hydroxyl radical (Saleh et al. 2013).

Choudhury et al. (2011) conducted an experiment using foxtail millet to study and optimize its germination conditions. Results showed that the germination of foxtail millet for 72 h after a soaking period of 20 h and at a temperature of 25–30 °C resulted in a significant reduction in the carbohydrate and fat content, minor cutback in protein, and increased digestibility of starch and protein. Besides, germination makes use of fats by activating lipolytic enzymes, thereby preventing the enzymatic action on fats and making millet more palatable. The lipases activity liberates free fatty acids which results in the bitter taste to the millets. Apart from this, starch molecules present in the grain are broken down into simple sugars by the amylase enzymes, thereby making it easily digestible and absorbable. There will also be a significant increment in the amount of dietary fiber in barnyard millet on germination. The process causes extensive biosynthesis of the cell wall and therefore increases the level of dietary fibers (Sharma et al. 2016). This modification has been attained by the modification of polysaccharides which constitutes the structure of cell wall and disrupting the carbohydrate–protein interaction (Duodu 2014). A remarkable elevation has been found in the flavonoid and total phenolic content after germination, which might be due to the action of cell wall disrupting enzymes. This enzymes releases the phenolic compounds that are linked through ether and ester linkage to the non-starch polysaccharides located in the cell wall (Sharma et al. 2016). The polyphenols are reductant, antioxidants capable of donating hydrogen, and have the potential to scavenge singlet oxygen, thereby improving the antioxidant activity of the millets.

Finger millet is found to have many anti-nutrients such as oxalates, phytates, and tannins. Abioye et al. (2018) studied the effect of the germination process on anti-nutrients factors in finger millet and observed that the tannins and phytates decreased with approximately 23% tannin reduction. A notable elevation in the bioavailability of iron, calcium, sodium, and magnesium has been observed in barnyard millet as a result of germination. The phytase enzyme gets activated during germination, which hydrolyzes phytates to free orthophosphate and inositol, resulting in the release of inorganic phosphates (Sharma et al. 2016). The reduced tannin content may be a consequence of the activation of polyphenol oxidase and other catabolic enzymes (Kalpanadevi and Mohan 2013). Another reason for the decrease in tannins maybe its hydrophobic association with seed proteins or its seepage into water on soaking (Shimelis and Rakshit 2007). Germination also lowers the amount of oxalic acid and trypsin inhibitors in finger millet. The decrease in trypsin inhibitor activity is due to its consumption as a source of energy for the process as well as due to the degradation caused by peptic enzymes (Sarita and Singh 2016). A similar reduction in trypsin inhibitor was observed in the case of germinated barnyard millet as well. Other anti-nutrients like polyphenols and saponins are also catabolized during germination and therefore enhancing the mineral availability (Saleh et al. 2013; Tharifkhan et al. 2021). Germinated millets are also a source of α-amylase and α-glucosidase inhibitors. The hypoglycemic activity associated with foxtail, proso, and barnyard has been linked with the attenuation of these enzymes activities (Pradeep and Sreerama 2015).

Germination also affects the functional properties of millets. Studies reported that the germination of foxtail millet increased the swelling capacity, water, and oil absorption capacity (WAC and OAC), flowability, gelatinization enthalpy, porosity and dispersibility occluded air content of the flour (Sharma and Niranjan 2018). Further, the emulsification activity (EA) and the emulsion stability (ES) of the millet are found to be improved after germination. However, germination decreases the bulk density, insolubility index, ability to form, and form stability of the flour. A similar trend was seen in the above properties of finger millets on germination (Abioye et al. 2018). Panda et al. (2020) studied the functional properties after germination of seven millets which included proso millet, kodo millet, little millet, finger millet, sorghum, pearl millet and foxtail millet. There was a remarkable elevation in the water absorption capacity and solubility index in the sprouted grains, except for foxtail millet and proso millet. All the millets exhibited an increase in the foam stability (FS) and foaming capacity (FC) particularly FS of pearl millet and the FC of sorghum. WAC and OAC of barnyard millet also increased on germination (Nazni and Devi 2016). A decline in the amylose content, swelling factor, starch paste viscosity, and enthalpy of retrogradation were also observed on germination. The fall in amylose content is perhaps because of the breakdown of amylopectin which successively brings on a lower swelling factor (Li et al. 2017). Germination also influences the color of millets by decreasing the lightness and elevating the yellowness of millets. This color change may be attained due to the Maillard reaction between the amino acids and the soluble sugars liberated on enzymatic hydrolysis that takes place in germination (Li et al. 2020).

10.2.1.2 Roasting

Roasting is an important processing technique in the value addition of millets. It brings significant changes in the nutritional, anti-nutritional, functional, and physicochemical properties of millets (Table 10.2). Roasting lowers the moisture content in millets when subjected to dry heat. Besides, a depletion in the carbohydrates and protein levels has been observed in millets upon roasting, which is possibly due to the Maillard reaction happening as a result of dry heat treatment. Obadina et al. (2016) studied the influence of roasting on the nutrients present in pearl millet. It was observed that the protein percentage in unroasted grains were high compared to the roasted grains. The lowering in protein content might be due to the alteration of endogenous protein structure and the annihilation of some amino acids upon the

Table 10.2 Effect of roasting on the properties of millets

Millet	Objective	Results	References
Foxtail millet	Influence on the volatile compounds	Rise in levels of heterocyclics and aldehydes; decrease in hydrocarbons and benzene derivative levels; positive effect on the odor quality	Jing-ke et al. (2014)
Finger millet	Effect of roasting on the physiochemical and proximate composition	Reduction in moisture, protein, fat and antioxidant activity; increase in carbohydrate and ash content; improved bioavailability of iron and calcium	Singh et al. (2018)
Foxtail millet	Effect on roasting on nutritional and anti-nutritional factors	Reduction in carbohydrates, protein, fat, fiber, and moisture content; reduction in potassium and magnesium content; increase in the levels of iron, calcium, and phosphorous; reduction in the polyphenols, tannins, and phytic acids	Khapre et al. (2016)
Pearl millet	Effect on the nutritional and physicochemical properties	Reduction in protein content; increase in ash content; increase in total energy value; Increase in iron content, decrease in potassium and phosphorous; reduction in amino acid content; increase in OAC and WSI; decrease in phenolic content	Obadina et al. (2016)
Jirani millet	Effect of roasting in the temperature range (112.5–120 °C) for (15–20 min) on nutraceutical and antioxidant properties	Increase in antioxidant and DPPH scavenging activity with rise in temperature; decrease in antioxidant and DPPH scavenging activity with rise in roasting time	Oluwole et al. (2019)

heating of millets. Further, the ash level of millet has also been elevated upon roasting which indicated an increased amount of minerals in the roasted samples. A study has been conducted to examine the effect of processing techniques such as puffing, roasting, steaming, and extrusion on the total phenolic content (TPC) and total flavonoid content (TFC) in broomcorn millet (Kalam Azad et al. 2019). It was observed that roasted millets showed increased TPC and TFC content, and this may be due to the polymerization reaction between the phenolic compounds through the Maillard reaction (Pradeep and Guha 2011). Roasting also helps in getting rid of odors and volatile aroma compounds. Hithamani and Srinivasan (2014) studied the influence of various local processing techniques on the properties of finger millet and pearl millet. It was found that roasting improved bioaccessibility of phenolics compared to other methods like pressure-cooking, open-plan boiling, and microwave treatment. Besides, there are reports on roasting causing a reduction in the hydrocarbons and benzene derivatives and increase in aldehydes and heterocyclics (Sharma and Niranjan 2018).

Roasting is also the simplest method to reduce anti-nutritional factors such as phytates, trypsin inhibitors, saponins, and tannins present in millets. The polyphenols, tannins, and phytic acid present in foxtail millet drop down considerably upon roasting. Similar results were also documented by Shobana et al. (2013) in finger millets. Nithya et al. (2007) studied the effect of roasting on the polyphenols and tannins present in traditional (CO7) and hybrid (COHCU-8) varieties of pearl millets. The TPC and tannins reduced considerably on roasting which may be due to the increased temperature during processing. Besides, roasting markedly reduces the anti-nutrient factors and thereby elevates the bioavailability of iron and calcium in the roasted finger millets. This may be attributed through the reduction of anti-nutrients (Singh et al. 2018).

Roasting also has influence on the functional and physiochemical attributes of millets. Studies have documented that the bulk density of barnyard and foxtail millet was increased upon roasting. However, the swelling power, WAC, and OAC of two of them decreased on roasting. The pasting temperature of the barnyard millet increased, whereas the pasting temperature of foxtail millet decreased on roasting (Nazni and Devi 2016). It was observed that the swelling capacity as well as the water solubility index of pearl millet increased on roasting. A study conducted by Erasmus et al. (2018) on the physicochemical and proximate changes associated with the processing of finger millet reported that the bulk density and capacity to foam lowered whereas the foam stability had no significant changes upon roasting.

10.2.1.3 Soaking

Soaking is one of the conventionally used basic food processing techniques for grains which involves simultaneous absorption of water and swelling. Soaking helps in improving the nutritional quality, increasing the digestibility and bioavailability of nutrients and diminishing the anti-nutrients in millets (Balkrishna and Visvanathan 2019).

Soaking can bring down the levels of anti-nutrients present in millets thereby improving the bioavailability and bioaccessibility of nutrients. The phytic acid and trypsin inhibitor present in finger millet were decreased by nearly 13% upon soaking (Patel and Dutta 2018). Also, soaking of pearl millet causes the reduction in phytate content, especially when combined with other methods such as cooking and milling (Saleh et al. 2013). A study conducted by Singh et al. (2017) documented that overnight soaking of millets reduced the content of tannin and phytic acid to a very low level. This can be attained by the leaching of the compounds upon soaking in water. Further, a remarkable increase in the activity of amylase and phenolic oxidase has been found after soaking which resulted in the reduction of polyphenols in soaked millets. Krishnan and Meera (2018) investigated the influence of processing on the bioaccessibility of minerals in pearl millet. It was reported that soaking reduced the polyphenol and phytic acid content by 11–15% and 10–14% respectively. Further, millets soaking in acidic or basic medium resulted in the diminution of anti-nutritional factors like polyphenols and phytic acid and thereby increases bioaccessibility of micronutrients. Jha et al. (2015) reported that soaking of bran-rich and endosperm rich fraction of decorticated pearl millet grains in acidic (0.1N tartaric acid solution) and alkaline solutions (0.1N calcium hydroxide solution) for a short duration of time (3 h) decreased the inhibitory factors without causing a loss in the amount of minerals. The flavonoid level lowered by 62.7% in the endosperm fraction and the phytic acid level of bran rich fraction decreased significantly on acidic soaking. As a result, bioaccessibility of iron increased by 2.5% in the endosperm fraction and the zinc bioaccessibility of the bran rich fraction increased by 35%. Soaking in alkaline conditions reduced the polyphenol content by 11% and 22% in the bran and endosperm rich fractions.

10.2.1.4 Fermentation

Fermentation is an important processing methods that aids in manufacture of foods with enhanced flavor and improved nutritional properties. Millet fermentation is carried out by souring and malting with a mixed culture of Lactobacilli and yeast. *Saccharomyces diastaticus*, *Saccharomyces cerevisiae*, *Lactobacillus brevis*, and *Lactobacillus fermentum* are some of the microbial types used in the fermentation of millet grains (Pawase et al. 2019). Fermentation causes significant changes in the proximate composition, anti-nutritional factors, physicochemical and functional properties of millets which has been listed in Table 10.3. Fermentation results in the modification of the chemical composition of millets and its products and hence has been aids in the manufacture of different fermented products. Fermentation can lower the level of anti-nutrients in millets and elevates the availability of protein and its digestibility. The enzymes like amylase and α-glucosidase present in the grains and the fermentation media degrade the starch and sugars present in millets. Fermentation causes remarkable elevation in the proximate composition of pearl millet (Saleh et al. 2013). The inflation in protein level on fermentation might be the result of protein synthesis from intermediate metabolic compounds produced by microorganisms (Amadou et al. 2014).

It is also suggested that fermentation contributes to decrease in tannins, phytic acid, and polyphenols of pearl millets, which increases in vitro protein digestibility (IVPD). The increased IVPD has also been attained by enhanced proteolytic activity during fermentation which leads to the formation of simple and soluble products by breakdown of complex proteins (Hassan et al. 2006). Moreover, an improvement in the digestibility of starch digestibility was observed due to the amylolytic action of microbes in the media (Arora et al. 2011). The influence of fermentation parameters such as time and temperature on the nutritional and anti-nutritional properties of different millets were studied by many researchers. Lactic acid fermentation of pearl millet for 72 h or longer showed almost complete omission of phytic acid by the action of phytase enzyme and lowering of polyphenols due to the activation of polyphenol oxidase present in the grains, along with the increased levels of extractable phosphorus content (Rani et al. 2018). Osman (2011) investigated the effect of fermentation on the nutritional composition, amino acids, soluble sugars, anti-nutritional factors like phytic acid and tannin, and enzyme inhibition in lohoh bread prepared from fermented pearl millet flour. Considerable reduction was

Table 10.3 Effect of fermentation on the nutritional, anti-nutritional, functional, and physiochemical properties of millet

Millet	Objective	Results	References
Foxtail millet	Effect of fermentation on the flour	Reduced total carbohydrate content; rise in crude protein improved physiochemical properties; increased pasting characteristics	Amadou et al. (2014)
Foxtail millet	Effect of fermentation by *Lactobacillus paracasei* FN032	Significantly better antioxidant and antimicrobial activity, a good source of peptides	Amadou et al. (2013a, b)
Foxtail millet	Effect of a fermentation process using yeast (*Saccharomyces boulardii*) and lactic acid bacteria (*Lactobacillus acidophilus*)	Improved physicochemical properties; enhanced mineral content: reduction in phytic acid	Munishamanna et al. (2014)
Pearl millet	Effect on microstructural and physicochemical properties	Significant increase in the swelling power, OAC and WAC; reduction in bulk density; increase in crystallinity	Adebiyi et al. (2016)
Pearl millet	Effect of fermentation by both natural and starter (*Lactobacillus plantarum*) on proximate, anti-nutritional, and physiochemical composition	Increase in titrable acidity for both natural and starter fermentation; reduced tannin and phytate content; increase in protein and moisture	Chinenye et al. (2017)
Sorghum	Effect of fermentation using *Lactobacillus plantarum* on functional properties and anti-nutritional components	Reduced phytate (77%), tannin (96.7%), oxalate (67.85%), hydrogen cyanide (52.3%); reduction in bulk density and viscosity; increase in WAC and OAC	Ojha et al. (2018)

found in the carbohydrate profile after fermentation for 24 h, which is probably due to its utilization by microorganisms. However, it was found that the total carbohydrate diminished between 8 and 12 h of fermentation, subsequently a rise in carbohydrates between 16 and 20 h of fermentation. This initial decrease was because of the action of α and β amylase in the first few hours, whereas the further increase at 16 and 20 h was due to attenuation of amylase action at low pH that terminated the starch degradation (Osman 2011). A decline in the phytic acid content was documented which is due to the action of microbial phytase activity. However, the tannin level showed an increase in fermentation and this may be due to the hydrolysis of condensed tannins such as proanthocyanidin. Ranasalva and Visvanathan (2014) investigated the textural and physical properties of bread prepared by substituting refined wheat flour at 10%, 15%, 20% level with fermented cooked pearl millet flour. The product showed excellent compatibility to the market

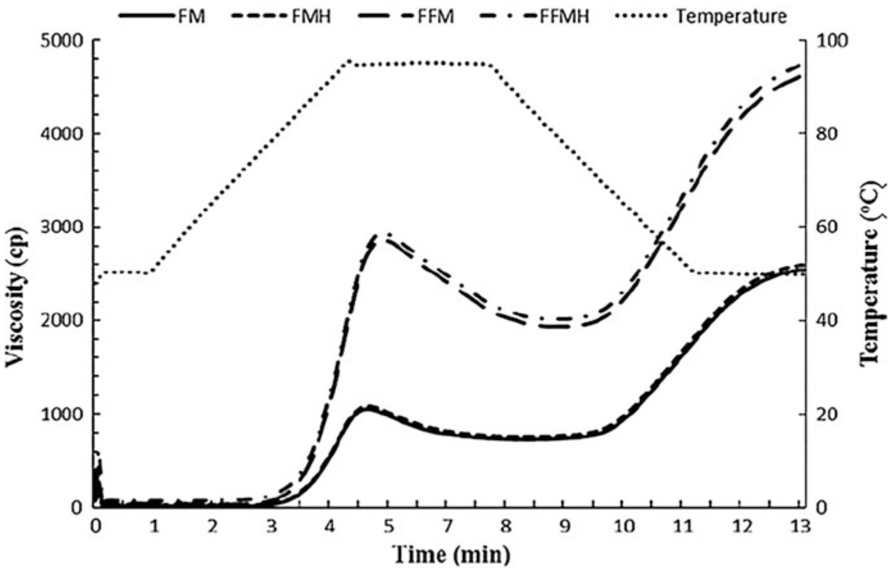

Fig. 10.1 Effect of fermentation and heat-moisture treatment on pasting characteristics of foxtail millet flour (FM), fermented foxtail millet flour (FFM), heat-moisture-treated foxtail millet flour (FMH), and heat-moisture-treated fermented foxtail millet flour (FFMH). (Adapted from: Amadou et al. 2014)

bread in all quality aspects. Similar results were obtained with cookies prepared in similar manner. Amadou et al. (2013a, b) studied the fermentation of foxtail millet using *L. paracasei* Fn032 and observed that it enhanced the physiochemical and nutritional properties. The microbes degraded the starch and protein, which resulted in the increase in reducing sugars and better protein quality. In addition, bioactive peptides developed as a by-product, with antioxidant and antimicrobial properties.

Amadou et al. (2014) studied the fermentation effect, singly and in combination with heat treatment, on the pasting properties of foxtail millet. Results stated that fermentation as well as the combined treatment significantly influenced the pasting properties of foxtail millet. The RVA viscoamylogram of both the samples showed higher peak viscosity, final viscosity, breakdown, and setback compared to the unfermented samples and heat-treated samples (Fig. 10.1). This alteration in viscosity can be due to the breakdown of the crystal structure of starch during fermentation. Akinola et al. (2017) studied the consequence of fermentation of pearl millet flour on the functional and physicochemical properties. It was found that the bulk density of the pearl millet flour reduced greatly by 22% on fermentation compared to the control sample. Besides, the foaming capacity and stability also reduced fermentation in pearl millet flour. The water holding capacity (WHC), solubility, swelling power, pasting viscosity, final viscosity, color lightness, and dispensability also reduced on fermentation compared to the control sample.

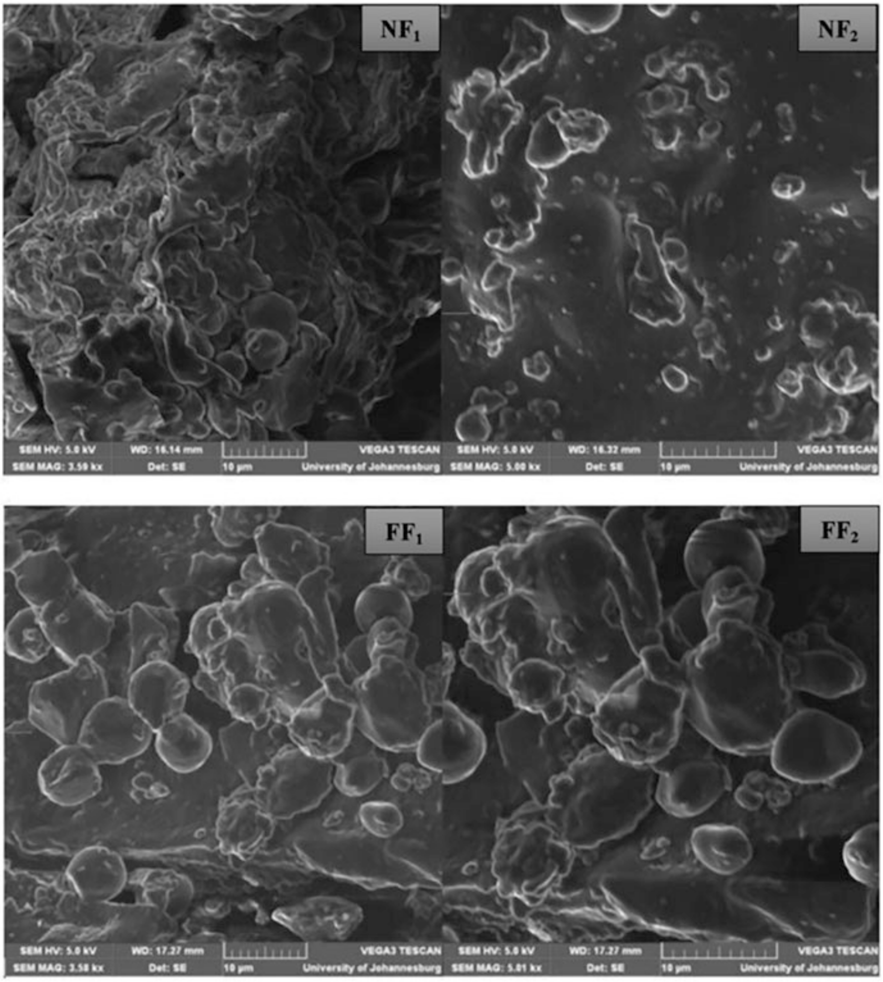

Fig. 10.2 SEM images of pearl millet flours; native (NF1), fermented (FF1); magnified images of native (NF2), fermented (FF2). (Adapted from: Adebiyi et al. 2016)

Studies documented on the microstructure of fermented and native pearl millet flour showed that native flour had irregular, small, compact granular structure, whereas, fermented flour had a smooth and regular structure (Fig. 10.2). Fermentation-dependent alterations in the flour made the structure smooth and regular. The SEM images show that the fermented flour has a porous, disoriented, and less condensed structure. This might also be the reason for the improvement in the swelling power, OAC, and WAC of the fermented flours (Adebiyi et al. 2016).

Adebiyi et al. (2016) also studied the textural characteristics (hardness) of the biscuits prepared from native, fermented, and malted millet flour. Hardness has great significance in determining the consumer perception of any product. It was observed that the hardness of native biscuits was significantly lower than that of malted and fermented biscuits, which is caused by modification of physiochemical properties during the processes. The better interaction of starch and protein facilitated by hydrogen bonding in fermented samples is responsible for its significantly higher hardness.

10.2.1.5 Popping/Puffing

Popping or puffing is a processing method used traditionally to produce ready-to-eat and shelf life-stable products that are porous and crunchy (Dutta et al. 2015; Singh and Raghuvanshi 2012). The puffed snack products have high desirability in terms of appearance, color, flavor, and consumer acceptability. It has been reported that popping increased the crude protein percentage of foxtail millet which is supposed to be a result of the removal of the seed coat on popping. As the popped seeds mainly consist of endosperm, the fat content also reduced significantly when compared to the unprocessed seeds. Due to the removal of germ and bran layers, which is the main source of minerals, the mineral content was also found to be reduced on popping. The cell wall structural constituents are the important sources of fiber in millet seeds. During popping, the endosperm of the seeds puffs out, which resulted in the disruption of cell wall. Hence, the seed coat gets removed to a certain limit, leading to low fiber content in pooped grains. Puffing improved the solubility of starch in foxtail millet as well as the starch digestibility due to gelatinization. The protein digestibility improved significantly on popping because of the reduction in anti-nutrients (Choudhury et al. 2011).

A study conducted by Chauhan documented that popping resulted in a reduction of calcium and phosphorous content and an increase in iron level in finger millet. Study documented that popping lowers phytic acid, tannin, trypsin inhibitor, and oxalic acid in millets.

10.2.1.6 Milling

The effect of milling on millets and milling fractions was reported by numerous researchers. Milling is done to separate endosperm, bran, and germ and produce fine flour by particle size reduction of the endosperm. Devisetti et al. (2014) studied the properties of various fractions (whole, brown and polished) of milled proso millet (TNAU-145) and two varieties of foxtail millet (PS-4, SIA-3126), and it was found that there were considerable changes in the properties. The brown grain flour was observed to have more protein content among the three fractions due to the presence of bran layers. There were no considerable alterations in the carbohydrate and lipid level of whole and brown grain flours as dehulling does not cause the removal of the bran layer. The elimination of the bran layer on the polishing of the grain resulted in a marked depletion of lipid level in polished grain flour. In addition, in polished grain very low ash content was documented.

Dehulling and bran-removal reduced the total dietary fiber level considerably with the least value for polished grain flour. The insoluble dietary fibers such as lignin, cellulose, and hemicellulose were more in whole millet flours, whereas the soluble dietary fiber content was high in brown grain flours. Same results were obtained on milling of pearl millet into whole, semi-refined, and bran-rich flours (Suma and Asna 2017). While considering the anti-nutritional factors present in different milled fractions, the levels of anti-nutrients will be more in the whole grain flour as most of the phytates and phenolics are concentrated in the pericarp, seed coat, and aleurone layer of seeds. The TPC, TFC, and proanthocyanidin content decrease gradually as dehulling and bran-removal take off the aleurone layer and outer layers of kernel (Sharma and Niranjan 2018).

Milling also has significant effects on the physicochemical and functional properties of millets. On comparing the bulk density of three milled fractions of proso millet (TNAU-145) and foxtail millet (PS-4, SIA-3126) it was found that the bulk density was highest for the polished grain flour than the whole grain flour. However, the brown grain flour showed higher bulk density than its polished ones. The nitrogen solubility of the milled fractions was in the range 2.90–16.35 mg/g and 4.73–16.96 mg/g respectively in water and 0.5 M NaCl. The brown fraction of both the millets had more solubility and the polished ones had the least solubility. Also, solubility was more in 0.5 M NaCl compared to water because of the less solubility of millet protein in neutral pH. Though proso millet has more protein compared to foxtail millet, nitrogen solubility was less in the case of proso millet. This is mainly due to the high level of hydrophobic amino acids in prosomillet flour. WAC of whole grain flour is more compared to the other two fractions and this may be due to loss of fiber on milling which can bind water. The OAC of whole-grain flour was also high compared to that of the brown and polished ones with the least value for polished grain flour. This is due to the low surface availability of hydrophobic amino acids in polished flours, which is essential for binding of oil (Devisetti et al. 2014).

Foaming capacity was found to be more for the brown grain flour than other flours but the foam stability was less compared to that of the whole grain flour. The polished grain flour exhibited the low capacity to set up foam and stabilize it. The potential to create foam and sustain its stability rely on the interfacial protein film which block the coalescence by creating the air bubbles in suspension. The emulsion activity was high in the brown milled fraction. The emulsion creation depends on the quality and quantity of protein present in the grain, which increases on dehulling. However, due to the loss of non-starch polysaccharides, protein, and fiber on the removal of the bran, the polished grain flour has the least emulsion activity. Emulsion stability also exhibited a trend similar to that of emulsion activity. All the milled fractions of both proso and foxtail millets showed good gelation properties (Devisetti et al. 2014).

10.2.1.7 Malting

Malting is the procedure of germination of cereal grains under controlled conditions. During malting, the grains are steeped in water to promote germination and then stopped from germination by passing hot air. Malting brings a significant effect on the composition and properties of millets (Table 10.4). The sprouting process is responsible for the stimulation of degradative enzymes such as amylase, protease, and lipases that hydrolyze starch, proteins, and fats (Aguilar et al. 2019). Malting results in the development of enzymes such as α-amylase and β-amylase that modify

Table 10.4 Effect of malting on the nutritional and anti-nutritional factors of millets

Millet	Objective	Results	References
Foxtail millet	Effect on nutritional composition	Enhancement of nutritional properties on steeping for 12 h and germination for 48 h at 25 °C	Laxmi et al. (2015)
Finger millet	Optimization of malting conditions for nutritional improvement for application in infant weaning industry	Germination at 30 °C for 48 h improved protein digestibility by 17%; 10% increase in total energy; 60% reduction in resistant starch	Najdi Hejazi and Orsat (2017)
Pearl millet	Effect of alkaline steeping	Steeping for 72 h in plantain ash solution improved the crude protein and crude fat content significantly; steeping for 72 h in lime solution significantly improved the crude fiber content; a significant decrease in total carbohydrate and ash content; reduction in tannin and phytate; ash steeping reduced bulk density, better WAC, OAC, gelatinization temperature, and emulsification capacity	Bello et al. (2017)
Pearl millet	Nutritional analysis and sensory quality of malted pearl millet flour-based biscuit	Improvement in the protein, crude fiber, carbohydrates, and energy values; lower fat and ash content; good sensorial acceptability	Adebiyi et al. (2017)
Finger millet	Effect on nutritional contents	Significant increase in reducing sugars and free amino acids; decrease in total protein; no significant changes in fat, crude fiber, ash content	Banusha and Vasantharuba (2013)
Sorghum	Effect on anti-nutrients and functional characteristics	Reduction in phytates (40%), tannin (16.12%), oxalate (49.1%); significant reduction of viscosity and bulk density; a significant increase in WAC and OAC	Ojha et al. (2018)

the grain starches into various sugars such as glucose, maltose, maltotriose, and maltodextrins (Santa Senhofa et al. 2016). It also causes the activation of other enzymes, such as proteases that breakdown proteins into simple forms that can be utilized by yeast (Singh et al. 2015). Malting helps in achieving better digestibility of nutrients, high energy density, and vitamin content (Rani et al. 2018). A study conducted by Laxmi et al. (2015) reported that malting increased the protein content in foxtail millet. This may be due to the buildup of storage proteins following the proteolysis during sprouting. It is also explained to be due to the synthesis of some additional amino acids on malting (Adebiyi et al. 2017). On the contrary, Choudhury et al. (2011) reported that the malting of foxtail millet resulted in a significant decrease in the protein content. This change in protein content has been justified to be due to the loss of nitrogenous compounds that have a low molecular weight, during soaking and rinsing. Shoots and roots are the major sources of nitrogen compounds in germinated seeds and the free α-amino nitrogen in them increases due to the translocation of degraded storage proteins from the kernel. Malting also brings significant changes in the amino acid content of millets. Obadina et al. (2017) found that the lysine and aspartic acid content of pearl millet increased significantly as a result of malting. The proteolysis of storage proteins caused by protease enzyme might have contributed to increment of these amino acids However, glycine, tyrosine, isoleucine, methionine, glutamic acid, and cysteine contents were reduced, and this may be due to leaching into the steeping water or due to the temperature to which it is subjected during kilning (Obadina et al. 2017). The hydrolysis of lipids and further oxidation of fatty acids during germination causes reduction in the fat content. The glycerol formed on hydrolysis becomes a part of the carbohydrate pool and fatty acids undergo α and β oxidation, thus causing the reduction of fat in malted grains (Choudhury et al. 2011). Similarly, a reduction in the ash content was also reported on malting which is explained to be due to the leaching of inorganic salts and removal of the seed coat during the process (Adebiyi et al. 2017). It was documented that the fiber level in finger and foxtail millet reduced significantly upon malting, which may be due to the cell wall disruption during germination (Choudhury et al. 2011). However, Adebiyi et al. (2016) and Laxmi et al. (2015) reported an elevation in the crude fiber level, and this was explained to be due to the buildup of dry matter during the growth and development of plant during germination. It may because of the buildup of structural constituents such as hemicellulose and cellulose (Arif et al. 2011).

Malting has a significant impact on the anti-nutritional factors present in millets. Malting reduced the phytic acid, tannins, and oxalates present in millets. The decreased phytic acid level in malting is due to the utilization of phytate as an inorganic source of phosphate for germination (Rani et al. 2018). The decreased phytic acid level is because of the activation phytase enzyme and leaching out during soaking. Ogbonna et al. (2012) reported that the tannin content decreased on malting and this is due to leaching loss during steeping. According to Rani et al. (2018), the polyphenols and phytic acid content showed a significant reduction from 764.45 mg/100 g to 468.27 mg/100 g and from 833.42 mg/100 g to 449.32 mg/100 g, respectively when subjected to 48 h of malting and was further reduced on 72 h of malting. The decreased levels of polyphenols is because of the elevated polyphenol oxidase activity. This is due to the consequence of hydrolysis of tannin protein and enzyme complex that promotes the elimination of polyphenols and tannins.

Malting also affects the functional and physiochemical properties of millets. The pearl millet flour after malting was found to have significantly higher WAC and OAC compared to the unprocessed flour. This shows that the malted flour has a greater affinity for water which is a result of the breakdown of starch structure

(Adebiyi et al. 2016). The mechanism of oil absorption is based on the oil entrapping and binding with the polar chain of the protein. Greater OAC signifies the existence of free amino acids that has been produced by the breakdown of proteins for the requirement of germination (Bolaji et al. 2014). The bulk density of millets also decreases on malting and this is because of the softening of seeds due to the breakdown of complex molecules into simple ones (Gernah et al. 2011). Malting also increased the swelling capacity of flour which indeed improved the flour functionality. Obadina et al. (2017) reported an improvement in the water solubility index (WSI) of pearl millet as a result of action of amylases and proteases in the crystalline regions that caused the formation of low molecular weight compounds, thereby increasing the hygroscopicity. The swelling power (SP) on the other hand decreased on malting due to the breakdown of nutritional compounds. Investigation on the pasting properties revealed that the final viscosity decreased with the increased malting period when compared to control samples. This is as a consequence of formation of nonpolar structures on starch–protein interaction. Further, it was also described to have occurred as a consequence of amylase enzyme action on the starch granules during germination, making them more receptive and vulnerable to breakdown on mechanical agitation.

10.2.2 Novel and Emerging Methods

10.2.2.1 Extrusion

Extrusion is a modern method of processing, which helps to manufacture excellent cereal-based products in terms of quality, functionality, physical state, and shelf-life. Extrusion is advantageous as it can produce ready-to-eat products with different shapes, sizes, texture, and sensory properties (Sharma and Niranjan 2018).

Extrusion is a high-temperature short-time process, controlled by parameters such as barrel screw speed, temperature, and moisture content, which causes alterations in the characteristics of millets (Table 10.5). On extrusion, the starch molecules present in millets undergo gelatinization, dextrinization and depolymerization (Ramashia et al. 2019). The combined application of pressure, screw speed, and temperature leads to a significant reduction in the levels of carbohydrates due to the breakdown of amylopectin (Chanvrier et al. 2015). It also significantly improved the starch digestibility, as the severe low moisture treatment caused the breakdown of hydrogen bonds and an elevation in extrusion temperature further elevates the digestibility (Dalbhagat et al. 2019). During the extrusion process, the protein structure gets disrupted on the application of high pressure and temperature. Besides, the protein forms a matrix around the starch molecules which resulted in the attenuation of enzyme interaction and thereby reducing the protein solubility (Arribas et al. 2017). It was also revealed that extrusion at low moisture and high temperatures caused dropping of amino acids by the Maillard reaction. Additionally, the extrusion disrupts the protein molecules by mechanical shearing and improves the digestibility of protein. The lipid–protein complex is formed during extrusion at a temperature of 100–200 °C, which decreased the lipid content. Along with this, at high temperature unsaturated fatty acids are oxidized to hydroperoxides (Tumuluru et al. 2013). Apart

Table 10.5 Effect of extrusion process parameters on millets

Millet	Objective	Results	References
Foxtail millet	Production of the extruded products	The temperature of 118 °C and a screw speed of 400 rpm with feed moisture 15.88% produced high-quality products	Kharat et al. (2015)
Finger millet	Effect on phenolics, flavonoids and antioxidant activity	Significant reduction in the TPC, TFC, and antioxidant activity	Patil et al. (2016a, b)
Pearl millet, foxtail millet and finger millet	Extrusion processing characteristics	Expansion ratio: foxtail millet (4.41) > Pearl millet (3.78) > finger millet (3.18); Water absorption index: foxtail millet > finger millet > pearl millet; least specific mechanical energy (SME) for foxtail millet	Kharat et al. (2019)
Finger millet	Effect of processing variables (amylose content, moisture content, screw speed, and barrel temperature) on the functional properties of the flour	Sectional expansion index (SEI) reduced with increase in amylose content; increase in moisture content reduced bulk density of product; Higher temperature and screw speed increased the WSI; increase in temperature caused an increase in resistant starch;	Nishani et al. (2017)

from this, the combined action of high pressure and shear stress causes oil expulsion from the flour and the high temperature applied converts these lipids into liquid oil enhancing its migration (Sandrin et al. 2018). The temperature and screw speed during extrusion also affect the fiber present in millets. Arribas et al. (2017) reported that extrusion caused a significant reduction in the dietary fiber content of gluten-free cereal products. This is as a consequence of the fiber getting embedded in the starch matrix on extrusion and thus reduces the starch–lipid complexion (da Silva et al. 2016).

Kharat et al. (2015) studied the optimization of extrusion processing of foxtail millet and found that at a temperature of 118.23 °C, the moisture level of 15.88%, and the screw speed of 400 rpm affected the nutritional and physicochemical properties of foxtail millet extrudates. It was found that higher expansion ratios (ER), WAC and solubility index, lower bulk density, and hardness have been observed in foxtail millet. Besides, extrusion exhibits more retention time and more thermal energy absorbed, resulting in a subsequent depletion in protein, carbohydrates, fiber, and fat content. More amount of fiber and fat restricts the expansion of extrudates, and protein supports the expansion of extrudates, whereas, fiber and protein reduce the water solubility (Sharma and Niranjan 2018). The extrusion process enhances the absorption of minerals by deactivating anti-nutritional factors such as tannins and phytates. The extrusion also reduced the amount of trypsin inhibitor present in millets. Patil et al. (2016a, b) studied the effect of extrusion processing on the antioxidant activity, total phenolic content (TPC), and total flavonoid content (TFC) of finger millet. It was found that the antioxidant activity, TPC, and TFC decreased significantly on extrusion. But, extrusion at an increased amount of moisture, low temperature, and high speed could help in the retention of bioactive compounds.

The expansion ratio (ER) of extruded millet products is directly related to the process parameters like the screw speed, temperature of extrusion and moisture content of the material. On the other hand, rise in the temperature and water content of feed reduced the bulk density of products (Swapnil Kharat et al. 2019). The water absorption index (WAI) and water solubility index (WSI) of the flour are also affected by the process parameters. WAI is an indication of starch conversion or amount of soluble polysaccharides liberated from starch by gelatinization and starch fragmentation due to extrusion. The increase in temperature resulted in the reduction of WAI and an elevation in the WSI. The reduction in WAI occurs because of the disruption of amylopectin and amylose which resulted in decreased water absorption.

It has been observed that elevated moisture level reduces WSI but boost up the WAI (Swapnil Kharat et al. 2019). During the extrusion process, moisture acts as a plasticizer and reduces the degradation of starch and resulting in an increase of WAI. However, the shearing force on the material decreased at elevated moisture content, which resulted in decreased dextrinization and thus reduces in WSI. The extrusion process leads to remarkable changes in the product color compared to the raw flour. This happens due to several reactions such as the Maillard reaction, caramelization, hydrolysis, and other non-enzymatic reactions occurring on extrusion (Geetha et al. 2014).

10.2.2.2 Microwave Treatment

Microwave cooking is an electro-thermal method of processing in which the electrical energy is converted into thermal energy Microwave lies in the frequency range of 300 MHz to 300 GHz. The commonly used frequencies for food applications are 915 MHz and 2.45 GHz (Gavahian et al. 2019).

The effect of microwave cooking on the properties of millets was studied by many researchers (Table 10.6). Kumar et al. (2020) conducted experiments to investigate changes in the properties of proso and little millet on microwave cooking. The nutritional composition of both the native and microwave treated samples were analyzed. The carbohydrate content of proso millet and little millet increased on microwave cooking. The ash content of proso millet increased from 1.25% to 1.32% on microwave cooking. But, in the case of the little millet, the ash level was found to have reduced significantly from 1.9% to 0.45% and this may be probably due to the leaching while soaking grains before the microwave treatment (Snehal and Neena 2018) and considering the protein level of microwave cooked, the protein content was significantly reduced in comparison with raw sample. However, the protein level of little millet showed increase after microwaving in comparison with the raw sample. This variation may be as a consequence of the nitrogen content changes after undergoing the treatment (Wani et al. 2017). The fat content in both proso and little millet was also reduced on microwave cooking.

Table 10.6 Effect of microwave cooking on millets

Millet	Objective	Results	References
Pearl millet	Effect of microwave treatment minerals, bioaccessibility, and polyphenols	Increase in mineral content; improved bioaccessibility of iron and zinc; decrease in total phenolics	Snehal and Neena (2018)
Proso millet	Effect on physicochemical properties of the starch	Increase in amylose and resistant starch content; increase in WHC and solubility; reduced swelling power; decreased pasting temperature, peak viscosity, final viscosity, setback	Zheng et al. (2020)
Little millet and proso millet	Study the effect of microwave cooking on physicochemical properties	Increase in the protein content; increase in WAI, WSI, WAC, and OAC; de-shaped starch structures	Kumar et al. (2020)
Long GU 25	Study the changes in structure and physicochemical characteristics of starch	A decrease in peak viscosity and swelling power and transparency; increased in vitro enzymatic digestibility; disruption of starch structure	Li et al. (2019)

Zheng et al. (2020) studied the effect of heat treatment (HT), autoclave treatment (AT), and microwave treatment (MT) on the proso millet starch. The amylose content of the proso millet starch was increased from 14.7% in the native sample to 22.1% in the microwave-treated sample. The amount of resistant starch was also profoundly incremented from 11.5% to 18.7%. The water holding capacity (WHC) increased from 132.47% to 197.13%, and this is a result of the gelatinization of starch and also the covalent bonding between hydroxyl group of water and starch molecules, contributing to bound water. Study documented that the solubility of HT, AT, and MT samples were all increased at 60 and 70 °C. But as the temperature increased to 80 °C the solubility reduced significantly and was lower than that of the native samples. The rise in temperature tightens the hydrogen bond and makes the structure more ordered. The swelling power of the starch was found to be decreased upon treatments and this is due to the reorganization of the amylose and amylopectin molecules and additional interaction between them, thus reducing the hydration power. In proso millet, the in vitro digestibility of starch decreased on microwave cooking. This changes may be attributed through different factors like structure of amylopectin, amylose/amylopectin ratio, and starch crystallinity (Ying et al. 2017).

On considering the various physical and functional characteristics of proso millet and little millet after microwaving, there were significant differences in all the properties when compared to the raw millets. The lightness, redness, and yellowness of the microwaved samples were improved after the treatment of both proso and little millet. The improvement in lightness is due to the denaturation of protein and subsequent attachment of fat droplets to it (Sharanagat et al. 2019). Maillard reactions and oxidation of polyphenols on heating is the reason for changes in the yellowness and redness of the samples (Bagheri et al. 2016). The bulk density values of both the millets were reduced after the cooking. It depends on the moisture content of the grain, which is reduced on cooking. The WAC of both the millet flours were observed to have improved considerably after the treatment. The partial protein denaturation and starch gelatinization increase the binding sites in cooked flours. The polar amino acid residues also have a great affinity for water molecules (Wani et al. 2017). OAC also had a significant increase after treatment and this is due to the variations in the nonpolar sides of the protein subunits generated, which interacts with the hydrocarbon side chains of fat. Oil absorption requires entrapping of oil within protein isolates by electrostatic, hydrophobic, and hydrogen bonds (Falade and Christopher 2015). High OAC indicates that the flour enhances the flavor and tastiness in food preparations. The foaming capacity was found to be decreased and this is mainly due to the reduced protein solubility as a result of protein denaturation. Studies on pasting properties revealed that the pasting temperature of proso millet increased significantly from 67 to 94 °C. This change is mainly due to the starch structure and arrangement alteration on heating (Qu et al. 2017). But there was no significant difference observed in the pasting temperature of little millet. The morphological analysis of raw and cooked proso and little millets revealed that raw millets had granular, spherical, and smooth structures, whereas cooked ones showed branched structures that formed an amorphous cohesive mass (Fig. 10.3).

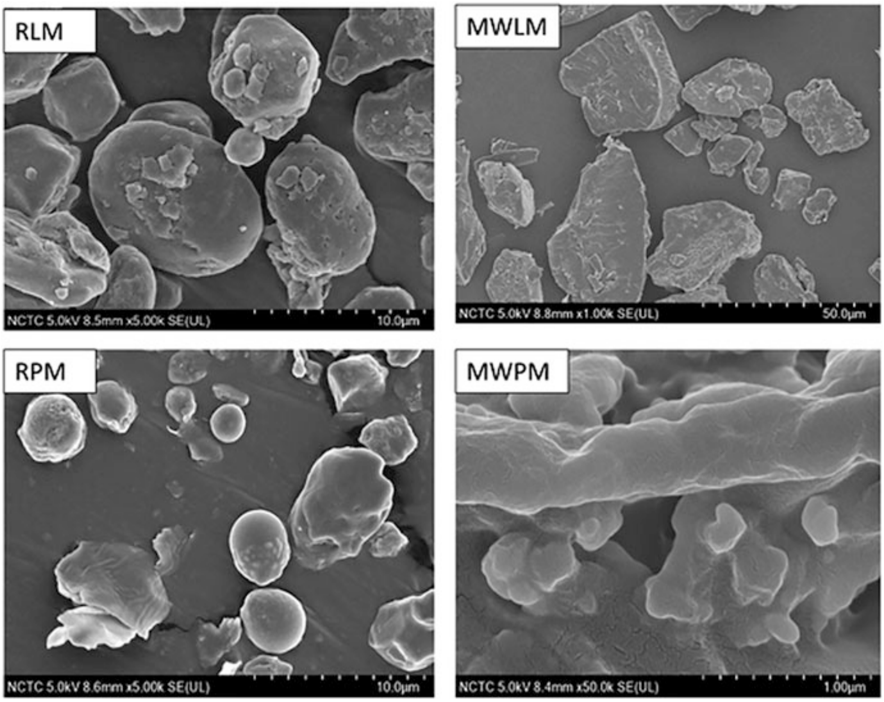

Fig. 10.3 SEM structures of raw little millet (RLM), microwaved little millet (MWLM), raw proso millet (RPM), microwaved proso millet (MWPM). (Adapted from Kumar et al. 2020)

10.3 Conclusion

As a drought-resistant crop, millets act as a good source of carbohydrates and proteins, particularly in regions where scarcity of water, unpredictable climatic changes, and rising prices of food grains are a serious concern. They are the richest source of important nutrients such as dietary fiber and phytochemicals, which have significant health benefits. This chapter discussed the impact of processing on the nutrients and anti-nutrients present as well as on the physicochemical and functional properties of millets. Various processing procedures such as milling, germination, roasting, popping, and fermentation are commonly aided in the processing of millets. Processing helps in upgradation of edible and nutritional characteristics of millets. Processing also helps in the enhancement of the physicochemical accessibility of micronutrients such as minerals, decreases the anti-nutritional factors, and elevates the number of compounds that improve the bioavailability of nutrients. Therefore, suitable processing techniques are necessary for better food security and increasing commercial utilization.

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Emerging Technologies in Millet Processing 11

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Abstract

Increasing demand for meeting the food requirements of future generations with drastic changes in climate, demand for renewable resources, reducing cultivable land area, increasing population, additional health and nutrient requirements and socio-economic changes, related to the ongoing global pandemic of COVID-19, points towards the need for sustainable solutions backed by innovative technologies—providing both an opportunity and challenge to the food scientists around the world. Existing technologies need to be evaluated and gaps identified in order to make them more efficient, for processing and value addition to millets. In addition, novel technologies like air jet milling, use of microbial strains in germination and fermentation, biochemical, nanotechnology, ultrasound and gamma irradiation also need to be leveraged in order to ensure both scientific and commercial benefit to the community, especially to farming communities as well as the consumers. With this background the chapter discusses and focuses on

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the emerging technologies that can be utilised for effective processing of millets. Millets have gained enormous attention recently for their nutrient values, gluten-free alternative, short crop period, ability to grow in adverse climatic conditions and high utility in varied food, nutraceutical and industrial applications (Saleh et al., Compr Rev Food Sci Food Saf 12(3):281–295, 2013). Further, acknowledging (United Nations General Assembly, International Year of Millets 2023, Resolution 75/263, 2021) the historical contribution of millets to food security, nutrition, livelihoods and incomes of family farmers and recognising the urgent need to invigorate market recognition of the benefits of millets and to promote efficient value chains the United Nations General Assembly has declared the year 2023 as the International Year of Millets (United Nations General Assembly, International Year of Millets 2023, 2021).

Keywords

Millets · Primary processing · Decortication · Secondary processing · Germination and malting · Fermentation · Popping/puffing · Enzymatic hydrolysis · Biochemical · Nanotechnologies · Gamma irradiation

11.1 Background

Increasing demand for meeting the food requirements of future generations with drastic changes in climate, demand for renewable resources, reducing cultivation land area, increasing population, additional health and nutrient requirements and socio-economic changes, related to the ongoing global pandemic of COVID-19, points towards the need for sustainable solutions backed by innovative technologies providing both an opportunity and challenge to the food scientists around the world. Millets are small seeds and are of different varieties such as pearl millet (*Pennisetum glaucum*), finger millet (*Eleusine coracana*), kodo millet (*Paspalum setaceum*), proso millet (*Penicum miliaceum*), foxtail millet (*Setaria italic*), little millet (*Panicum sumatrense*) and barnyard millet (*Echinochloa utilis*). Millet grains like any other cereal needs to be processed for human consumption. Traditional primary processing methods, at farm and household level, include hand pounding to remove outer bran and further cleaning to remove dirt and impurities. These methods are labour-intensive, time-consuming and are inefficient. Presently, secondary processing of millets, includes use of machinery meant for processing of wheat, corn or rice for size reduction. In addition, food processing technologies like malting, soaking, roasting and optimised cooking to improve nutritional properties are used for value addition to millets. Low yield, insufficient bioaccessibility/bioavalibility of micronutrients and lack of standardised processing equipment and methods limit utilisation of millets in industrial processing (Saleh et al. 2013). Hence, this chapter explores technologies that can cover the gaps in traditional processing, along with the exploring the potential of different novel technologies that can promote higher consumer acceptability and enhance the utilisation of millets across the globe, in foods, nutraceuticals, medicine, renewable energy and other industrial applications.

11.2 Innovations in Primary Processing

Primary processing generally includes cleaning, sorting, grading and dehulling/decortication of millets, undertaken to prepare them for the next stage of usage, marketing as quality graded commodity, ingredient for use in preparation of different value added products such as flour and flour mixes, instant porridge mixes, bakery and confectionery products, Indian flat bread (roti), traditional snacks, sweets and beverages etc.

11.2.1 Decortication

Decortication means the process of removal of the top fibre seed coat/hull or removal of bran of cereal grains. It is also known as debranning or dehulling. Traditional methods involve hand pounding of the grains at the field level, which often does not yield complete removal of the seed/hull. In millets there is no hull but the outer covering is part of the endosperm. In case of sorghum and pearl millet which are "naked" caryopses and do not have a hull "dehulling" actually involves removal of the pericarp layers. Seed coat is firmly attached to the grain, pre-processing treatment like hydrothermal processing and nixtamalization seems to address the issue of improper removal of bran which gives better yield, ease of removal of husk and improvement of nutritional characteristics.

11.2.1.1 Hydrothermal Processing

Hydrothermal processing is the moisturising of the grains with water to get the desired moisture content. With a set temperature and time, the grains are then spread and steamed. These millet grains are then brought to a moisture content of $14 \pm 1\%$ by drying them in a dryer. The grains are then decorticated in carborundum disc mill (Dharmaraj et al. 2013). With this conditioning, grains are hardened and the texture of endosperm gets hardened enabling easy decortication of the grains, with good efficiency. This also enables the easy gelatinisation of starch in the grains when compared to untreated grains.

From Table 11.1 it is evident that hydrothermally treated millet has more hardness compared to untreated and decorticated millet. Improved solubility at all temperatures is observed in case of decorticated finger millet. Swelling power increased with increasing temperature. Swelling power was more at higher temperatures (95 °C) for untreated, hydrothermally treated and decorticated finger millet. The gelatinisation temperatures were found to be 72.7 °C, 81.0 °C and 68.0 °C for untreated, hydrothermally treated, and decorticated millet grains, respectively. Cold paste viscosity (10% slurry), which is not shown in the untreated millet, is found to increase with hydrothermal treatment as well as on decortication;

Table 11.1 Functional and physical characteristics of untreated finger millet, hydrothermally processed finger millet and decorticated finger millet

Property	Untreated finger millet	Hydrothermally treated finger millet	Decorticated finger millet
Textural parameters			
Hardness (N)	38 ± 8.60	235 ± 8.10	161 ± 5.00
First peak force (N)	14 ± 4.10	40 ± 7.10	34 ± 7.60
Solubility (g%)			
30 °C	1.0 ± 0.31	1.6 ± 0.30	2.9 ± 0.32
95 °C	1.5 ± 0.40	3.3 ± 0.21	3.5 ± 0.12
Swelling (g%)			
30 °C	85 ± 1.00	299 ± 2.10	306 ± 2.30
95 °C	505 ± 2.20	494 ± 2.00	496 ± 2.10
Viscosity 10% slurry (cPs)			
Cold paste	–	11 ± 1.00	22 ± 1.10
Cooked paste	1717 ± 5.20	350 ± 3.20	463 ± 2.00
Pasting profile			
Peak viscosity (BU)	453 ± 4.20	84 ± 3.50	152 ± 2.80
Hot paste viscosity (BU)	390 ± 4.20	84 ± 3.50	152 ± 2.80
Cold paste viscosity (BU)	576 ± 4.20	116 ± 4.20	171 ± 2.80
Gelatinisation temperature (°C)	72.7 ± 0.28	81.0 ± 0.42	68.0 ± 0.14

Source: Dharmaraj et al. (2015)

decortication showed doubling of cold paste viscosity as compared to hydrothermally treated millets. However, cooked paste viscosity of the untreated millet sample was greater than that of hydrothermally treated and decorticated millet samples. The pre-gelatinisation of starch after hydrothermal treatment may be the cause for the reduction in cooked paste viscosity. Pasting properties of untreated millet elucidated in the study, was similar to that reported for any other cereals. The break down in viscosity was 63 BU, set back viscosity was 173 BU and the total set back was 186 BU. The setback value of the starch paste is defined as the difference between the hot paste viscosity and cold paste viscosity. Cooling of starch leads to increase in paste viscosity (setback viscosity), also called retrogradation.

11.2.1.2 Nixtamalization

Nixtamalization is a process in which grains such as maize (Billeb de Sinibaldi and Bressani 2001) are processed by soaking in alkaline solution, like calcium hydroxide (lime) solution, followed by rinsing with water and dehulling. In summary, it involves the removal of outer pericarp through alkaline processing. With incorporation of this processing step the grains are more easily milled resulting in increase in nutritional profile, improved aroma and flavour and decrease in

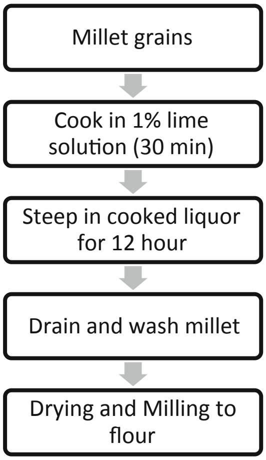

Fig. 11.1 Flowchart for nixtamalization of millets

mycotoxins. The alkalinity of lime cooking helps in the solubilising of hemicellulose and cell walls, resulting in loosening and softening of the hulls from the kernels. However, in the case of sorghum, millets and little millets, there is also difference in grain structure. Some species like sorghum, pearl millet and teff are referred to as naked kernels as the edible grain does not contain hull. In others, for example, finger millet, foxtail millet, and proso millet, the "hull" is loose and can be relatively easily removed, whereas in fonio, the husk is tightly attached. (Taylor and Duodu 2018). To obtain similar advantages of nixtamalization for millets, the processes is now being applied to millets (Owusu-Kwarteng and Akabanda 2013), and have proven to be successfully accepted by consumers in addition to improved crude protein, ash content and superior functional properties of their flours. Results (Ocheme et al. 2010) showed that cooking millets in lime solution followed by drying and milling into flour resulted in flours with comparatively higher ash, water absorption capacity, protein, crude fibre, pH, hygroscopicity, emulsion capacity and stability and swelling power as compared to untreated flour. Results also showed that the treated flour had lower oil absorption capacity, fat, trypsin inhibitor, tannin and hydrogen cyanide than flours from untreated millet. The flow-diagram (Fig. 11.1) represents the process of nixtamalization using millets.

The studies undertaken on the effects of nixtamalization (Ocheme et al. 2010) on pearl millets grains showed that protein, ash and crude fibre increased in the nixtamalization millet flour. Table 11.2 gives an insight into the comparison of proximate values between flour from untreated millet grains (UMF), water soaked millet flour (WSMF), lime solution soaked millet flour (LSMF), water cooked millet flour (WCMF) and lime solution cooked millet flour (LCMF).

In another study (Owusu-Kwarteng and Akabanda 2013) sensory evaluation using a 5-point scale on Maasa (millet-based fermented food) prepared with nixtamalized pearl millet showed higher overall acceptability in terms of odour, colour and texture, thus showing the potential of using of nixtamalization processing in varied food preparations, using millets.

Table 11.2 Pearl millet flours (untreated millet grains (UMF), water soaked millet flour (WSMF), lime solution soaked millet flour (LSMF), water cooked millet flour (WCMF) and lime solution cooked millet flour (LCMF)) proximate composition

Parameters[a]	UMF	WSMF	LSMF	WCMF	LCMF
Protein	12.40 ± 0.47	13.00 ± 0.65	11.57 ± 0.43	11.87 ± 0.67	14.57 ± 0.33
Ash	1.12 ± 0.00	1.38 ± 0.00	1.52 ± 0.00	1.67 ± 0.00	3.23 ± 0.03
Crude fibre	4.05 ± 0.12	4.35 ± 0.12	4.15 ± 0.02	4.81 ± 0.03	6.23 ± 0.31
Carbohydrate	76.55 ± 0.98	73.81 ± 0.87	77.14 ± 0.54	74.73 ± 0.34	71.95 ± 0.33
Dry matter	93.75 ± 2.27	90.21 ± 1.72	90.00 ± 1.00	89.60 ± 1.40	89.51 ± 1.49
Fat	5.88 ± 0.21	7.43 ± 0.11	5.63 ± 0.00	6.92 ± 0.32	4.02 ± 0.21

Source: Ocheme et al. (2010)

[a] Values on dry weight basis (in %)

The potential of the above-disussed primary processing technologies, with the aim towards promoting commercial production of millet based foods, by bridging the technological gaps and improving the efficiency of existing indegenious methods of primary processing of millets, needs to be leveraged.

11.3 Secondary Processing

The secondary processing of millets involves value addition such as milling and sieving the millet grain into flours, germination or malting, fermentation and enzymatic hydrolyzation, roasting/popping or puffing of millets, utilisation as a source of biofuels, extraction/preparation of novel nano-biochemical compounds and use in nanotechnologies. Many of the processes have been long used and are still in practice. With major changes in lifestyle and human health, increasing demand for new ingredients from millets and evolving consumer needs, each of the secondary processes has been further modified to produce nutritious, healthy and innovative millet-based products, thus leading to new emerging innovations.

11.3.1 Milling and Sieving

Milling is the process of size reduction of cereal grains into fine flour. Presently, milling of millets is done by adoption of both wheat and rice milling technologies. Traditional mills use plate mills, roll mills (shear and crushing) and hammer mills (impact and pulverisation) working on principles of abrasion. These milling techniques are still in practice in small-scale units. These milling techniques (Ebunilo et al. 2010) that are used in the processing of grains have a number of drawbacks that greatly affect their efficiency, when milling millets. The main drawbacks of conventional milling techniques are:

1. Fine particle size of lesser than 400 μm is not produced.
2. Moisture of raw material can decrease the milling efficiency.
3. Operating area of mills are usually scattered with dust/flour particles including the surroundings, leading to effects on respiratory system of human operators and causes surrounding environmental pollution.

The section below discusses on the different innovations and improvements to the various milling techniques, to overcome the above-mentioned drawbacks.

11.3.1.1 Innovation in Hammer Milling Technique with End Suction Lift

Hammer mill being the most commonly used, a number of trials have been undertaken (Ebunilo et al. 2010) to address the problems as described in Table 11.3. The results of the trials showed that a hammer mill with an end suction lift was able to operate continuously without clogging. It increased milling percentage and particle size lower than 400 μm was produced, which are suitable for

Table 11.3 Problems associated with conventional flour mills and potential solutions for improvement of conventional mills

S. No.	Problems	Solutions
1	Sieve screen openings can get corroded and enlarge due to stress leading to the passing of flour with a size larger than desired.	Screens needs to be eliminated. Endless sieve, which is a dimensionally controlled "open gate", needs to be introduced.
	Similarly, screen holes are blocked due to flour adhering at the holes leading to reduced efficiency and capacity.	
2	Impact energy of hammer mill is absorbed by wet materials which are elastic in nature and results in less efficiency of mill.	Instant drying and forced convection can be induced, by introducing a fan.
3	Large broken particles are not collected properly due to gap between hammers and screen.	Solution 2 eliminates problem 3 as fan will air-lift particles of sufficient sizes.
5	Materials once crushed cannot be blown back until they reach the required size.	A mechanical separator that rotates at a rate equal to the shaft ensures that oversized particles are recirculated back into the hammer mill chamber until they are finely milled.
6	Nearly 5–10% of raw material escapes into atmosphere causing health hazard to humans working and polluting the surrounding.	At the point of dust generation, a large sedimentation chamber with long tubes should be installed.

Source: Ebunilo et al. (2010)

producing composite and basic flours used in various food preparations. The design (hammer mill with end suction lift capability) included removing the sieves, and introducing a mechanism to ensure that large particles are blown back again (using mechanical separators) for efficient milling. To avoid flour/dust particles from escaping into the surroundings sedimentation chambers are provided.

Briefly, the operating concept of hammer mill with end suction lift is: The cereal grain is introduced into the feed hopper of hammer mill. Unidirectional flow of raw materials to milling chamber is observed in the feed hopper. Milling chamber consists of hammers which pulverise the material to the desired particle size with help of mechanical separators, which rotate at the same speed as the shaft. The fan induces air/particle mixtures which are vented through the two ducts provided overhead. The two ducts are designed to increase the movement of the dust carrying air which reduce the sedimentation of the particles in the ducts. The velocity of particles is reduced as air from the overhead vents passes through cyclone. The fine particles fall and are collected and bagged.

11.3.1.2 Air Jet Milling

Air jet milling can be an alternate process to achieve desired particle size reduction of millet flours (Protonotariou et al. 2014). With diminishing particle size there is more surface area available, which greatly affects the physiochemical properties of flour. Air jet milling works on the principle of fluid energy impact milling technique, which enables it to create particle sizes no more than 40 μm. With this method a final particle size of around 1000 nm can be produced depending upon the material being processed. Materials are accelerated to high velocity air which produces superfine powders; inter-particle impact or collisions lead to the size reduction.

Starch hydrolysis kinetics are enhanced (Angelidis et al. 2016) due to small particle size which have higher surface-to-volume ratio. This higher surface-to-volume ratio increases high surface interaction of enzymes throughout the particles. With enhanced surface area of the flour particles, the water absorption capacity of the flour is increased and good solubility is obtained. Air jet milling successfully produces starch-rich fine flours with improved separation of starch from protein. Lower gelatinisation enthalpy was recorded by differential scanning calorimetry for doughs with fine flour particles than from dough made with coarse particle size.

Thus, air jet milling seems to be a promising milling technology that needs to be explored more to gain benefits from it for milling of millets, especially to obtain millet flours with improved physicochemical and functional properties. Further research can prove its potential application in producing diversified foods from millet flours with fine particles.

11.3.2 Innovations in Germination or Malting of Millets

Germination is a biochemical process (Chauhan and Sarita 2018) where the seeds are transitioning from passive/dormant state to active state. The process increases the nutritive value of the grains with reduction in anti-nutrients and enhanced bioavalibility of nutrients. Malting (Baranwal 2018) involves steeping, germination and drying. During the steeping process, grains are soaked in water until sufficient water is taken up by kernel to start the metabolic processes of germination. Germination is carried out in controlled conditions: temperature (25–30 °C), moisture content and germination period (2–6 days). After germination, drying (kilning) is the last stage of the malting process where the moisture content and water activity of grains are reduced giving a shelf-stable product with active enzymes and enhanced nutritional traits. The grains can be powdered into fine flour to obtain highly nutritious malted flour. Drying temperatures are between 50 and 60 °C for about 24 h or higher depending upon the mode of drying used.

Various studies on effects of different time parameters for soaking, germination and kilning temperatures have been studied. Characteristics and bioaccessibility have varied depending upon the varieties of millets, soaking time, germination time and kilning time and drying temperatures.

In a study done on pearl millet (Suma and Urooj 2014) (two varieties Kalukombu and Maharashtra rabi bajra) for bioaccessible iron and calcium, where grains were soaked overnight and left for germination for 72 h followed by kilning in oven at 50 °C and then milling, showed higher bioaccessibility of iron and calcium than raw grains. Germination resulted in a significant reduction of phytate and oxalate values. A number of research studies showed that germination for varying period changes

Table 11.4 In vitro extractability (in %) of calcium, iron and zinc in finger millet during processing by the HCl-pepsin (HCl-P) and pepsin-pancreatin (P-P) method

	Finger millet (HCl-P)		Finger millet (P-P)	
Process	Mean	Standard deviation	Mean	Standard deviation
Calcium (%)				
Unprocessed	70.87	0.23	38.02	1.19
Soaked	75.02	0.25	50.62	1.81
Germinated	95.70	0.55	67.08	0.93
Autoclaved	96.14	0.61	74.98	0.57
Fermented	97.58	0.71	82.00	0.72
Iron (%)				
Unprocessed	5.06	0.18	4.49	0.22
Soaked	6.01	0.10	5.88	0.49
Germinated	29.91	1.82	10.57	0.81
Autoclaved	42.99	0.90	4.40	0.33
Fermented	51.98	1.35	4.98	0.05
Zinc (%)				
Unprocessed	50.60	0.24	30.24	1.59
Soaked	54.16	0.50	33.94	1.03
Germinated	78.41	0.58	39.20	1.30
Autoclaved	76.01	1.31	47.34	0.92
Fermented	81.93	0.37	51.12	0.66

Source: Mamiro et al. (2001)

values of available minerals and vitamins. The different malting parameters including germination period can be optimised to obtain maximum/required bioaccessibility.

Effect of combining malting and fermentation on Finger millet (*Eleusine coracana*) has also been studied (Mamiro et al. 2001). The processes included soaking, germination, autoclaving and fermentation. In vitro HCl-Pepsin and Pepsin-Pancreatin methods were used after each processing step to determine the extractability of zinc, calcium and iron. In vitro extractability increased for: calcium (in the order of fermented, autoclaved, germinated and soaked for both HCl-PP and P-P methods), iron (in the order of fermented, autoclaved and germinated for HCL-P method and in case of P-P method, significant increase was noted only in germinated) and zinc (in the order of fermented, germinted and autoclaved for HCl-P method and in case of P-P method, extractability was increased in the order of fermented and autoclaved) (Table 11.4).

Malting is reported to reduce (by up to 43%) the assayable levels of sorghum tannins (Osuntogun et al. 1989). In another study (Beta et al. 2001), effectiveness of steeping a high-tannin and a non-tannin sorghum in HCl (0.25 M), formaldehyde (0.017 M) or NaOH (0.075 M) for 8 and 24 h before germination for 2 and 5 days, was evaluated. All treatments decreased the polyphenol content as compared to unprocessed grain. Treatments with NaOH or formaldehyde gave better results than treatment with water or HCl. The diastatic power of the high-tannin sorghum malt

Table 11.5 Chemical composition of instant "Fura" powders as affected by germination and fermentation

Sample[a]	Calcium (mg)	Iron (mg)	Phosphorous (mg)	Phytic acid (mg)	pH (%)	Titratable acidity (%)
GGF	1.69	4.77	17.55	220.00	4.50	0.25
GF	1.69	4.48	16.54	230.00	5.64	0.22
FF	1.61	3.45	7.30	1.87	2.35	83.20
TF	1.21	3.34	715.81	416.00	5.86	0.20

Source: Inyang and Zakari (2008)

[a] *GFF* germinated and fermented Fura, *GF* germinated Fura, *FF* fermented Fura, *TF* traditional Fura

was markedly enhanced by the NaOH and formaldehyde treatments. The studies show that steeping in dilute NaOH was most effective in reducing the tannin content in high-tannin sorghums and resulted in superior quality malt.

Innovations in the germination process, towards enhancing the nutritional and functional properties of millets, involve combining the process of fermentation and with special focus on probiotic fermentation. The section below discusses these innovations.

11.3.2.1 Germination and Fermentation

Recent development processes and studies involved using germination and fermentation as alternative to traditional germination and malting processes to obtain maximum benefits from the millet grains. Nutritional and sensory evaluation of "Fura" (a Nigerian cereal food) was conducted (Inyang and Zakari 2008) using germination (soaked for 12 h and sprouted for 48 h) followed by natural fermentation (for 48 h at room temperature) of pearl millet grains, which resulted in significant reduction in phytic acid levels compared with the control. The phytic acid levels noted were 416 mg/100 g for the control TF (traditional Fura), 230 mg/100 g for GF (germinated Fura), 266 mg/100 g for FF (fermented Fura), and 220 mg/100 g for GFF (germinated and fermented) Fura. Table 11.5 shows that germination improved the nutrient content of Fura and even further in association with fermentation. Fura with reduced phytic acid content (enhanced bioavailability) content was obtained for GFF treatment.

In another study (Sripriya et al. 1997), finger millet variety CO 13 (brown variety) was soaked (12 h at 30 °C), germinated (24 h at 30 °C) and ground in a blender. The slurry was allowed to ferment naturally for 48 h, dehydrated at 65 °C. The dehydrated mass was ground to flour. This flour was subjected to studies to determine differences in carbohydrate, free amino acids, organic acids, phytate and HCl extractability of minerals (Table 11.6) during germination and fermentation.

Results showed that germination alone causes less biochemical changes than germination followed by fermentation. Germination was effective in promoting protein and starch hydrolysis, while fermentation was more effective in reducing phytate and pH. Fermentation also increased the free sugars, amino acids and mineral bioavailability.

Table 11.6 Finger millet sprouts HCl-extractability of minerals (%) during a process involving combination of germination (24 h) and fermentation (up to 48 h) of the germinated slurry at different time intervals

Sample	Minerals (%)					
	Calcium	Phosphorous	Iron	Zinc	Copper	Manganese
Unprocessed	47.6 ± 1.2	17.8 ± 0.8	5.9 ± 0.8	57.2 ± 2.6	58.7 ± 4.7	119.3 ± 0.6
Sprouted (24 h)	53.0 ± 0.9	20.0 ± 2.0	8.6 ± 0.0	70.4 ± 2.5	82.9 ± 0.0	131.1 ± 7.0
Fermented						
6 h	56.6 ± 0.9	28.0 ± 0.2	13.4 ± 1.4	73.8 ± 2.1	96.8 ± 1.9	142.8 ± 4.3
12 h	60.8 ± 1.3	29.0 ± 0.4	18.2 ± 1.3	77.8 ± 8	97.3 ± 7.5	142.6 ± 5.2
18 h	66.7 ± 1.5	36.6 ± 1.5	22.8 ± 1.5	76.3 ± 3.8	121.0 ± 10.7	161.9 ± 2.2
24 h	65.7 ± 0.6	38.8 ± 2.4	23.5 ± 1.5	71.5 ± 1.8	114.5 ± 4.7	161.2 ± 3.1
36 h	64.0 ± 0.7	36.4 ± 1.1	24.1 ± 0.2	76.8 ± 7.2	113.1 ± 1.9	151.6 ± 4.0
48 h	60.6 ± 1.5	37.8 ± 2.3	21.4 ± 8	77.4 ± 2.3	114.5 ± 8.9	144.4 ± 5.0

Source: Sripriya et al. (1997)

Work on two pearl millet cultivars (Gazira and Gadarif) were undertaken to see the effects of different processing methods (Eltayeb et al. 2007), followed by fermentation for 12 and 24 h. The different processing methods included pearling or debranning, soaking, grinding, autoclaving and germinating. Phytic acid contents were determined, which are shown in Table 11.7. The results show decrease in phytate content after processing for both cultivars. Significant decrease was observed in grains that were germinated prior to fermentation.

11.3.2.2 Germination and Probiotic Fermentation

The grains are germinated and fermented with probiotic strains of interest to obtain additional nutritional benefits, unlike traditional methods of fermentation with naturally present grain slurry microbes. The additional step (Jood et al. 2012) of germination and probiotic fermentation have shown to have additional advantages. In sorghum the process resulted in enhancement of nutritional quality, leading to additional health benefitting properties. Several comparisons have been carried out involving varying factors to see the outcome of germination and probiotic fermentation. Two types of food combinations were created with raw and germinated (soaked for 12 h at room temperature, sprouted for 24 h at 37 °C and dehydrated at 55–60 °C) sorghum flour along with tomato pulp and whey powder in 2:1:1 proportion (w/w). These combinations were fermented at 37 °C for 12 h with *Lactobacillus acidophilus* curd containing 10^6 cells/mL after mixing with water, autoclaving and cooling. The analysed results of β-glucan, thiamine, riboflavin and niacin content are shown in Table 11.8. From the data it is evident that using germination food combination along with probiotic fermentation results in increased values of thiamine, riboflavin and niacin content, as compared to using non-germinated food combination.

Studies undertaken (Kunchala et al. 2016) indicate the potential of selected probiotic bacteria isolated from flour and batter samples of sorghum and pearl millet, to be used in production of new probiotic foods. A total of five different selective media including plate count agar, yeast glucose chloramphenicol agar, Bifidobacterium agar, Actinomycetes isolation agar and de ManRogosa and Sharpe agar were utilised in the study to isolate the bacteria, and the isolates were maintained on the respective media slants at 4 °C for further analysis. The bacteria were characterised for different attributes: Gram staining, morphology (colour, size, shape, elevation, margin, form and surface), biochemistry (urease, catalase, oxidase, hydrogen sulphide, nitrogen reduction, gelatin, liquefaction, starch hydrolysis and carbohydrate utilisation), IMViC tests (indole, methyl red, Voges Proskauer and citrate utilisation), probiotic potentials [acid (pH 2, 3), bile (0.5%), NaCl (6% and 9%)], phenol tolerance [0.4%], antibiotic tolerance (tetracycline, streptomycin, kanamycin, chloramphenicol, ciprofloxacin, ampicillin, penicillin, erythromycin and vancomycin) and antimicrobial activity against human pathogens (*Escherichia coli*, *Staphylococcus aureus* and *Salmonella typhi*). Finally, nine probiotic bacterial isolates were identified based on the above-mentioned attributes. The sequences of 16s rDNA gene of these nine isolates were found to match with *Bacillus subtilis* (two isolates), *Bacillus cereus* (three isolates), *Bacillus pumilus* (one isolate), *Bacillus amyloliquefaciens* (one isolate), *Sphingobacterium thalpophilum* (one isolate) and

Table 11.7 Phytic acid (mg/100 g) content affected by processing followed by fermentation in two different pearl millet cultivars

	Phytic acid (mg/100 g) in cultivars					
	Gazira			Gadarif		
	Time of fermentation (h)			Time of fermentation (h)		
Treatment	0	12	24	0	12	24
Finely ground	987.19 ± 0.00	393.19 ± 1.89	341.92 ± 0.00	952.51 ± 7.72	578.27 ± 0.00	456.10 ± 7.46
Coarse ground	604.67 ± 6.41	196.99 ± 0.00	163.95 ± 6.11	714.63 ± 0.90	348.95 ± 9.38	195.57 ± 5.29
Soaked	597.50 ± 0.00	226.08 ± 0.00	138.31 ± 4.70	722.20 ± 0.00	549.49 ± 0.00	421.07 ± 0.00
Autoclaved	363.27 ± 0.00	153.32 ± 0.49	102.35 ± 0.00	338.21 ± 1.58	158.61 ± 0.00	105.25 ± 1.15
Germinated	327.50 ± 0.42	175.50 ± 0.00	111.10 ± 0.00	329.20 ± 1.67	165.41 ± 1.91	108.79 ± 0.43
Debranned	400.47 ± 0.00	209.36 ± 1.51	109.51 ± 1.51	401.76 ± 5.09	208.14 ± 1.81	136.41 ± 0.00

Source: Eltayeb et al. (2007)

Table 11.8 Effect of germination and probiotic fermentation on β-glucan, thiamine, riboflavin and niacin contents of sorghum-based food combinations (g/100 g, on dry matter basis)

Type of food mixture	β-glucan			Thiamine (mg/100 g)	Riboflavin (mg/100 g)	Niacin (mg/100 g)
	Soluble	Insoluble	Total			
Non-germinated						
Unprocessed (control)	3.14 ± 0.02	2.18 ± 0.04	5.32 ± 0.06	0.15 ± 0.02	0.06±0.01	1.71±0.04
Autoclaved	4.01 ± 0.06	0.74 ± 0.02	4.75 ± 0.08	0.14 ± 0.02	0.05±0.01	1.69±0.02
Autoclaved + fermented	3.10 ± 0.06	1.10 ± 0.05	4.20 ± 0.02	0.23 ± 0.07	0.10±0.01	2.20±0.02
Germinated						
Unprocessed (control)	2.56 ± 0.05	1.45 ± 0.10	4.01	0.34 ± 0.01	0.19±0.01	2.84±0.05
Autoclaved	3.21 ± 0.04	0.51 ± 0.03	3.72 ± 7.23	0.33 ± 0.02	0.17±0.01	2.82±0.01
Autoclaved + fermented	1.02 ± 0.08	0.22 ± 0.02	1.24 ± 0.69	0.51 ± 0.02	0.32±0.01	3.10±0.02

Source: Jood et al. (2012)

Brevibacterium sp. (one isolate) in BLAST analysis. The NCBI accession numbers of these isolates are presented in Table 11.9.

11.3.3 Fermentation

The process of conversion of carbohydrates (sugars) to simpler compounds or alcohols (ethanol) in anaerobic conditions using yeast or bacteria is called fermentation. Traditional fermentation (24 h) effects (Osman 2011) of pearl millet flour on the phytic acid, tannin, proximate composition, amino acids and soluble sugars were studied. No significant changes were seen in protein and lipid contents. Soluble sugars content significantly increased with parallel decrease in complex carbohydrates.

Study on antioxidant content of pearl millet rabadi (traditional Indian fermented drink from pearl millet and butter milk) (Gupta and Nagar 2010) made with different processes and utensil used were determined, which revealed fermentation at 16 h improved flavonoids content. Crude protein was improved in pearl millet rabadi made in steel and clay pot at 16-h fermentation in fermented-cooked-fermented rabadi. High protein was seen in steel pot rabadi cooked with fermented-cooked-fermented method, while better ash and quercetin content was observed in earthen pot rabadi cooked similarly. Fermented-cooked-fermented rabadi in steel pot showed high likeliness while least liked was fermented-cooked in earthen pot, in sensory evaluations.

In a study (Elyas et al. 2002) Composite Population III and Baladi (pearl millet cultivars) fermented at ambient temperature (30 ± 2 °C) naturally for a period of 36 h. After every 4 h, parameters like moisture content, pH, protein, total polyphenols, tannin, IVPD (in vitro protein digestibility) and phytic acid content were determined. Phytic acid and total polyphenols were reduced, while not much change was observed in tannin content at 36-h fermentation.

11.3.3.1 Fermentation with Microbial Strains

Use of millets as functional ingredients can diversify utilisation of millets. Fermentation with desired strains can help in improving the desirable functional traits, like improved dietary fibre. Study (Chu et al. 2019) showed that millet bran which was fermented with *Bacillus natto* enhanced soluble dietary fibre content from 2.3% to 13.2%. Structural and functional characteristics of dietary fibre were improved significantly along with properties like water and oil holding capacity, glucose adsorption capacity and swelling capacity. Increase in total phenolic profile and 2,2-diphenyl-1-picrylhydrazyl (*DPPH*) free radical scavenging capacity was also observed.

The bioaccessibility (Chandrasekara and Shahidi 2012) of phenolic compounds from five different millets (kodo, finger, proso, foxtail and pearl) was assessed. The millets were dehulled and cooked and treated using in vitro enzymatic digestion and microbial (colonic) fermentation under physiological conditions. Total phenolic content (TPC) at the end of intestinal digestion ranged from 12.7 to 35.4 μmol

Table 11.9 NCBI accession numbers, identity and probiotic properties of the nine probiotic bacteria isolated from flour and batter samples of sorghum and pearl millet

Isolate	Bile tolerance (%)	Acid tolerance (pH)	NaCl tolerance (%)	Phenol tolerance	Identified isolate	Accession number
PHFB-22	0.3	2	9	0.2%	*Bacillus subtilis*	-
PHFF-11	0.5	3	6	0.2%	*Bacillus cereus*	KM624626
S6SF-44	0.3	2	3	Nil	*Bacillus amyloliquefaciens*	KM624628
S8CF-32	0.5	2	9	Nil	*Bacillus subtilis*	KM624629
S8SF-4	0.5	2	3	Nil	*Spingobacterium thalpophilum*	KP326566
SKSB-14	0.3	3	3	Nil	*Brevibacterium* sp.	KM817772
SKSB-55	0.3	3	6	Nil	*Bacillus cereus*	KM658265
SKSF-7	0.3	2	6	Nil	*Bacillus cereus*	KM658262
SKSF-8	0.3	3	9	Nil	*Bacillus pumilus*	KM658263

Source: Kunchala et al. (2016)

ferulic acid equivalents per gram of grain, on a dry weight basis. Similarly, TPC at the end of colonic fermentation ranged from 21.2 to 47.4 μmol ferulic acid equivalents per gram of grain, on dry weight basis. Significant antioxidant activity was shown in case of all five millet varieties. Colonic fermentation was found to release the phenolics bound to the insoluble fibre in the grain.

In a study (Sharma and Kapoor 1996), pearl millet grains were treated with different methods like fine and coarse grinding, debranning, soaking, germination, dry heat treatment and autoclaving followed by fermentation. Fermentation at 30 °C for 48 h was done with *Lactobacillus acidophilus* and *Rhodotorula* being isolated from naturally fermented pearl millet and *Lactobacillus acidophilus*, *Candida utilis* and natural fermentation as inoculum using freshly ground pearl millet flour. Protein and starch digestibility improved in all processing treatments except for coarse grinding. As compared to pure culture, significant increase in protein and starch digestibility was seen in combination of *Lactobacilli* and yeast fermentation.

11.3.4 Use of Enzymatic Hydrolysis Technology for Value Addition of Millets

Acid hydrolysis is now majorly replaced by enzymatic hydrolysis due to its effectiveness, ease of process control, and most importantly is eco-friendly (does not produce any harmful contaminants). A study on (Felix 2020), production of malt-based sugar syrup by enzymatic hydrolysis of malted sorghum and millet grains (Pearl millet) were carried out. Malt-based syrups are produced by three stages which involve malt production (steeping for 50 h, sprouting for 5 days at room temperature and kilning for 48 h), wort preparation and use of external glucoamylase enzyme for further saccharification of wort. Table 11.10 shows the physiochemical properties of the resulting syrups.

Another study on (Zainab et al. 2010), investigation of glucose syrup prepared by the enzymatic hydrolysis of starch from maize, millet (pearl millet) and sorghum was undertaken at laboratory scale. The starches were extracted by steeping the grains for

Table 11.10 Physiochemical properties of enzymatically hydrolysed syrups from sorghum and pearl millet

Parameter	Syrup sample Sorghum	Syrup sample Pearl millet
Ash content (%)	0.02 ± 0.003	0.04 ± 0.003
Degree baume (°˜Be)	43.00 ± 0.13	43.00 ± 0.10
Total reducing sugar (glucose %)	70.30 ± 0.26	65.45 ± 0.37
Moisture (%)	12.35 ± 0.13	13.46 ± 0.25
Total solids (%)	82.20 ± 0.10	80.21 ± 0.12
Dextrose equivalent	85.52 ± 0.26	81.60 ± 0.30
pH	4.5 ± 1.20	5.0 ± 1.40

Source: Felix (2020)

72 h followed by purification using sedimentation method. The highest starch yield was observed in maize 86.71% (4.34 ± 0.37 g) then the starch extracted from millet followed by sorghum with a yield of 65.94% (3.30 ± 0.25 g) and 64.71% (3.23 ± 0.09 g), respectively. The extracted starches were converted to Glucose using pure amyloglucosidase from *Rhizopus* mold. The yields of glucose obtained from maize, millet and sorghum were 17.15 ± 0.10 mg/mL, 15.79 ± 0.20 mg/mL and 11.32 ± 0.26 mg/mL, respectively. Pure amyloglucosidase produced liquid glucose which had dextrose equivalent for sorghum 78.28 ± 0.57%, yellow maize 65.66 ± 0.61% and 73.50 ± 0.66% for millet, respectively.

Apart from millet grains, a study (Kumar et al. 2016) on pre-treatment and enzymatic hydrolysis of pearl millet stover by multiple enzymes from *Aspergillus nidulans* AKB-25 was carried out. This study aimed at investigating the effect of pre-treatment followed by enzymatic hydrolysis on various parameters and changes in the physical and chemical structure of pearl millet stover. Different dosages of the enzyme were used to study the effect on the hydrolysis of pearl millet stover, both in presence and absence of surfactants. Compared to untreated sample, alkali pre-treatment improved the Brunauer-Emmett-Teller (BET) surface area and water retention value (WRV) by 322.92% and 78.66%, respectively. With increasing alkali dose (up to 3%) the rate of conversion of biomass into reducing sugars increased. At 3% alkali dose and hydrolysis time of 72 h the yield of reducing sugars was at 53.13%. Maximum reducing sugars 57.77% was found at enzyme concentration of 15 FPU/g of dry substrate after 72 h of hydrolysis. Incorporation of surfactants Tween-80 and Tween-20 (0.15 g/g dry substrate) resulted in enhanced saccharification yield of up to 62.14% and 64.77%, respectively, when compared to the control (57.64%). Thus, partial removal of lignin and hemicelluloses by alkali pre-treatment enhances the enzyme accessibility of pre-treated pearl millet stover, making it effective for hydrolysis treatment for conversion into reducing sugars.

In another study (Akoma et al. 2010), effect of thermal enzymatic hydrolysis of cereal starch on the physico-chemical quality of Kunun-Zaki (a fermented non-alcoholic cereal beverage) was evaluated when millet grains were steeped for 5 min in 1% sodium metabisulphite (1:2 w/v) followed by washing and wet milling; and the paste obtained was further gelatinised with boiling water (1:1 w/v, 76 ± 2 °C) and hydrolysed either with α + β-amylases, α + amyloglucosidase or rice malt separately. The 12-h starter culture (2% v/w) of *Lactobacillus plantarum*, *Lactobacillus fermentum* and *Lactococcus lactis* was used to inoculate the hydrolysed starch and fermented for 6 h. The results showed that the pH and total soluble solids of the products reduced with increase in viscosity and titratable acidity in all samples. The results of this study show that "Kunun-zaki" of acceptable sensory attributes can be obtained within 7 h using combinations of hydrolytic enzymes/rice malt and starter cultures of lactic acid bacteria (LAB), as compared to traditional method requiring > 7 h and up to 12 h, thus enabling efficient large-scale production (Table 11.11).

In another study (Zhu et al. 2018), foxtail millet (*Setaria italic*) bran was used to obtain dietary fibre by enzymatic methods, and the changes in functional and physicochemical properties of foxtail millet bran dietary fibre (FMBDF) were

Table 11.11 Physical characteristics of "Kunun-zaki" produced by enzyme-treated gelatinised starch

Treatment/processing time	Analysis		
	Total soluble solids (°˜Brix)	Viscosity (cPs)	Specific gravity
Slurry (ground millet paste)			
α + β-amylases	20.27 ± 0.15	230.7 ± 5.81	1.145 ± 0.028
α-amylases + amyloglucosidase (AMY)	20.83 ± 0.44	196.4.93	1.118 ± 0.001
Malted rice	22.33 ± 0.33	183.3 ± 6.01	1.112 ± 0.001
0 h			
α + β-amylases	15.33 ± 0.33	Not determined (ND)	ND
α-amylases + (AMY)	15.70 ± 0.50	ND	ND
Malted rice	15.73 ± 0.50	ND	ND
6 h			
α + β-amylases	16.03 ± 0.09	241.7 ± 4.01	1.222 ± 0.002
α-amylases + (AMY)	14.23 ± 0.12	215.0 ± 8.66	1.203 ± 0.003
Malted rice	15.33 ± 0.33	208.0 ± 1.15	1.118 ± 0.001

Source: Akoma et al. (2010)

detailed. The findings showed that FMBDF has a huge potential to be used as functional ingredient in food products due to its chemical composition and microstructure of FMBDF along with improved physiochemical attributes like enhanced water holding capacity and swelling properties, good lipophilic properties and bile salts adsorption capacity.

11.3.5 Popping or Puffing

When grains (Mishra et al. 2014) are exposed to high temperature for short time, starch gelatinisation and simultaneous expansion occurs resulting in a process called "Popping". It is a process in which the grain is cooked and expansion of endosperm occurs instantaneously breaking out the outer skin due to the escape of super-heated vapours produced. Similarly puffing is carried out where the expansion is controlled. These methods are used for oil-free snacks and produce acceptable taste. Popping/puffing can be done using different methods. Traditional methods include use of sand and salt for heat transfer, dry heat and gun puffing. Novel technologies like high temperature short time (HTST) and microwave puffing are being used recently.

11.3.5.1 High Temperature Short Time (HTST) Popping of Millets

High Temperature Short Time (HTST) is a process where grains are heated at high temperature ranging between 230 and 270 °C for a very short period of time.

In a study (Kumari et al. 2018) several pearl millet varieties were popped to study nutritional and popping characteristics. Cleaned pearl millet grains were raised to a moisture content of 18% with addition of water and conditioned for 6 h. These grains were popped at 230 °C in grain popper. The popping percent ranged from 43.0% to 85.0% depending on the pearl millet varieties. Higher the volume of the popped grains, higher was the puffing index which ranged from 5.27 to 9.29 depending upon the varieties. Decrease in phytic acid content in popped millet was noted compared to raw millet. The study showed the suitability of popping of pearl millet, as an ingredient to obtain nutritious and healthy snacks.

In another study (Jaybhaye et al. 2011), optimisation of parameters for developing of barnyard millet flour puffs was carried out using high temperature short time (HTST) to develop a ready-to-eat (RTE) puffed snack. Optimum conditions for puffs which were made by cold extruded dough sheet being steam cooked and then puffed in hot air puffing setup was found to be: steaming pressure 0.85 kg/cm^2, steaming time 10.0 min, hot air temperature 234 °C and puffing time of 39 s. The texture characteristics were attributed to moisture content while volume expansion is highly dependent on steaming pressure and puffing time. The study showed the potential for successful development of RTE snack utilisation barnyard millet.

Similarly (Ushakumari et al. 2007), the optimal conditions to develop expanded finger millet with use of HTST process were explored. The study shows that maximum expansion ratio was critically dependent on factors like moisture content and the flattening of grains to required shape factor. Moisture content of about 40% prior to flattening, shape factor ranging from 0.52 to 0.58 and drying time varying from 136 to 150 min were found to be optimal conditions to develop fully expanded finger millet.

The above studies show that HTST process as a potential technology to develop RTE snacks from millets, for promoting healthy and cost-effective snacking.

11.3.5.2 Microwave Puffing or Popping

Heating (Mishra et al. 2014) of product in microwave occurs through the vibrational energy which results in oscillation of bipolar water molecules. This moisture in the grain gets heated up and transforms into superheated steam, which is necessary for expansion, and accumulates at the glassy matrix, leading to high pressure internally. Expansion takes place during phase transition of cereal matrix from glassy to rubbery state. It is then that the product starts to expand under high superheated steam pressure. The final glassy state and structure sets as the matrix cools down with stopping of microwave heating and loss of moisture.

In comparative studies (Sharma et al. 2014), sorghum was puffed at different moisture contents, 18%, 21% and 24%, with conventional (cooking pan with LPG) and microwave (microwave oven) method. At 21% moisture for 3 min puffing time both conventional and microwave methods gave: puffing yield (83%, 89%), expansion ratio (4.44, 8.67) and flake size (0.18 mL/grain, 0.28 mL/grain), respectively. The results concluded that conventional puffing had lower values of mean moisture, fat and ash compared to microwave puffing.

In a study (Pawar et al. 2014) to develop puffed product using a mixture of sorghum and soya flour and optimal condition were determined for optimal product quality. Cold extruded dough sheet pieces prepared from sorghum and soy powder in the proportion 90:10 were steam cooked and then puffed in microwave oven. The steamed cold extruded dough sheets were further kneaded, granulated and heated convectively at 210 °C for 240 s followed by microwave heating with 80% of total power of 1350 W for 60 s for optimal puffing. The optimised conditions resulted in the desired quality, hardness, crispiness and expansion ratio.

Studies on (Mishra et al. 2015) pre-treatment and popping parameters were done to determine the optimum conditions. Preconditioning of grains was done, by spraying pre-calculated amount of water, to a moisture content of 12–20%. Further, conditioning was achieved by using 0–2% salt solutions. The preconditioned grains were coated with oil (0–10% w/w). Popping yield, sensory score and volume expansion ratio were considered for optimised pre-treatment conditions. The optimised conditions were found to be: moisture, salt and oil at 16.62% (wet basis), 0.55% and 10% respectively, resulting in popping yield of 82.23%. The sensory score acceptability score of the product obtained under the optimised conditions was 8.49 and volume expansion ratio was 14.56. The optimum microwave power density of 18 W/g and microwave time of 140 s gave best quality popped sorghum.

11.3.6 High Hydrostatic Pressure Processing for Modification of Viscoelastic Properties of Millet and Sorghum Dough

The impact on dough viscoelastic reinforcement of highly replaced wheat cereal matrices due to high hydrostatic pressure (HP) was investigated (Angioloni and Collar 2012). The HP hydrated oat, millet, sorghum and wheat flours gelatinisation/pasting and gelling profiles have been determined. Keeping the time (10 min) and temperature (20 °C) constant the oat, sorghum, millet and wheat hydrated flours, at dough yield (DY) 160 (flour–water ratio of 1:0.6 w/w) and 200 (flour–water ratio of 1:1 w/w), were treated at 200, 350 or 500 MPa. For all cereal flours, HP changes flour viscometric features, particularly in softer doughs (DY 200), leading to increased values for viscosity parameters, concerning pasting and paste cooking. Visual appearance, especially colour and consistency, was affected by HP treatments of hydrated cereal flours. Irrespective of flour type and flour hydration, increase in pressure levels (200–500 MPa) changed consistency in all samples from fluid (200 MPa), to cake batter like (350 MPa) to solid-like (500 MPa). HP-caused strong hydration and swelling of starch granules were irreversible. With starch granules, hydration and swelling of amorphous regions occurred with increase in pressure. The granule integrity, modification of starch occurs in HP treatment, unlike in thermal-treated starches. DY during cooking (pasting/gelatinisation) and cooling (gelling) was critical in determining how effective HP treatment was. Incorporation of 350 MPa pressure-treated flours into bread dough formulation provided increased dynamic moduli values, particularly for wheat and oat/wheat blends, associated to a reinforced dough structure, thus proving that HP can serve as an effective strategy for modification of gelatinisation and gelling her properties of oat, sorghum, millet and wheat flours. However, more research needs to be undertaken on exploring the use of HP for large-scale replacement of wheat flour with millets and sorghum flour, in the baking industry.

11.3.7 Application of Novel Biochemical and Nanotechnologies for Use of Millets in Nutraceutical, Functional Food and other Industrial Uses

Millet has long been used as staple food in many traditional dishes in Africa and India and serves as a potential solution to the food security. Presence of various bioactive and functional compounds makes them potential source as raw material as well as ingredients to be used in functional and nutraceutical foods.

11.3.7.1 Understanding Role of Millet Phenolics in Development of Functional Foods and Diabetes Management

Millets are source of both soluble and insoluble bound phenolic compounds. Phenolics from millets, can be used as natural ingredient against several pathophysiological conditions due to their bioaccesiblity and bioactivities (Shahidi and Chandrasekara 2013).

In a study on barnyard millet (Anis and Sreerama 2020) *p*-coumaric and chlorogenic acids were found to be major phenolic acids. The study revealed that the said phenolic compositions were very effective in scavenging >78% reactive carbonyl intermediates and 68.3% inhibition of protein glycation. The results suggest that these phenolics exhibit various antioxidant properties involving different mechanisms such as, protecting the oxidative DNA damage and hydroxyl radical-induced protein fragmentation showing the possibility of using barnyard millet as an ingredient in development of functional foods for managing protein glycation related with diabetic complications.

In another study on foxtail millet (Xiang et al. 2019), the varied profile of phenolics in dehulled foxtail millet was studied. In the free fraction 21 phenolics including a series of nine hydroxycinnamic acid spermidines and three flavonoid C-glycosides of kaempferol and apigenin, were identified. 23 phenolic acid derivatives, with ferulic acid being the predominant phenolic acid, along with four ferulic acid dimers (DFAs) were reported in the bound fraction. Total phenolic contents (TPC) of free fraction varied from 161.86 to 224.47 mg ferulic acid equivalent (FAE)/kg dry weight basis, and bound fraction 170.69–294.75 mg FAE/kg dry weight basis. Thus, foxtail millet is a potential ingredient in formulation of functional foods, due to the presence of different phenolic compounds and their related antioxidant characteristics.

In a study involving six cultivars of little and foxtail millet (Pradeep and Sreerama 2018), total phenolic content in different cultivars of little and foxtail millets was found to range between 24.12 and 19.42 μmol ferulic acid equivalents/g. In soluble fractions ferulic, sinapic and caffeic acids were the predominant phenolic acids and kaempferol and luteolin were major flavonoids. Ferulic and *p*-coumaric acids were detected in the bound fractions. Foxtail millet cultivars revealed less inhibition of α-glucosidase and α-amylase than little millet cultivars. The results of the study show the potential of using the underutilised millets in formulating functional foods, to regulate postprandial hyperglycemia.

In another study (Chandrasekara and Shahidi 2011) millet extracts from seven of different millets namely kodo, finger (Ravi), finger (local), proso, foxtail, little and pearl were analysed for total phenolic content (TPC), total flavonoid content (TFC), ferrous ion chelating activity and singlet oxygen scavenging capacity. The TPC and TFC were found to range between 146 μmol and 1156 μmol ferulic acid equivalents and 25–1203 μmol catechin equivalents per gram crude extract, respectively. The inhibition of peroxyl and hydroxyl radical induced supercoiled DNA scission, as well as xanthine oxidase and the anti-proliferative activities of the millet phenolic extracts against HT-29 cells (human colon adenocarcinoma) was also demonstrated. Millet phenolic extracts employed in this study showed suppressing action, demonstrating time- and dose-dependent anti-proliferation of HT-29 cells. The different millet extracts studied inhibited cell proliferation in the range of 28–100%. All varieties employed in this study also exhibited notable inhibition of lipid peroxidation in liposomes, singlet oxygen quenching and DNA scission inhibition to varying degrees. Thus there is a potential of use of millet phenolics as nutraceutical ingredient which can be efficient in the prevention of initiation and progression of cancer as proved in vitro. Further research needs to be undertaken to develop bioavailable millet phenolics-based nutraceuticals based on in vivo studies using human subjects.

Two foxtail millet varieties Jingu 28 and Jingu 34 (Zhang and Liu 2015) were compared for their anti-proliferative activity. Jingu 28 and Jingu 34 showed a total phenolic content (TPC) of 78.79 mg and 114.22 mg gallic acid equivalent/100 g on dry weight basis, respectively. Both variances contained acids like ferulic, chlorogenic, caffeic, *p*-coumaric and syringic. The proliferation of MDA (human breast cancer cell lines) and HepG2 cancer cells (human liver cancer cell lines) were significantly reduced in amount dependent manner after being subjected to the foxtail millet extracts, in in vitro assays.

Table 11.12 gives an overview of the phenolic compounds found in different varieties of millets and their potential use in treatment of various medical conditions.

11.3.7.2 Exploring Novel Nanotechnologies for Promoting Food and Other Industrial Applications of Millets

With the growing demand (Kumari et al. 2020) for bionanoparticles like starch nanoparticles (SNP's), millets are being explored as a source of starch to prepare starch granules with distinct functional characteristics. Methods like acid or enzymatic hydrolysis, mechanical processing, regeneration and integrated enzymatic and precipitation can be used in preparation of starch nanoparticles/nanocrystals. Modification of SNPs can be done by chemical, physical and enzymatic methods to increase the diversity in applications profile. SNPs' utilisation ranges in various food systems: reinforcement materials in nanocomposites, emulsion stabilisers, encapsulating agents and releasing and carrier ingredients.

Table 11.12 Phenolic compounds found in millets and their potential uses

S. No.	Phenolic compound	Millet variety	Potential use in treatment of	References
1	*p*-Coumaric and Chlorogenic acids	Barnyard millet	Diabetic complications	Anis and Sreerama (2020)
2	Ferulic and *p*-Coumaric	Foxtail and Little millet	Postprandial hyperglycaemia	Pradeep and Sreerama (2018)
3	Ferulic acid and Catechin	Millets: Kodo, Finger, Proso, Foxtail, Little and Pearl	HT-29 (Colorectal cancer)	Chandrasekara and Shahidi (2011)
4	Ferulic acid, Chlorogenic acid, Caffeic acid and *p*-Coumaric acid, Syringic acid	Foxtail millet	MDA (breast cancer) and HepG2 (human liver cancer cell)	Zhang and Liu (2015)

In studies, properties of starch nanoparticles from Proso (Pr) and Pearl (Pe) millets were characterised (Jhan et al. 2020), which are necessary to be considered for application of nanoparticles in food and in various other industrial applications. Collision ball milling was used to produce nanoparticles. Dynamic light scattering (DLS) showed the average hydrodynamic particle diameter of 417 nm and 636 nm for nano-reduced porso (PrN) and pearl (PeN) millet starch, respectively. X-ray diffraction (XRD) showed loss of crystallinity in starch granules. Increase in results of antioxidant assays showed nano-reductions of starch as a potential in nutraceutical applications.

Lipophilic bioactive compounds can be encapsulated using proteins derived from plants, as delivery systems. Extracted protein from porso millet from wet milling and 60% (v/v) aqueous ethanol was used as the coating material to encapsulate curcumin (Wang et al. 2018). Millet protein comprises of prolamines. The diameter of millet protein-curcumin encapsulate was observed to be around 250–350 nm. Ethanol extraction showed better entrapment efficiency compared to wet milling process, ranging from 11.2% to 78.9%. Low degradation rate was found in curcumin that was encapsulated than that of free curcumin at 60 °C. DPPH (2,2-diphenyl-1-picrylhydrazyl) and ABTS (2,2-azino-bis-3-ethylbenzothiazoline-6-sulphonic acid) assays showed no side effects of encapsulation on antioxidant activity.

A combination of green and simple techniques combined with enzymolysis and recrystallisation were used to produce starch nanoparticles from porso millet (Sun et al. 2014). Effect of different retrogradation time (0.5, 4, 12, and 24 h) on morphology and crystal structure were determined using, Scanning electron microscopy (SEM), X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), differential scanning calorimeter (DSC) and thermal gravimetric analysis (TGA). Starch nanoparticles were sized between 20 and 100 nm. Compared to native particles, increase in relative crystallinity of the nanoparticles was observed. Highest degree of crystallinity (47.04%) was observed in nanoparticles at 12 h retrogradation.

11.3.7.3 Millets for Medical Science

Comparative studies (Osman et al. 2020) using paracetamol as model drug was done on pearl millet starch for comparing disintegrant and physicochemical properties with other starches. Yield of starch from millet ranged between 30% and 40%. Potato and maize starch had similar hardness, friability (%) and disintegration times as compared to millet starch. Physicochemical properties of millet starch were similar to potato starch and maize, making it a possible alternative source of starch for use in the pharmaceutical industry.

In another study anti-hypertensive effect of foxtail millet was studied (Hou et al. 2018) where volunteer participants were taken through a 12-week open-label and self-controlled trial. Whole foxtail millet products were provided. Regular meal was replaced with daily average of approximately 50 g of whole foxtail millet for 45 participants suffering from untreated mild hypertension. A number of parameters (blood pressure, renin–angiotensin–aldosterone system, blood lipids, fasting blood glucose, anthropometric indices, body composition and bone density) were measured. Significant reductions in systolic blood pressure (4.13 mmHg, $p = 0.022$) and diastolic blood pressure (3.49 mmHg, $p = 0.002$) were noted in the volunteers after completion of 12 weeks. The body mass index, body fat percentage and fat mass significantly decreased ($p < 0.05$). Fasting blood glucose ($p = 0.051$) improved with intake of foxtail millet. The study implies that foxtail millet has the properties to reduce hypertension and decrease cardiovascular diseases.

Uncontrolled expression of xanthine oxidoreductase (which plays a vital role in formation of uric acid and its regulation during purine catabolism) leads to overproduction and deposition of uric acid in blood. Consequently, DNA and protein molecules can breakdown and are potentially injurious, triggering many diseases. Treatment of hyperuricemia can be targeted by inhibition of Human Xanthine oxidoreductase (HsXOR). Thus, there is a need to explore and develop new HsXOR-inhibitor drugs which are low in toxicity or non-toxic, for the future treatment or avoidance of hyperuricemia-related diseases. A study (Pathak et al. 2018) involving millet-derived compounds luteolin and quercetin in terms of their interaction with target, HsXOR through molecular docking and dynamic simulation, is reported. Luteolin and Quercetin from millet showed more binding affinity with HsXOR than reference drugs, Febuxostat and Allopurinol. Energetically Luteolin-protein was more stable than Quercetin-protein complex. Allopurinol and Febuxostat showed binding energy −5.5 kcal/mol and −8.0 kcal/mol respectively, whereas millet derived compounds luteolin and quercetin showed binding energy of −9.7 kcal/mol. Based on the study, luteolin from millet is proved to have a high potential for developing future HsXOR-inhibitor drug.

11.3.7.4 Potential Processing of Millets into Renewable Resources

Xylan is a plant derivative used in various industrial, food and pharmaceutical industries. In a study (Palaniappan et al. 2017) involving seed coat of finger millet and rice bran, xylan was extracted with water without the use of chemicals. This water soluble xylan (WSX) revealed the presence of xylose, arabinose and glucose respectively. FTIR showed structural presence of β-glycosidic linkages and acetyl groups; substituents of β-D-1,4-xylopyranose backbone with α-L-arabinofuranose and 4-*O*-methylglucuronic acid confirmed the presence of xylan. Extracted WSX from both sources showed similar characteristics (SEM, particle size, XRD and TGA). This suggests the potential use of both rice bran and finger millet seed coat as source for xylan extraction and further improvement in the process can provide environmental and economic benefits through value addition to by-products of millet processing.

In a study (Boubacar Laougé et al. 2020) fast pyrolysis of pearl millet (PM) was done to obtain bio-oil yield (BOY). The sample analysis of BOY by GC–MS showed the existence of many useful chemicals such as acids, alcohols, aldehydes, aromatics, ketones, phenols and others. This study thus shows the potential of using millets for production of industrial chemical compounds through fast pyrolysis.

In a recent study (Dong et al. 2020) thermo-gravimetric analysis was undertaken to investigate the combustion properties of hydrochars from millet stalk (MS) and dilute-acid-impregnated millet stalk (AMS). Activation energies were determined with iso-conversional approaches of the Flynn-Wall-Ozawa (FWO) and Kissinger-Akahira-Sunose (KAS). The pre-exponential factors were estimated by the compensation effect. The combustion behaviours of the MS and AMS hydrochars were determined by derivative thermo-gravimetric (DTG) curves. AMS hydrochar presented better fuel properties, including a higher yield, higher carbon content, lower ash content and lower nitrogen content, fuel ratio and specific surface area than MS hydrochar. The average activation energy of MS hydrochar was more than that of AMS hydrochar. The study thus points towards the potential of development and commercialisation of millet-based hydrochars.

Generalized Distance Function (Zhang et al. 2019) was employed to obtain ideal processing parameters for preparing the millet bran briquette. Moisture content ranging from 5% to 10%, temperature from 80 to 110 °C and pressure from 110 to 130 MPa gave high-quality briquettes. The optimum conditions established are: moisture content 5.4%, temperature 101.9 °C and pressure 122.7 MPa. The potential of obtaining good quality solid biofuel from millet bran is successfully demonstrated through this study.

11.3.8 Emerging Use of Ultrasound in the Extraction of Polyphenols, Starch and Bioactives from Millets

Ultrasonication (UA) and enzyme treatment, followed by ultrasonication, using xylanase (XUA) were studied/compared (Balasubramaniam et al. 2019) with the conventional heat reflux method (HR) to determine effectiveness of polyphenols extraction from finger millet grains (variety GPU 28) and its seed coat (FMSC). Phenolic yield of UA was equivalent to HR while it increased to 2.3 times in XUA compared to heat reflux extraction (HR), respectively. Total flavonoids (1.4 fold in UA and 1.3 fold in XUA) and tannins (1.1 fold in UA and 1.2 fold in XUA) also increased in UA and in XUA. Thus, the study shows the potential of using a combination of enzymes along with ultrasonication, as a green technology for utilization of polyphenols from millets, in nutraceuticals and functional food applications.

Pearl millet grain starch was extracted (Bouhallela et al. 2020) using ultrasound-assisted isolation and was compared with conventional process of wet milling. The ultrasound-assisted isolation gave a yield of 30.63–52.65% with high recoveries of 46–75.70% and purer starch 91.32–94.58% showing a greener way to generate pearl millet starch in a short period.

A study investigated (Čukelj Mustač et al. 2019) the potential for enhanced extraction of free bioactives by the use of high intensity ultrasound, as a pre-treatment from proso millet bran. Enzymatic browning, protein digestibility and water retention, which are important parameters in the bakery and pasta industry, were investigated for the effects of high intensity ultrasound. 400 W ultrasound probe for varying time in range 5, 12.5 or 20 min, with the varying amplitude of 60%, 80% or 100% was used to treat suspension of 15% millet bran in water. Most significant improvement in nutritive value was found at 80% amplitude for 12.5 min, an increase in 15% of antioxidant activity and total phenolic content increased by 16%, as measured by FRAP (Ferric Reducing Antioxidant Power) assay. Water-soluble and ethanol-insoluble dietary fibre was increased by 38% after being treated for 20 min at 100% amplitude. Limited browning (of proso millet bran) and high water retention was shown at ultrasound treatment at 100% amplitude for 5 min. Interestingly, it was found that polyphenol oxidases were activated due to high intensity ultrasound procedure irrespective of the heat input. Final optimisation of the pre-treatment was observed at 15% millet bran suspended in water at 100% amplitude for 9.3 min.

A comparative study (Hassan et al. 2017) was conducted to evaluate emerging technologies such as ultrasound (US) and microwave (MW) on sorghum seeds fatty acids and oil yield before and after germination. The oil yield in sorghum before germination ranged from 6.55% to 7.84% while after germination ranged from 6.28% to 7.57%. Treatment by ultrasound and microwave of the samples resulted in improved oil yield as compared to yields from raw/untreated sorghum grains. At microwave power of 700 W for 30 s in combination with ultrasound intensity of 60% for 10 min showed the highest yield (7.84 $\pm$ 0.31%). The study also showed that these processing technologies do not affect the quality of the oil, expressed in terms of essential fatty acids content.

Similarly, another comparative study (Li et al. 2019) to evaluate the action of ultrasound (UC) and microwave (MC) on various functional properties of millet starch was conducted. Changes in millet starch properties along with focus on viscosity, transparency (TR), swelling power (SP), short-range molecular order

(FT-IR spectrum), long-range molecular order (X-ray diffraction), thermal properties (DSC), in vitro enzymatic digestibility and morphological characteristics were studied. The changes in peak viscosity and relative crystallinity for UC starch was 14.8% and 23.2% compared to MC starch which was 74.9% and 100%. UC increased the SP, DCS, TR and ratio of the absorbances. However, MC caused reversal in trend of these properties. Increase in the in vitro enzymatic digestibility was observed in MC and UC.

In a study (Nazari et al. 2018), changes in functional characteristics of millet protein concentrate (MPC) by the effect of high power ultrasound (US) probe at different intensities and varying times (18.4 W/cm^2, 29.58 W/cm^2, and 73.95 W/cm^2 for 5 min, 12.5 min and 20 min, respectively) were evaluated and also the structural characteristics to establish the most effective treatment were evaluated by FTIR, DSC, Zeta potential and SDS-PAGE techniques. According to the data analysis it was found that the solubility increased in all US treated MPC than those of the non-treated MPC. Foaming capacity increased at high intensities (749.7 $\pm$ 2 mL) and decreased on with low intensity treatment (82.37 $\pm$ 5.51 mL) compared to native MPC (271.03 $\pm$ 4.51 mL). In addition, increase in EAI (emulsifying activity index) and ES (emulsion stability) was observed after US treatments. With further research and studies, US treatment can be adopted as green technology to enhance the functional characteristics of MPC, for utilisation in different food applications.

11.3.9 Gamma Irradiation for Improving Keeping Quality and Nutritive Value of Millets

In a study (Mahmoud et al. 2016), the effect on germination, protein solubility, fungal incidence, digestible protein, free fatty acids and anti-nutritional factors due to processing by gamma irradiation on millet grains were evaluated. Pearl millet grains were treated with varying dosage of gamma irradiation: 0.25, 0.5, 0.75, 1.0 and 2.0 kGy. Notable decrease in free fatty acid and fungal incidence in the grains were observed in case of irradiation doses higher than 0.5 kGy. Increase in in vitro protein digestibility, improved protein solubility and notable decrease of phytic acid and tannins were noted. Results show that gamma irradiation can be used to enhance the quality characteristics of millets and the technology also has potential application postharvest, for keeping millet grains safe from infestations.

In another study involving finger millet, the grains (Reddy and Viswanath 2019) were exposed to four different gamma irradiation levels: 2, 5, 10 and 15 kGy. Finger millet flour properties like pasting, proximate composition, lipoxygenase activity and antioxidant activity were evaluated. According to the results gamma irradiation was found to significantly reduce the moisture content, pasting properties, fat content, lipoxygenase activity and malondialdehyde. Increase in protein content, catalase and superoxide dismutase activities and radical scavenging activity in the irradiated flour was observed with increase in gamma irradiation doses. In summary, the study concludes that the physiochemical properties and antioxidant activity of finger millet flour can be effectively improved by the use of gamma irradiation treatment.

11.4 Conclusion

Given that the humble millets are set to go global, with the United Nations General Assembly declaring 2023 (United Nations General Assembly 2021) as the International Year of Millets this chapter on “Emerging Technologies in Millet Processing” is written with the aim to contribute significantly towards raising awareness among the global scientific community on the potential of using various innovative technologies to leverage on the nutritional and functional properties of millets. Further research and development, scale up and adoption of these emerging technologies is the need of the hour, in order to mainstream millets. The development of the emerging technologies, as detailed in the chapter, shall lead to efficient processing of millets through innovative processing, development of innovative and healthy food products and diversification of the use of millets and ingredients sourced from millets in areas beyond food and fodder, such as medical science and renewable energy. In the long run these emerging technologies, once developed and adopted, shall help to integrate smallholders into global value chains. This shall ensure the sustainable production, consumption and industrial use of millets.

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Millet Food Products

12

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Abstract

Recent trends in globalization of non-diversified diet of energy-dense cereals fuel the rise in diabetes and heart disease. Hence, millets have become a major part of the present food revolution to reverse this trend. Millets are termed as "smart food" "superfoods", which have high levels of desirable nutrients, easily digestible, distinct flavour, non-acid forming, and gluten-free, non-allergic unique food properties. Due to these functional properties, millets have gained an important role in functional foods for consumers. This chapter explores the knowledge on conventional and non-conventional millet products and novel food products and their nutritional, functional importance and production to re-popularize millets for implementation into everyday meals as functional food. The comprehensive details are given for the conventional processing such as milling, roasting, germination and fermentation for producing primary products at milling industry such as millet rice into various forms like raw rice (dehusked), dehusked semi-polished rice, parboiled rice, semolina, whole grain flour, dehusked flour and composite flour and secondary products such as flaked, parched, puffed and popped millet, porridge, gruel, weaning and supplementary food. The contemporary food processing technologies such as extrusion, baking, spray drying, gun puffing and popping, malting, instant mixes and brewing are employed for millet grains to produce instant mixes, convenient, ready-to-eat and ready-to-cook products; novel food products namely millet milk and *dahi* analogue, meal bar, pellet, muesli, edible film, etc. and traditional millet food products including *bhat, kheer* (sweetened thin porridge), *mudde* (stiff porridge), *roti/chapatti* (unleavened bread), *idli* (fermented savoury cake), *dosa* (fermented pancake),*koozh*, *koko*,

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togwa, *dambu*, *chhyang*, *ogi, uji and brewed drink*. The diversification of millet products will be amplified through adoption of traditional knowledge with advanced technologies to produce convenient food to make easy access for consumers.

Keywords

Millet products diversification · Nutritional functional profile · Convenient foods · Specialty foods · Extruded foods · Bakery foods · Traditional foods

Whole grain foods have become necessary in the diet all around the world at present. They are the heart of natural foods, which most of the people have developed interest on, realizing their importance and health benefits. Under this changing scenario, exploiting the situation in favour of millet based conventional and non-conventional foods appears to be a challenging one. Millets is a grain of Middle Eastern origin which is highly nutritious with a distinct flavour of its own. The millet grain invariably needs a processing technique for food preparation.

Milling, malting, roasting, popping and refining processes are some of the primary processing of millets. The products of primary processing can be further processed for the preparation of traditional foods, specialty foods, baked foods, extruded foods and healthy foods (Kulkarni et al. 2018). Processing of millet grains has nutritional advantage as it minimizes the anti-nutritional factors like tannin as well as improves the bioavailability of nutrients (Begum 2007). However, minimal documentation is available on scope of processing, value addition and the traditional food uses of millets. Hence, there is an urgent need for collection and dissemination of detailed information about the processing techniques and traditional foods of millets.

Though millets have good potential nutrients, their consumption is limited. The main reason for the poor consumption of millet as food is its tedious pre-food preparation and operations, time consumption in processing, energy intensive, laborious, cumbersome cooking operation and lack of diversified millet foods. This chapter will elaborate the information about various conventional and non-conventional processing of millet food products which leads to explore the knowledge to improve the production, consumption of millet foods as well as to improve the healthy well-being of consumers.

12.1 Millet Rice

"Millet rice", a product of millet decortication, retains most of the nutrients of the millet and can be used for preparing ready-to-cook grains similar to rice. Foxtail millet (thinai), proso millet (panivaragu), kodo millet (varagu), little millet (saamai) and barnyard millet (kuthiraivali) are processed into various categories of de-husked, semi-polished and parboiled grain. The age-old practice of de-husking and de-branning is normally carried out manually using hand pounding system but with the development of various milling technologies, polishing of these millets to prepare ready-to-cook grains has been made possible.

The conventional processing of small millets namely thinai, panivaragu, varagu, saamai and kuthiraivali (except ragi) by manual stone pounding has prevailed in Southern Parts of India. Traditionally, millets are parboiled in hot water and sun-dried for a week, before de-husking and eaten as cooked grains. Parboiling is a pre-milling process in which the cereal grains are subjected to hydrothermal treatment which in turn reduces the breakages of grains, improve shelling efficiency during milling thus increasing milling recovery. It is accomplished by three steps: soaking, steaming and drying. The practice of millet parboiling is in vogue. Observations have shown that parboiling can enhance the nutritional benefit and improve the milling qualities and culinary characteristics of the grains. The millets can be parboiled by shella or dry heating methodology. The grains can be soaked at a higher temperature (70 °C). Higher temperature soaking reduces the time of hydration. Once the grains attain their equilibrium moisture content (35%), they can be steamed at atmospheric or at higher pressure to gelatinize the starch. Since the millets resemble rice in their morphological features, the husk protects the grains from bursting during steaming process. The parboiled millets will have better retention of vitamins, especially the thiamine, and enhanced storage life (Kar 2007).

During parboiling, the outer cover of the grains gets loosened which enables its de-husking by rice huller or dhal mill (Kar 2007). Millet milling systems differ from rice milling system as de-husking and de-branning is done in a series of emery coated inverted cones which reduces the head grain yield to hardly 45%. Thus, millets can be de-husked in rubber roll or centrifugal shellers and the husked material can be de-branned in rice milling machinery. Husk and bran can be separated in pure form by this technology with a head grain yield of 55%. Also, the bran, which contains about 15% oil, can be used to supplement rice bran for oil extraction. The de-oiled bran can be used as animal feed and as a source of dietary fibre (Ushakumari and Malleshi 2007). The milling is done mechanically and various milling parameters are compared for thinai and saamai are given in Table 12.1.

Parboiled millet rice has good culinary characteristics which allow it to be cooked to soft and non-sticky texture within 5 min. Parboiling of millet grain provides translucent kernels while cooking it increased swelling than raw rice which leads to get desired softness. Millet rice products can be utilized similar to rice along with other adjuncts or can be seasoned with spice and condiments to prepare various types

Table 12.1 Comparison of milling characteristics of mechanically milled thinai and saamai (Kar 2007)

Type of millet	Grain yield (%)	Husk yield (%)	Bran yield (%)	Oil content of bran (%)	Protein content of grains (%)	Cooking time of grains (min)
Thinai	66	30	3	12	13.6	6
Saamai	73	20	5	3	9	8

of meals (Mal et al. 2010). Besides, it can be size graded to produce semolina which can be used in preparing traditional food products such as *Upma* and *Porridge*. Such food products can enhance the consumption of millets among the non-millet consumers (Malleshi 2007).

12.2 Puffed and Popped Millets

The millets can be popped and puffed similar to other cereals. Snack industry is one of the predominant and ruling the food industry which needs to satisfy both health and taste aspect of the consumer expectation. Puffed and popped grains are more prevalent in the snack industry for a long time. Thus, millet grains can also be puffed and popped to produce healthy snack foods. Puffing can be done by hot air, hot sand, microwave heating and gun puffing methods while popping is a type of starch cookery, where grains are exposed to high temperature for short time (Mishra et al. 2014).

In puffing process, the millet grains are parboiled, de-husked, polished and then puffed in a grain-puffing machine. The popped ragi flour or puffed varagu flour with sugar and cardamom commonly known as "*hurihittu*" is a ready-to-eat product. The precooked puffed millet flour also can be used as "*sattu*", a savoury dough, popular in North and Eastern India. Puffed kodo can further be made into "moa" or "*laddu*" with molten Jaggery (Kar 2007). Nutritious mix of popped and puffed millets with higher bioavailability can be produced which can be taken directly without further cooking requirement (Begum 2007). The puffed ragi mix (per 100 g) has a protein content of 12.0 g, fat 16.7 g, carbohydrate 67 g, calcium 132 mg, phosphorus 131 mg and iron content of 1 g.

In popping, the grain has to be equilibrated in closed container to bring the moisture content between 16% and 19%. The millet grains are then mixed with 3–5% additional water or buttermilk and tempered for 2–4 h and then popped by agitation. High Temperature Short Time (HTST) treatment has been observed as the best way to produce the popped grains with higher expansion ratio. The popping temperature has to be maintained at 175–230 °C (Begum 2007). When the grain is subjected to HTST treatment, the moisture in the grain turns into steam which gelatinizes the starch and explodes. Normally the volume of the expanded material varies from 5 to 9 mL/g. During popping, the grains undergo "maillard reaction" wherein the sugars in the aleurone layer react with amino acids thus developing a highly desirable aroma (Malleshi 2007). Non-popped grains can be sieved and separated. Generally, husk gets detached from the grain during popping, thus making it a ready-to-eat product. The popped millet grains retain whole bran which makes it a good source of dietary fibre. Since the grains undergo high temperature short time treatment, the popped product will be free from microbial contamination.

Traditional popping method involves sand as a heat transfer media which contaminates the product with minute sand particles. This problem can be neglected by the air-popping method which uses air as the heat transfer media. A major drawback of air popping is that some portion of aroma is lost during the process making the product blunt. Since popping is a dry process, the products generally have good shelf life. Besides, the presence of antioxidants and inactivation of lipase content of the millets during heat treatment adds to the shelf life of the products. The popped grain is a good source of pre-gelatinized starch and can get hydrolysed easily during mashing resulting in the formation of components suitable for fermentation. Thus, the popped millet is a precooked ready-to-eat product (Ushakumari and Malleshi 2007). Popped products from thinai and saamai had an expansion volume of 9 mL/g (Kar 2007).

Complementary foods are prepared using puffed and popped kodo millets (varagu), foxtail millet (thinai), and little millets (saamai), which are rich in calories and micronutrients to provide for children's nutrient needs. They can be either pulverized into flour or directly blended with legumes, oil seeds, milk powder, sugar or Jaggery and fortified with necessary vitamins and minerals to formulate nutritious food supplements.

12.3 Breakfast Cereals and Expanded Millet

The expanded grain is a novel product from the millets which can be made into readily acceptable food product among non-traditional millet consumers. The expanded millet has a porous and crisp texture and is devoid of seed coat. It can be seasoned with spice and condiments or coated with desirable adjuncts for use as a snack food (Malleshi 2007).

The expanded millets possess all the desirable characteristics for preparation of snacks and also adjuncts in specialty health products. Nowadays, there is a growing demand for ready-to-eat high fibre products and hence the expanded millets will be of great commercial value. Aesthetic and crispy snack foods can be prepared by blistering the expanded millets by High Temperature Short Time (HTST) treatment using air or oil as the heat transfer media (Ushakumari and Malleshi 2007). The decorticated millet can be subjected to HTST treatment after pre-conditioning to prepare expanded millet. The millets grains should be hydrated to their equilibrium moisture content by allowing them to soak in water. The hydrated grains are then steamed and pressed in roller flaker to prepare expanded flakes. The flakes are dried to safe moisture level for further storage and packaging. The parboiled millets also can be processed to prepare ready-to-eat expanded millet rice. However, by incipient germination and hydrothermal treatment to the millets, the expansion could be enhanced to 4–5 times. Expanded varagu can also be consumed as breakfast cereal with or without milk/curd and can be cooked in 8 min.

Breakfast cereals are one of the most popular types of ready-to-eat cereals flakes. Cereal flakes are popular breakfast products and at present they are mostly made from corn and oats. A various process techniques are used in the preparation of ready-to-eat cereals from millets, including extrusion, flaking, puffing and shredding and granule formation (Desikachar 1975). By suitable extrusion processing it might be feasible to produce breakfast cereals from sorghum and millet.

The cereal processing technologies can be successfully applied to foxtail millet. Ready-to-eat or ready-to-use products in the form of flaked, extruded, roller dried and popped grains can be prepared from foxtail millet by subjecting native grains (12% mc) to HTST treatment at 230 ± 5 °C (Ushakumari et al. 2004). The high temperature treatment results in starch gelatinization. Roller dried millet exerted higher degree of gelatinization followed by popped, flaked and extruded products. Studies have revealed that the microstructure of starch granules were spherical shaped in puffed grains while they were honeycomb structured in popped and extruded products (Fujita et al. 1996). Ragi and Thinai can be cooked with different levels of water (100–130 mL) at 80–100 °C at different time periods to form dough. This dough can be extruded and expanded to a thickness of 0.6 mm to prepare expanded millet product (Viswanathan et al. 2009).

12.4 Millet Flakes and Flattened Millet

Millet flakes are popular convenient food and it could also be processed as cereals and snack. Flattened millet from sorghum and millet could be produced adapting the conventional cereal flaking method. By suitable processing it might be feasible to produce flattened flakes from sorghum. Millets can be hydrated relatively easier coupled with their smaller size makes them suitable for preparation of better flaked products. However, the rigid endosperm texture makes it difficult for edge runners to flake the millets as it does for rice flakes. Thus, heavy duty roller flaker is essential for millet flaking. Flaking inactivates the lipase leading to better shelf life of the product. This will be a boon to millet flakes especially pearl millet as its products normally develop rancidity quickly. The flakes can be further processed into snack or supplementary foods by toasting in hot air or sand. These ready-to-eat flattened flakes products are very popular among the obese and calorie conscious people. After toasting, it could be conveniently used as ingredients of muesli and such other convenient food products namely namkeen or savoury snack foods such as poha, chiwda or Bombay mix, veggie chips, snack bar and cereal (Malleshi n.d.). The process details of sorghum flakes or flattened sorghum and chiwda are shown in Fig. 12.1.

For the processing of millet flakes or flattened sorghum from whole sorghum, the grains are cleaned and soaked in water for around 12–16 h. After that they are roasted at 320 °C for 5 min and then rested to for 3–4 h obtain wrinkle-free flakes. Grains are then pressed, flattened and sifted. Finally, flattened sorghum or flakes are dried and packed. The prepared millet flakes is used as ready-to-cook poha, which is a delicious south Indian breakfast dish made with flattened sorghum with savoury. The yield is around 60–70% followed by sifting and remaining percentage was husk and broken flakes. The preparation of poha from flattened sorghum and health mix from broken sorghum flakes are presented in Fig. 12.2.

The broken flakes can be pulverized and used for health mixes which can be used as a beverage for adults and weaning drink for children (Divya et al. 2017). These were cleaned for dust and other extraneous material and stored at room temperature

Flattened Sorghum and Chiwda

The ingredients required for the preparation are whole sorghum 50g, oil 10g, turmeric powder 0.5g, chana dhal 5g, peanuts 10g, mustard and cumin 0.2g, chilli powder 2g, curry leaves 2-3 leaves and salt 1g.

Millet grains
↓
Cleaning
↓
Sun drying (5-6hrs)
↓
Washing (2-3times)
↓
Conditioning (12-16hr in closed stainless steel drum)
↓
Roasting (320^{0}C for 5 min)
↓
Flatening in flaking machine
↓ → *Husk separated*
Sieving → ***Broken flakes** separated*
↓
Flattened Sorghum/Flakes
↓
Fry in sufficient quantity of oil
↓
Fry cumin, mustard, chana dhal, groundnut,
curry leaves, chilli powder, turmeric powder in other pan
↓
Add fried flakes in it and mix well
↓
Millet Chiwda
↓
Serve it while hot

Fig. 12.1 Processing of sorghum flakes or flattened sorghum and chiwda (Chavan et al. 2015; Divya et al. 2017)

in an air tight container. Flakes broken, pulse and oilseed are added in the ratio so that the mixture provides essential amino acid contents similar to the milk powder. Roasting is employed for the processing of pulses and oilseeds are simple in operation and improve taste, flavour and digestibility of the nutrients. The dried broken flakes are slightly roasted in a pan to enhance the flavour and acceptability of healthy mixes. The addition of pulses and oil seeds could enhance the nutritional status of the healthy mixes as well as sensory attributes (Divya et al. 2017).

The decorticated millet can also be used for the preparation of flattened millet or flakes, for that the grains are steeped in potable water at ambient conditions (30 ± 2 °C) for 10 h. The unabsorbed water will be drained off and the hydrated

Flattened Sorghum Based Poha	Broken Flakes Based Health Mix
Millet flakes 50g, peanuts 10g, oil 10g, onion 10g, coriander leaves 2g, salt 1g, green chilli 2g, cumin 1g and mustard 1g Sorghum flakes ↓ Sprinkle small quantity of water on sorghum flakes to moisture it ↓ Soak for 1-2 min. ↓ Fry cumin, mustard, groundnut, curry leaves, green chilli (chopped) and turmeric powder in oil ↓ Add moistured flakes in it and mix well ↓ **Savory Poha**	Millet broken flakes, black gram, puffed Bengal gram, green gram, Almonds, Skimmed Milk powder, Cardamom. Millet broken flakes, black gram, puffed bengal gram, green gram and almonds separately Roasting for 5mins ↓ Cooling for 3-4hr and Milling ↓ Adding Skimmed milk powder and Cardamom powder to the milling flour ↓ Mixing it all together ↓ **Health mix**

Fig. 12.2 Preparation of poha using flattened sorghum and health mix using broken flakes

millet is autoclaved at 1 kg/cm^2 pressure for 10 min, followed by dried at 50 °C in a mechanical dryer to 18 ± 1% moisture content and flaked or flattened in a heavy duty roller flaker in a single pass (Holm et al. 1988). Furthermore, the decorticated millet was pulverized in a burr mill and a flour of <500 μm particle sizes was prepared and used for roller drying and extrusion cooking.

12.5 Millet Malt

Among the various tropical cereals, finger millet (ragi) has good malting characteristics. It has excellent germinating capacity to the extent of 99%, resistant to fungal infection and develop highly desirable aroma and taste which makes it ideal raw material for malting. Traditionally the millet malt is utilized for infant feeding purpose and also to prepare milk-based beverage from good old days (Shigihalli et al. 2018). Besides, the ragi malt is a good source of sulphur amino acids and calcium (Verma and Patel 2012).

The malting process involves cleaning or washing, soaking, germination, drying, de-rooting or de-vegetation, kilning, de-branning, grounding or milling and sieving. Malting is the most important process as hydrolytic enzymes that bring endosperm modification are developed. Besides, some of the vitamins are synthesized and the bioavailability of the minerals increases. Soaking the millet is the initial process where the moisture content of the millet is increased to 30%. The water used for soaking has to be changed to drain out the leachates and to prevent unwanted growth of micro-organisms. The soaked grains are then spread on moist cloth or gunny to about 2–3 mm thick bed and then covered with another moist cloth to germinate.

Overturning and air resting the grains is necessary during malting for better aeration and heat dissipation. Normally, germination up to 48 h is desirable, but in summer, the germination period can be reduced to 24–36 h. The protease and cell wall degrading enzymes developed during germination partially digest the cell walls while the amylases digest the starch thus softening the endosperm of the malted ragi. The germinated sprouts are then dried either by sun drying or by mechanical means at 60 °C to stop the germination process.

De-rooting should be done to separate the root and shoot of the germinated grains. It can be achieved manually by gentle brushing or mechanically with the help of rice huller. Kilning or curing is the next process which is done by roasting the de-rooted malt grains at 70 °C. Generally, rotary heaters are used for roasting as they have the advantage of proper mixing with uniform distribution of heat which develops a desirable aroma.

The malt is pulverized to obtain malt flour which can be used for infant feeding and also as a base for milk-based beverage. The malt flour should be free from husk as the fibre content has to be as low as possible. Generally, the malt flour sieved through a nylon or thin fine cloth to get rid of the husk but the yield is affected with hardly 35–40%. Alternatively, the malt flour can be suspended in excess water and the starchy portion can be collected by settling but the soluble nutrients could be lost with the discarded water. To overcome this disadvantage, dry malt milling process along with tempering can be done by just wetting the surface of the grains by uniformly spraying the kilned malt with about 5–7% additional water. It is then heaped up and left for about 10 min for the seed coat to absorb the water. In this process, the husk becomes leathery allowing the inner grain to be powdered easily during pulverizing. The leathery husk is cut into big pieces and can be easily separated in the form of coarse flaky bran on sieving. The yield of millet malt flour shoots up to 65% in this process. As the malt flour is a good source of amylases, it is generally termed as "Amylase Rich Food" (ARF) as it serves as a good source of amylases.

The malt is not a ready-to-eat product which needs further processing for consumption. "Ragi Malt", popular in South India, is prepared by mixing the malt flour with powdered sugar, milk powder and flavouring agents such as cardamom. The malt flour can be fortified with necessary vitamins and minerals to enhance its nutritional quality (Malleshi 2007).

Generally, barley malt extracts are used in preparing milk-based beverages. The maillard reaction occurring during the preparation process damages the lysine content thus affecting the protein quality of the product. Instead of using barley malt extract, the spray dried millet malt can be dry blended to prepare health foods wherein, the interaction between amino acids and glucose will be very low due to this, the product retains its good nutritional value. Thus, the ragi malt has the potential of becoming a new ingredient in specialty food and health food industry. The processing of ragi malt, ragi malt based vermicelli and *shrikhand* are presented in Fig. 12.3.

Ragi Malt (Sarkar et al. 2015)	**Ragi Malt Based Vermicelli (Begum 2007)**	**Ragi Malt Based *Shrikhand* (Mugocha et al. 2000)**
Ragi grain (70%) + Wheat (15%) + Green gram (15%) ↓ Soaking (12 to 16 h) ↓ Sprouting green gram (24 hrs), wheat and ragi (48 h) ↓ Sun/oven drying at 60^0C ↓ Kilning and toasting ↓ Conditioning (5% moisture) ↓ Tempering (10 minutes) ↓ Milling, sieving (60 mesh) ↓ **Ragi malt**	Ragi malt (500g) + whole wheat flour (400g) + defatted soy flour (100g) ↓ Premix in blender for 2 minutes ↓ Add 180 ml water and remix for 2 minutes ↓ Extrude and cut attaching cutter ↓ Oven dry at 60^0C ↓ **Ragi vermicelli**	Skimmed Milk ↓ Heated to 90 ^{0} C/10 minutes ↓ Heat reduced to 60 ^{0} C ↓ Added ragi malt (raw and boiled in 5 to 15%) ↓ Added carrot juice (3%) ↓ Inoculated with 1% starter culture ↓ Incubated for 8 to10 hrs at room temperature ↓ Drainage of Whey ↓ Chakka ↓ Added sucralose ↓ Added flavor ↓ **Ragi *Shrikhand***

Fig. 12.3 Processing of ragi malt and ragi malt based products

12.6 Weaning and Supplementary Foods

The simplest preparation for weaning food is a combination of a millet and legume. Malted millets have enhanced amylase activity which provides the necessary energy and legume provides protein in adequate quantities. It can also be added with vegetables and fruits to make a complete food enriched with vitamins and minerals (Begum 2007).

One of the popular weaning foods namely “Malted Weaning Food” (MWF) can be prepared by blending two parts of malted millet with one part of malted green gram (Mal et al. 2010). It has superior nutritional qualities and textural properties. The food on reconstitution with water and heating to boiling forms nutrient dense slurry (low bulk) and under comparable consistency, malted weaning food contains twice the amount of nutrients than the roller dried weaning foods. It is important that the food sources selected for weaning mix should be grown locally, easily available in the market and of low cost. Considering these factors, Ragi becomes the best choice of millet for utilization in infant food formulation. The malt flour can be substituted to maltodextrin in preparing infant foods.

Table 12.2 Formulation for ragi malt and weaning food

Food sources	Ragi malt (Sarkar et al. 2015)	Weaning food (Krishnappa 2017)
Malted Ragi flour	1 kg	2 kg
Green gram flour	–	1 kg
Milk powder	750 g	2.25 kg
Sugar	1 kg	3 kg
Cardamom powder	10 g	–

Table 12.3 Nutritional composition of weaning food and supplementary food (g/100 g)

Nutrients	Malted weaning food (Begum 2007)	Extruded supplementary food
Moisture (%)	6.0	–
Protein (g)	12.0	14.7
Fat (g)	2.0	4.7
Ash (g)	1.8	–
Crude fibre (g)	2.0	1.2
Carbohydrate (g)	76.2	65.2
Energy (kcal)	396	362
Calcium (mg)	250	48
Phosphorous (mg)	210	314
Iron (mg)	5.2	7.1
Bulk density (g/mL)	0.57	–

Now-a-days, about 5% ragi malt is invariably blended with the protein rich energy food to improve its texture. This food is produced on bulk and supplied to the weaning children. The formulation of ragi malt and malt based weaning food is given in Table 12.2.

Malted weaning food contains 12–14% protein which can be blended with vegetable or animal protein source such as grain legumes, milk powder, egg powder, etc., to prepare supplementary food for children. The nutritional composition of malted weaning food and extruded supplementary food is given in Table 12.3.

Weaning is a process in which an infant change from breast milk to a mixed diet, other foods being given regularly over time in increasing amounts until replacement is virtually complete (Mishra et al. 2014). It is important that foods are selected properly so as to provide adequate balance between the nutrients.

Supplementary foods are suitable during the infant's weaning period which can be fed for older infants and young children and for feeding young children as a supplement to breast milk or breast milk substitutes. They are not suitable for use for infants before the beginning of the weaning period. These foods provide those nutrients which either are lacking or are present in insufficient quantities in the base staple foods.

The special feature of the malt flour to form nutrient dense free flowing slurry has been utilized towards the development of "enteral foods". For this purpose, the malt flour is blended with other ingredients such as milk powder, sugar, soya flour, legume flours, vegetable oils and the blend is fortified with essential vitamins and minerals. The blend can be cooked to use as low-cost enteral food or can be spray dried to prepare ready-to-eat enteral foods. The enteral foods prepared using the millet malt were found to be cost effective and clinically efficient in improving the nutritional status of patients and in reducing the hospitalization period.

12.7 Millet Milk Analogue and Milk Powder

Millets are one of the best substitutes to other plant source for the production of milk analogue in which it has rich source of minerals, good source of vitamins, dietary fibres, antioxidants and phytochemicals such as lignans, flavonoids and phenolics. Millet milk analogue are lactose-free and gluten-free which is suitable for celiac disease and gluten allergic patients. Milk analogue from millets is processed by hydrothermal liquefaction (HTL) or hot extraction, cold extraction (Aruna Nair et al. 2019), enzymatic and mashing techniques. The method of extracting milk varies from the source of materials used for the milk preparation; these are (a) extraction of milk from dehulled raw millet; (b) extraction of milk from cooked millet; (c) extraction of milk from whole millet powder (Afroz et al. 2016).

Preparation of millet milk from dehulled raw millet undergoes various processes such as washing, soaking; grinding, filtering and also malting will improves the physiochemical characteristic of the product. Soaking is an important step to moist or wet the millets to soften the seeds to produce good quality of milk. Optimum soaking time for the milk analogue preparation is 8–12 h. Soaked water was removed from the grains and thoroughly washed. The soaked seeds are grounded with water to make slurry consistency, where the wet milling time depends upon the soaking time of various millet cultivars. The lower and higher soaking time will also increase the wet milling or grinding time (Munu et al. 2016). The slurry was subjected to a filtration process where the course and insoluble parts are removed from the milk. Extracting millet milk from cooked millet is similar to the millet milk extracted from the raw millet and the only difference is here after soaking, the millet was boiled and cooked then blended with water to make slurry consistency. After that, filtration was carried out to obtain milk. Millet milk can also extracted by using whole dehulled millet powder. In this method millet flour was blended with water and continuously stirred to prevent clumps and filtered using muslin cloth to remove the unwanted residues. Then the mixture was subjected to heat for 10–15 min to obtain millet milk (Di Stefano et al. 2017).

The milk analogue obtained from millets such as kuthiraivali, saamai, varagu, ragi and sorghum using enzymatic method improves the nutritional quality of milk and can be served with palm sugar has higher acceptability and consumed as vegan milk and non-dairy milk by all age groups (Shunmugapriya et al. 2020).

Processing of millet milk to powder will be improved the shelf life stability of the aqueous liquefaction of millet by removing the water content from the milk and also reduce the bulk density of the product which is an essential parameter for product

Table 12.4 Proximate composition of millet milk powder (g/100 g)

Proximate value (%)	Spray dryer	Tray dryer	Drum dryer
Protein	8.75	8.312	9.18
Ash	0.90	1.02	1.35
Fat	2.15	3.05	1.80
Carbohydrates	61.00	65.62	68.67
Energy (Kcal)	302.37	323.14	327.59

development. Various drying equipment such as tray dryers, fluidized bed dryers, tunnel dryers, spray dryers, rotary dryers, belt dryers, freeze dryers, drum dryer, low-humidity-low-temperature dryer and refractive-window dryer can be used for drying millet milk analogue. Spray dryer and drum dryers are commonly used drying technique in milk powder production due to its high efficiency. The effect of various drying method on proximate composition of milk powder using malted millet by cold extraction technique is shown in Table 12.4.

Physicochemical properties of the milk powder produced by the spray dryer depend upon the feeding material as well as spray dryer parameters. Standardization has to be done for the particular feeding material of millet milk at various spray dryer parameters to obtain the good quality powder. Millet milk powder can be utilized and used for many food product preparations (Afoakwah et al. 2012). The extracted millet milk can be dehydrated using hot air oven at 70–80 °C for 8 h and the dried milk is grounded and it could be utilized for the extruded products (Devi and Sangeetha 2013).

12.8 Millet Pellet

Millet pellets can be processed by compressed moulded technique and semi-extruded or indirect extrusion technique. The proper pre mixture should be prepared for making pellet prior to granulation and compression or extrusion. The millet milk powder is base compound which will be blended with binder, lubricant and flavour. Blending time and granulation should be optimized to get proper mixture. Granulation is the mandatory process to obtain uniform particle size and smooth flow of mixture and drying has to done to prevent deterioration. The final step involved in pellet formation is compaction or compression is mixture directly compressed into pellets (Vink 1996). Semi-extruded millet pellet is prepared by introducing dough which is made from millet milk powder in the extruder at low presser and low temperature to prevent expansion and shaped into different structure based on the die used. After that it was dried and cooked by using various process techniques like frying, baking and hot air puffing to make ready-to-eat snack.

12.9 Millet Papads

Millet papad prepared by combination of other ingredients like black gram, green gram and other cereals are the primary materials for making papad. Papads are commonly used as dietary adjuncts. The first step in making of papad, (a) Preparation of dough by mixing flour and water; (b) Making thin sheet from dough by rolling it; (c) Drying the papad until get desire moisture content.

Traditionally, black gram is used in the preparation of Papad. However, it has been observed that finger miller flour can be substituted to an extent of 60% without affecting the rolling quality and appearance (Begum 2007). The prepared flour is cooked with appropriate quantity of water during which the starch is gelatinized completely. The dough is then flattened and is dried. Initially, the millet papads appear dark and less appealing but on deep frying, the product turns light coloured due to their better expansion characteristics (Malleshi 2007). The process details of finger millet papad is shown in Fig. 12.4 and its nutritional composition is given in Table 12.5.

Finger Millet Papads

The ingredients required for the preparation of papad are finger millet flour 600 g, black gram dhal flour 300 g, sago flour 200 g, papad khar (seasoning) 25 g, cumin, pepper and redchilli 5g, and salt 50 g.

Ragi flour + Black gram dhal flour + Sago flour
↓
Add papad khar and salt
↓
Add coarsely pounded cumin, pepper and red chilli
↓
Make dough with hot water and knead oil
↓
Rest for 30 minutes
↓
Divide the dough into 16 balls
↓
Press using papad press
↓
Dry in sun/shade
↓
Finger millet Papads
↓
Deep fry/Roast

Fig. 12.4 Processing of finger millet papad (Prabhakar et al. 2016)

Table 12.5 Nutritional composition of finger millet papad (g/100 g) (Begum 2007)

Nutrients	Ragi papads
Moisture (%)	4.8
Protein (g)	8.6
Fat (g)	1.4
Ash (g)	5.3
Crude fibre (g)	1.8
Carbohydrate (g)	78
Energy (Kcal)	359
Calcium (mg)	157
Phosphorous (mg)	265
Iron (mg)	5.4

12.10 Extruded Products

The milled grains contain good amount of starch and exhibit good extrusion cooking characteristics. Millets can be easily adopted to advance processing such as extrusion owing to their nutrient composition and some functional properties. This indicates their potential for preparation of man-made engineering foods in the form of ready-to-eat and ready-to-cook food products (Ushakumari and Malleshi 2007).

The millet grits that are equilibrated to about 18% moisture form well expanded grains on extrusion cooking which can be utilized as ready-to-eat food or hot extruded products with porous and crunchy structure. The extruded ready-to-eat food products can be prepared in different forms such as breakfast cereals and couscous or grits. The end product can be prepared based on the requirement of the consumer. For supplementary foods, the millet flour (70%) can be blended with legumes (30%) and also can be fortified with essential vitamins and minerals for extrusion. It can be further pulverized and can be blend with milk powder to prepare supplementary foods for children and mothers. For snack foods, the extruded millet can be coated with different spices and condiments besides co-extrusion with sweet or hot stuffing.

The ready-to-cook extruded millet products are convenience food prepared through cold extrusion system. At present, extruded pasta from millet is gaining more popularity. A ready-to-cook pasta product is available in the form of spaghetti, macaroni, vermicelli and noodles which are generally hard and brittle. For preparation of pasta, the millet flour is blended with wheat flour to derive the benefits of wheat gluten, which enables cold extrusion (Begum 2007). Pasta could be exclusively millet based and the process involves pretreatment of millet to facilitate extrusion and retention of the texture of the pasta products such as noodle and vermicelli without fissuring when cooked in water. The noodles and vermicelli can also be prepared mainly for kids by malted ragi flour which has the benefits of enhanced nutrients especially for children. Millet vermicelli can also be cut into desired size to get uniform pieces. The prepared *vermicelli* can be utilized in many traditional local Indian popular food products such as *kheer*, *uppuma*, *pongal*, *dhokla*, *pulao* and *bath*.

12.11 Milled Flour and Atta

The milled millet grains have tremendous potential to be prepared as ready-to-cook products. It can be cooked as discrete grains or can be size graded into grits or semolina or can be pulverized into milled flour and finely milled whole millet flour such as atta for various food uses (Ushakumari and Malleshi 2007).

The most commonly practiced primary processing for preparation of flour and atta is pulverization or milling. The grains should be cleaned to get rid of the foreign materials. Destoners can be used to remove stones while the grains can be deglumed using abrasive mills to remove the outer pericarp (Malleshi 2007). These grains are generally hand pounded though at some places, dehulling is being done using emery stone type flour mills and generally the whole meal is used for food preparation. Rarely, some consumers separate out a small portion of seed coat as coarse material by sieving.

The milled millet flour and atta are gluten-free and has nutty flavour which makes it potential ingredient for gluten-free products in bakery and extruded products. Refining of millet helps in improving the colour and bioavailability of nutrients for utilization in commercial products especially functional bakery and extruded products. Conventional milling can be done to prepare refined flour. Tempering the millet grain kernels with 5–7% of the water for 10 min before milling makes the bran tougher, lower the bran brittle which improves the efficiency of flour extraction, and mellows the endosperm of the kernel. Thus, sieving the flour with 80 mesh after pulverizing removes the husk which in turn gives refined flour with very low level of seed coat (Begum 2007). The seed coat which forms the by-product of the refining process contains about 60% calcium and may serve as a natural source of this important dietary mineral or as an ingredient for calcium bio fortification (Malleshi 2007).

12.12 Instant Millet Food Mixes

Millet is consumed after processing into grits and flour, from which traditional meals and snacks are prepared. It is consumed in the form of thin or thick fermented or unfermented *porridge*, *flat breads* and *nutri balls* or *flat cubes*. For different products preparation, sometimes millet flour is fortified with other cereal and legume flours. The details of processing of millet based instant food mix and preparation of Indian traditional snack and breakfast namely *laddu* or avinsh (sphere-shaped sweet), *kola puttu* (*portioned steamed breakfast*) and *roti* (round flat bread) are given in Fig. 12.5.

The flour from the milled millet grains has potential for preparation of fabricated food such as *noodle*, *vermicelli* and *bhujia* (mildly spicy, crispy and deep fried local snack in Bikaner, Western state of India) and to use for the preparation of many

Instant Snack Mix	***Laddu* or Avinsh (sphere-shaped sweet) (Verma et al. 2015; Rashid et al. 2019; Manvi and Mamta 2015)**
The ingredients required for the preparation of instant snack mix are sorghum (500 g) and maize (500 g). The processing of multi-purpose instant snack and breakfast mix is shown in Fig 4. Grains ↓ Cleaning ↓ Drying ↓ Grinding in to flour (pulverizer) ↓ Sieving (60 mm sieve) ↓ Roasting ↓ **Instant Mix** ↓ Packing ↓ Storing at ambient temperature	The ingredients required for the preparation of *laddu* or avinsh sphere-shaped sweet using instant snack mix are powdered sugar (50g) and instant snack mix (100g). Take instant snack mix in a bowl ↓ Add powdered sugar ↓ Add fat ↓ Rounding and shaping ↓ ***Laddu* or Avinsh**
***Kola Puttu* (portioned steamed breakfast) (Mamatha Rani et al. 2019)**	***Roti* (round flat bread) (Panghal et al. 2019; Kulkarni and Sakhale 2018)**
The ingredients required for the preparation of *kolaputtu* using instant breakfast mix are coconut scrapping (50g), sugar (50g), water (300ml), salt (5g) and instant mix (1000 g). Instant breakfast mix ↓ Adding water and salt ↓ Mixing well ↓ Placing wet flour 1 ¼ inch (*kolaputtu*maker) ↓ Adding coconut scrapping on the top of the flour ↓ Adding wet flour ↓ Adding coconut scrapings on the top of the flour ↓ Repeating till it reaches the end *puttu* maker ↓ Closing the mouth of *kolaputtu*maker ↓ Steaming for 10 min ↓ Removing from fire ↓ Adding sugar and coconut scrappings ↓ Mixing well ↓ ***Kola Puttu***	The ingredients are required for the preparation of *roti* using instant breakfast mix are onion (20g, green chillies (20g), chilli powder (10g), cumin (5g), turmeric powder (2.5g), water (500ml), salt (5g), oil (100ml) and instant mix (1000g). Instant breakfast mix ↓ Adding chopped onion, green chillies, chilli powder, Cumin, turmeric powder, salt and water ↓ Mixing well and shape (roti shape) ↓ Cooking for 5 min in hot thava (by adding oil) ↓ ***Roti***

Fig. 12.5 Processing of millet based instant mix for the preparation of *laddu*, *puttu* and *roti*

Instant *Adai or Crepe* Mix (Balasasirekha and Santhoshini 2016)

The ingredients required for the preparation of multigrain *adai mix* are sorghum (100 g), italian millet (100 g), kodo millet (100 g), raw rice (100 g), bengal gram dhal (100 g), red gram dhal (100 g), horse gram (100 g), green gram whole (100 g), soya bean (100 g), cowpea (100 g), red chilli powder (20 g) and salt (20 g). Optional ingredients are dried shredded carrot, beetroot, cabbage, beans with cumin seeds.

Grains (1000g)
↓
Cleaning (to remove dust and stone)
↓
Washing
↓
Drying
↓
Grinding (by using pulverizer)
↓
Sieving (60 mm sieve)
↓
Mix
↓
Adding red chilli powder, asafoetida and salt
↓
Mixing well
↓
Instant *Adai* or *Crepe* Mix

Adai or *crepe* is a kind of *dosa*, a popular South Indian food mainly consumed by people of Tamil Nadu. It is high in protein which makes a healthy breakfast for kids.

Instant *Adai* or *Crepe* Mix
↓
Adding water (200 ml)
↓
Adding 5 g coconut pieces, 2 g chopped fresh onion and curry leaves
↓
Mixing well
↓
Soaking (one hr)
↓
Spreading on hot tava
↓
Smearing oil
↓
Cooking
↓
Adai* or *Crepe

Fig. 12.6 Processing of millet based instant *adai* mix

Instant *Koozh* or Gruel Mix (Thirumangaimannan and Gurumurthy 2013)	**Instant *Sathu Maavu* or Health Mix (Vijayakumar and Mohankumar 2009)**
Millet *koozh* or gruel is consumed as a traditional breakfast as well as lunch food in some regions of India. The ingredients required for the preparation of millet *koozh* are kodo millet (400g), raw rice flour (400g) and black gram flour (200g). Grains ↓ Cleaning (to remove dust and dirt) ↓ Washing ↓ Drying separately (2 h) ↓ Roasting separately (3 min.) ↓ Powdering (using pulverizer) ↓ Sieving (80 mm) ↓ Flour → adding raw rice flour and black gram flour ↓ Mixing salt (0.75 g) ↓ **Mix** ↓ Adding water (50 ml) ↓ Mixing well ↓ Thick batter ↓ Boiling 200 ml of water ↓ Adding the batter ↓ Cooking for 5min ↓ **Millet *koozh***	The ingredients required for the preparation of *sathu maavu* or health mix are pearl millet (1kg), palm sugar (½ kg), pepper (10g), dry ginger with cardamom (5g). Pearl Millet ↓ Cleaning ↓ Hand pounding ↓ Pearling ↓ Roasting ↓ Sieving ↓ Roasting ↓ Pulverizing ↓ ***Sathu maavu*** The mix (per 100 g) has a carbohydrate content of 79 g, protein of 7.89 g and energy content of 363 kCal.

Fig. 12.7 Processing of millet based instant *gruel* and health mix

Table 12.6 Nutritional composition of millet based instant food mix, *adai* and gruel mix (g/100 g) (Thirumangaimannan and Gurumurthy 2013; Balasasirekha and Santhoshini 2016)

Nutrients	Instant mix	Adai/crepe mix	Koozh/gruel mix
Moisture (%)	9.95	11.35	9.80
Carbohydrate (g)	65.4	59.64	66.5
Protein (g)	7.80	19.42	8.83
Crude fibre (g)	2.40	4.26	4.20
Calcium (mg)	5.52	56.00	10.32
Phosphorous (mg)	240.00	0.19	250.00
Sodium (mg)	8.23	25.50	1.48
Potassium (mg)	56.63	11.30	131.4
Iron (mg)	6.50	3.35	7.57
Copper (mg)	0.31	0.33	0.18
Zinc (mg)	4.85	1.23	1.06
Manganese (mg)	1.40	0.99	1.06

traditional food items and its instant mixes. The details of processing of millet *adai* or *crepe*, *koozh* or *gruel*, *sathu maavu* or *health mix* are given in Figs. 12.6 and 12.7 and nutritional composition of instant mix, *adai* or *crepe* mix and *koozh* or gruel mix are given in Table 12.6.

12.13 Millet Meal

The millet meal is called as *Mudde* which is very healthy staple food and is prepared using millet flour. It is a wholesome traditional food in the state of Karnataka and Andhra Pradesh. The flour from the millets could also be roller dried to prepare a ready-to-eat food, most suitable as a thickener in soup or porridge. The roller dried millet may also find usage as a component of millet value addition in the form of millet starch and edible film.

Since, there is growing demand for ready-to-cook products; a need has arisen on preparation of the millet flour especially suitable for traditional food product such as millet meal. Slurry is formed by mixing small quantity of flour with water. The slurry is boiled and predetermined quantity of flour is gradually added to the boiling slurry. The flour is steamed and mixed to a smooth consistency. Steaming the flour reduces the stickiness which improves the hand and mouth feel. The boiled mix is then rolled into balls of particular size and is served in bamboo baskets in many regions of India. *Mudde* balls can be rolled in sauce and can be swallowed without chewing. Studies reveal that amylase inhibitor in ragi retains its activity even after preparation of *mudde* which partially inhibits the amyloglucosidase activity in the digestive tract leading to slow digestion of its carbohydrate. This offers advantage with respect to slow digestibility because the *mudde* does not undergo partial digestion by the salivary amylase in the mouth (Malleshi 2007). Pictorial representation on

Fig. 12.8 Pictorial representation on indigenous method of preparation of sorghum *mudde*

indigenous method of preparation of sorghum *mudde* or meal is shown in Fig. 12.8 and process details of sorghum and bajra *mudde* are shown in Figs. 12.9 and 12.10.

12.14 Traditional Millet Foods in India

In India, many different kinds of traditional foods are made and they form the staple diet for many rural and urban households. Each region has its own traditional food habits. It is interesting learn that rural consumers are familiar with traditional products of millets. In several rural households, a vast variety of traditional snacks are made from ragi and other small millets. Milled small millets namely ragi, panivaragu, kuthiraivali, thinai, varagu and saamai are similar to rice in cooking properties and used in making several kinds of food items. The origin and common names of millets are as follows:

The cooking style of these small millets in India are *bhat*, *kheer* (sweetened thin porridge), *roti/chapatti* (unleavened bread), *gruel* (thin porridge), *mudde* (stiff porridge), *dosa* (fermented pancake), *shavige* (noodles), *hurihittu* (popped grain flour), *sattu*, *pappad* (deep fried or roasted), *halwa* (cooked sweet product), malted

Sorghum *Mudde* or Meal
The meal prepared with sorghum (per 100g) has a moisture content of 45.6%, protein content of 5.1 g, crude fiber 1.2 g and carbohydrate content of 45.3 g. Cleaning the sorghum ↓ Soaking in water (15 min) ↓ Draining the water & surface drying ↓ Gentle pounding in mortar using pestle ↓ Sifting → Outer husk ↓ Vigorous pounding and sifting (repeated for 3 to 5 times) ↓ Selection of larger size grits, smaller size grits and fine sorghum flour (equal in quantity) ↓ Boiling water (3 times weight of sorghum) (Vessel size 4 to 4.5 times volume of sorghum to be cooked) ↓ Addition of larger size grits ↓ Cooking (complete gelatinization) ↓ Addition of smaller size grits (complete gelatinization) ↓ Reduce the flame ↓ Addition of fine flour and stir vigorously (pasty and completely gelatinized food is formed) ↓ Homogenous semisolid food ↓ Level the top surface and cover with lid ↓ Leave it for 15 min on hot stove ↓ Cooked food ↓ Take out the food after mixing in the form of ball (8 to 10cm dia) ↓ **Sorghum meal / *mudde*** ↓ Consume with *sambar, thin rasam/bassaru/uppesru, butter milk/curd*, etc. ↓ Immerse the balls in potable water for later use with *curd* and *butter milk*

Fig. 12.9 Processing of sorghum *mudde* or meal (Sarkar et al. 2015)

Bajra *Mudde* or Meal
The ingredients required for the preparation of ready-to-cook millet *meal* using bajra meal mix are water 250 ml, salt 5 g, pasteurized milk 225 ml, 12 hr fermented curd 20 ml, small onions 40 g (4× 2× 1.5 mm size), green chillies 10 g (2-3 mm size pieces), ginger 1 g (2× 1.5× 1.0 mm), curry leaves 5 g (10 mm), cumin seeds 2 g, bengal gram 2 g and bajra meal mix100 g. Bajra meal mix ↓ Add water ↓ Add salt ↓ Mix thoroughly and heat on direct flame for 5 min ↓ Cook in a pressure cooker till 1st time release of pressure ↓ Keep the stove simmer / low flame for 10 min ↓ Remove the pressure cooker from the stove and cool it for 15 min ↓ Add milk at 80°C to the cooked mix and mix well ↓ Inoculate with culture/curd @ 43°C and mix well ↓ Add small onions ↓ Add other ingredients after seasoning ↓ Mix well and keep it for 4h ↓ Package and storage at 10°C / Serve ↓ **Bajra *Curd meal*** ↓ Shelf life 36 hours

Fig. 12.10 Processing of bajra *mudde* or meal (Sarkar et al. 2015)

beverage and fermented beverages. Many other traditional foods are made from popped ragi flour mixed with sugar or jaggery or ghee or milk or butter milk and salt. In south India traditional millet products namely, *koozh-porridge* also called *kanji* (made from ragi, bajra) *puttu* (jowar, maize, ragi), *kali* (ragi, bajra), *adai/roti* (ragi, bajra, varagu) are more popular.

Mixture of wheat and millets with the perfect proposition makes the chapatti tastier one. Indian flatbread or chapattis and phulkas are the most popular daily bread in various parts of North India. It can be prepared from millet flour and millet composite flour or blended with wheat flour for making softer chapatti and lowering the retrogradation with shelf stability. It is an excellent substitute for whole meal wheat flour or chakki atta as gluten-free alternatives will make the dough easy to roll and puff well on the pan and flame. Millet chapattis have a higher amount of fibre, rich in antioxidants and has essential minerals which are non-glutinous wholesome bread suitable for those with celiac disease and for those suffering from gluten-associated inflammation and health risk. Apart from the taste, it became nutrition rich food and has slower digestion will makes us feel fuller.

Rice from decorticated saamai, thinai and ragi are most commonly consumed foods. Local sweet products like *hurakkiholige*, *halubai* and sweet *cheese* from thinai (*ginna*), fried products like *chakkali*, *dosa* and *hurihittu* from ragi are some of the traditional foods having cultural significance. Fermented and malted beverages of millets are also consumed by people at large quantities. Decorticated saamai has a special significance and is used as food during fasting in the form of cooked rice (Yenagi 2007).

Ragi is normally consumed in the form of flour-based foods such as *roti* (unleavened pancake), *mudde* (stiff porridge/dumpling) and *ambli* (thin porridge) and each of these foods have their own characteristics features (Kar 2007). The finer millet flour containing about 10% of damaged starch is more suitable for roti whereas slightly coarse flour is desired for *mudde*. The damaged starch in the flour absorbs more water during dough preparation and facilitates its flattening for *roti* making. On the other hand, the slight grittiness of the flour prevents lump formation during *mudde* preparation.

The thin *porridge* or *ambali* of millets is normally a mild fermented product. For its preparation, the millet flour is mixed with water along with a small quantity of buttermilk and the contents are left overnight for mild fermentation. This improves the bioavailability of minerals and imparts feeble sour taste. The millet *porridge* is consumed in the summer season because of its soothing effect (Malleshi 2007).

Idli and *dosa* which are conventionally prepared from rice can also be prepared using the millet as base. *Dosa* from batter prepared by soaking, grinding and fermenting parboiled and raw varagu grains, black gram dhal (3:1:2) and methi seeds were well appreciated. *Idli* prepared by soaking raw kodo and blackgram in the ratio of 2:1 was soft and well accepted. *Uthappam* was made from dosa/idli batters. Raw varagu grains were also made into *kheer* and substituted rice in traditional products like *bhakri* (unleavened bread), *idli*, *dosa* and *uttapam*. The textures of these products are nearly comparable to rice. In view of the special nutritional features, nowadays even ready mixes of *idli* and *dosa* from ragi are available in the market.

Among the food grains, millets are the cheapest source of energy and rich micronutrients and are consumed as staple food predominantly among the millet growers. Preparation of few selected millet products during festivals is strictly followed by rural communities and thus has preserved the traditional cultural significance of millet use in their regular diet. Rural consumers are more familiar with traditional products of millets only. The use of millets is becoming less popular especially among urban population due to non-availability of suitable post-harvest technologies to develop consumer attractive processed products similar to rice or wheat (Yenagi 2007).

Development of such millet products of urban-domestic and commercial use will enhance the contribution of these underutilized crops to the food basket. Thus, it is evident that appropriate processing of small millets by modern technique with futuristic approach will lead to the development of nutritious products and heath foods, lessen the load on major cereals, be remunerative to marginal farmers and improve the economy of hilly and tribal areas and dry lands (Kar 2007).

The knowledge of use of millets as *roti*, *mudde*, *ambali* and rice was found in 50% consumers. Only few consumers (5–25%) had the knowledge of use of millet for other diversified uses like *idli*, *malt*, *porridge* and other health foods. None of the consumers were aware of availability of secondary processed products like bakery products, extruded products, *papad*, *fryums* and malt in local markets. Nearly 50% consumers had the knowledge of medicinal value of millets and its health benefits. Only 15% mentioned the high satiety value of millets and its role in the management of diabetes. The list of popular traditional millet products in various regions of India and Africa are shown in Table 12.7 and the pictorial representation of tradition millet food products are shown in Fig. 12.11.

12.15 Traditional Millet Foods in Africa

12.15.1 Koko

It is utilized by many people in West Africa. Steeping is initial step involved in *koko* preparation. After steeping, the water is removed and grind with some spices. Incorporation of water into the ground material makes thick slurry and incubated. Sedimentation takes place in slurry and the top liquid layer was separated and cooked. The bottom layer of sediment was added and the cooking process continuous until get the perfect consistency. The microorganism presents in the *koko* enhance the nutritional value and well suitable for sick people (Amadou et al. 2011).

12.15.2 Fura

It is prepared by bajra in the region of Sahel. Moistened bajraare dehulled and dried. Flour was obtained by grinding the dried milled and sieved. The flour was combined with black pepper, ginger powder and water make soft dough. Small round balls as shown in Fig. 12.11 are prepared by dough and cooked for 30 min under atmospheric pressure. Finally, fura produced by rebuilt the dough to porridge like consistency with sour milk (Amadou et al. 2011; Adebayo-Oyetoro et al. 2017).

12.15.3 Mangisi

It is an alcoholic beverage. In rural African country, fermented beverages play an important role in diet. It tastes like sweet-sour and prepared by natural fermented

Table 12.7 Popular traditional millet food products in various regions of India and Africa

Product	Source	Type	Region	Reference
Koko	Pearl millet	Porridge	West Africa	Amadou et al. (2011)
Fura	Pearl millet	Porridge	Sahel	Amadou et al. (2011), Adebayo-Oyetoro et al. (2017)
Uji	Finger millet, or sorghum	Porridge	Tanzania	Wanjala et al. (2016)
Mangisi	Finger millet	Beer	Zimbabwe	Amadou et al. (2011), Hassan et al. (2021)
Bushera	Sorghum	Beer	Uganda	Amadou et al. (2011), Muyanja et al. (2003)
Ben-saalga	Pearl millet	Gruel	Burkina faso	Amadou et al. (2011), Tou et al. (2007)
Togwa	Finger millet	Sweet beer	Tanzania	Amadou et al. (2011), Kitabatake et al. (2003)
Ogi	Sorghum	Porridge	West Africa	Amadou et al. (2011), Inyang and Idoko (2006)
Dambu	Maize, or sorghum	Dumplings	Africa	Amadou et al. (2011), Agu et al. (2008)
Jandh	Finger millet	Beer	Nepal	Amadou et al. (2011), Dahal et al. (2005)
Chhyang	Finger millet, or sorghum	Beer	India Nepal	Thapa et al. (2015)
kununzaki	Sorghum	Sweet beer	Nigeria	Nkama et al. (2010), Olaoye et al. (2016)
Boza	Common millet	Beer	Turkish	Arici and Daglioglu (2002)
Injera	Teff	Flatbread	Ethiopia	Neela and Fanta (2020)
Malt	Foxtail millet/ barnyard millet/ finger millet/ sorghum	Beverage	India	Sarkar et al. (2015)
Milk	Foxtail millet/ barnyard millet/ finger millet/ sorghum	Beverage	India	Aruna Nair et al. (2019)
Papad	Finger millet/ sorghum	Seasoned flat bread	India	Prabhakar et al. (2016)
Vermicelli	Finger millet/pearl millet	Pasta	India	Lande et al. (2017), Ezhilarasi and Nazni (2018)
Kola Puttu	Finger millet/foxtail millet	Breakfast food	South India	Mamatha Rani et al. (2019)
Roti	Finger millet/ sorghum/foxtail millet/pearl millet	Flat bread	India	Panghal et al. (2019), Kulkarni and Sakhale (2018)
Mudde	Sorghum/pearl millet	Dumbling	India	Krishnappa (2017)

(continued)

Table 12.7 (continued)

Product	Source	Type	Region	Reference
Laddu	Finger millet/foxtail millet/barnyard millet/pearl millet	Sweet	India	Verma et al. (2015), Rashid et al. (2019), Manvi and Mamta (2015)
Adai	Sorghum/little millet/barnyard millet/foxtail millet	Pan cake	India	Balasasirekha and Santhoshini (2016)
Weaning Food	Germinated millet	Gruel	India	Sarkar et al. (2015)
Koozh	Finger millet/pearl millet	Porridge	South India	Thirumangaimannan and Gurumurthy (2013)
Sathu Maavu	Multimillet	Flour	South India	Vijayakumar and Mohankumar (2009)
Bogob (ting)	Sorghum/pearl millet	Porridge	South Africa	Adebiyi et al. (2018)

millet mash. The preparation methods vary place to place. One method is malted ragi is milled and mixed with water. It is heated near boiling now it is called “masvusvu” then cooled, diluted and allowed to stand for several hours which take spontaneous fermentation leads final product Mangisi. Another method is similar until the process fermentation, after that more malt is added and further fermentation takes place until third day. Due to excess addition of malt on second day gives more alcohol content (Amadou et al. 2011; Hassan et al. 2021).

12.15.4 Uji

It is lactic acid fermented porridge-like food as shown in Fig. 12.11a. It is prepared by fermentation of cereals with different combination of cassava flour. Most commonly used combination is 1:1 and the inoculums prepared by backslopping technique. Uji is consumed by both adult (as beverage) and children (as weaning food) (Wanjala et al. 2016).

12.15.5 Ben-saalga

It is famous fermented food produced by bajra. Ben-saalga is a type of fermented gruel that is frequently used as a complementary food for infants and young children in Africa. The ben-saalga is prepared from single millet or composite millets that are soaked for 6–24 h depending on the cultivars. In this stage, the first fermentation occurs during soaking. After that, the grains are wetmilled with or without the addition of spices, and then dissolved in water and filtered to remove the sludge followed by the filtrate decanted for 6–10 h. During this stage lactic acid fermentation takes place. Then water is added to the supernatant and boiled. Finally, the

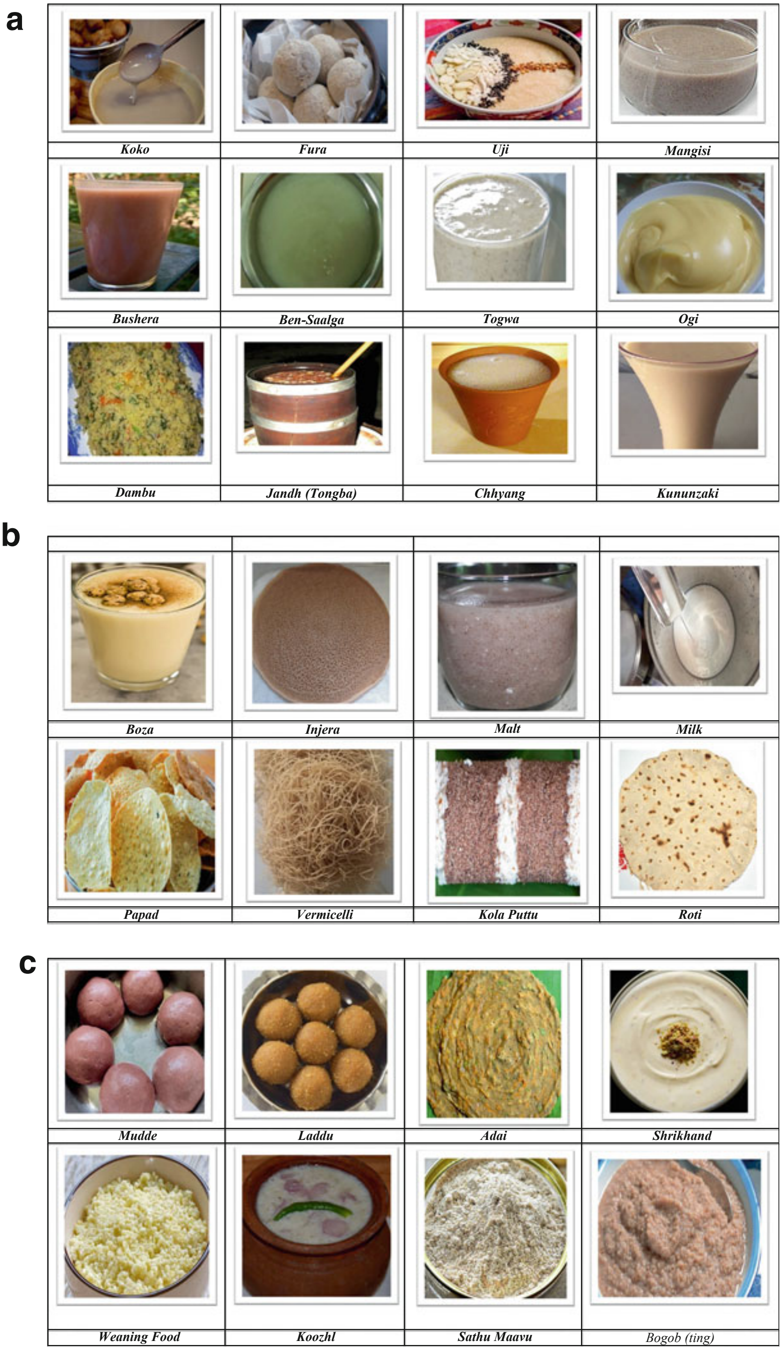

Fig. 12.11 (**a**–**c**) Popular traditional millet foods from various regions of India and Africa

homogenized pellet or precipitate is mixed and cooked for 6–20 min (Amadou et al. 2011; Tout et al. 2007). Benkida is also prepared as similar to ben-saalga. Millet flour is used for the preparation of benkida. Initially, water is sprinkled on milled flour and kneaded gently to make granules. After kneading the flour is sieved to prepare the granules. The extracted granules are boiled with diluted supernatant. After that, the pellet is mixed with the whole and cooked for 6 min. Ben-saalga of pearl millet is as shown in Fig. 12.11a.

12.15.6 Bushera

Bushera is a fermented beverage consumed traditionally by all age groups. It is the most popular thirst-quenching drink available in the Southwestern region of Uganda. It is produced from malted black sorghum and unmalted brown sorghum. It is prepared by soaking grains in water for 12 h followed by malting for 48 -72 h. During malting, the wood ash is mixed with soaked grains to hasten the malting process and also to increase iron, magnesium, and zinc in malted grain. The malted grain is then dried at 13% moisture. One part of malted flour is mixed with three parts of water and boiled for 5 min. After cooling, it is allowed for fermentation at an ambient temperature of 28 ± 2 °C for 2 -6 days. If unmalted millet flour is used for the production of bushera, millet malt is added ranging from 5 to 7.5 g to initiate the fermentation and enhance flavour and sweetness in the unmalted grain-based beverage. The most predominant lactic acid bacteria isolated from this bushera are *Lactobacillus*, *Lactococcus*, *Leuconostoc*, *Enterococcus* and *Streptococcus. Lb. brevis (*Amadou et al. 2011*;* Muyanja et al. 2003*)*.

12.15.7 Togwa

It is generally prepared from maize and ragi malt in the region of southern Tanzania. It is taken by both adult and children as an energy drink and also a weaning food. It is cooked with cereal or cassava flour with water and then old togwa added as a starter culture. The spontaneous fermentation takes place and produces a togwa as shown in Fig. 12.11a with a different taste. *Lactobacillus plantarum*, *L. brevis*, *L. fermentum*, *L. cellobiosus*, *Weissella confuse* and *Pediococcus pentosaceus* are all common bacteria present during fermentation of togwa (Amadou et al. 2011; Kitabatake et al. 2003).

12.15.8 Ogi

It is porridge prepared by fermented millet, sorghum or maize paste or cake in West Africa. It is also called as wet cake and sold in polythene bag or wrapped with leaves. Gelatinized form of ogi known as pap and consumed by children as a weaning food and adult are consumed as a breakfast meal. Organism formed during fermentation process is responsible for the enhancement of nutritional character in ogi. Lactic, acetic, butyric and formic acids in ogi are the key reason for the aroma and sour flavour. Mild sour flavour with light coloured ogi is most preferred character by the consumer (Amadou et al. 2011; Inyang and Idoko 2006).

12.15.9 Dambu

It is steamed, granulated dumblings as shown in Fig. 12.11a made from available millet. The flour is moistened and mixed with spices and steamed for 30 min. Then it is served with fermented milk and sugar (optional). It is nonfermented millet product prepared by both home and commercially (Amadou et al. 2011; Agu et al. 2008).

12.15.10 Kunun Zaki

It is a non-alcoholic fermented beverage and also a famous food in Nigeria. It is spread on other places and highly preferred by South. It consumed as a breakfast drink, appetizer and also a weaning food for infants. It mostly prepared by sorghum, maize and rice and also with some spices (optional) like ginger, garlic, red pepper, black pepper and cloves. It has very poor shelf life due to high moisture content. Researchers investigate to increase the shelf life of the product to enhance the quality of the food. Obanevo and Zidon stated that increasing of shelf life can be achieved by produce powdered Kunun Zaki up to 2 months (Nkama et al. 2010; Olaoye et al. 2016).

12.15.11 Jandh

It is a type of beer and have slightly acidic and sweet flavour. It is produced by fermentation of ragi and sometimes small amount of wheat or corn will add. The seeds are softened by applying steam and then placed on leaves. After that starter culture added to the seeds and mixed thoroughly and incubates the seeds for 24 h at ambient temperature. Next day, it filled in earthen pot and covered with leaves and straws. After fermentation the seed coats are removed and placed in bamboo vessel with water. After 10 min it ready to drink and it is best tonic for postnatal women (Amadou et al. 2011; Dahal et al. 2005).

12.15.12 Chhyang

Chhyang or kodo ko jaanr is one of the most popular fermented drinks that is known to be brewed at the domestic level in a small capacity due to its quite simple process. It is becoming most popular in the world of liquor, and it is often considered more as food than liquor. It is a unique sweet-flavoured mild alcoholic beverage that is high in calories, vitamins, and beneficial lactic acid bacteria and yeast. It is consumed by many poor people in the region of Asia and Africa. In India and Nepal, it is prepared traditionally and consumed since ancient time. It is nutritious and cheaper traditional drink. It is best tonic for cold and used as a remedy for common cod, fevers and allergic rhinitis. The preparation method varies from place to place. The millet is washed and cooked for 30 min after that murcha (Culture) was added. It is placed on the container and allowed to stand for fermentation for several days based on the preference After the fermentation process is complete in the aerobic condition for 2 days and in anaerobic condition for 8 days at a temperature of 28 ± 2 °C, the fermented substrate is transferred from the pot to wooden drums. At this stage, lukewarm water is added to the fermented substrate in the ratio of 2:1 till it gets immersed and kept for 2–5 h. In the final stage, water extraction of the beverage is performed 2–4 times with a time interval of 15–20 min and kept for a day for the final filtrate. The substrate commonly used for the production of chhyang is finger millet. Marcha is the traditionally prepared mixed culture used for the preparation of chhyang in parts of the eastern Himalayas, Yakkha, and Limbu (Thapa et al. 2015).

12.15.13 Boza

It is a traditional lactic acid fermented beverage in Turkish. The term boza derived from the Persian word buze means millet. Apart from the Turkish, this beverages name varies from place to place, for example, the Turkish people who lived in Middle Asia named this beverage as bassoi. Boza is believed as *origin of beer* because it considers as 8000–9000 years old. Boza is also prepared by using rice, wheat or maize but most preferable is millet only. The raw materials are washed and broken into small size like semolina and then cooked in open boiler or steam jacketed kettle. Then the processed material is dehulled and the foreign material was removed. For the preparation of boza, the millet grains are broken into small sizes or soaked for 12 h and cooked as porridge and kept for cooling. Meanwhile, the sourdough culture is prepared using a mixture of yeast, sugar, and flour. After cooling of cooked millet the sourdough culture and yoghurt are added and fermented at a temperature of 30 ± 2 °C for 24–48 h. The prepared boza is commonly used as the starter culture to make the next batch production and the refrigerated boza is preferable for serving. (Arici and Daglioglu 2002).

12.16 Millet Bakery Products

Non-gluten cereals like millet and sorghum can be blended with wheat flour to produce acceptable functional bakery products. The yeast leavened bakery products, namely breads, rolls, doughnuts and sweet dough products; chemical leavened bakery products, namely biscuits, cookies, crackers, muffins and cakes and partially leavened products like puffs, croissants and danish pastries are commonly consumed widely throughout the world. Small millets, ragi and bajra are mainly used for gluten-free bread, biscuit and cake (Shadang and Jaganathan 2014). Sorghum, ragi and bajra have been used either alone or in combination with wheat flour for making bakery products in various parts of the world. Much attention has been given for using millet in composite flour and utilized malted grains with improved nutrients in the preparation of bakery products (Sambavi et al. 2015).

Mechanical dough development method is successfully used to prepare bread containing up to 40% of non-wheat flours such as millet and sorghum. Chemical dough development method employing 35 ppm of cystine, 50 ppm ascorbic acid and 30 ppm potassium bromate is to be quite suitable to prepare bread from millet composite flour. The white sorghum flour to the extent of 30% could be blended with wheat flour to prepare breads and sweet buns at a lower cost. The acceptable bread loaves could be prepared by substitution of wheat flour with sorghum flour to the extent to 15% and 20% in case of 75% and 85% extraction rate of refined sorghum flour, respectively. The optimum level of millet incorporation is to be 20% in all other bakery products.

Cookies are one of the most common snack foods due to their general acceptability, convenience and shelf life. Hydration of flour for 3 h with 2% malt syrup, followed by air drying and use of 0.6% soy lecithin was found to improve the top grain and spread of sorghum in millet cookies equal to wheat products. The cookies could be prepared by incorporation of ragi flour to a level of 50%. The optimum level of addition of minor millet flours in bakery products was up to 25% with some loss of colour and volume. The high protein and calorie biscuits could be from prepared from sorghum, bajra, saamai and ragi substituted with 30% full fat soy flour. Acceptable quality cakes also could be prepared by incorporating foxtail millet flour up to 25% in cake formulations (Jaybhaye et al. 2014).

12.17 Conclusion

The development of millet food products in food industry will create a new avenue to utilize tropical raw materials. The millet food products will help to tide over the problem of malnutrition and under-nutrition in developing countries with nutritious advantage. Considerable interest has been generated by the possibility of improving the nutritional value of processed foods by the addition of millet. This will result in the advantages like:

- Utilization of indigenously grown millets.
- Reduces the cost of products
- Helps to bring varieties with different texture and flavour.

Moreover, the addition of millets will enhance the economic value of the native crops. The nutrient content of millets will improve the functional properties of food products. Complementation of millets in processed food products will serve as a therapeutic food for certain diet conditions.

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By-products from Millet Processing Industry

13

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Abstract

Millets are gaining attention globally due to their varied advantages over the conventionally consumed grains. Hence the issues related to the by-product and waste production following millet processing need to be addressed. The present chapter discusses about various by-products generated during unit operation for millet processing. Further it also deliberates the scopes of utilization of millet by-products and wastes for reducing the carbon footprint.

Keywords

By-product · Waste · Straw · Husk · Broken seeds

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13.1 Introduction

Waste to wealth is an emerging concept, for effectively reducing the carbon footprint and to bring on sustainability to environment. Reuse or extraction of the intended compound from by-products and waste produced from the food industries is a crucial and important aspect for economic, nutritional, and environmental reasons. By-products and waste generated from the food industries are the sources of organic compounds, which leads to an increase in the biological and chemical oxygen demand (Amadou et al. 2013). Extracted compounds from the food industry by-products or waste have a scope to be utilized in the preparation and stabilization of different food products, which includes bakery products, instant breakfasts, wine, sports drinks, ice cream, noodles, and meat analogues (Sharma et al. 2015). By-products are a rich source of carbohydrate, protein, fat, fiber, vitamins, mineral, organic acids, phenolic compounds, pigments etc. Millet crops importantly constitute a group of small grains, and these are widely grown crops especially in harsh climatic conditions. Pearl, finger, foxtail, kodo, browntop, proso (*Panicum miliaceum*), fonio (*Digitaria exilis*), and barnyard (*Echinochloa frumentacea*) are the important millet varieties grown worldwide.

By-product and waste from these varieties are produced at various stages during the processing of millets in industries. Agro-industrial waste millet bran is a rich source of phytochemicals like polyphenol. Millet bran can be used for the production of antioxidant rich-wine (Guo et al. 2018). Microbial fermentation of millet bran increases the soluble dietary fiber that can be in fields like the dairy, bulking agent, and oil retention in baked foods (Chu et al. 2019). By-products generated in industries during processing are different due to the composition of millet varieties (Kumar and Parameswaran 1998).

Seed coat (SC) is one of the important by-products that contains a good fraction of dietary fiber, minerals, and phytochemicals. SC is an important waste generated during the milling, malting, and decortication process that can be used as flour in biscuit preparation. Apart from SC, straw, bran, glumes, and millet broken seeds are an important by-product of millet industries. By-products generated in industries are used for the preparation of activated carbon, biscuits, production of amylase, proteases and lignolytic enzymes, production of bioethanol, as animal feed, etc. (Krishnan et al. 2011).

13.2 By-products of Millets

Husk/seed coat, bran, and broken seeds are produced during agro-industrial processing of millet; husk constitutes carbohydrate-based polymers whereas broken seeds have the same proximate composition as raw seed. By-products such as straw and stem after harvesting of millet are generally used for feeding of cattle as well as for making the concentrated feed and ingredients in cattle feed industries. By-products generated after harvesting and industrial processing of millet are shown in Fig. 13.1.

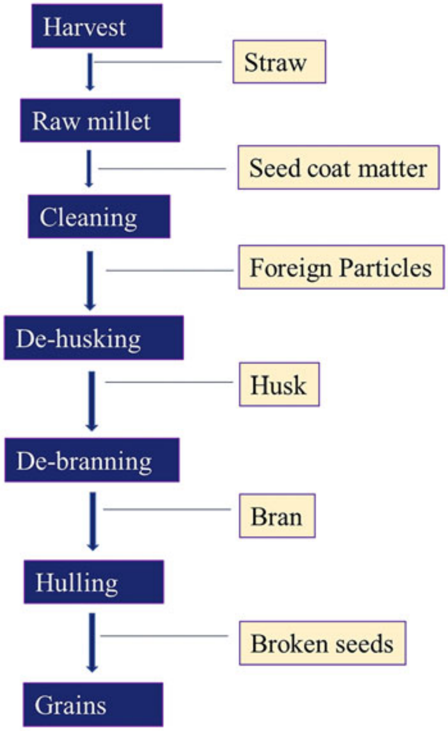

Fig. 13.1 By-products production during millet processing

13.2.1 Finger Millet By-products and Their Utilization

Milling of finger millet results in the removal of bran and SC of the grain (Singh and Raghuvanshi 2012). SC from native, malted, and hydrothermally treated finger millet is a by-product of the processing industry (Devi et al. 2014). SC contains a good fraction of minerals, dietary fiber, and phytochemicals. In recent years, SC has been utilized as additives in cereal foods to produce products with a high percentage of dietary fiber, calcium (Ca), iron (Fe), and zinc (Zn) (Krishnan et al. 2012). The potential use of phytase-active *Lactobacillus pentosus* enzyme to dephytinize seed coat extracted from processed, malted, and hydrothermally treated finger millets are to improve Zinc availability (Sakamma et al. 2018). Finger millet broken seeds have a concentration of 5–8% of protein, 1–2% of ether extractives, 65–75% of carbohydrates, 15–20% of dietary fiber, and 2.5–3.5% minerals, which are a good source for feeding mammals (Muthamilarasan et al. 2016).

13.2.1.1 Bioethanol Production

Brewed grain of finger millet is used for the production of bio-ethanol which has gained significant interest due to its use as an alternative fuel. There are different processes that are applied on the finger millet brewed grains for high yield of bio-ethanol like fermentation. To date, researchers are focusing more on low-cost lignocellulosic materials derived from agriculture wastes and forest residues as well, along with herbaceous materials and municipal waste (Tsigie et al. 2013). Bioethanol can be used as an alternative and reduce the dependence on fossil fuels (Verma and Patel 2013). Bioethanol also reduces the total emission of greenhouse gases. The burning of fossil fuels such as coal and oil releases CO_2, which increases the possibilities of global warming, a manmade disaster, while finger millet-produced bioethanol has been considered as clean, safe, and sustainable to the environment (Erdei et al. 2012).

13.2.1.2 Production of Proteases and Lignolytic Enzymes

Finger millet (*Eleusine coracana*) waste has sufficient microbial protein after a solid-state fermentation process and can be used as an additive in food products. Fermentation of finger millet straw led to solubilization and degradation of fungal protein which was observed as the increase in crude protein content (Belewu and Belewu 2005). Lignin can be degraded by the white-rot fungi on behalf of their ligninolytic enzymes (Arora 1994). Crude protein increases due to converting starch to glucose by hydrolysis and its use as a source of carbon to synthesize the bioavailable waste which is rich source of protein (Bender 1970; Wood 1985).

13.2.1.3 Preparation of Biscuit Using Seed Coat (SC)

The seed coat matter of the millet varieties, which constitutes 15% of the kernel, is recognized as a rich source of dietary fiber, calcium (Ca), and polyphenols (Chethan and Malleshi 2007a, b). The seed coat of millet, which is edible, shows rheological properties such as chewiness and imparts dark color to the food products. SC is a consumable part of the millet varieties and also used for the preparation of glucotype biscuits. Studies have been conducted to prepare high fiber and nutritious biscuits by incorporating fiber material from different sources in biscuits and some other bakery products like bread (Abdul-Hamid and Luan 2000). SC from finger millet can be used for making the composite flour to increase the nutritional qualities of the cookies (Dharmaraj and Malleshi 2011). Treatment with different hydrothermal methods considerably differentiate the nutritional qualities and rheology of finger millet. Therefore, treatment methods concerned with the processing of millets will result in the change of nutrition composition of SC and physical properties such as high concentration of protein, calcium, iron, zinc, and dietary fiber in the biscuits, which are prepared using composite flour (Siwela 2009). Biscuits prepared from millet seed coat increase the health benefits due to the presence of antioxidants (Vratania and Zabik 1978).

13.2.2 Pearl Millet

Pearl millet grain has an average of 75%, 17%, and 8% of endosperm, germ, and bran respectively. The innermost component of the pericarp is the endocarp composed of both cross and tube cells, below outer layer of endosperm of aleurone cells, which may be pigmented (Hill and Hanna 1990). Decortication of millet leads to the production of bran that constitutes three layers of the pericarp, which separates it from the endosperm (Abdelrahman and Hoseney 1984). A range of food products with numerous names are made from pearl millet waste (bran). A major constraint with the utilization of pearl millet waste is the propensity of the flour (or damaged grain) to acquire a mousy rancid odor after few days of milling, which is accentuated once water is used to temper the grain before milling.

13.2.2.1 Pearl Millet Broken as Feed

Pearl millet is also grown for forage purposes worldwide, it has the potential to be used as the alternative feed of maize and sorghum for poultry, swine, and beef cattle (Hanna and Wright 1995).

13.2.2.1.1 Poultry Feed

The metabolizable energy (ME) content of ground pearl millet forage varies from 2.891 to 3.204 kcal/g' dry matter, depending on the cultivar, and values were estimated up to 21%. Dehydrated feed products of coastal Bermuda grass and pearl millet were good in metabolizable energy values to dehydrated alfalfa, also used as the supplementary to xanthophyll in the feeding of poultry. The potential of dehydrated forage to be used as an ancillary to dehydrated alfalfa in supplying supplementary xanthophyll in poultry feeds which need future research (Fancher et al. 1987).

13.2.2.1.2 Beef Cattle

Compared to sorghum grain, pearl millet broken grain has a large composition of fat and protein, protein constitutes a balance of essential amino acids. The estimated net energy of millet was 4% higher than that of finely rolled sorghum. Steers gained 1.32 kg/day on pearl millet compared to 1.26 kg/day on sorghum Hill and Hanna (1990).

13.2.2.1.3 Pig Feeding

Millet broken grains fed to pigs should be finely ground, which will result in a reduced risk of internal irritation caused by the hard hull of the grain. The concentrate prepared by grazing made the pearl millet crop worth $250 per hectare (Burton 1980).

13.2.2.1.4 Sheep Feeding

Broken grains of pearl millet fed to sheep were less digested since higher percentage passed into the faeces (French 1948).

13.2.2.2 Pearl Millet Forage

Forage is a by-product generated after the harvesting of pearl millet which is used for animal feeding purpose. Pearl millet has improved forage production potential which has been developed and are in use in countries such as United States and Australia. Recent varieties have good summer grazing for milk cows and all class of livestock that give a desirable seasonal distribution of forage and also suitable for green chop, dehydration, pelleting, and production of quality silage.

13.2.2.3 Silage

Pearl millet produces good quality silage which is a rich source of carbohydrates where dry matter content has low or no excess moisture (Boyle and Johnson 1968). The stage of maturity at harvest is an important factor that influences the composition as well as the nutritive value of silage. Animals performance to work after feeding the pearl millet silage were found to be higher than that of corn silage (Johnson Jr and Southwell 1960). Feeding of millet silage is much economical to provide high energy per dry matter intake compared to other crop silages. Crude protein percentage was found to be increased from 7.2 in the fresh material to 8.6 in the silage (Silveira and Crocomo 1981).

13.2.2.4 Production of Amylase

Pearl millet residue (PMR) is a rich source of carbon, nitrogen and other metabolites which is essential for the growth and maintenance of fungi. The different agro-industrial residues like pearl millet residue, neem oil cake (NOC), and wheat bran (wb) can be utilized for the production of α-amylase by using both liquid static surface and solid-state fermentation in developing countries like India (Sethi et al. 2016). Glycoside hydrolases which also known as amylases are omnipresent enzymes that are produced by different plants, molds, fungi, bacteria, and animals. The application of these enzymes is higher for biotechnological purposes because of their fungal and bacterial origin. The α-amylase has a higher concentration of tryptophan and tyrosine amino acids which denatures after reaching the temperature approximately 60 °C. These enzymes has the ability to break the starch molecules at different places in order to find maximum yield of maltose, maltotriose and dextrin. This improved yield is due to cleaving from the 1, 4-α-D-glucosidic bonds with nearby glucose units using a straight chain of amylose (Pandey et al. 2000).

13.2.2.5 Compost

Pearl millet boobla (flower glumes and rachilla) with paddy and mustard straw in different mixture ratios can be used for composting for increasing the nutrient (major and minor) content in soils. Composting is used in order to recycle and utilize the organic waste and by-products which has found to be economically viable, socially accepted and eco-friendly technology. Composts prepared from pearl millet and other organic wastes differ in their quality and stability, which depends upon the composition of the raw material used (Ranalli et al. 2001). Compost quality is related to its stability and maturity, which cannot be established by single parameter (Bernal et al. 2009). Several parameters such as temperature, organic matter loss, C/N ratio, cation exchange capacity, humification index, and seed germination index have been proposed for evaluating compost stability (Iglesias Jiménez and Pérez García 1992; Bernal et al. 1998; Benito et al. 2003; Ko et al. 2008).

13.2.2.6 Biogas Production

Pearl millet is a largely grown millet variety worldwide. Africa and Asia provide a suitable environment for the production of biogas. Straw is an important lignocellulosic waste generated after harvesting of Pearl millet. Among different bioenergy production methods from agricultural waste, anaerobic digestion is a widely accepted and efficient method of biogas production. Weak alkaline (lime) pretreatment of pearl millet straw increases the yield of biogas production (Kumar et al. 2019).

13.2.2.7 Laccase Production

Laccase is an oxidase enzyme which is used to increase the reaction rate in organic and inorganic substrates like oxidation of phenolics and polymer degradation. Laccase is produced by fungi and bacteria, etc. Husk produced after agro-industrial processing of pearl and foxtail millet can be used for the production of laccase enzyme (Zhu et al. 2018; Srinivasan et al. 2019).

13.2.3 Kodo Millet (*Paspalum scrobiculatum*)

13.2.3.1 By-products Utilization

Kodo millet is rich source of carbohydrate and phosphorus, accounting 65–67 (g/100 g) and 188 (mg/100 g), respectively. Kodo millet by-products utilization includes the following:

13.2.3.1.1 Integrated Nutrient Management

To date, chemical fertilizers are used in farming to increase the minor nutrient content of the farm field. Excessive use of these fertilizer degrades the biological and physicochemical properties of the soil, that led to decrease in soil health and environment. Recently, the cost of fertilizers is much higher which is not affordable to small-scale farmers, and also these are insufficient to provide economic health benefits for soil and crop (Imam 2002). Organic fertilizer produced from kodo millet residue can provide all the micronutrients and soil health benefits. (Choudhari et al. 2018).

13.2.3.1.2 Fly Ash Mycorrhizoremediation

Fly ash is a residue produced from the combustion of coal, and its disposal is major environmental concern worldwide. These particles have an average diameter of less than 10 mm, which results in a high specific surface area. However, fly ash can ameliorate soil by improving its physical, chemical, and biological properties. Mycorrhizae is a common and widespread symbiosis formed between plants and fungi its major role is to enhance nutrient and water uptake by the host plant and Kodo millet has been reported as a good host for mycorrhizal fungi. (Channabasava et al. 2015).

13.2.3.1.3 Activated Carbon

Kodo millet has been used as raw material for preparation of activated carbon, and was observed to be efficient in the removal of the synthetic dyes like methylene blue from the wastewaters. Adsorption of synthetic dye and heavy metals in wastewater depends on the adsorbent dose, the temperature, and dye concentration. Preparation of activated carbon involves two steps a) physical activation and b) carbonization. The activation process is most widely done using chemical activating agents. Activated carbon prepared using kodo millet husk has good adsorption capacity and high specific surface area which can be used for removal of impurities from low-quality water and distilled dihydrogen oxide (Valliammai et al. 2017).

13.2.3.1.4 Production of Lactic Acid Using Bran

Kodo millet (*paspalum scrobiculatum*) bran has a significant amount of starch, protein, and other essential nutrients and possesses a powder consistency. Kodo millet bran can be used as a nutrient source for the production of D-lactic acid. The bran should be sun-dried for nearly 5–6 days to remove moisture to avoid microbial deterioration. The kodo millet bran is fermented in presence of the lactic acid bacteria (LAB) to produce optically pure lactic acid. Lactic acid has many applications including food packaging, healthcare, apparel manufacturing, and synthesis of fine chemicals. Polylactic acid is emerging as an important biopolymer owing to its physical characteristics, which opens up the avenue for extensive demand for lactic acid production (Balakrishnan et al. 2018).

13.2.3.1.5 Forage

Kodo millet straw contains a good composition of nutrients for the growth and reproduction of domestic animals. It is an annual, drought-resistant crop that is well suited to dry conditions as well as in gravelly soils (Sampath 1989).

13.2.4 Little Millet

Little millet by-products are a rich source of phytochemicals, like phenolic acids, flavonoids, and phytate. The polyphenolic contents in cereals usually have less than 1% of dry matter, except for little millet varieties (Chethan and Malleshi 2007a). The food fortification by little millet can enrich the phenolic acid contents and imparts antimutagenic, anti-glycemic, and antioxidative properties. By-product utilization of little millet includes the following:

13.2.4.1 Forage

The little millet straw contains 4.13% crude protein, 37.86% crude fiber, 0.41% calcium, and 0.06% phosphorus on a dry weight basis. Little millet straw stem is used as cattle feed. Straw is a by-product generated by the removal of the grain after harvesting. The average yield of little millet straw has been reported as 8–12 q/ha. The dry matter intake by the animals range from 1.08 kg to 2.04 kg with an average of 1.52 kg/ 100 kg body weight during the preliminary feeding period. The nutritive value in terms of digestible crude protein, starch equivalent, and total digestible nutrients of the straw is 0.55, 27.92, and 47.07 kg respectively for per 100 kg dry matter. The straw has been reported as a good source of roughage for cattle feeding (Ramashia et al. 2018).

13.2.4.2 Seed Coat

Little millet seed coat has high nutritional and medicinal value, high dietary fiber content and easy digestibility. Seed coat per 100 g consists of carbohydrate 47.85, protein 6.26, fat 2.03, ash 20.51, flavonoids 0.18 and phenolics 0.32 g respectively (Tully et al. 1981).

13.2.5 Properties of Millet By-products

By-products generated by millet industrial processing are rich sources of fiber, oil, cellulose, polyphenol, etc. These compounds present in millet processing waste can be used for many industrial and commercial purposes like food product development, cement industries, and pharmaceutical industry. Novel processing methods can improve the physical and nutritional properties of millet by-products (Čukelj Mustač et al. 2019). By-product (seed coat) constitutes zinc, calcium, polyphenols, iron, dietary fiber, etc., which can be used in potential cereal food product development to enhance physical and functional properties (Amritha et al. 2018). Millet by-product bran is a potential source of fat, fermentable sugars, protein, dietary fiber and vitamins etc. (Chu et al. 2019). Millet bran oil is nutritious containing 23% oil, 72% fatty acids, oryzanol and tocopherol etc. (Guifeng et al. 2018). Husk produced after millet processing constitutes furfural and cellulose etc. Its ash is widely used in concrete industries due to its good mechanical properties (Malk 2020; Bheel et al. 2021).

13.2.5.1 Physicochemical and Functional Properties

A carbohydrate-based polymer, dietary fiber generated from by-product bran is a good source for functional foods. Physicochemical and functional properties of the dietary fiber have been reported to have good water holding capacity, oil binding capacity and (cholesterol, nitrate ions, glucose, bile acid) adsorption/exchange of compounds (Chu et al. 2019). Some important properties of millet by-products are given in Table 13.1.

Table 13.1 Composition of millet by-products generated by processing industries

S. No.	By-product	Variety	Composition	References
1.	Seed coat matter	Finger millet	Dietary fiber, calcium (Ca), 53 iron (Fe), and zinc (Zn)	Amritha et al. (2018)
2.	Bran	Foxtail millet	Oil, fermentable sugars, protein, dietary fiber, and vitamin	Chu et al. (2019)
3.	Husk	All	Furfural, cellulose, and ash	Bheel et al. (2021)
4.	Broken grains	All	Same as raw millet	Hanna and Wright (1995)

13.2.6 Recovery of Bioactive Compounds of Millet By-product

Foxtail millet bran oil was extracted using supercritical fluid extraction and reported to have higher yield compared to the conventional extraction method (Pang et al. 2015). Bioactive compounds present in by-products can be extracted using several methods that include liquid extraction (pressurized) and supercritical carbon dioxide extraction. Normally, supercritical carbon dioxide extraction is an economical method for polar compounds like carotenoids, whereas (pressurized) liquid extraction is used for the extraction of large amount of polar compounds such as polyphenols. These techniques are economic and environment friendly for the extraction, pre-treatment of nonthermal methods are used to increase the extraction yield of bioactive compounds (Shirsath et al. 2012). Different parameters like solvent, extraction time, temperature, and mode of stirring affects the extraction amount of bioactive compounds.

Bioactive compounds of millet by-product were recovered using enzymatic and chemical modification. Enzymatic and/or chemical modifications have been used in protein-rich by-products for the elaboration of specialized food products. Demiray et al. (2011) studied the extraction of phenolic acids and flavonoids using the ginja cherries to alcohol production by using plant (leaves, stems) wastes by application of different novel thermal and non-thermal methods, and solvents. The supercritical fluid extraction method is used for the removal of high-value compounds from agricultural waste (Herrero et al. 2010).

13.3 Economy and Market

Millet bran can be an efficient resource for increasing the farmers revenue with decreased agricultural wastes which also improves their standard of living (Ji et al. 2019). Functional foods are the current trend in the market, which provide health benefits and prevent diseases. Millets which fall under this category also have a wide scope of the market in modern-day lifestyle and eating habits (Shobana et al. 2013). The activated carbon from the kodo millet husk serves to be a good adsorption material and can be effectively used in removing the dyes from wastewaters, which has a wide scope in the market (Valliammai et al. 2017). The different types of bioactive peptide fractions can be extracted from millet by-products which are an excellent source of proteins. These extracted peptide fractions provide excellent health benefits and contribute to the growth of millet market potential (Majid and Priyadarshini 2020).

13.4 Challenges

The main challenge faced in millet production is the loss of advanced machinery for the processing of millets and the market potential of the millets in the urban areas. The various factors that contributed to the decline of millets are agronomic, economic, and social factors also the advent of the Green revolution which increased the area of cultivation of rice and wheat to eradicate hunger at that time, which also paved the way for the reduction of millet cultivation in India (Padulosi et al. 2015). The value addition of millet becomes a necessity, and products must be made from the millets which meet and satisfy the modern consumers taste and demand (Padulosi et al. 2007). Lack of knowledge among people about the various applications of the millets and their by-products as cattle feeds, production of the enzymes etc. is the biggest challenge to overcome in millet production. Millet suffered a greater challenge in loss of spicy attractive recipes and lack of awareness among people which has changed now due to the nutritionists and dieticians who promote the consumption of the millets (Padulosi et al. 2015).

13.5 Future Scope

The increased usage of the millets can increase the volume of the by-products obtained and can be efficiently used as feeds, enzyme production, and extraction of bioactive compounds and biofuels. The by-product utilization of millets increases the revenue of manufactures and also aids in reducing the carbon footprint of the company. The government also takes necessary steps in propagating the nutritional values and benefits of millets as the millets can be a potential crop in replacing the staple food crops. The millets play a major role in determining the global water crisis and climate change. Scientists are emphasizing the increase in millet cultivation as it requires a very less amount of water compared to paddy and wheat, and millets are also resilient to climate change which is endangering the world. These various factors can lead to increased production and consumption of millets and their products in the future, and thus the study of millet by-products becomes the need of the hour. Thus, the efficient production and usage of millets can lead to promising food security to the entire world considering the global issues present today.

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14 Quality Standards for Millets

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Abstract

Millets comprise of small, grained cereal species. These nutricereals, being one of the most nutritious and important dry-land crops, are drought-tolerant and can be grown with minimal agricultural inputs. The development of appropriate seed certification and quality management protocols are central to preventing the post-harvest losses of millets. From farm to fork, there are several stages through which the quality of these grains needs to be monitored. Across the world, different types of millets are grown, and each grain is unique. Hence, internationally, varied parameters, standards, and grades have been devised for every millet variety, depending on its procurement and shelf-life. This chapter deals with the international standards and specifications pertaining to the quality of millet grains.

Keywords

Millets · Quality standards · Seed testing · Certification · Germination · Moisture content · Proximate composition

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14.1 Introduction

Millets, the "miracle grains," are small-seeded grasses that grow efficiently in dry regions as rain-fed crops, under minimal conditions of moisture and soil fertility. These are one of the ancient grains known to man. African countries amount to 55% of the international production of millets, which covers 38% of the global regions and 42% of the worldwide production (Himanshu et al. 2018), followed by the Asian countries. Almost all the millets are natives of India and are popularly called as nutricereals as they serve almost all the nutrients needed for the normal functioning of the body. The millet group includes sorghum (*Sorghum bicolor* (L.) Moench), pearl millet (*Pennisetum glaucum*), and the small millets including finger millet (*Eleusine coracana*), Italian or foxtail millet (*Setaria italica*), proso millet (*Panicum miliaceum*), Kodo millet (*Paspalum scrobiculatum*), little millet (*Panicum miliare*), barnyard millet (*Echinochloa frumentacea*), fonio (*Digitaria exilis*), and teff (*Eragrostis tef*) (Patil 2016). All the aforesaid grains have a brief growing span and finish their maturation within 4 months, suit a broad array of cropping systems, and adjust themselves to the changing climatic conditions, particularly during unpredictability of monsoon. These ancient grains are sometimes referred to as "famine crops" as they yield even during famine conditions.

Millets are unique and nutritionally superior among most of the food grains especially cereals, due to their abundance in calcium, dietary fiber, polyphenols, flavonoids, and protein (Devi et al. 2014). Consequently, these grains could be used to combat micronutrient malnutrition by the biofortification of staple crops. In addition to their high nutritional value, they also have several other health benefits, including the prevention of cancer and cardiovascular diseases, lowering hypertension, reducing the risk of heart disease, cholesterol, and fat absorption, slowing down gastric emptying, and providing gastrointestinal bulk (Truswell 2002; Gupta et al. 2012).

Globally, 815 million people suffer from hunger, according to the World Bank (2017). With the increase in the world population, there will be an increase in food demand. There is therefore a need for sustainable crop substitutes to alleviate hunger (cereal demand) and improve farmers' incomes. Millets will, therefore, play a significant role in achieving sustainable nutritional security (Kumar et al. 2018) (Fig. 14.1). Therefore, maintaining the quality standards of millets is essential for both import and export activities. Seed acts as a carrier of the genetic potential of varieties. Provision of good seeds on a timely basis ensures high yield and economic returns to the farmers. Quality seed production follows stringent certification procedures.

A total of about 330 specifications currently apply to cereals and cereal products at the national and international levels (in over 50 countries), of which, at least 12 are global in scope. These specifications describe the nature of commodities on a pass-or-fail basis (Proctor, FAO 1994). Usually, grain quality is perceived differently among different stakeholders in the value chain of millets (Fig. 14.2). Growing the plant, followed by harvesting, and storing the grains is the first step. A cereal may be contaminated with chemical, physical, or microbiological hazards, resulting from

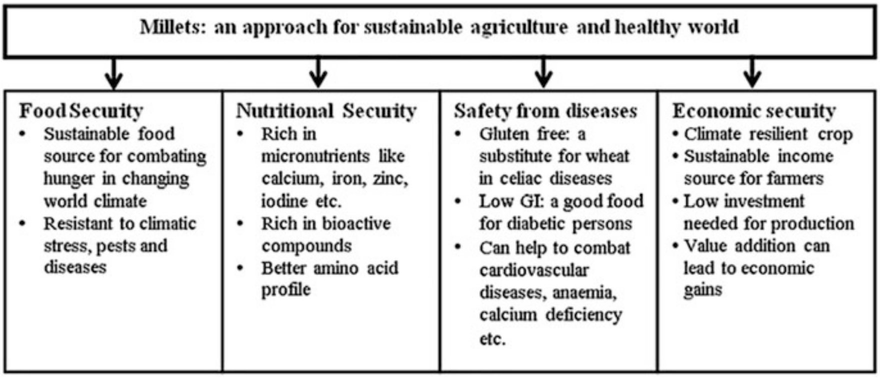

Fig. 14.1 Benefits of millets (Kumar et al. 2018)

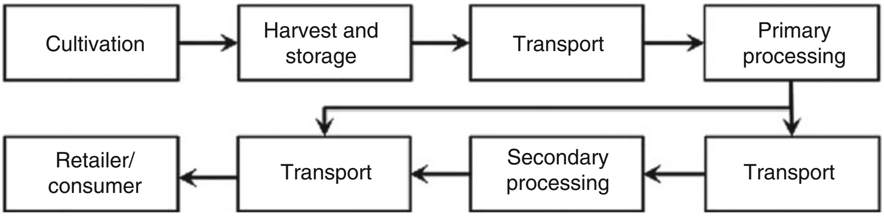

Fig. 14.2 The value chain of grain-based foods (Anton 2017)

either the effects of nature or human intervention. During cultivation, soil composition is an essential factor since mycotoxigenic molds can invade crops due to heavy metal bioaccumulation. Further, the errors made during the post-harvest cleaning and drying of grains along with the misapplication of pesticides may influence the development of phytotoxins associated with certain co-harvested seeds and mycotoxins due to the proliferation of certain mycotoxigenic fungi (Anton 2017). The above list of hazards can be mitigated by effective agricultural practices.

Hitherto, at least three diverse concepts of quality have been proposed: (1) food safety in grain production, (2) compliance to specifications of trade, and (3) meeting the requirements of end-use. The existing quality management systems for different sorghum and millet varieties lay emphasis on different aspects of the aforementioned three concepts (Taylor and Duodu 2017). Thus, in this chapter, a comprehensive discussion will be presented on the Indian and international standards for millet quality.

14.2 Post-harvest Losses and Food Safety Hazards: The Underlying Factors for the Development of Millet Quality Standards

Different regions suffer different post-harvest losses of millet grains, which are related to climate and post-harvest grain handling techniques (Abass et al. 2014; Alam 2010). Pest damage is considered one of the biggest factors, and generally begins at the field and before storage (Fig. 14.3) (Beta and Ndolo 2019). The moisture content in the grain and the amount of water in the vapor phase immediately surrounding the grains determine the concentration of intergranular water vapor used by molds (Proctor, FAO 1994). *Aspergillus terreus*, a producer of patulin, has been isolated from pearl millet (*Claviceps fusiformis* Loveless), which produces alkaloids and jeopardizes the yield and quality of the crop (Kajuna, FAO 2001).

14.2.1 Seed Quality Control

Seed certification ensures the genetic purity, physical purity, and other qualities of crop plants, by monitoring their production and dissemination to ensure that the seed is of a high quality and remains available to the public (Vilas et al. 2015). The Seed Act of 1996 regulates the seed quality in India. "According to this Act, all the seeds of certain notified varieties or kinds when sold to farmers must meet the minimum standards of germination as well as physical purity. The seed should also be packed in a suitable container, and a label has to be affixed on the container, which gives information about germination, physical purity, variety, date of the test and the name of the seed producer. The standards of germination specified on the label are valid for eight months, after which, it has to be revalidated for a subsequent period of four months after retest (ICAR-IASRI 2020)."

The subsequent sections of this chapter would elaborate on the quality standards and parameters framed by the following agencies:

1. Seed certification standards of India;
2. Codex Alimentarius Commission;
3. United States Department of Agriculture/Grain Inspection, Packers and Stockyards Administration (USDA/GIPSA) sorghum classes;

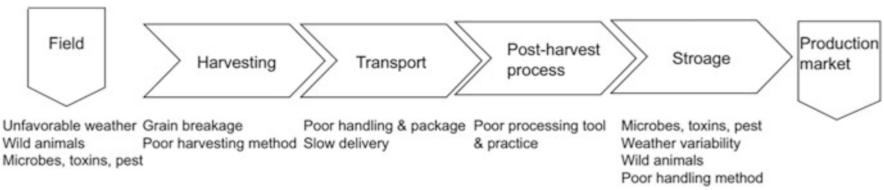

Fig. 14.3 Overview of factors contributing to post-harvest losses (Beta and Ndolo 2019)

4. East-African standards for sorghum and pearl millet and,
5. Australian sorghum standards.

Before proceeding to understand the millet quality standards, it is important to understand certain related terminologies, which are compiled in Table 14.1.

14.2.2 Seed Certification Standards for Millets (India)

"Certified seeds shall be the seeds that are endorsed by the Certification Agency notified under Section 8 of the Seeds Act, 1966. Alternatively, it can also be the seed certified by any Certification Agency established in any foreign country, provided the Central Government has reorganized the Certification Agency through a notification in the Official Gazette. The General Seed Certification Standards apply to all crops which are eligible for certification, and with the field and seed standards for individual crops, shall constitute the Minimum Seed Certification Standards. A certified seed shall comprise two classes, namely, Foundation seed (FS) and Certified seed (CS) (Refer Table 14.1, for definitions)." During the production of certified foundation seed, the following guidelines shall be observed:

(a) "Certified Foundation seed produced directly from Breeder seed shall be designated as Foundation seed stage-I;"
(b) "Certified Foundation seed produced from Foundation seed stage-I shall be designated as Foundation seed stage-II;"
(c) "Certified Foundation seed stage-II will not be used for further increase of Foundation seed and shall be used only for the production of Certified seed class;"
(d) "Minimum Seed Certification Standards shall be the same for both Foundation seed stage I and II unless otherwise prescribed;"
(e) "Certification tag shall be of white color for both Foundation seed stage-I and II and shall contain the information as to its stage;"
(f) "Production of Foundation seed stage-II shall ordinarily be adopted in respect of such crop varieties provided when the Certification Agency expressly feels that Breeder seed is in short supply;"
(g) "Production of Foundation seed stage-II may be adopted for the following group of crops:
    - vegetatively propagated crops;
    - apomictically reproduced crops;
    - self-pollinated crops;
    - often cross-pollinated and cross-pollinated crops, these being gene—pools should not lose their genetic identity and purity if measures to safeguard the same are adequately taken;
    - composite and synthetics;
    - parental line increase of hybrids."

Table 14.1 Glossary of terminologies related to the quality of millets

Terms	Definition	References
Seed	The word seed or seeds as used in the standards shall include all propagating materials	Trivedi and Gunasekaran (2013)
Breeder seed	Seed or vegetative propagating material directly controlled by the originating or sponsoring plant breeder of the breeding program or institution and/or seed whose production is personally supervised by a qualified plant breeder and which provides the source for the initial and recurring increase of foundation seed. Its genetic purity must be maintained at 100%	
Foundation seed (FS)	The progeny of breeder seed whose purity is to be maintained at 99.5%	
Certified seed (CS)	The progeny of foundation seed and its production is supervised and approved by a certification agency. It is the commercial seed with 99% purity	
Apomictical (apomixis)	Reproduction from unfertilized eggs or from somatic cells associated with the egg	
Genetic identity	A measure of the proportion of genes that is identical in two populations	
Genetic purity	The percentage of contamination by seeds or genetic material of other varieties or species	
Truthful label	Certified seeds are known as “truthfully labeled seeds,” i.e., self-certified with respect to germination, genetic purity, and so on. Truthful labeling promotes the commerce of improved seed in areas where certification systems do not work well]	Codex Alimentarius Commission, FAO (2018)
T.P (Top of paper)	This method is commonly used for species with seeds smaller than 2 mm in diameter such as small-seeded vegetables and forage grasses. The seeds are germinated on top of moist absorbent paper in containers with close-fitting lids to prevent moisture loss. Commonly used containers include 9 cm glass or plastic Petri dishes	Codex Alimentarius Commission, FAO (2018)
B.P (Between paper)	The seeds are germinated between two layers of paper. The seeds are placed between two layers of paper and rolled in towels. The rolled towels are placed in the germinator in an upright position	Codex Alimentarius Commission, FAO (2018)
Seed in the sand (S)	Seeds are planted in a uniform layer of moist sand and then covered to a depth of 1–2 cm with sand	Bradbeer (1988)
Germination test	The test to determine the maximum germination potential of a seed lot. This information can be used to compare the quality of different lots and also estimate the field planting value of a seed lot	Codex Alimentarius Commission, FAO (2018)
Dockage	The foreign material (other grains, stones, sticks, metals, pieces of glass, and so on) contaminating a particular lot of grains	Rooney and Serna-Saldivar (2015)

(continued)

Table 14.1 (continued)

Terms	Definition	References
Somatic embryogenesis	Artificial process in which a plant or embryo is derived from a single somatic cell. Somatic embryos are formed from plant cells that are generally not involved in the development of embryos, viz. normal plant tissue	Sahoo (2018)
Cereals	Cereals refer to wheat, barley, oats, cereal rye, triticale, sorghum, maize, and rice	GTA Sorghum Standards 2018/2019 (2018)
Cereal Smut	Cereal Smuts comprise all smuts on all cereal grains, which include but is not limited to: *Ball Smut:* Are those infected by the spores of the fungus *Tilletia caries*. They have the appearance of pale, plump, slightly oversized grains. These grains are easily crushed between the fingers and contain a mass of black powder (spores) with a distinctive rotten egg smell. Ball smut may also be called Stinking Smut or Bunt *Covered Smut*: Various fungi of the Ustilago spp. cause covered smut *Loose Smut*: Loose smut is the result of the fungus *Sporisorium sorghi* developing in the head during the growing phase. The tolerance applies to the number of blackened pieces of backbone in the sample	GTA Sorghum Standards 2018/2019 (2018)
Contaminants	Contaminants refer to the following: • Cereal Ergot • Cereal Smut • Chemicals exceeding the maximum residual limit (MRL) • Chemicals not approved for Sorghum • Foreign Material • Foreign Seeds • Insects—Large • Insects—Small • Objectionable Material • Odor • Pickling Compounds or Artificial Coloring • Ryegrass Ergot • Sand/Soil • Sorghum Ergot • Stones • Stored Grain Insects and Pea Weevil—Live	GTA Sorghum Standards 2018/2019 (2018)
Defective Grains	Defective grains refer to millets that have been damaged to some degree, as outlined in different standards. They include the following: • Field Fungi • Insect Damaged • Mold • Sappy • Severely Damaged	GTA Sorghum Standards 2018/2019 (2018)

(continued)

Table 14.1 (continued)

Terms	Definition	References
	• Smut • Sprouted	
Ergot	Ergot contaminates cereal and ryegrass kernels and is caused by infection of the fungus *Claviceps purpurea*. Specifically, Sorghum Ergot, *Claviceps africana*, occurs during flowering and results in the accumulation of a grey/white fungal mass, often found in empty seed glumes. Another ergot, *Cerebella* spp. is not a true ergot as such, but it is a fungus that often grows on the *Claviceps africana*, producing a large black mass	GTA Sorghum Standards 2018/2019 (2018)
Field Fungi	Refers to kernels affected by the growth of fungi on the seed coat. The fungal growth can vary in color from white to grey to black. It does not refer to the more serious mold	GTA Sorghum Standards 2018/2019 (2018)
Foreign Material	Foreign Material includes: *Trash*: Trash may consist of whiteheads, chaff, backbone, seedpods (less than 5 mm in diameter and not listed elsewhere in the standards), Skeleton Weed Seed Heads/Flowers and other light material which remain above the 2.00 mm screen after a sample of grain is subjected to the screening process *Chaff*: Chaff is defined as the protective material surrounding the mature seed before thrashing or harvesting. Backbone is the material to which seeds are attached to the plant stem *Other Material*: Includes all material not already explicitly categorized in the other definitions within the standard. It excludes contaminants for which tolerances have been stated in these Standards	GTA Sorghum Standards 2018/2019 (2018)
Foreign Seeds	Foreign seeds are defined as seeds of any plant, other than the species of the crop being tendered for delivery. Foreign seeds are classified into two broad groups; those with specific tolerances listed in the Standards, and those without. The latter is termed "Small Foreign Seeds"	GTA Sorghum Standards 2018/2019 (2018)

Further, the production of Foundation seed stage-I and II shall be supervised and approved by the Certification Agency and be handled in such a way that the specific genetic identity and genetic purity are maintained and shall be required to conform to certification standards specified for the crop/variety being certified. Certified seed may be the progeny of certified seed as long as this reproduction does not surpass three generations beyond the Foundation seed stage-I. The Certification Agency verifies the same by affirming that there is no significant change in the genetic identity and genetic purity. Also, the certification agency must be confident about the genuine prevalence of the shortage in Foundation seed despite all the reasonable efforts made by the seed producer. For the Certified seed class, the certification tag shall be of blue color (shade ISI No. 104 Azure Blue). On the other hand, Certified seed produced from Certified seed shall not be deemed suitable for further seed increase under certification. For such production under certification, wherein, Certification tags are not eligible for further seed increase shall be super scribed with the words, "not eligible for further seed increase under certification" (SeedNet India Portal 2020).

14.2.3 Seed Standards for the Inspection and Certification of Millets

Certification of a seed crop such as millet is relevant from the perspectives of maintaining its genetic purity and identity. This is accomplished via the propagation and distribution of grains produced from the varieties of superior crop plants. Another important rationale of seed certification is to confirm the compliance of seed quality with the standard technical specifications and thereby assure the supply of quality seeds to the farmer. Seed testing involves assessing the quality of a shipment of millet grains for parameters such as germination, physical purity and moisture content. This can be obtained by the verification of seed sources, field inspection to validate conformity to prescribed standards and seed analysis to verify conformity to seed standard (Kajuna 2001). Accordingly, seed testing can be classified as pre-harvest and post-harvest inspection. Seed testing must be conducted either in a national seed laboratory or in an ISTA recognized laboratory.

14.2.3.1 Pre-harvest Inspection

Pre-harvest inspection is conducted after the seed has attained maturity, before harvesting the millet, intending to discard diseased plants. This inspection is mainly carried out to observe the prescribed standards for seed-borne diseases, which should be met as put forth by the governing agencies. The pre-harvest inspection considers parameters such as the color of grain, shape and size of ear head, compactness, and so on (FAO 1972).

14.2.3.2 Post-harvest Inspection

The list of factors/parameters under the seed standards for the post-harvest inspection of millets includes (Vilas et al. 2015):

1. ***Pure Seed:*** Pure seed denotes the particular species that is specified by the dispatcher as the dominant one in the entire seed lot. Even seeds that are immature, underdeveloped, shrunken, diseased, or germinated can be considered as pure seed, provided the seeds are not infected by fungal sclerotia, smut balls, or nematode galls. A minimum requirement is specified for the pure seed content.
2. ***Inert Matter:*** It includes seed-like structures consisting of damaged or broken seed, glumes, or chaff, or any other foreign matter like stone, sand, soil, leaves, pieces of stem and bark, flowers, nematode galls, fungal bodies, insect larvae, and so on. A maximum limit is specified for the inert matter content.

3. ***Other Crop Seeds:*** This signifies seeds or structures that are similar to seeds from other plant species, but not pure seeds. The distinct characteristics set out for the pure seed hold for the other seeds as well, but excluding some weed seeds that are categorized independently. A maximum limit is specified for the other crop seeds content.
4. ***Other Distinguishable Varieties Based on Kernel Color and Texture:*** Within the millet crop species, there would be several other different kinds of these crops, which are termed as varieties or cultivars. Plants originating from the seeds of the same variety depict the same characteristics (morphological, physiological, cytological, chemical or others) that are reproducible across generations, irrespective of whether these are reproduced sexually or asexually. Amongst the characteristics as mentioned above, the color and texture of kernel are considered for distinguishing between the crop varieties and a maximum limit is specified for this factor under the seed standard specifications.
5. ***Weed Seeds:*** Good quality seeds must be devoid of weed seeds, especially the toxic weeds and chaff, stones, dirt and seeds of other crops. However, it is possible to remove these impurities either during processing or conditioning. A maximum limit is specified for this factor.
6. ***Germination:*** The germination percentage (Eq. 14.1) indicates the capability of the seeds to emerge from the soil and produce a plant in the field under normal conditions. It also provides an estimate of the viability of a population of seeds.

$$\text{Germination percentage(GP)} = \left(\frac{\text{Number of seeds germinated}}{\text{Total number of seeds}}\right) \times 100 \quad (14.1)$$

   A minimum requirement is specified for the germination percentage.
7. ***Moisture Content (maximum) [for seeds stored in open containers and vapor-proof containers]:*** The moisture content of the seed is an essential factor in seed storage. The sample preparation involves mandatory grinding of the millet grains. Then, the moisture content is estimated based on the gravimetric loss of mass on drying the ground millets at 130 °C for 2 h, using a hot air oven.

The seed standards pertaining to the factors described above for different millets are compiled in Table 14.2.

14.2.4 Truthful Labeling

In the above context of seed standards, it is noteworthy to explain the concept of “truthful labeling” (Fig. 14.4). On the contrary to Certified seed, for which the certification is voluntary, truthful labeling, is mandatory for notified varieties of millets. Apart from the notified varieties, it is applicable for the released varieties as well. Under truthful labeling, the seeds are tested for physical purity and germination, for which the samples can be withdrawn only by the seed inspectors. Thus truthful labeling is different from the Certified seeds, wherein seed certification

Table 14.2 Seed certification standards: Factors and prescribed limits (Trivedi and Gunasekaran 2013)

Millet species	"Pure seed (minimum)"		"Inert matter (maximum)"		"Other crop seeds (maximum)"		"Other distinguishable varieties based on kernel colour and texture (maximum)"		"Weed seeds (maximum)"		"Germination (minimum)"		"Moisture content (for grains stored in open containers) (maximum)"		Moisture content (for grains stored in vapor-proof containers) (maximum)	
	FS	CS	FS	CS	FS	CS	FS	CS	FS	CS	FS	CS	FS	CS	FS	CS
Maize (*Zea Mays* L.)	98.0%	98.0%	2.0%	2.0%	5/kg	10/kg	10/kg	20/kg	None	None	90%	90%	12%	12%	8%	8%
Sorghum (*Sorghum bicolor L.*) (Moench) Open-pollinated varieties	98.0%	98.0%	2.0%	2.0%	5/kg	10/kg	10/kg	20/kg	5/kg	10/kg	75%	75%	12%	12%	8%	8%
Sorghum (*Sorghum bicolor L.*) (Moench) Hybrids	98.0%	98.0%	2.0%	2.0%	5/kg	10/kg	10/kg	20/kg	5/kg	10/kg	75%	75%	12%	12%	8%	8%
Pearl millet (Bulrush Millet, Spiked Millet), (*Pennisetum americanum* (L) Leek) Composites,	98.0%	98.0%	2.0%	2.0%	10/kg	20/kg	–	–	10/kg	20/kg	75%	75%	12%	12%	8%	8%

(continued)

Table 14.2 (continued)

Millet species	"Pure seed (minimum)"		"Inert matter (maximum)"		"Other crop seeds (maximum)"		"Other distinguishable varieties based on kernel colour and texture (maximum)"		"Weed seeds (maximum)"		"Germination (minimum)"		"Moisture content (for grains stored in open containers) (maximum)"		Moisture content (for grains stored in vapor-proof containers) (maximum)	
	FS	CS	FS	CS	FS	CS	FS	CS	FS	CS	FS	CS	FS	CS	FS	CS
Synthetics and Open-pollinated Varieties																
Pearl millet (Bulrush Millet, Spiked Millet), (*Pennisetum americanum* (L) Leek) Hybrids	98.0%	98.0%	2.0%	2.0%	10/kg	20/kg	–	–	10/kg	20/kg	75%	75%	12%	12%	8%	8%
Barnyard millet (*Enchinochloa colona* (L.) Link)	97.0%	97.0%	3.0%	3.0%	10/kg	20/kg	–	–	10/kg	20/kg	75%	75%	12%	12%	8%	8%
Common millet [Proso millet, Hog millet]	97.0%	97.0%	3.0%	3.0%	10/kg	20/kg	–	–	10/kg	20/kg	75%	75%	12%	12%	8%	8%

[*Panicum miliaceum* L.]																
Finger millet (*Eleusine coracana* L. Gaertn)	97.0%	97.0%	3.0%	3.0%	10/kg	20/kg	–	–	10/kg	20/kg	75%	75%	12%	12%	8%	8%
Italian millet [Foxtail millet] [*Setaria italica* Beauv.]	97.0%	97.0%	3.0%	3.0%	10/kg	20/kg	–	–	10/kg	20/kg	75%	75%	12%	12%	8%	8%
Kodo millet [*Paspalum scrobiculatum* L.]	97.0%	97.0%	3.0%	3.0%	10/kg	20/kg	–	–	10/kg	20/kg	75%	75%	12%	12%	8%	8%
Little millet [*Panicum sumatrense* Roth. Ex.] Roem. & Schult (syn. *P. miliare* Lam.)	97.0%	97.0%	3.0%	3.0%	10/kg	20/kg	–	–	10/kg	20/kg	75%	75%	12%	12%	8%	8%

– Data not available

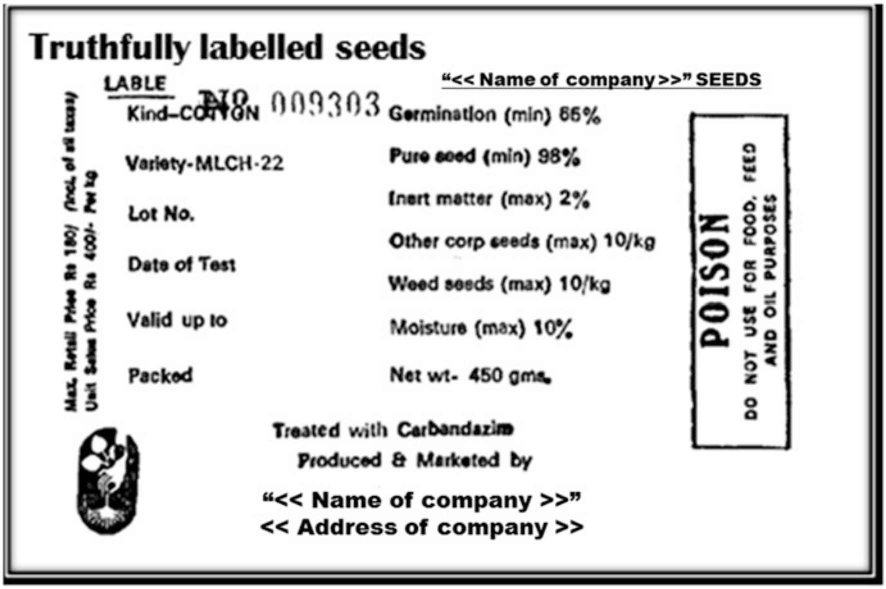

Fig. 14.4 An example of a truthful label. (Modified from: http://43.242.124.74:8080/iimsdatafiles/IIMSData/UploadFile/77_2069_TLS-Characteristics.pdf; SeedNet India Portal)

officers or seed inspectors can take the samples for seed quality test. The seeds under the truthful labeling scheme do not come under the purview of the Department of Seed Certification. Minimum standards (purity, germination etc.) for truthfully labeled seed may be decided by the state regulatory agency or left to the decision of the seed producer. Consumers monitor compliance to standards and report failure to meet standards; however, the regulatory agencies supervise the situation and conduct spot checks. Examples of countries that have adopted truthful labeling include the United States of America and India. In the USA, truthful labeling permits the companies to define their own quality standards and conduct their own tests. Companies are necessitated to label the seeds with accurate information on variety, germination, purity, and inert matter. On the other hand, in India, privately produced seed may be sold under the truthful label. A stringent mechanism exists for seed quality control along with voluntary seed certification and compulsory labeling, which are scrutinized by provincial level seed law enforcement agencies (Codex Alimentarius Commission, FAO 2018). In this context, the minimum germination percentage for sorghum and pearl millet under truthful labeling is 70% (SeedNet India Portal 2020).

14.3 Codex Alimentarius Commission Standards

The standards put forth by the Codex Alimentarius Commission (1996) cover the food safety issues pertaining to sorghum grain and pearl millet grain. "The quality monitoring parameters include toxic seeds, heavy metals, pesticide residues, and mycotoxins. Regarding tannin content, sorghum is subject to certain quality requirements. For whole and decorticated grains, tannin content cannot exceed 0.5% and 0.3%, respectively. For sorghum and pearl millet, the proximate chemical compositional standards have also been specified" (Table 14.3).

14.4 USDA-GIPSA Sorghum Classes (Grain Inspection, Packers, and Stockyards Administration 2013)

As defined by the United States Grains Standard Act, the grain sorghum can be a mixture of colors, including white, yellow, pink, orange, red, or bronze. According to the USDA, the following definitions are given for sorghum quality:

- "**Tannin sorghum:** Sorghum, which has a pigmented testa (sub-coat) and contains not more than 10% kernels without a pigmented testa."
- "**White sorghum:** Sorghum, which lacks a pigmented testa (sub-coat) and contains not less than 98.0% kernels with a white pericarp, and contains not more than 2.0% of sorghum of other classes. This class includes sorghum containing spots that, singly or in combination, cover 25.0% or less of the kernel."
- "**Non-grain sorghum:** Seeds of broomcorn, Johnson-grass, *Sorghum almum* Parodi, and Sudan grass; and seeds of *Sorghum bicolor* (L.) Moench that appears atypical of grain sorghum."
- "**Sorghum:** Sorghum, which lacks a pigmented testa (sub-coat) and contains less than 98.0% White sorghum and not more than 3.0% Tannin sorghum. The pericarp color of this class may appear white, yellow, red, pink, orange or bronze."

Table 14.4 presents the grade limits and breakpoints for Sorghum, as specified by the USDA, which are based on:

1. "**Minimum test weight per bushel (pounds):** This is the pounds of grain per Winchester bushel (Eq. 14.2), which is determined by an approved device after the removal of dockage. Dockage includes all matter except wheat that can be removed from the original sample by use of an approved device (USDA 2003).

$$\text{Bushels} = \frac{\text{Metric tons} \times 2204.622 \text{ pounds}}{\text{Legal test weight/Bushel of grain}} \tag{14.2}$$

   where the legal test weight per Bushel of Sorghum is 56 pounds/bushel."

Table 14.3 Summary of the Codex standards for sorghum and pearl millet grains (Codex Alimentarius Commission 2008; Duodu and Dowell 2019)

Factor	Sorghum Grain (CODEX STAN 172-1989)	Pearl Millet Grain (CODEX STAN 169-1989)
General	"Safe and suitable for human consumption Free from abnormal flavors, odors, and living insects Free from filth (impurities of animal origin, including dead insects) in amounts that may represent a hazard to human health"	"Safe and suitable for human consumption Free from abnormal flavors, odors, and living insects Free from filth (impurities of animal origin, including dead insects) in amounts that may represent a hazard to human health"
Moisture content	14.5% (weight/weight; w/w), maximum	13.0% (w/w). Maximum
Defects	"Not more than 8.0% total defects Not more than 2.0% extraneous matter, of which not more than 0.5% shall be inorganic matter Filth—0.1% m/m maximum"	"Whole grain—not more than 2% extraneous matter Decorticated grain—not more than 0.5% extraneous matter Free from dirt, animal debris, mineral particles, and diseased grains"
Toxic or noxious seeds	"Free from the following in amounts that may represent a hazard to human health: Crotolaria (*Crotolaria* spp.) Corncockle (*Agrostemma githago* L.), Castor bean (*Ricinus communis* L.), Jimson weed (*Datura* spp.), and other seeds that are commonly recognized as harmful to health"	"None specified"
Tannin content	"Whole sorghum grains—not exceed 0.5% on a dry matter basis Decorticated sorghum Grains—not exceed 0.3% on a dry matter basis"	None specified
Heavy metals	"Free from heavy metals in amounts that may represent a hazard to human health"	"Free from heavy metals in amounts that may represent a hazard to human health"
Pesticide residues	"Comply with maximum residue limits established by Codex Alimentarius Commission"	"Comply with maximum residue limits established by Codex Alimentarius Commission"
Mycotoxins	"Comply with maximum mycotoxin limits established by Codex Alimentarius Commission"	"Comply with maximum mycotoxin limits established by Codex Alimentarius Commission"
Hygiene	"Free from objectionable matter according to Good Manufacturing practices (GMP)" "Free from microorganisms, parasites, or substance originating from microorganisms in amounts that may represent a hazard to health"	"Free from objectionable matter according to GMP" "Free from microorganisms, parasites, or substance originating from microorganisms in amounts that may represent a hazard to health"
Appearance or color	"White, pink, red, brown, yellow, or any mixture of these colors"	"Brown, white, or green"

(continued)

Table 14.3 (continued)

Factor	Sorghum Grain (CODEX STAN 172-1989)	Pearl Millet Grain (CODEX STAN 169-1989)
1000 kernel weight	"None specified"	"Whole grain: 5–10 g Decorticated grain: 4–8 g"
1 L weight	"None specified"	"750–820 g"
Ash	"Decorticated grains: maximum 1.5% on a dry matter basis"	"Decorticated grains: 0.8%–1% on a dry matter basis"
Protein	"Minimum 7% on a dry matter basis (N = 6.25)"	"Minimum 8% on a dry matter basis (N = 5.7)"
Fat	"Maximum 4% on a dry matter basis"	"Whole grain: 3.5%–6% on a dry matter basis" "Decorticated grain: 2%–4% on a dry matter basis"
Crude fiber	"None specified"	"Whole grain: 3%–4.5% on a dry matter basis" Decorticated grain: maximum 2% on a dry matter basis
Flour particle size	Not applicable	Not applicable

Table 14.4 Grade Limits (GL) and Breakpoints (BP) for Sorghum (Grain Inspection, Packers and Stockyard Admin (FGIS), GIPSA, USDA 2018)

Grade	Minimum test weight per bushel (pounds)		Maximum limits							
			Damaged kernels				Broken kernels and foreign material			
			Heat-damaged (%)		Total (%)		Total (%)		Foreign material (%)	
	GL	BP	GL	BP	GL	BP	GL	BP	GL	BP
U.S. No. 1	57.0	−0.4	0.2	0.1	2.0	1.1	3.0	0.5	1.0	0.4
U.S. No. 2	55.0	−0.4	0.5	−0.4	5.0	1.8	6.0	0.6	2.0	0.5
U.S. No.3	53.0	−0.4	1.0	0.5	10.0	2.3	8.0	0.7	3.0	0.6
U.S. No. 4	51.0	−0.4	3.0	0.8	15.0	2.8	10.0	0.8	4.0	0.7

2. "**Damaged kernels:** Damaged kernels (total) include kernels, fragments of wheat kernels, and other grains that are severely ground-damaged, badly weather-damaged, frost-damaged, heat-damaged, insect-bored, mold-damaged, sprout-damaged, diseased, or otherwise materially damaged (USDA 2003)."
3. "**Broken kernels and foreign material:** Shrunken and broken kernels are kernels, kernel parts, and other matter, which pass through a 0.064-by 3/8-inch oblong-hole sieve. Foreign material is all matter except wheat that remains in a sample after the removal of dockage and shrunken and broken kernels (USDA 2003)."

14.5 South African Sorghum Standards

"According to the quality specifications laid down by the South African standards for grading purposes, sorghum is divided into the following classes based on the tannin content (South African Department of Agriculture, Forestry and Fisheries 2016):"

- "**Class GM (Malting class, no condensed tannins)*:*** This includes malt sorghum that does not have a dark testa (condensed tannins), is listed as a GM cultivar, and meets the requirements of Class GM sorghum as stipulated by the grading regulations."
- "**Class GL (No condensed tannins)*:*** This includes sorghum, which does not have a dark testa (condensed tannins) and is from a GM cultivar that cannot be graded in the Class GM sorghum or from a GL cultivar as stipulated in the cultivar list, and meets the requirements of Class GL sorghum as stipulated by the grading regulations."
- "**Class GH (Condensed (high) tannin sorghum)*:*** This includes malt sorghum, which has a dark testa (condensed tannins) and is from a GH cultivar as determined by the cultivar list, and meets the requirements of Class GH sorghum as stipulated by the grading regulations."
- "**Other sorghum:** This includes sorghum, which does not meet the requirements of Class GM, Class GL, and Class GH sorghum."

According to the South African standards (South African Department of Agriculture, Forestry and Fisheries 2016), all grades of sorghum shall;

(a) "be free from black smearing as a result of smut;"
(b) "not contain 10 or more smut balls or portions of smut balls which are collectively equivalent to 10 or more smut balls, per 100 g of sorghum;"
(c) "be free from a musty, sour or other undesirable smell;"
(d) "be free from any substance that renders it unsuitable for human consumption or animal consumption or processing into or the utilization thereof as food or feed;"
(e) "contain not more poisonous seeds than permitted in terms of the Foodstuffs, Cosmetics and Disinfectants Act, 1972 (Act No. 54 of 1972);"
(f) "with the exception of Class Other, be free from insects; and"
(g) "with the exception of Class Other, have a moisture content of not more than 14%."

"The presence of purple anthocyanic blotches in or on the pericarp shall not be taken into consideration when determining the grade of a consignment of sorghum."

14.6 East African Standards

14.6.1 Sorghum Grain Specifications

"The East African Standard (EAC 2011; EAS 757:2011) specifies the quality and grading requirements and methods of sampling and test for sorghum grains of varieties (cultivars) grown from *Sorghum bicolor* (L.) Moench intended for human consumption, i.e., ready for its intended use as human food, presented in packaged form, or sold loose from the package directly to the consumer. It does not apply to other products derived from sorghum grains."

- "According to the EAS, sorghum includes: Grain that, before the removal of dockage, consists of 50% or more of whole kernels of sorghum (*Sorghum bicolor* (L.) Moench), excluding non-grain sorghum and not more than 10.0% of other grains for which standards have been established."
- "**Broken kernels:** pieces of sorghum grain which passes through a screen having round holes of diameter 1.8 mm"
- "**Damaged grains:** kernels, pieces of sorghum kernels, and other grains that are badly ground-damaged, badly weather-damaged, diseased, frost-damaged, germ-damaged, heat-damaged, insect-bored, mold-damaged, sprout-damaged, or otherwise materially damaged."
- "**Decorticated grains:** grains from which the external casings and whole or parts of the germ have been removed appropriately, using mechanical treatment"
- "**Foreign matter:** all organic and inorganic material except pearl millet, broken kernels, other grains, and filth. Foreign matter comprises loose seed coats of Pearl millet."
- "**Immature and shriveled grains:** grains that are underdeveloped."
- "Poisonous, toxic, and/or harmful seeds any seed which, if present in quantities above the permissible limit, may have damaging or dangerous effects on health, organoleptic properties, or technological performance. Such toxic seeds include Jimson weed—Datura (*D. fastuosa* Linn and *D. stramonium* Linn.) corn cokle (*Agrostem magithago* L., *Machai Lallium remulenum* Linn.) Akra (Vicia species), *Argemone mexicana*, Khesari and other seeds that are generally considered as unsafe to health."
- "**Sprouted:** Sprouted grains are those with any visible evidence of the root system beginning to emerge."
- "**Test weight:** the density of a measured volume of grain expressed in kilograms per hectoliter."

14.6.1.1 Grading of Sorghum Millet

Based on the tolerable limits mentioned in Table 14.6, Sorghum grains are categorized into three grades. These are in addition to the general requirements set out in this standard (EAC 2011; EAS 757:2011).

- "**Ungraded sorghum grains:** Shall be the sorghum grains that do not fall within the requirements of Grades 1, 2 and 3 of this standards; however, these are not equivalent to the rejected sorghum grains."
- "**Reject grade sorghum grains:** This includes sorghum grains exhibiting objectionable odor, off-flavor, living insects, or which do not possess the quality characteristics specified in Table 14.5. The rejected sorghum grains cannot conform to the conditions of ungraded sorghum grains and shall be graded as reject sorghum grains and shall be regarded as unfit for human consumption."

Table 14.5 Grading of sorghum grains (EAC 2011; EAS 7572011; ICS 67.060)

Quality parameter	Grades			Method of test
	1	2	3	
Description	Grain sorghum of red, white, or yellow varieties only.			
Moisture (% w/w maximum)	13	13	13	ISO 711/712
Test weight (kg/hl minimum)	71	62	62	ISO 605
Total admixture, (% w/w maximum) (total of foreign material, screenings, and trash)	11.0	30.0	50.0	
Foreign material, %m/m (maximum)	2.0	3.0	4.0	
Foreign matter, %m/m (maximum) (decorticated seed)	0.5	0.5	0.5	
Screenings, %m/m (maximum) (all matter passing through a 2.0 mm slotted screen, 40 shakes in the direction of the slots using an agitator)	11.0	25.0	50.0	
Trash, %m/m (maximum) (chaff and other sorghum trash retained above a 2 mm slotted screen following the screenings process)	5.0	15.0	15.0	
Crude protein (dry matter basis) %m/m (maximum)	7.0	7.0	7.0	EAS 82
Ergot affected grains, %m/m (maximum)	0.05	0.05	0.05	
Tannin content (dry matter basis), %m/m (maximum)	Whole grains: 0.5 Decorticated grains: 0.3	Whole grains: 0.5 Decorticated grains: 0.3	Whole grains: 0.5 Decorticated grains: 0.3	ISO 9648
Defective grains, % by count, 300-grain sample (maximum)				ISO 605
Weather stained	5.0	20.0	20.0	
Field fungi	5.0	10.0	10.0	
Dry green	5.0	10.0	10.0	
Immature grain (fully green in color)	5.0	10.0	10.0	
Split/broken	7.0	10.0	10.0	
Total defective	5.0	8.0	10.0	
Small foreign seeds, %m/m (maximum)	1.6	1.6	1.6	
Total aflatoxin, ppb (maximum)	10	10	10	ISO 16050
Aflatoxin B1, ppb (maximum)	5	5	5	
Fumonisin, ppm (maximum)	2	2	2	

14.6.2 Pearl Millet Specifications

"According to the East African standards, Pearl millet shall be classified into three grades based on the tolerable limits listed in Table 14.6 (East African Community, EAC 2011)."

- "**Ungraded pearl millet:** Shall be the pearl millet which does not fall within the requirements of Grades 1, 2, and 3 of this standard but is not equivalent to the rejected pearl millet."

Table 14.6 Specific requirements for pearl millet grains (EAC 2011; EAS 284:2011 ICS 67.060)

Characteristic		Grade			Method of test
		1	2	3	
Foreign matter, whole grains, % by mass, *max.*	Organic	0.25	0.50	0.75	ISO 605
	Inorganic	0.10	0.25	0.25	
Foreign matter, decorticated, % by mass, *max.*		0.5			
Other edible grains, % by mass, *max.*		2.0	2.5	3.0	
Damaged grain, % by mass, *max.*		1.0	2.0	4.0	
Immature and shriveled, % by mass, *max.*		3.0	5.0	8.0	
Weevilled grains per cent by count		2.5	4.0	6.0	
Moisture content		12.0	13.0	13	ISO 711/712
Crude protein, % by dry mass basis, *min*		8.0			EAS 82
Ergot affected grains %m/m		0.05			EAS 82
Fat content, % by dry mass basis					
Whole millet grains		3.5 to 6.0			ISO 5986: 1983
Decorticated millet grains		2.0 to 4.0			ISO 5986: 1983
Total ash (decorticated) % by dry mass, max		1.0			EAS 82
Tannin content, % by mass, *max.*		0.5			ISO 9648
1000 Kernel weight, g					
Whole millet grains		5.0 to 10.0			Undefined
Decorticated millet grains		4.0 to 8.0			Undefined
1-liter weight, g		750 to 820			Undefined
Decortication %m/m max		20			Undefined
Crude fiber, % by dry mass basis					
Whole millet grains		3.0 to 4.5			ISO 5498
Decorticated millet grains %m/m max		2.0			
Total aflatoxin (AFB1 + AFB2 + AFG1 + AFG2) (ppb maximum)		10			
Aflatoxin B1 only, ppb max		5			
Fumonisin ppm max		2			

Note: Foreign matter refers to mineral or organic matter (dust, twigs, seed coats, seeds of other species, dead insects, fragments, or remains of insects, other impurities of animal origin). Pearl millet grains shall have not more than 1% extraneous matter of which not more than 0.25% shall be mineral matter and not more than 0.10% shall be dead insects, fragments or remains of insects, and/or other impurities of animal origin

Table 14.7 Microbiological limits (EAC 2011; EAS 284:2011 ICS 67.060)

	Type of micro-organism	Limits	Test method
1.	Yeasts and molds (maximum per gram)	10^4	EAS 217
2.	*Staphylococcus aureus* (per 25 g)	Not detectable	
3.	*E. coli* (maximum per gram)	Not detectable	
4.	*Salmonella* (maximum per 25 g)	Not detectable	

- "**Reject grade pearl millet:** This includes pearl millet grains that exhibit objectionable odor, off-flavor, and living insects or which do not possess the quality characteristics specified in Table 14.6. The reject grade pearl millet cannot satisfy the conditions of ungraded pearl millet grains and shall be classified as reject pearl millet grains and shall be considered as unfit for human consumption".

In addition to the specifications on physicochemical characteristics, the microbiological limits pertaining to pearl millet are charted in Table 14.7.

14.6.3 Finger Millet Specifications

Finger millet shall meet the following general requirements/limits (EAC 2011; EAS 758:2011 ICS 67.060):

- "shall be the dried mature grains of *Eleusine coracana* (L.) Gaertner;"
- "shall be hard, clean, wholesome, uniform in size, color and in sound merchantable condition;"
- "shall be safe and suitable for human consumption;"
- "shall be free from abnormal flavors, obnoxious smell;"
- "shall be free from micro-organisms and substances originating from microorganisms or other poisonous or deleterious substances in amounts that may constitute a hazard to human health."
- "Finger millet grains shall be in the form of well-filled seeds of uniform color."

14.6.3.1 Grading of Finger Millet

Based on the tolerable limits listed in Table 14.8, Finger millet shall be grouped under the following three grades (EAC 2011; EAS 758: 2011; ICS 67.060):

- "**Ungraded finger millet:** Shall be finger millet which does not fall within the requirements of Grades 1, 2, and 3 of this standard but is not equivalent to the rejected finger millet."
- "**Reject grade finger millet:** This comprises finger millet grains which have an objectionable odor, off-flavor, and living insects or which do not possess the quality characteristics specified in Table 14.1. They cannot satisfy the conditions of ungraded finger millet grains and shall be classified as reject finger millet grains and shall be condemned as unfit for human consumption."

Table 14.8 East African Standards for Finger millets (EAC 2011; EAS 758: 2011; ICS 67.060)

Characteristic		Grade 1	Grade 2	Grade 3	Method of test
Foreign matter, whole grains, % by mass, maximum	Organic	0.25	0.50	0.75	ISO 605
	Inorganic	0.10	0.25	0.25	
Other edible grains, % by mass, maximum		1.5	2.0	4.0	
Damaged grain, % by mass, maximum		2.0	3.0	5.0	
Immature and shriveled, % by mass, maximum		3.0	4.0	4.0	
Weevilled grains per cent by count		0.2	0.3	0.5	
Moisture content		12.0	13.0	14.0	ISO 711/712
Crude protein, % by dry mass basis, minimum		8.0			EAS 82
Ergot affected grains %m/m		0.05			EAS 82
1000 Kernel weight, g					
Whole millet grains		5.0 to 10.0			Undefined
Decorticated millet grains		4.0 to 8.0			Undefined
1-liter weight, g		750 to 820			Undefined
Decortication %m/m maximum		20			Undefined
Fat content, % by dry mass basis		3.5 to 6.0			ISO 5986
Tannin content, % by mass, maximum		0.5			ISO 9648
Crude fiber, % by dry mass basis		3.0 to 4.5			ISO 5498
Total aflatoxin (AFB1 + AFB2 + AFG1 + AFG2)), ppb maximum		10			ISO 16050
Aflatoxin B1 only, ppb maximum		5			
Fumonisin ppm maximum		2			

Note: Foreign matter is mineral or organic matter (dust, twigs, seed coats, seeds of other species, dead insects, fragments, or remains of insects, other impurities of animal origin). Finger millet grains shall have not more than 1% extraneous matter of which not more than 0.25% shall be mineral matter and not more than 0.10% shall be dead insects, fragments or remains of insects, and/or other impurities of animal origin

14.7 Australian Sorghum Standards

"The Sorghum Trading Standards (Standards) are being published by the Grain Trade Australia (GTA), since 1999. The Standards Committee of GTA reviews, produces and publishes these standards annually, on behalf of the industry. GTA provides inputs into the development of these standards so as to deliver a constant and reliable message to both the domestic industry and international buyers. Also, GTA necessitates the industry to comply with the Standards, appropriately while buying and trading Australian sorghum. Under the Sorghum Trading Standards, any commercially bred red, white or yellow varieties of grain sorghum may be grown and be accepted within each sorghum grade (Grain Trade Australia, GTA 2018/2019 2018). Table 14.9 lists the specifications published by the GTA."

Table 14.9 Australian Sorghum Standards (Grain Trade Australia, GTA 2018/2019 2018)

Name	CSG1 Sorghum No. 1	CSG2 Sorghum No. 2
QUALITY PARAMETERS		
"**Description:** Grain Sorghum of Red, White, or Yellow varieties only"	N/A	N/A
"**Moisture Max (%)**"	13.5	13.5
"**Test Weight Min (kg/hl)**"	71.0	62.0
"**Foreign Material Max (% by weight):** All matter other than already specified in this Standard"	2.0	4.0
"**Screenings Max (% by weight):** All matter passing through a 2.0 mm slotted screen—40 shakes in the direction of the slots"	11.0	25.0
"**DEFECTIVE GRAINS MAXIMUM (% by count, 300-grain sample, unless otherwise stated)**"		
"**Total Defective:** Includes Field Fungi, Sappy, Insect Damaged, Severely Damaged and Mold"	5.0	25.0
"**Field Fungi.** Included in Total Defective"	3.0	10.0
"**Severely Damaged (% by weight per half-liter):** Heat damaged/bin burnt, diseased or other serious visual defects. Included in Total Defective"	0.5	1.0
"**Mold (% by weight per half-liter):** Included in Total Defective"	0.05	0.1
"**Sprouted:** Not included in Total Defective"	3.0	10.0
"**Foreign seed contaminants maximum:** Count of seeds in total per half-liter; unless otherwise stated. Tolerances apply to whole seeds or their equivalent in pieces and refer to the maximum total of all seeds named in each type per half a liter. Except Type (1) in which the maximum applies on an individual seed basis per half a liter"		
"**Type 1 (Individual seed basis*):** Colocynth, Double Gees/ Spiny Emex/Three Cornered Jack, Jute, Long Headed Poppy, Mexican Poppy, Field Poppy, Horned Poppy, Wild Poppy, New Zealand Spinach, Parthenium Weed**"	8	8
"**Type 2 (entire load):** Castor Oil Plant, Coriander, Crow Garlic/Wild Garlic, Darling Pea, Opium Poppy, Peanut seeds and pods, Ragweed, Rattlepods, Starburr, St. John's Wort"	Nil	Nil
"**Type 3 (a):** Bathurst Burr, Bellvine, Branched Broomrape, Bulls Head/Caltrop/Cats Head, Cape Tulip, Cottonseed, Dodder, Noogoora Burr, Thornapple/False Castor Oil"	2	2
"**Type 3 (b):** Vetch (Blue/Tare) and Vetch (Commercial)"	4	4
"**Type 3 (c):** Heliotrope (Blue), Heliotrope (Common). Note: Tolerance listed for seeds, where 4 seeds = 1 pod"	2 pods/ 8 seeds	2 pods/ 8 seeds
"**Type 4 (a):** Bindweed (Field), Cutleaf Mignonette seeds, Damel, Hexham Scent/King Island Melilot (Hexham Scent is only acceptable if no tainting odor is present), Hoary Cress, Mintweed, Nightshades, Paddy Melon, Skeleton Weed, Variegated Thistle"	20	20
"**Type 5:** Knapweed (Creeping/Russian), Patterson's Curse/ Salvation Jane, Sesbania pea"	40	40

(continued)

Table 14.9 (continued)

Name	CSG1 Sorghum No. 1	CSG2 Sorghum No. 2
"**Type 6:** Saffron Thistle"	10	10
"**Type 7 (a):** Adzuki Beans, Broad Beans, Chickpeas, Corn (Maize), Cowpea, Faba Beans, Johnson Grass or Columbus Grass, Lentils, Lupin, Onion Weed Pods regardless of size, Peas (Field), Safflower, Soybean, Sunflower, and any other seeds or pods greater than 5 mm in diameter"	50	50
"**Type 7 (b):** Barley, Bindweed (Australian), Bindweed (Black), Wheat, Durum, Oats (Black), Oats (Sand), Oats (Wild), Oats (Common), Rice, Rye (Cereal), Ryegrass on Stalk, Sorghum (Forage), Triticale, Turnip Weed and any other weed seeds not specified in Types 1–7(a) or SFS"	400	400
"**Small Foreign Seeds (% by weight):** All foreign seeds not specified in Types 1–7(b) that fall below the 2.0 mm screen during the Screenings process"	1.6	1.6
** QLD only. Nil tolerance in NSW, VIC, SA		
"**Other contaminants maximum: Count per half a liter, unless otherwise stated**"		
"**Cereal Smut (entire load):** Ball and Gall Smut or any other smut species"	Nil	Nil
"**Cereal Ergot (entire load):** Pieces or whole affected kernels of all cereal ergots except Sorghum Ergot"	Nil	Nil
"**Sorghum Ergot (% by weight):** *Claviceps africana* and *Cerebella sclerotes*"	0.3	0.3
"**Ryegrass Ergot (entire load)**"	Nil	Nil
"**Stored Grain Insects & Pea Weevils:** Live (entire load)"	Nil	Nil
"**Insects—Large:** Dead or alive"	3	3
"**Insects—Small:** Dead or alive"	10	10
"**Sand/Soil (% by weight)**"	0.06	0.06
"**Stones (g per 2.5 L):** Maximum total weight of all Stones retained above the 2.0 mm screen per 2.5 L"	4.0	4.0
"**Objectionable Material (entire load).** Sticks, glass, concrete, pickled grain, artificial coloring or any other commercially unacceptable contaminant"	Nil	Nil
"**Odor (entire load).** Grain which has any commercially foreign odor due to tainting agents or improper storage causing mold, souring or musty odors"	Nil	Nil
"**Maximum Temperature (Celsius):** Grain temperature ex grain dryer"	35	35
"**Chemicals Not Approved for Sorghum (entire load).** Residues of any chemical compound not approved for grain sorghum, used in contravention of the labeled instructions or chemicals above the maximum residual limit (MRL)"	Nil	Nil

14.8 Conclusions

From the information presented in this chapter, it is apparent that there are only a finite number of official quality standards and tests that are available for millets. Generally, it can be observed that the tests for sorghum are generally applied to the other millets as well. Hence, the need for variety-specific quality parameters and specifications for each millet type is apparent. The trend of future developments concerning millet quality is oriented towards improving the end-use quality through the genetic modification (GM) approach. Recent studies have elucidated the GM-based strategies to improve the millet quality characteristics such as amylose and tannin content, endosperm texture, and protein digestibility. However, the actual likelihood of gene transfer between GM crops and their natural counterparts is ambiguous. The potential of molecular biology-based tools has been identified in augmenting the quality assessment of millet grains and result in millet varieties with high nutritive (ex. protein and calcium) value. Thus, there exists an enormous opportunity for advancements in the millet quality standards, in the near future.

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Millet Industry Scenario

15

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Abstract

Millets are one of the important cereal grains superior in protective nutrients and are easily digestible. They have high content of calcium and low glycaemic index. Foxtail, little, kodo, proso, barnyard, and brown top millets are among the most commonly cultivated millets that have hard cellulosic husk outer layer. Processing of millets for human consumption essentially involves cleaning, grading and dehusking of the grains. The processing of millets involves the removal of outer husk in the process of millet grain processing. The modern millet processing technique involves different equipment and machines to process large quantities with an intention to reduce drudgery and improve the quality and quantity of output. Improved millet dehusking machines, namely rubber roll sheller and single-stage and double-stage centrifugal dehuskers, with various capacities have been developed. Millets have been utilised since prehistoric times for culinary, medicinal, livestock etc. The various value-added products have been developed to utilise the nutritional components of these important healthy foods. Products such as flaked millet; puffed millet; extruded and roller-dried millet products; fermented, malted and composite millet flours; and weaning foods have been developed for the utilisation of this important health food.

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Keywords

Millets · Processing and value addition of millets · Millet business model

15.1 Introduction

Millets are a group of small grains belonging to grass family and grown widely around the world. They are considered cereal crop used as both human food and fodder. Millets are considered to be the sixth-most important cereal crop in the world, providing food to about a third of the population. Generally millets are small in size with round shape and can have varied colours like white, grey, yellow and red. It is a tiny seed having a nutty flavour and is considered to be the least allergic and most digestible grain available among the food grains. Millets play a very important role in food and nutrition security particularly during drought as it can be grown well even in the substantial low rains (Umanath et al. 2018).

Millets are classified into two categories based on the seed size, namely major millets and minor millets. Sorghum (*Sorghum bicolor*) and pearl millet (*Pennisetum glaucum*) are considered as major millets and little (*Panicum miliare*), kodo (*Paspalum Scrobiculatum*), proso (*Panicum miliaceum*), barnyard (*Echinochloa frumantacea*), finger (*Eleusine coracana*) and Italian (*Setaria italica*) millets are minor millets. Further, the minor millets are considered to be higher in protective nutrients such as proteins, vitamins, minerals, fibre and phytochemicals. Because of their biochemical composition, millets are considered as highly nutritious and are also the major source of energy contributing 70–80% of energy intake of Indian diet. Millets are considered as diabetic food due to higher amount of minerals and lower glycaemic index. Millets do not contain gluten, hence safe for consumption by people with gluten sensitivity and suffering from Celiac disease (Kulkarni et al. 2018).

A total of 28.82 million tonnes of millets is produced globally every year in an area of 36.79 million ha, with India having the largest market share with 41.0%. In India, 18 million tonnes of millets is produced annually by cultivating in 18–19 million hectares of area (FAO 2018). Millets, specifically small millets, are observed to be in crisis situation. The intense decrease was observed in cultivation area under millets during 1961–2009 (Small millets—80%, Sorghum—59%, finger millet—46% and pearl millet—23%). The total production of small millets was decreased by 76%, which led to a steep fall in overall consumption and per capita availability of all millets. The detailed global production data from different countries are depicted in Fig. 15.1.

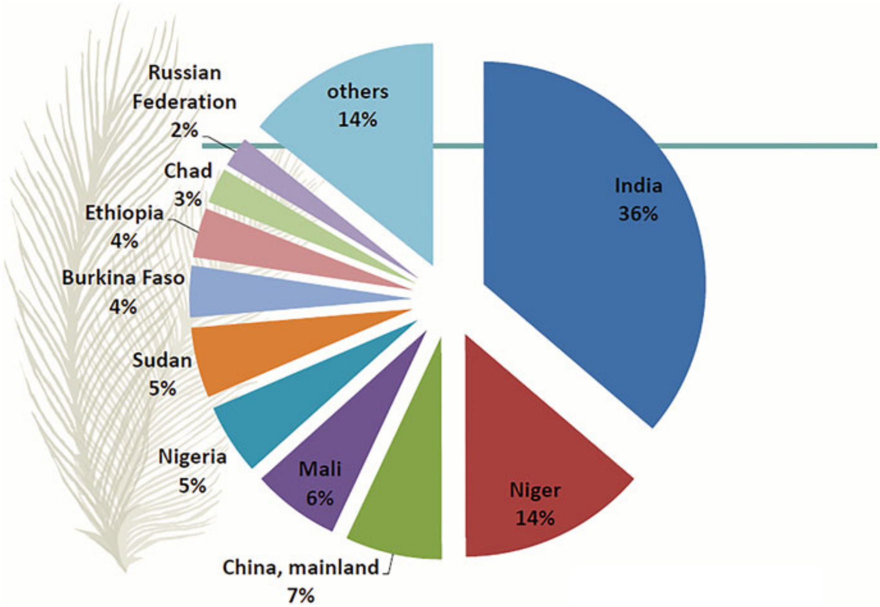

Fig. 15.1 Global millet production statistics (FAO 2018)

15.2 Millets Processing and Utilisation

The millet seeds can be divided into two types as utricles and caryopses. In the utricle, the seed is surrounded by pericarp like a case/cover and attached to the seed at only one point. Finger millet, proso millet and foxtail millets are utricles. In these types of utricle millets, the pericarp usually breaks away from the seed coat or testa, which is well developed, thick and forms a strong barrier over the endosperm. In a caryopsis, the pericarp is completely fused to the seeds. (iasri.res.in). The endosperm comprises the majority of the kernel weight for all millets. There are four structural parts of the endosperm. The aleurone layer and the peripheral, corneous and floury endosperm areas (Fig. 15.2).

Foxtail, little, kodo, proso, barnyard, and brown top millets are among the most commonly cultivated millets. These millets have hard cellulosic husk as outer layer that humans cannot digest. Processing of millets for human consumption essentially involve cleaning & grading, dehusking and polishing of the grains. The dehusking is the major activity in processing of millets and the husk can be removed by either the process of shear or impact force(https://www.udawat.in/blog/processing-millets). Traditional methods of grinding grains include using a wooden pestle and a wooden or stone mortar to smash dry the moistened or wet grains. By moistening the grain to about 10% water, the grain not only can be removed of its fibrous bran but also separated into its germ and endosperm. In the existing small millets sector, small and

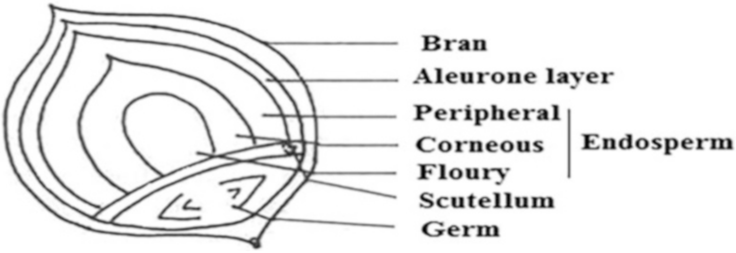

Fig. 15.2 Structure of millet grains

Fig. 15.3 Rubber roll sheller type, single-stage and double-stage centrifugal type millet dehusker (from left to right)

medium enterprises (SMEs) had problems separating hulled and unhulled grains and had lower head-rice recovery rates. For small millets, there were no suitable dehullers that could meet the processing needs in villages and regions.

In modern millet processing techniques different types of equipment and machines are used to process large quantities of millets continuously with an intention to reduce the drudgery and improve the quality and quantity of the output. Recently, improved millet dehusking machines namely rubber roll sheller, single-stage and double-stage centrifugal dehuskers having capacity 100–1000 kg per hour have been developed by different firms and introduced in the local market. The different dehusking machines are shown in Fig. 15.3. The dehusking efficiency of these machines varies from 80 to 95%. The dehusking of remaining grains is accomplished by pearling. The supporting equipment namely cleaner cum grader, destoner and pearler of matching capacities (Fig. 15.4) are used to produce high-quality dehusked millets (Nidoni et al. 2018).

Fig. 15.4 Cleaner cum grader, destoner and pearler (from left to right) for millet processing

Table 15.1 Recommended sieve size for grading of millets before dehusking

Small millets	Top sieve (mm)	Middle sieve (mm)	Bottom sieve (mm)
Little millet	2.20–2.40	1.35–1.46	0.80–1.00
Foxtail millet	2.00–2.40	1.35–1.46	0.80–1.00
Barnyard millet	2.40–2.80	1.46–1.60	0.80–1.00
Proso millet	2.50–2.80	1.70–2.00	0.80–1.00
Browntop millet	2.40–2.80	1.70–1.90	0.80–1.00
Kodo millet	2.50–3.00	1.90–2.10	0.80–1.00

The small millets are graded before removal of husk to enhance the milling efficiency, head rice recovery and reduce the brokens in the milling process. The size of the grading sieves is based on the average size of the millet. The recommended sieve openings for grading of different types of millets before milling are given the Table 15.1.

A wide range of millet processing machinery with different designs and capacities are sold in the market by various manufacturers. The various types of millet processing machinery fabricated by some of the manufacturers in Tamil Nadu and Karnataka are presented in Table 15.2. These processing equipment adopted by small-scale processing units in different parts of the country were found functional.

15.3 Utilisation of Millets

The increasing population has proportionately increased the demand for food while satisfying the total calorie intake mainly from cereals. Despite contributing less than 2% of global cereal utilisation, millet is considered an important staple crop in many semi-arid tropical countries with poor soils and lower precipitation. The millets are nutritionally on par and/or superior to major cereals with additional benefits like gluten-free proteins, low glycaemic index, high fibre and rich bioactive compounds.

Table 15.2 Details of some of the millet processing equipment available in the market

Sl. No.	Processing machines	Capacity (kg/h)	Some of the manufacturers involved
1.	Aspirator cum grader	50–500	AVM Engineering (AVM), VICTOR AGRO SALES (Victor), Perfura Technologies Private Ltd. (Perfura), KMS Industries (KMS) and Vishra Agro Sales in Tamil Nadu, and Bhavani Industries, Vishwa Agro Tech and Bio-tech in Karnataka
2.	Destoners	50–500	
3.	Aspirator cum destoner cum grader	50–500	
4.	Single-chamber centrifugal impact huller	100–200	Improvised by Victor and AVM, and improved by DHAN Foundation (DHAN) and Tamil Nadu Agricultural University (TNAU) under IDRC & GAC supported project
5.	Double-chamber centrifugal impact huller	100–200	Developed by DHAN and TNAU under IDRC & GAC supported project and currently offered by AVM, Victor and Perfura
6.	CIAE model abrasive huller	50–200	Developed by Central Institute of Agricultural Engineering (CIAE) and offered by Perfura
7.	Portable impact huller	200–400	Developed by Small Millet Foundation of DHAN and offered by Kalanjium Thozhilagam Limited (KTL)
8.	Tabletop impact huller	50–80	

Rich nutritional composition and drought-resistant property of the crop has aroused the interest of many research scientists and institutions all over the world. These properties have made it to be utilised for production of many health products (Kannan et al. 2013).

Millets have been utilised for human consumption in the form of culinary and medicinal purposes since prehistoric times. The studies conducted on processing and value addition of millets show encouraging outcomes in utilisation as number of traditional and convenience health foods. Consequently, many researchers have developed various millet products such as flaked millet, popped millet, puffed millet, extrudates and roller-dried millet products, as well as fermented, malted, composite flours and baby food.

Millet rice: Millets generally have mild flavour which makes them get blended with other food products. More often, in order to bring out its flavour, it is combined with different grains and roasted before cooking. The significant increase in the dietary fibre, mineral, protein and antioxidants content was observed in the final developed product by addition of millets (Ronda et al. 2015).

Millet flour: Millets are ground into coarse or fine flour and used for preparation of chapatis and bakery products (Collar 2016). Addition of millet flour to baked foods will enhance texture, flavour and richness of nutritional value. The possibility of making leavened pancakes called dosa and thinner, unleavened roti has also been reported.

Millets have been used in various food processing industries including biscuits and confectionary, beverages, weaning foods and fermented foods like beer (Laminu et al. 2011). Sorghum, maize and wheat composites are being made into soft biscuits and cookies, while millets are being used to create cakes and non-wheat bread, with encouraging results (Hama 2012; Laminu et al. 2011). Whereas, in spite of unlimited potential the progress in the infant weaning food sector has been slow due to limited installed capacity for industrial malting (Laminu et al. 2011). Various unique and innovative foods are developed by incorporation of millets like Bajra lassi supplemented with healthy lactic acid bacteria (Charalampopoulos et al. 2002). The millets are also used for production of synbiotics (Thakur and Tiwari 2019). A general process flow chart for the production of composite food products from millets is presented in Fig. 15.5.

15.4 Millets Marketing and Trade

Rice and wheat are staple food for the major population in the world. However, they are considered to be unsustainable due to higher water requirements and contribution to greenhouse gases emission (18%). Whereas, millet are the dryland crops grown easily in dry climate, have shorter harvesting period requiring less quantity of water. Hence, they can be sustainable alternative staple food to rice and wheat ensuring food security to large population of the globe. Millets were cultivated instead of rice and wheat due to the increased demand from urban populations in Asia Pacific, particularly in India and China. Thus, from a health, environmental, and economic perspective, improving India's livelihood would be improved by expanding millet agribusinesses.

In India, minor millets are cultivated predominantly by small and marginal farmers in the dry lands and especially by tribal communities leading to declining area under millet cultivation. However, there is a growing need in the country for millets to be assessed due to their ability to withstand climatic changes and provide excellent nutrition. The urban population is inclining more towards healthy foods and increased unsustainable issues in the cultivation of rice and wheat is driving the demand for millets is forecasted. As a result of modern lifestyles and eating habits, there are many diseases like diabetes, obesity, heart attacks, coronary artery disease, and arrhythmias. Millets are packed with minerals and proteins, which can prevent these diseases.

By 2025, the popularity of millet and its associated health benefits will boost the industry's growth. The global millets market is unorganized and fragmented with a large number of medium-sized processors. Most millets are grown by small landowners and farmers' organisations. The supply channels hold more importance in marketing millets, as it give a way for enhanced exposure to the common market. The processing industry should have tie up with growers to procure crops directly

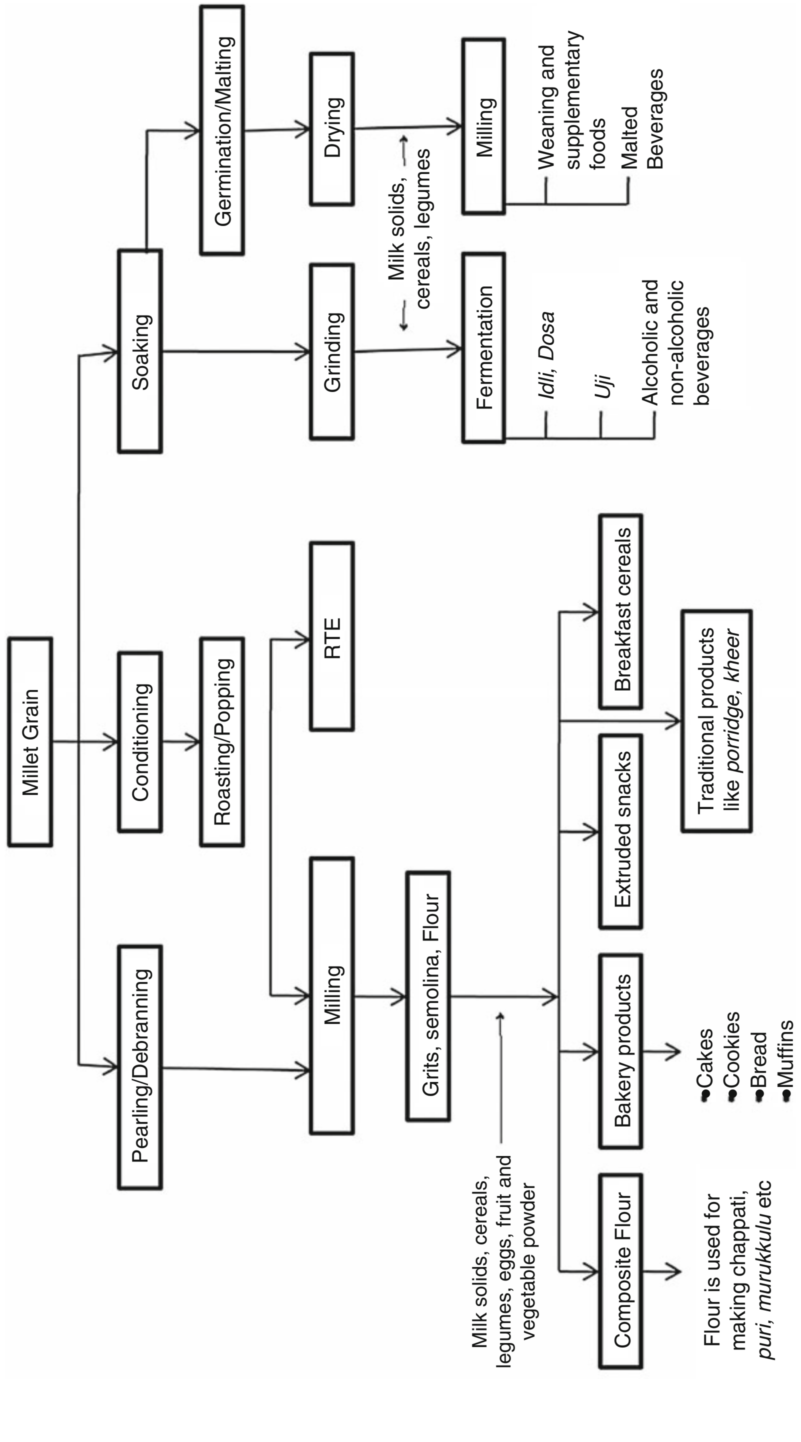

Fig. 15.5 Schematic diagram for developing millet-based food products. (Source: Kumar et al. 2018)

from farmers. Farmer producer organisations (FPOs) are also playing vital role in procurement and distribution of product. Grocery stores are important part of open market where consumers directly purchase the processed and value added products like bakery products and cereals. E-commerce sites and online stores are becoming easy and quick distribution channels for processors and consumers with a growth rate of more than 3% CAGR by 2025. Online marketing is one of the prominent channels for packed millet brands and help industries to create their own supply chain with doorstep delivery services. Thereby reducing their dependence on godowns, retailers and grocery stores. Participation of various distribution channels like trade associations, will strengthen millets business in the future years. Value addition and value added products like beer, infant and breakfast foods will increase demand over the forecast period (Vetter et al. 2017).

Numerous initiatives are being taken by various agencies to enhance millet cultivation and marketing. Integrating approaches among key players and fostering networking have been shown to have a significant impact on impact. Growing nutrition, health, and resilience factors are driving the revival of millet farming in this country. In dry and hot climates, these cereals do well and have supported millions of poor and marginal farmers struggling to overcome poor soil conditions, low moisture levels and the lack of external inputs. Due to their hardiness and good nutritional profile, they are effective at coping with climate change.

15.5 Challenges and Opportunities

Increasing urbanisation and disposable incomes are contributing to the growth of pre-processed and convenience foods. This has enhanced the preferred market for commercially milled wheat and maize flour. Whereas, millets are comparatively cheaper, but are unprocessed and therefore not convenient for use. This has caused markets for locally grown millets to shrink, incentives for local production to deteriorate, and foreign exchange reserves to diminish in order to meet the increasing demand for pre-processed flour.

The various challenges that need to be addressed for the popularisation of millets in India are discussed here:

Poor Supply Chain: In contrast to rice and wheat, there has been stagnant/declining growth in the supply chain, including support for farmers, traders, markets, subsidiaries and processing units to ensure speedy and smoothness. Accordingly, the cost components are on the rise. The manufacturers claim that the cost of middlemen can be increased by up to 40%.

Awareness of Customers: The nutritional value of millets and the quality evaluation of millets are not properly understood by customers. Many people are aware of millets from word-of-mouth or through informal discussions about its potential nutritional benefits. However, when a survey was conducted on customer preferences, more than half of non-consumers indicated that they were interested in buying millets.

Lower Yields: The annual average yields of millets is relatively lower with 4–5 quintals as compared to rice with 20–25 quintals, wheat with 18–20 quintals and maize with 25–30 quintals (Adekunle et al. 2018). However, small millets have higher yield potential if other factors are taken into account, since they require less land than rice and able to grow in less fertile soils.

Inadequate or Inefficient Processing Facilities: It was also observed from the study reports that the processing facilities are very less. The feedback loop required to improve the innovation and development, while reducing drudgery is missing. The recovery is also one of the important parameters and it was observed to be only 60–65%. Apart from the recovery, the utilisation of by-products of processing are also contributing to the higher selling price.

Policy Issues: Following the green revolution, policymakers in India have promoted the cultivation of intensive crops in more suitable resource areas, contributing to the reduction of area under millets (despite the fact that millets require less land to cultivate). Another example is that India's Public Distribution System (PDS) did not include millets in 2017.

The other challenges in processing of small millets are: (1) variations in raw materials and (2) lower shelf-life of processed millets and grits due to rancidity and infestation. The grains of different small millet crops vary in terms of shape, nature of grain surface, hardness, husk-grain bonding and expected rice recovery. Furthermore, the variations are also observed for varieties, cultivation practices and micro-climate across production regions.

Millets provide similar health benefits and nutrition like other major cereals such as rice, wheat and maize, but by processing them properly can enhance the nutrition and other properties that are suitable for household consumption. Presently, the average selling price of small millets is Rs. 70 per kg compared to Rs. 40 per kg for rice, creating problems of affordability. Fortunately, there exists a favourable economic environment for the growth of small millets value chain agribusinesses. This is due to advancement in post-harvest and value addition technologies, increased average disposable income and consumer awareness about the nutritional importance of millets.

15.6 Millet Processing Business Models

Millets are rich sources of minerals, fibres, polyphenols and antioxidants required for proper functioning of human body. They are also considered to be gluten free and have lower glycaemic index compared to rice and wheat. Despite these benefits, small millet industries are declining, due to several factors attributed to reduced demand, decreasing/stagnant area under cultivation and limited access to markets by small producers. Several attempts have been made to overcome the failure in marketing have resulted in the innovative business models. These business models emphasise on collective marketing and negotiating forward contracts thereby earning better prices for growers and reducing the transactional costs. The warehouse receipt systems (WRS) is another opportunity for the growers, which allows them to store commodities until prices rise and contract farming that provides buyers with a reliable supply of high-quality products.

The business model essentially explains how a company generates, distributes and captures value. "Business models that do not leave small-scale farmers behind and in which the views and demands of those players in developing nations are respected", according to the definition of an inclusive business model. As a result, these business models are meant to benefit both producers and low-income areas (creating jobs and increasing incomes).

15.6.1 Business Model-I

15.6.1.1 Millet Rice Processing Unit

Millets are consumed in dehusked form, and dehusking is the process of removal of the outer husk of the grains. The husk is not edible by humans. Traditionally, millets are dehulled manually using pestle and mortar mechanisms or wooden or stoner grinders due to lack of availability of local processing infrastructure in the production catchments. The production and consumption of millets has drastically declined in the recent due to drudgery and time involved in the traditional milling process. Hence, the processing of millets became important step in the enhancement of the consumption and thereby production of millets.

The processing of millets is undertaken in three different levels.

1. Primary Processing:
   The activities consist of cleaning, grading and packaging of millets without changing its physical structure.
2. Secondary Processing:
   The secondary processing involves dehusking, polishing, coating and powdering activities involving little change in the physical structure of millets.
3. Tertiary Processing:
   Tertiary processing is value addition of the millet into various products.

Flow diagram for millet dehusking

Millets
|
Cleaning, grading and destoning
|
Drying (if required)
|
Dehusking - removal of husk and broken
|
Separation and Grading
|
Dehusked millet rice
|
Polishing
|
Bagging

15.6.1.2 Capital Inputs

15.6.1.2.1 Land and Building

The processing plant can be established in a land measuring totally 1200 sq. ft. with a capital cost of approx. Rs. 2.0 lacs. The required processing shed can be constructed at the said land and the cost estimate for construction of building as per the valuation will be approx.Rs. 5.00 lacs.

15.6.1.2.2 Plant and Machinery

The plant and machinery will be finalised based on viable capacity being processed per year on one working shift considering 200 working days per year. The processing machinery required are listed below with the capacity and price:

Millet processing machines

Sl. No.	Name of machinery	Installed capacity	Quantity	Price/unit, Rs in lacs	Total amount, Rs in lacs
1.	Cleaner cum grader	1.0 QPH	1 No.	0.75	0.75
2.	De-stoner	1.0 QPH	1 No.	0.90	0.90
3.	Mini millet dehusker (centrifugal type)	1.0 QPH	1 No.	2.25	2.25
4.	Mini millet dehusker (rubber roll type)	1.0 QPH	1 No.	1.00	1.00
5.	Polisher	1.0 QPH	1 No.	0.35	0.35
6.	Weighing machine	100 kg	1 No.	0.25	0.25
7.	Packaging machine		1 No.	0.35	0.35
Total (X)					*5.85*
Installation, testing and commissioning of machines					0.15
Grand Total = 6.00					

15.6.1.2.3 Miscellaneous Assets

The essential miscellaneous assets including furniture and fixtures, storage facilities and electrification are to be covered by making a provision of Rs.0.30 lakh.

15.6.1.2.4 Raw Material

The major raw material required for running the unit is millet grains. The total raw materials required for 1 month cost Rs.25 lakh.

15.6.1.2.5 Utilities

Power

The total power requirement estimated based on the machinery would be 10 kW or 13–15 HP. The suitable standby generator provision is also made for uninterrupted operation. The approximate total annual expenditure could be around Rs.1.10 lakh.

Water

Water is one of the essential utility required for processing, cleaning and domestic consumption purpose. Arrangements for regular and continuous supply of water is ensured.

15.6.1.3 Manpower Requirements/Organisational Setup

The unit also requires manpower for running and managing operations and other activities of the unit. Depending upon the capacity of the unit, the required manpower is presented below.

Particulars	Nos.	Monthly salary (Rs.)	Total monthly salary (Rs.)
Manager	1	10,000	10,000
Supervisor cum operator	1	7000	7000
Cleaner	1	3000	3000
Total			*20,000*

15.6.1.4 Implementation Schedule (Tentative)

Activity	Period (in months)
1. Application and sanction of the loan	2
2. Civil work	1
3. Placement of orders for machinery and procurement	2
4. Installation, commissioning and trials	1

15.6.1.5 Insurance

The processing unit will be covered for adequate insurance for fixed assets and stocks.

15.6.1.6 Project Cost and Means of Financing (Rs. in Lacs)

Item	Amount
Land	2.00
Building/civil works	5.00
Plant and machinery	6.00
Miscellaneous assets	0.50
Total term loan	13.50
Raw materials	25.00
Labour	2.40
Utilities	1.45
Total working capital loan	28.85
Means of finance as term loan	
Promoters contribution	4.0
Loan from bank	9.5
Subsidy from GOK @ 50%	

15.6.1.7 Profitability Analysis

15.6.1.7.1 Production and Sales

The monthly production and sales of unit is as presented below considering foxtail millet as reference material

Items	Quantity in Qtl	Whole sale rate per Qtl	Total profit Rs.
Raw materials			
Millets (foxtail millet)	1000	2500	2,500,000.00
Processed products			
Millet rice	650.0	6500	4,225,000.00
Husk	400.0	1000	400,000.00
			4,625,000.00

The total processing capacity is considered as 1000 qtls per month working on single shift. The sales revenue is totalling to Rs. 46.25 lakh per month.

15.6.1.7.2 Raw Materials Required at 100%

The raw materials required for production will be procured at 100% of the capacity as per the annual production schedule and it shall be 1000 qtls.

15.6.1.7.3 Utilities

The expenditure towards utilities at 100% activity level is estimated to be Rs. 50,000/- per annum.

15.6.1.7.4 Interest

The Interest charged by banks towards the repayment of term loan of Rs. 9.50 lacs is calculated at 14% with repayment schedule of 5 years which includes the moratorium period of 6 months.

15.6.1.7.5 Depreciation

The depreciation of the all the fixed assets will be calculated on WDV basis considering 10% on building, machinery and miscellaneous assets.

15.6.1.8 Projected Profitability (Monthly) (Rs. in Lacs)

No.	Particulars	Cost in Rs.
A	Sales realisation	46.25
B	Cost of production	
Raw materials		25.00
Utilities		0.50
Salaries		2.40
Stores and spares		0.50
Repairs and maintenance		0.50
Administrative expenses		0.50
Total		*29.40*
C	Profit before interest and depreciation	16.85
Interest on term loan		1.33
Depreciation		0.77
Profit before tax		*14.75*
Income-tax @ 20%		2.95
Profit after tax		11.80
Repayment of term loan (5 years)		1.90
Net profit		*9.90*
Cash accruals		10.67

15.6.1.9 Break-Even Analysis (Rs. in Lacs)

No	Particulars	Amount	
A	Sales		46.25
B	Variables		
Raw materials		25.00	
Utilities		0.50	
Salaries		2.40	
Stores and spares		0.50	
Repairs and maintenance		0.50	
Administrative expenses		0.50	29.40
C	Contribution (A–B)		16.85
D	Fixed cost		4.00
Break-even point (D/C)			*23.70%*
B:C ratio			*1.57*

15.6.1.10 [A] Leverages

Financial leverage

= EBIT/EBT

= 16.08 ÷ 14.75 = 1.09

Operating leverage

= Contribution/EBT

= 16.85 ÷ 14.75

= 1.14

Degree of total leverage

= FL/OL

= 1.09 ÷ 1.14

= 0.96

15.6.1.10.1 [B] Debt Service Coverage Ratio (DSCR) (Rs. in Lakhs)

Particulars	First year (80%)	Second year (90%)	Third year (100%)	Fourth year (100%)	Fifth year (100%)
Cash accruals	8.53	9.60	10.67	10.67	10.67
Interest on term loan	1.33	1.06	0.80	0.53	0.27
Total [A]	*7.20*	*8.54*	*9.87*	*10.14*	*10.40*
Interest on term loan	1.33	1.06	0.80	0.53	0.27
Repayment of term loan for 5 years	1.90	1.90	1.90	1.90	1.90
Total [B]	*3.23*	*2.96*	*2.70*	*2.43*	*2.17*
DSCR [A] ÷ [B]	*2.23*	*2.88*	*3.65*	*4.17*	*4.79*
Average DSCR	*3.54*				

First and second year only 80 and 90%of plant capacity is utilised

15.6.2 Business Model-II

15.6.2.1 Millet Flour and Semolina (Rawa/Suji)

The flour is one of the basic ingredients used in various product preparation recipes. Millets are processed by the method of dry milling. Process flowchart includes the cleaning of grains followed by milling in hammer mill. The milling separates the endosperm, germ and bran layer grinding it to get fine flour. Semolina is a ready-to-cook product also processed pulvering millets into various particle sizes. The mesh size will be selected to process semolina of different variants.

15.6.2.2 Procedure for Production of Millet Flour and Semolina:

Flow diagram for millet flour

Millets
↓
Cleaning
↓
Dehusking
↓
Hammer mill
↓
Cooling
↓
Flour
↓
Packaging

Flour – 89%, by-product – 11% (Bran)

15.6.2.3 Unique Qualities of the Product

The millet flour is rich in protein, dietary fibre and minerals (Mg, Zn, Fe). The flour is utilised for the preparation of rotis and bakery products (cakes and biscuits).

Flow diagram for millet semolina

Millets
↓
Cleaning & grading
↓
Conditioning
↓
Hammer mill/Pulveriser
↓
Cooling
↓
Shifting
↓
Millet Semolina
↓
Packaging

15.6.2.4 Unique Qualities of the Product

Millet semolina is used for the preparation of upma, kichadi, laddu, idli, dosa, kesari etc. The products are rich sources of protein, fibre, iron, magnesium and zinc. The storage life of semolina is 3–4 months according to the type of packaging.

15.6.2.5 Capital Inputs

15.6.2.5.1 Land and Building

The processing plant can be established in a land measuring totally 1200 sq. ft. with a capital cost of approx. Rs. 2.0 lacs. The required processing shed can be constructed at the said land and the cost estimate for construction of building as per the valuation will be approx. Rs. 5.00 lacs.

15.6.2.5.2 Plant and Machinery

Considering the minimum viable capacity being processed annually on one working shift with 200 working days per year, the machinery and equipment required for installing the processing unit are listed below:

Processing machines required

Sl. No.	Name of machines	Capacity	Qty.	Rate/unit, Rs in lacs	Amount, Rs in lacs
1.	Cleaner cum grader	1.0 QPH	1 No.	0.75	0.75
2.	De-stoner	1.0 QPH	1 No.	0.90	0.90
3.	Mini millet dehusker (centrifugal type)	1.0 QPH	1 No.	2.25	2.25
4.	Hammer mill/pulveriser	0.9–1.0 QPH	1 No.	1.00	1.00
5.	Sifter	1.0 QPH	1 No.	0.50	0.50
6.	Weighing machine	100 kg	1 No.	0.25	0.25
7.	Packaging machine		1 No.	0.35	0.35
Total (X)					*6.00*
Installation, testing, commissioning of machines					0.15
Grand Total = 6.15					

15.6.2.5.3 Miscellaneous Assets

The essential miscellaneous assets including furniture and fixtures, storage facilities, and electrification are to be covered by making a provision of Rs.0.30 lakh.

15.6.2.5.4 Raw Material

The major raw material required for running the unit is millet grains. The total raw materials required for 1 month cost Rs.25 lakh.

15.6.2.5.5 Utilities

Power

The total power requirement estimated based on the machinery would be 10 kW or 13–15 HP. The suitable standby generator provision is also made for uninterrupted operation. The approximate total annual expenditure could be around Rs.1.10 lakh.

Water

Water is one of the essential utility required for processing, cleaning and domestic consumption purpose. The arrangements for regular and continuous supply of water is ensured.

15.6.2.6 Manpower Requirements/Organisational Setup

The unit also requires manpower for running and managing operations and other activities of the unit. Depending upon the capacity of the unit, the required manpower is presented below.

Particulars	Nos.	Monthly salary (Rs.)	Total monthly salary (Rs.)
Manager	1	10,000	10,000
Supervisor cum operator	1	7000	7000
Cleaner	1	3000	3000
Total			*20,000*

15.6.2.7 Tentative Implementation Schedule

Activity	Period (in months)
1. Sanction of loan	2
2. Civil work	1
3. Placement of orders for machinery	2
4. Erection, installation and trials	1

15.6.2.8 Insurance

The unit is covered under adequate insurance, covering all fixed assets and stocks.

15.6.2.9 Cost of the Project and Means of Financing (Rs. in Lacs)

Item	Amount
Land	2.00
Building/civil works	5.00
Plant and machinery	6.15
Miscellaneous assets	0.50
Total term loan	*13.65*
Raw materials	25.00
Labour	2.40
Utilities	1.45
Total working capital loan	*28.85*
Means of finance as term loan	
Promoters' contribution	4.15
Loan from bank/FI	9.50
Subsidy from GOK @ 50%	

15.6.2.10 Profitability Analysis

15.6.2.10.1 Production and Sales

The monthly production and the sales of unit are tabulated below considering the foxtail millet as reference material.

Items	Quantity in Qtl	Whole sale rate per Qtl	Total profit Rs.
Raw materials			
Millets (foxtail millet)	1000	2500	2,500,000.00
Processed products			
Millet semolina (55%)	550.0	7500	4,125,000.00
Millet flour (10%)	100.0	8500	850,000.00
Husk	400.0	1000	400,000.00
			5,375,000.00

The processing capacity is taken at 1000 qtls per month considering single working shift. The sales revenue is totalling Rs. 53.75 lakh per month.

15.6.2.10.2 Raw Materials Required at 100%

The raw materials required for production will be procured at 100% of the capacity as per the annual production schedule and it shall be 1000 qtls.

15.6.2.10.3 Utilities

The expenditure towards utilities at 100% activity level is estimated to be Rs. 50,000/- per annum.

15.6.2.10.4 Interest

The interest charged by banks towards the repayment of term loan of Rs. 9.50 lacs is calculated at 14% with repayment schedule of 5 years which includes the moratorium period of 6 months.

15.6.2.10.5 Depreciation

The depreciation of the all the fixed assets will be calculated on WDV basis considering 10% on building, machinery and miscellaneous assets.

15.6.2.11 Projected Profitability (Monthly) (Rs. in lacs) monthly

No.	Particulars	Cost in Rs.
A	Sales realisation	53.75
B	Cost of production	
Raw materials		25.00
Utilities		0.50
Salaries		2.40
Stores and spares		0.50
Repairs and maintenance		0.50
Administrative expenses		0.50
Total		*29.40*
C	Profit before interest and depreciation	24.35
Interest on term loan		1.33
Depreciation		0.80
Profit before tax		*22.22*

(continued)

No.	Particulars	Cost in Rs.
Income-tax @ 20%		4.45
Profit after tax		17.77
Repayment of term loan (5 years)		1.90
Net profit		*15.87*
Cash accruals		16.67

15.6.2.12 Break-Even Analysis (Rs. in Lakhs)

No	Particulars	Amount	
A	Sales		53.75
B	Variables		
Raw materials		25.00	
Utilities		0.50	
Salaries		2.40	
Stores and spares		0.50	
Repairs and maintenance		0.50	
Administrative expenses		0.50	29.40
C	Contribution (A–B)		24.35
D	Fixed cost		4.00
Break-even point (D/C)			*16.43%*
B:C ratio			*1.83*

15.6.2.13 [A] Leverages

Financial Leverage
= EBIT/EBT
= 23.55 ÷ 22.22 = 1.06

Operating Leverage
= Contribution/EBT
= 24.35 ÷ 22.22
= 1.09

Degree of Total Leverage
= FL/OL
= 1.06 ÷ 1.09
= 0.97

15.6.2.13.1 [B] Debt Service Coverage Ratio (DSCR) (Rs. in Lakhs)

Particulars	First year (80%)	Second year (90%)	Third year (100%)	Fourth year (100%)	Fifth year (100%)
Cash accruals	13.33	15.00	16.67	16.67	16.67
Interest on term loan	1.33	1.06	0.80	0.53	0.27
Total [A]	*14.66*	*16.06*	*17.47*	*17.20*	*16.94*

(continued)

Particulars	First year (80%)	Second year (90%)	Third year (100%)	Fourth year (100%)	Fifth year (100%)
Interest on term loan	1.33	1.06	0.80	0.53	0.27
Repayment of term loan for 5 years	1.90	1.90	1.90	1.90	1.90
Total [B]	*3.23*	*2.96*	*2.70*	*2.43*	*2.17*
DSCR [A] ÷ [B]	*4.54*	*5.42*	*6.47*	*7.08*	*7.80*
Average DSCR	*6.26*				

First and second year only 80 and 90% of plant capacity is utilised

Conclusion: Millets are one of the nutritionally rich cereal grains being utilised since prehistoric times. Processing is an important unit operation for removal of hard undigestible outer husk. Various improved equipment and machineries have been developed by different institutes for processing and value addition of the millets. The properly designed business models show the profitability in the processing and value addition of millets.

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Toxins in Millets

16

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Abstract

Mycotoxins are an emerging threat to humans, mainly through microbial infected food. Though millets are versatile crops, during the unit operation and storage there are chances of it being contaminated by mycotoxigenic microorganisms leading to development of mycotoxin in them. Millets have been reported to be mainly contaminated by fungi. Present chapter informs about the different microorganisms and the types of toxins products in variety of millets. It also gives information about the strategies to mitigate them.

Keywords

Contamination · Microorganisms · Mycotoxin · Fungi

16.1 Introduction

Millet-based foods are traditionally consumed by larger population in tropical areas especially in Africa and Asia. Because millets can survive/be grown well in an extreme environmental condition and does not require any additional care. Millets

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are normally pest-free crops and can be stored for longer periods (Ajani and Vali Pasha 2017). During food/ nutritional insecurity due to agronomic, socioeconomic and other factors, millets could be the best alternative and also provide food and nutritional security (FAO 2009; Issoufou et al. 2013; Girish et al. 2014). The millets contain rich nutraceuticals such as protein, carbohydrates, fat, minerals, secondary metabolites, antioxidants and other nutrients which are having health benefits against chronic diseases (Shahidi and Chandrasekhara 2013; Saleh et al. 2013; Issoufou et al. 2013). In addition, millets contains B vitamins, (B3, B6 and B17), folic acid, Ca, Fe, K, Mg and Zn (Seenappa 1987). Eventhough mostly the millet crops are free from pest, the microbial-mediated contamination has caused serious health threats to humans (Fazekas et al. 1996; Trucksess 2001) and animals (D'Mello et al. 1999; Pestka and Smolinski 2005), and economic losses in many countries (Astoreca et al. 2019; Ajani and Vali Pasha 2017). Food and Agricultural Organization reported that 25% of the food crops were contaminated with mycotoxins worldwide (Boutrif and Canet 1998).

The millets were reported to be contaminated by a range of fungi (*Aspergillus* sp., *Rhizopus* sp., *Penicillium* sp., *Fusarium* sp., *Alternaria* sp., *Epicoccum* sp., *Cerebella* sp., *Cladosporium* sp., *Pithomyces* sp., *Gloeocercospora* sp., *Cercospora* sp., *Coryospora* sp., *Curvularia* sp., *Macrophomena* sp., *Helminthosporium* sp. *and Phoma* sp.) during field level and post-harvest level (Logrieco et al. 2002; Atehnkeng et al. 2008; Wilson et al. 1993; Jurjevic et al. 2007; Badau 2006; Ojochenemi et al. 2016). The mycoflora were reported to be found in both the external and internal parts of plant tissues which were associated with the soil, stems and leaves, further, they also affect the growth and productivity of plants (Astoreca et al. 2019). Most of the cereals, pulses and millets are highly vulnerable to fungal contamination due to the influence of moisture. Further, the fungal strains can easily adhere to the dry food stuffs and could survive for longer duration based on the following conditions: (1) Less moisture—as this favors the fungal growth, (2) The fungal spores will be retained in the same niche for a long period, (3) The fungal strains could survive in extreme environment than other microorganisms (4) The fungal strains can release metabolites and enzymes during an unfavorable condition.

Fungal metabolism is a complicated process and respond individually/collectively based on several environmental factors such as substrate, pH, oxygen availability, water potential, temperature and especially moisture (Vismer et al. 2019). Based on environmental factors and nutrients, some fungi could substantially multiply and secrete enormous toxins. The fungal species may also be involved in ripening and organoleptic activities on the particular food substances (Huerta et al. 1987). Toxin production is subject to modification based on different factors such as genetical changes, substrate modification, light source, pH, water potential, oxygenations, temperature, exposure to preservatives and plant extract (Proctor et al. 2004; Marín et al. 1995, 1999, 2004; Cendoya et al. 2017; Lazzaro et al. 2013; Li et al. 2017a, b; Fanelli et al. 2011; Matic et al. 2013; Keller et al. 1997; Samapundo et al. 2005; Ryu et al. 1999; Etcheverry et al. 2002; Stepien et al. 2015). Mycotoxins can easily contaminate/ enter into the millets during cultivation, packing, transporting, storing and also in raw and processed product (Molinié et al. 2005; Ajani and Vali Pasha 2017). Aflatoxins, deoxynivalenol (a.k.a. vomitoxin), nivalenol, fumonisins, ochratoxin, zerealenone and moniliformin are among the mycotoxins most commonly produced by fungi (Miller 2008). Worldwide, some of the mycotoxins such as trichothecenes, DON, acetyl deoxynivalenol, NIV and fusarenone X are secreted by a wide range of fungal strains and contaminate millets (Dalcero et al. 1997; Jennings et al. 2000; Magan and Olsen 2004) (Table 16.1).

16.2 Finger Millet

The finger millet crops have been reported to be contaminated by a wide range of fungi at different stages such as field harvest, post-harvest, transporting, storage, processing and product storages, which cause significant yield and quality loss (Brandfass and Karlovsky 2008; Chala et al. 2014). Generally, finger millets are susceptible to fungi, especially *Fusarium* sp. and *Aspergillus* sp., and these strains contaminate in a larger scale with their excretion of mycotoxins (Shilpa et al. 2010; Shilpa et al. 2011; Chala et al. 2014). Among the millet varieties, sorghum and pearl millet are highly susceptible to fungal contamination when compared to finger millet (Bandyopadhyay et al. 2007; Wilson et al. 2006a, b). Chala et al. (2014) and his co-workers observed that sorghum was highly affected by the infection of *Fusarium* sp. and *Aspergillus* sp. than finger millet, whereas Wilson et al. (2006a, b) proposed that the possibility of contamination on finger millet might be lesser than other millets. *Fusarium* sp.-based contamination was found in finger millet constituting to about 70% of the total incidence, in which 13 *Fusarium* sp. caused the contamination. Marasas et al. (1984) determined that both *F. culmorum* and *F. graminearum* secreted type B Trichothecenes, (DON—deoxynivalenol and NIV—vivalenol), whereas the quantity of toxin production may vary, and depend on the *Fusarium* sp. (Muthomi et al. 2000; Walker et al. 2001; Llorens et al. 2006). The following *Fusarium* sp. secreted mycotoxins such as trichothecenes DON, NIV, 3-acetyl deoxynivalenol and acetyl T2 toxin, ZEA and Fuasrins commonly occur in finger millet (Demeke et al. 2005; Llorens et al. 2006; Shilpa et al. 2011).

16.3 Kodo Millet

The incidence of *Aspergillus* sp.-based infestation on Kodo millet was reported by Antony et al. (2003) especially *Aspergillus tamarii*. Janardhanan et al. (1984) observed that fumigaclavin A and indole alkaloid were isolated from *Aspergillus tamarii* which was associated with Kodo millet. It was responsible for causing Kodo poisoning iin humans and the symptoms were characterized by nausea, vomiting, delirium, depression, intoxication and unconsciousness. In addition, Kodo millet was often contaminated with *Aspergillus tamarii* and it also produced significant amount of mycotoxins such as cyclopiazonic acid (CPA) (Dorner 1983; Rao and Husain 1985; Antony et al. 2003). CPA has been produced by wide range of fungi such as *Penicillium cyclopium*, *Penicillium camembertii*, *Aspergillus versicolor*, *Aspergillus oryzae*, *Aspergillus flavus, Aspergillus tamarii and Phomopsis paspalli*

Table 16.1 Mycotoxins and causative organisms found in different millets

S. No	Name of the crop/ millet	Contaminant/toxin (s) producing organisms	Name of the toxin (s) produced by organisms	Sub-type of the toxin	References	Health implications	References
1.	Finger Millet	*F. culmorum* and *F. graminearum*	Trichothecenes, deoxynivalenol (DON) and nivalenol (NIV)	Trichothecenes—Type B	Marasas et al. (1984)	–	–
2.	Finger Millet	*Fusarium* sp.	Trichothecenes, DON, NIV, 3-acetyl deoxynivalenol, acetyl T2 toxin, ZEA and fuasrins	–	Demeke et al. (2005), Llorens et al. (2006)	–	–
3.	Millets	*Fusarium* sp.	Trichothecenes, DON, acetyl deoxynivalenol, NIV and fusarenone X	–	Jennings et al. (2000), Magan and Olsen (2004)	–	–
4.	Kodo Millet	*Aspergillus tamari*	Fumigalavin A and indole alkaloid	–	Janardhanan et al. (1984)	'Kodo Poisoning'—Nausea, vomiting, delirium, depression, intoxication, and unconsciousness	Janardhanan et al. (1984)
5.	Kodo Millet	*Penicillium cyclopium*, *Penicillium camembertii*, *Aspergillus versicolor*, *Aspergillus oryzae*	Cyclopiazonic acid (CPA)		Holzapfel (1968), Ohmomo et al. (1973), Orth (1977), Luk et al. (1977), Still et al. (1978)	CPA-induced toxicity affected dogs gastrointestinal tract and kidneys	Neuhring et al. (1985)

		and *Aspergillus flavus*					
6.	Kodo Millet	*Penicillium cyclopium*, *Aspergillus versicolor*, *Aspergillus oryzae*, *Aspergillus flavus*, *Aspergillus tamari*, *Penicillium camembertii*	Cyclopiazonic acid	–	Lalitha Rao and Husain (1985)	–	–
7.	Pearl Millet	*Claviceps fisifoumis*, *Claviceps fusiforrnis* and *C. purpurea*	Total alkaloids, clavinet alkaloids Alkaloids of ergotoxine, ergotamine and ergometrine	–	Bhat et al. (1976)	–	–
9.	Pearl Millet	*Aspergillus flavus*	Aflatoxins	–	Wilson et al. (1995, 2006a, b)	–	–
10.	Pearl Millet	*Aspergillus flavus*	Aflatoxins	B1, B2, G1 and G2	Raghavender et al. (2007)	–	–
11.	Pearl Millet	*Fusarium* sp.	Zearalenone, nivalenol, deoxynivalenol	–	Wilson et al. (1995)	–	–
12.	Pearl Millet	*Fusarium chlamydosporum* and *F. equiseti.*	Nivalenol	–	Wilson et al. (1995)	–	–
13.	Pearl Millet	*Fusarium moniliforme*, *Fusarium semitectum*,	Moniliformin, beauvericin and fumonisins	–	Wilson et al. (2006a, b)	–	–

(continued)

Table 16.1 (continued)

S. No	Name of the crop/ millet	Contaminant/toxin (s) producing organisms	Name of the toxin (s) produced by organisms	Sub-type of the toxin	References	Health implications	References
		Fusarium pseudonygamai, Fusarium chlamydosporum, Fusarium verticillioides					
14.	Pearl Millet	*Fusarium* sp.	Fumonisin	B1	Henry et al. (2000)	Toxic to swine, equines	Henry et al. (2000)
15.	Sorghum and Pearl Millet	*Fusarium proliferatum*	Fumonisins	–	Hester F. Vismer et al. (2019)	Carcinogenic to humans (Group 2B); Neural tube defects in newborns	Ostry et al. (2017), Gelineau-van Waes et al. (2009)
16.	Sorghum and Pearl Millet	*Fusarium proliferatum*	Moniliformin	–	Hester F. Vismer et al. (2019)	Inhibits thiamine pyrophosphatase dependent enzymes in the tricarboxylic acid (TCA) cycle	Pirrung et al. (1996)
17.	Millet	*Fusarium nygamai*	Moniliformin		Marasas et al. 1991	Toxic to poultry—Heart problem	Gruber-Dorninger et al. (2017)
18.	Sorghum Millet	*Fusarium* sp. and *Fusarium graminearum*	Zearalenone (non-steroidal estrogenic mycotoxins)	–	Andrea L Astoreca et al. (2019)	Zearalenone has major effects on reproduction in females, but it affects the male reproductive system	Andrea L Astoreca et al. (2019), Gupta et al. (2018)
19.	Sorghum Millet	*Fusarium verticillioides* and	Fumonisin	–	Andrea L Astoreca et al. (2019)	Cause of porcine pulmonary edema and	Andrea L Astoreca et al. (2019)

		Fusarium proliferatum				equine leukoencephalomalacia	
20.	Sorghum Millet	*Fusarium graminearum*	Trichothecene	–	Piacentini et al. (2019)	Affect human and animal health	Piacentini et al. (2019)
21.	Sorghum Millet	*Fusarium* sp.	Deoxynivalenol (DON)	–	CAST (2013)	Decrease in feed intake (anorexia, decreased nutritional efficiency, reduced weight gain), immunosuppression (higher susceptibility to bacterial infections) and affect also the reproductive system in some animal species	CAST (2013)
22.	Sorghum Millet	*Alternaria* sp. + *Epicoccum sorghinum*	Tenuazonic acid (TeA)	–	Rychlik et al. (2016)	Children's health	Rychlik et al. (2016)
23.	Sorghum Millet	*Aspergillus fumigatus*	Gliotoxin	–	Andrea L Astoreca et al. (2019)	–	–
24.	. Millet	Not mentioned	Ochratoxin A	Group 2B	Elbashir and Ali (2014)	Human nephropathies and kidney cancer	Marquardt and Frohlich (1992), Ringot et al. (2006), Pfohl-Leszkowicz and Manderville (2007)
25.	Sorghum Millet	*Aspergillus ochraceus*	Ochratoxin B	–	Doster et al. (1972, 1974)	–	–
26.	Sorghum Millet	*Fusarium* sp.	Zearalenone (ZEN) contain	–	Elbashir and Ali (2014)	Hazardous to animals	

(continued)

Table 16.1 (continued)

S. No	Name of the crop/millet	Contaminant/toxin (s) producing organisms	Name of the toxin (s) produced by organisms	Sub-type of the toxin	References	Health implications	References
			non-steroidal resorcyclic acid lactone				European Commission (1996)
27.	Sorghum Millet	*Aspergillus* sp.	Aflatoxins	AFB1	Elbashir and Ali (2014), Ibrahim et al. (1998)	–	–

(Holzapfel 1968; Ohmomo et al. 1973; Orth 1977; Luk et al. 1977; Still et al. 1978; Antony et al. 2003). The infected millet extract was also found to be with mycotoxins (Rao and Husain 1985). Neuhring et al. (1985) stated that CPA caused severe gastrointestinal tract and kidney problems in dogs, whereas Antony et al. (2003) reported the acute hepatotoxicity and preneoplastic changes in rat liver by oral administration of CPA. Ajani and Vali Pasha (2017) detected the aflatoxin AFB1 in finger millet, foxtail millet, pearl millet and sorghum, whereas no response was observed in little and kodo millet.

16.4 Pearl Millet

Loveless (1967) reported that the ergot of pearl is caused by *Claviceps species. C. fisifoumis* produced clavinet alkaloids while *C. purpurea* produced alkaloids of ergotoxine—rgotamine ergometrine group on pearl millet, and the total amount of alkaloids ergoty pearl was 32 mg/l00 g (Bhat et al. 1976). Pearl millet was most frequently infected by certain fungal species such as *Fusarium* sp. *Phyllosticta* sp., *Cerebella* sp., *Cladosporium* sp., *Epicoccum* sp., *Penicillium* sp., *Rhizopus* sp., *Aspergillus* sp., *Candida* sp., *Pithomyces* sp., *Torulopsis* sp., *Helminthosporium* sp., *Curvularia* sp., *Alternaria* sp. and *Gloeocercospora* sp. (Jurjevic et al. 2007; Gardner 1971; Wells and Winstead 1965; Badau 2006). *Aspergillus* sp. and *Fusarium* sp. most frequently infected the pearl millet in different environmental conditions.

Generally, the aflatoxins were observed in pearl millet at every stage of its growth like milky stage, pre-mature, mature and post-harvest stages, and all types of aflatoxins (Gl, G2, B2, B1) (Raghavender et al. 2007). The aflatoxin was found predominantly during rainy season than other seasons and mostly 16–40% of insect-damaged pearl seeds contained aflatoxins. Aflatoxin contamination was less in drought regions (Wilson et al. 1991; Raghavender et al. 2007). Jurjevic et al. (2007) noticed that the fungal growth was high in rainy season at the moisture level 21–36% and also detected the following: (a) Growth of *A. flavus* increased in high-moisture environment especially at 25 °C; (b) The average aflatoxin level was 174 ng/g and it went up to 798 ng/g in their experimental time; c) The aflatoxin was stable and was not easily affected by environmental factors such as temperature and relative humidity.

Ppearl millet was one of the important poultry rations in many countries, and the effect of mycotoxins in poultry caused some serious illness such as reduced levels of weight loss, serum albumin and other proteins and suppression of humoral and cellular immunity (Huff et al. 1986; Kubena et al. 1997; Qureshi et al. 1998). There are few instances that infection in broiler chicks with combination of moniliformins (Kubena et al. 1997). In west Africa, the albumin adducts in the blood of children was reported by Gong et al. (2003) due to aflatoxin-contaminated maize consumption. Higher levels of aflatoxin exposure affect children's growth and also reduce salivary IgA (Gong et al. 2002; Turner et al. 2003). In India, aflatoxin B1 contamination has been noticed at substantial level in cooked pearl millet, and also

A. flavus and *A. parasiticus* growth was dominant in the pearl millet (Mishra and Daradhiyar 1991; Jurjevic et al. 2007). Aflatoxin B1 levels were high in pearl millet, 185 μg/kg, than aflatoxin B2, 105 μg/kg, while the order of decreasing the aflatoxin level after 6 months' storage was: 190 (B1) > 140 (B2) > 40 (G2) > 30 (G1) μg/kg (Raghavender et al. 2007).

Apart from aflatoxins, *Fusarium* sp.-related mycotoxins also caused contamination and were most frequently detected in pearl millet (Wilson et al. 1993, 1995). Many *Fusarium* sp. were involved in pearl millet infestation, i.e. *F. chlamydosporum, F. semitectum, F. moniliforme, F. roseum, F. equiseti, F. verticillioides, F. pseudonygamai* (Jurjevic et al. 2005; Wilson et al. 1993, 1995) across the world. Luttrell (1954) noted that a complex of *Fusarium* sp. infested various grains, and Wells and Winstead (1965) determined that 7% of the total pearl millet was infected by *Fusarium* sp. in Georgia. *Fusarium* sp. were common pearl millet contaminants in the southeastern US especially *F. semitectum* Berk & Ravenel and *F. chlamydosporum* Wollenweb. & Reinking (Wilson et al. 1993, 1995). *F. pseudonygamai* is commonly found in pearl millet in Africa (Leslie and Summerell 2006) and United States (Jurjevic et al. 2005) and fumonisins toxin was substantially present in pearl millet (Chilaka et al. 2016). Wilson et al. (2006a, b) observed that the *F. semitectum* infestation was high in pearl millet HGM 100 (hybrid variety) while isolation frequency of *F. chlamydosporum* was greater from pearl millet Tifgrain 102 (hybrid variety). In addition, the frequency of *F. moniliforme* was high in pearl millet and it secretes moniliformin mycotoxin. The beauvericin contamination was also greater in pearl millet.

The *Fusarium* sp. affected pearl millet in various environmental conditions especially 2–4 weeks prior to harvest (Wilson et al. 1993). The isolation frequency of *F. chlamydosporum* increased in grain stored at 86% and 91% r.h and nivalenol was detected at 100% r.h of pearl millet (Jurjevic et al. 2007). Also the zearalenone mycotoxins were detected at 20–22% of grain moisture (Jurjevic et al. 2007). Wilson et al. (1995) reported that complex of *Fusarium* sp. caused infection on grains and the decreased pattern of infestation is *F. semitectum* (35.6%), F. *chlarnydosporurn* (17.2%), *F. moniliforrne* (0.4%) and *F. equiseti* (Corda) Sacc. (0.3%). The frequency of infection also varied according to the species such as 12–45% for *F. semitectum* and 4–17% for *F. chlamydosporum*. The mycotoxins in pearl millet such as zearalenone, nivalenol and deoxynivalenol average concentration were 0.17 ppm, 0.42 ppm and 0.01 ppm, respectively. The Wilson et al. (2006a, b) found that the moniliformin (92.1 μg/kg) and beauvericin (414.6 μg/kg) mycotoxins in the pearl millet were secreted by *Fusarium* sp. Leslie et al. (2005) detected fumonisins from *F. verticillioides* and moniliformin from *F. pseudonygamai* in pearl millet. The fumonisin B1 is highly toxic to swine/ equines, whereas 80,000 μg/kg concentrations did not cause adverse effects on growing broilers. The 50,000 μg/kg concentrations of fumonisin B1 caused reduced feed intake in turkey poults (Henry et al. 2000; Broomhead et al. 2002). But, in the range of 16,000–27,000 μg/kg moniliformin resulted in mortality of young broilers and 1,00,000 μg/kg of moniliformin can cause lower feed intake in turkey poults (Li et al. 2000). The combination of fumonisin and moniliformin caused immunosupression in turkey poults, and beauvericin associated with other *Fusarium* mycotoxins and caused human and animal health implications (Li et al. 2000).

16.5 Sorghum Millet

Sorghum has to survive in diverse conditions of climate and soil nature and even the attack of various pathogens such as bacteria, viruses, parasites, insects and/or fungi (Garba et al. 2017). Though it is resistant to microbes, pest and other factors, sorghum is endangered by fungal diseases that resulted in the reduction of crop yields and quality with substantial economic losses. Certain fungal genera involved in the contamination of sorghum grains across the world such as *Aspergillus* sp., *Pennicilium* sp. and *Fusarium* sp. and it responsible for production of some mycotoxins such as aflatoxins, fumonisins, zeralenone and deoxynivalenol (Astoreca et al. 2019). Navi (2005) has demonstrated that the sorghum harvest corresponds with severe rainfall, hurricane, flood and other factors or all of which induce the mycotoxins producing fungi infestation. WHO (2006) reported that the mycotoxin-contaminated sorghum causes serious illnesses in humans and animals and lso affect animal reproduction. It also causes severe economic loss in several countries due to the quantitative and qualitative reduction of crop yield. Seven toxigenic *Fusarium* strains were isolated from sorghum in Nigeria (Hester F. Vismer et al. 2019) and zearalenone mycotoxins were also observed in sorghum, which are produced by several *Fusarium* sp. especially *F. graminearum* (Astoreca et al. 2019). Although, the deoxynivalenol (DON) is not a major problematic toxin to sorghum and it caused some health issue to human and animals with the combination of trichothecene as co-occurrence of mycotoxins (Piacentini et al. 2019).

Sorghum-based foods contaminated with tenuazonic acid (TeA) mycotoxins pose a potential risk to children's health. The food and feeds have traditionally been contaminated by *Alternaria* sp. and *Epicoccum sorghinum* (*Phoma sorghina*) (Rychlik et al. 2016). The TeA mycotoxin was produced by *E. sorghinum*, and it is considered as an important component in the fungal disease which affects the sorghum grains in large extent (CCCF 2012; Oliveira et al. 2018). Gliotoxin is produced by *Aspergillus fumigatus* and it is mainly observed in sorghum samples (Astoreca et al. 2019). Elbashir and Ali (2014) detected that sorghum samples were contaminated by AFB1 mycotoxin in two different regions of Nigeria. The range of aflatoxin level in sorghum grains was 0.1–11.2 μg/kg in Egypt (Ibrahim et al. 1998) while 10–80 μg/kg of aflatoxin was noted in sorghum at Nigeria (Salifu 1981). Likewise, Uriah and Ogbadu (1980) reported 100% contamination of sorghum samples by aflatoxin in Nigeria while Makun et al. (2009) detected 31.25% and 57.85% of contamination in the field and stored sorghum samples. Ochratoxin A and Ochratoxin B were also detected in sorghum and other cereal samples at Nigeria (Elbashir and Ali 2014; Blesa et al. 2004; Juan et al. 2008).

16.6 Effect of Mycotoxins

Aflatoxins are the most important mycotoxins and some of the environmental factors such as soil type, climate, heat, high humidity, lack of aeration, improper agricultural practices, insect and rodent damage, phytoalexin production, maturity, weather condition during harvesting, timely drying, maintaining safe moisture level during post-harvest conditions and other factors were helped to aggravate the aflatoxin production (Diao et al. 2015; Hell and Mutegi 2011). Some researchers (Egan 1982; Williams et al. 2004; Waliyar et al. 2016) observed that aflatoxin contamination was substantially high during post-harvest condition than during pre-harvest conditions, and it also contaminates most of the staple foods, affecting 25% of the crops in the world (Niessen et al. 2018). Aflatoxins are carcinogenic and mutagenic mycotoxins. The highest aflatoxin level (1164 μg/Kg) was detected in a sample collected from Nigeria Hussaini et al. (2009). Aflatoxins are found in urine of liver disease patients, blood, semen, breast milk and blood of umbilical cord of babies in Nigeria and death was reported on consumption of mouldy groundnut cake (Adegoke et al. 1996; Ikeorah and Okoye 2005; Oluwafemi and Ikeowa 2005; Adejumo et al. 2013). Ojochenemi et al. (2016) stated that the results of acute aflatoxin was death whereas results of chronical aflatoxin caused immune suppression, mutagenicity, teratogenicity and carcinogenesis.

Fumonisins are considered as a carcinogenic agent to humans, causing neural tube defects in newborns (Ostry et al. 2017; Gelineau-van Waes et al. 2009), porcine pulmonary oedema and equine leukoencephalomalacia (Astoreca et al. 2019). The provisional maximum tolerable daily intake (PMTDI) of fumonisins for humans is 2 μg/kg body weight/day according to Joint FAO / WHO Expert Committee on Food Additives (JECFA 2011). The largest producer of fumonisins are isolated from *F. proliferatu* and *F. verticillioides* whereas the highest production of moniliformin (by *F. nygamai*) was observed in millets at Africa (Marasas et al. 1991). Commonly, poultry are most sensitive to moniloformins and it effected on heart problems (Gruber-Dorninger et al. 2017) and it inhibit thiamine pyrophosphatase-dependent enzymes in Kreb's cycle (Pirrung et al. 1996). In Europe, human exposure to the moniliformins in foods are higher (Vismer et al. 2019). The zearalenone (ZEN) contained non-steroidal resorcyclic acid lactone and was produced by several *Fusarium* sp. especially *F. culmorum* and *F. graminearum*. ZEN is mainly found in animal feed and it is being potentially hazardous to animals (European Commission 1996). Zearalenone has a major effect on both male and female reproductive systems and sometimes it may act associated with trichothecenes (Gupta et al. 2018).

Deoxynivalenol (DON) causes chronic effects on animals like decrease in feed intake (anorexia), weight loss, immunosuppression and reproduction system problem (CAST 2013). Ochratoxin A-based disease known as ochratoxicosis and the main target of this mycotoxins was kidney (Elbashir and Ali 2014) It has been declared as a carcinogen (Group 2B) by the International Agency for Research on Cancer (IARC 1993), and it also causes human nephropathies, kidney cancer (Marquardt and Frohlich 1992; Ringot et al. 2006; Pfohl-Leszkowicz and

Manderville 2007). Ochratoxin B is produced by *Aspergillus ochraceus* and is less toxic than Ochratoxin A (Doster et al. 1972, 1974).

16.7 Strategies to Mitigate the Presence of Toxins in Millet

Since microorganisms are ubiquitous, it is necessary that special care be taken to mitigate them. Traditionally various methods exist which can improve the safety of the millet source food, such as physical methods, chemicals methods and biological methods.

Physical method: Washing and sorting is one of the common steps in the unit operation of grains. This ensures that the lower quality unhealthy millet grain can be separated during washing and sorting. Floatation methods can be employed to remove the unhealthy low density infected millet grains.

Chemical method: The idea of using the chemical method is to modify the structure of mycotoxins making them less toxic, these chemicals include acids, bases, reducing agents and oxidizing agents (Shanakhat et al. 2018). Treatment with chemicals such as ammonia has shown to reduce mycotoxins such as aflatoxins, fumonisins and ochratoxins (Peraica et al. 2002). Similarly, chemicals such as sodium bisulfite, sodium hydroxide and ozone havebeen reported to reduce aflatoxin in grains (Jalili et al. 2011; Trombete et al. 2017).

Biological methods: Biological methods for mitigation of mycotoxins is gaining interest in recent years. The basic idea for the inhibitions of mycotoxins in this case is the use of competitive microflora (bacteria, yeast and mold) for exclusion together with the production of secondary metabolites and volatile compounds (Medina et al. 2017). Of these lactic acid bacteria has shown high efficacy for inactivation of mycotoxigenic molds, and thus inhibiting mycotoxin formation. Some pre-harvest beneficial fungi such as *Trichoderma harzianum* have also been reported to retard the growth of mycotoxigenic molds e.g. *Aspergillus* species (Braun et al. 2018; Wan et al. 2020).

16.8 Conclusion

The mycotoxigenic microorganisms infecting millets mainly constitute fungi, which are responsible for the mycotoxin formation in millets. Though the research on millets is ongoing, only less information is available at this point. Future research, needs to address the unit operations for millet processing for pilot as well as industrial scale which also includes improved equipment design for handling and processing of millet grains. Further research is also required to identify the strategies which can inactivate and inhibit the mycotoxigenic microorganisms in millets. Special focus in the area of biological methods for mitigation of mycotoxigenic microorganisms is warranted.

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