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

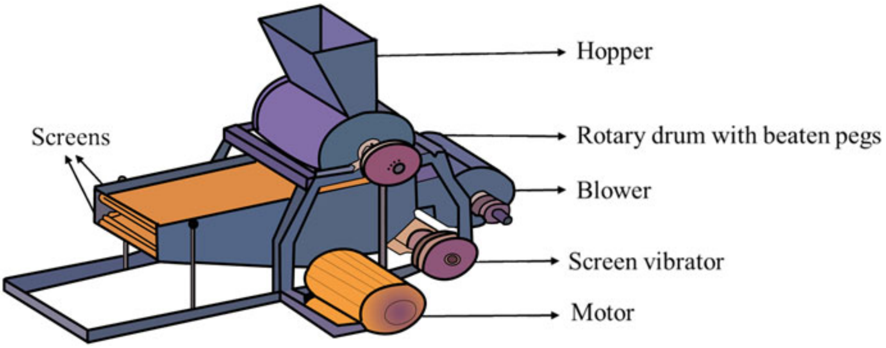

Fig. 4.1 Millet thresher. (Reproduced from Gbabo et al. 2013)

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 $\O = 0.302$ 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

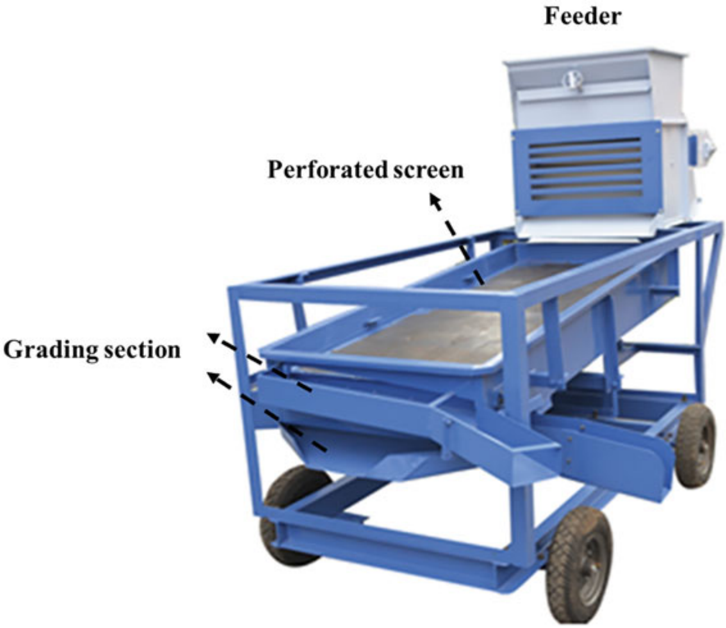

Fig. 4.2 Destoner-cum-grader-cum-aspirator. (Reproduced from https://perfura.in/wp-content/uploads/2019/03/Destoner.jpg)

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.

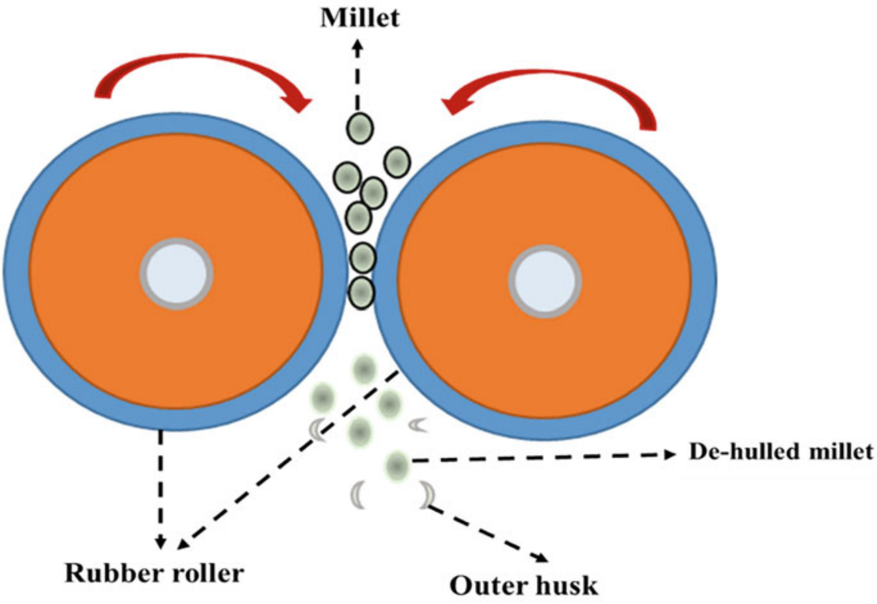

Fig. 4.3 Rubber roll huller

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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