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Mechanization of millet cultivation: Status, technological innovations and future directions

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Abstract

Millet cultivation stands at the intersection of traditional agricultural knowledge and modern technological advancements, especially in arid and semi-arid regions where these crops contribute significantly to climate resilience and food security. India's emphasis on agricultural mechanization is quite important in improving output, efficiency, and sustainability since it is the leading producer of millets in the world. Emphasizing precision agronomic practices including improved varietal selection, optimized water use, and targeted fertilizer application; this review investigates the transforming effects of mechanization in millet farming. It also appears at developments in weed and pest control through robotic systems and smart pesticide delivery techniques that lower labour reliance and promote ecological sustainability. Harvesting and post-harvest innovations combining conventional methods with mechanical threshing and processing techniques are also demonstrated to significantly reduce losses. Development of machinery appropriate for smallholder farms and scaling new technologies like seed-planting robots continues to be a challenge, though. Bridging traditional methods with cutting-edge technologies, millet mechanization holds the potential to sustainably address the demands of a growing population while conserving critical resources. This paper effectively illustrates the transition of agricultural practices from traditional manual methods to modern mechanized systems, highlighting the progressive adoption of advanced machinery.

Keywords: Millet, mechanization, advanced machinery, sustainable farming, post-harvest

Introduction

Globally, millets serve as a staple food, specifically in developing nations, while also maintaining cultural significance in several nations. Their consumption has been steadily increasing due to their exceptional nutritional profile. Millets are a significant source of nutritional energy and possess numerous health-promoting properties (Samtiya *et al.*, 2022) [62]. Millets, a diverse group of small-seeded dryland cereals from the *Poaceae* family, were among the earliest domesticated crops. Being naturally gluten-free and low in Glycemic Index (GI) (Chakraborty *et al.*, 2020) [14], they are an ideal alternative for individuals with wheat allergies or gluten intolerance. Additionally, millets are abundant in essential micronutrients, including B vitamins, calcium, iron, potassium, magnesium, and zinc (Tripathi *et al.*, 2021) [76]. The term "millets" refers to a diverse group of small-seeded cereal grasses, which are broadly classified into two categories based on grain size: major millets (such as sorghum and pearl millet) (Gowri *et al.*, 2020; Naik *et al.*, 2022) [26, 50] and small millets (including finger millet, foxtail millet, and little millet, among others) (Anbukkani *et al.*, 2017; Singh *et al.*, 2020; Doggalli *et al.*, 2024) [6, 19].

The world is undergoing rapid transformations, with climate change posing an immediate threat rather than a distant concern. Agriculture, in particular, faces a critical challenge: without urgent reforms in farming practices, the consequences may become irreversible. While the Green Revolution of the 1960s successfully addressed food security in India, it also introduced unintended consequences, such as environmental degradation and nutritional deficiencies. These challenges necessitate a shift in agricultural paradigms, particularly moving away from the unsustainable dominance of the rice-wheat cropping system. Millets exhibit unique agronomic and nutritional characteristics that distinguish them from other cereals

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(Nithiyanantham *et al.*, 2019; Bhatt *et al.*, 2022) [49, 10].

Millet Known for their resilience to drought (Brahmachari *et al.*, 2025; Tripathi *et al.*, 2021) [76, 12], pests, and diseases, millets thrive in low-fertility soils with minimal agricultural inputs, making them well-suited for harsh climatic conditions (Vidhya *et al.*, 2023) [78]. Beyond their agronomic advantages, millets play a crucial role in mitigating soil degradation and preserving biodiversity.

Millets present a viable solution to this anthropogenic crisis. As ancient, nutrient-dense grains, they offer both environmental sustainability and nutritional benefits. Their low resource requirements make them ideal for climate-resilient agriculture (Satyavathi, *et al.*, 2021; Joshi, *et al.*, 2025) [63, 33]. Adopting millet-based production systems can reduce input costs, conserve water resources, enhance soil health, and improve agricultural resilience to climate variability. Beyond their ecological advantages, millets significantly contribute to nutritional security. They are rich in proteins, essential amino acids, minerals, and vitamins. Small millets, in particular, are excellent sources of phosphorus and iron, are highly digestible, and contain lecithin, which supports nervous system health. Thus, millets provide a triple benefit: food security, nutritional security (Renganathan, *et al.*, 2020; Srivastava, S., & Arya, C. 2021), and economic security (Brahmachari *et al.*, 2019) [12, 58]. As a cornerstone of sustainable agriculture, they promote soil conservation, ecosystem stability, and overall human well-being.

India holds the distinction of being the world's leading producer and consumer of millets, accounting for over 40% of global production and consumption (Aruna *et al.*, 2020). Millets have a major part in rainfed agriculture, sustaining approximately 50% of India's rural workforce and nearly 60% of its cattle population. Recognizing their agro-ecological and nutritional significance, the United Nations General Assembly declared 2023 the *International Year of Millets (IYM 2023)*—a proposal spearheaded by India to revive traditional farming systems and enhance resilience against climate variability.

Despite millets' socio-economic importance, their cultivation remains hampered by low mechanization. Globally, agricultural mechanization has often been neglected in development agendas (Mehta *et al.*, 2019) [43], though its role in improving productivity is undeniable. In India, the overall farm mechanization level stands at just 47% (Mehta *et al.*, 2023) [44], with millet farming lagging further due to high machinery costs, limited access to technology, and socio-economic barriers**.** This reliance on manual labor perpetuates inefficiencies, increases production costs, and exacerbates post-harvest losses, ultimately diminishing farmer incomes.

Mechanization in millet production spans tillage**,** sowing**,** weeding**,** harvesting**,** and post-harvest processing **(**Kate, A., & Singh, A. 2021) [37] each stage critical for optimizing yield and quality (Chakraborty *et al.*, 2024) [13]. While mechanized operations reduce human intervention, ensure uniformity, and enhance marketability, their adoption remains limited. Smallholder farmers, particularly women who dominate the agri-food value chain (Sukumaran *et al.*, 2023) [74] still depend on labor intensive traditional methods (e.g., hand-hoeing) to meet culinary and cultural needs. This gap underscores the urgent need for scalable, appropriate machinery solutions that fulfil to millet cultivation demand.

This paper presents a study of the machinery utilized in millet production, encompassing from tillage to post-harvest operations. Currently, no such study exists; therefore, we have consolidated all material regarding machineries into a single Paper. By synthesizing existing knowledge, this work aims to highlight technological gaps, opportunities for innovation, and policy-relevant insights to advance sustainable millet farming.

Status of millet production

Millets, members of the grass family, are hardy crops with small seeds that flourish in arid and semi-arid ecosystems, particularly as rainfed crops on marginal lands with low soil fertility and moisture. Their ability to withstand high temperatures and drought conditions, requiring only 350 mm of water compared to 1200 mm for rice, positions them as ideal crops for climate change and contingency planting (ICAR, 2023) [32]. Globally, millet production reaches 30.59 million metric tons, spanning 30.86 million hectares (FICCI, 2023) [22]. The top 10 millet-producing countries collectively represent 89% of the global millet cultivation area and contribute 90% to the world's millet supply. Interestingly, the top 10 countries, excluding India and China, share the same rank in both production and area under millet cultivation. Excluding India and China, the remaining eight countries are all in Africa as shown in fig. 1. India leads global millet production, contributing 41% to the world's total, followed by Niger and China with 10% and 9% production shares, respectively. On the consumption front, Africa stands as the largest consumer, consuming 40% of the world's millets.

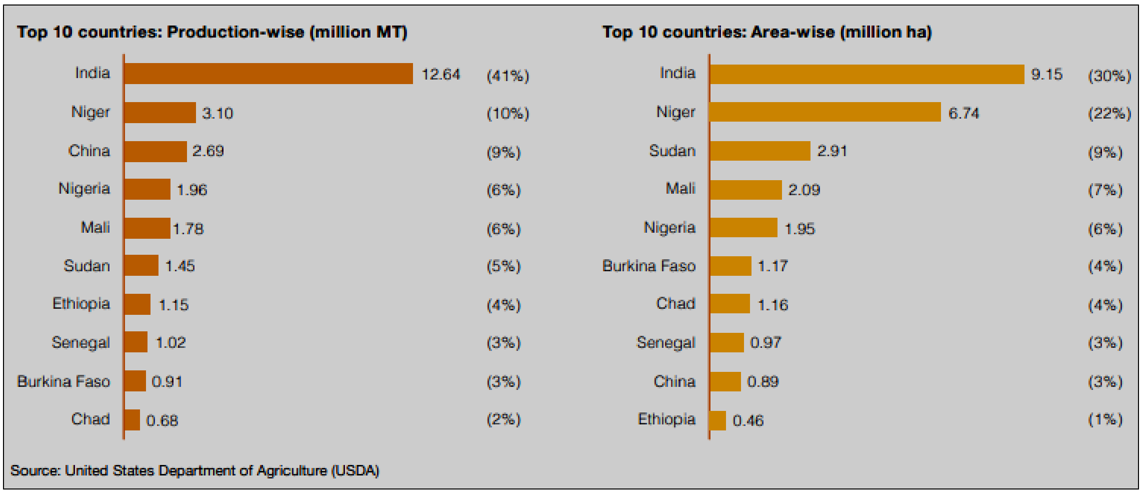
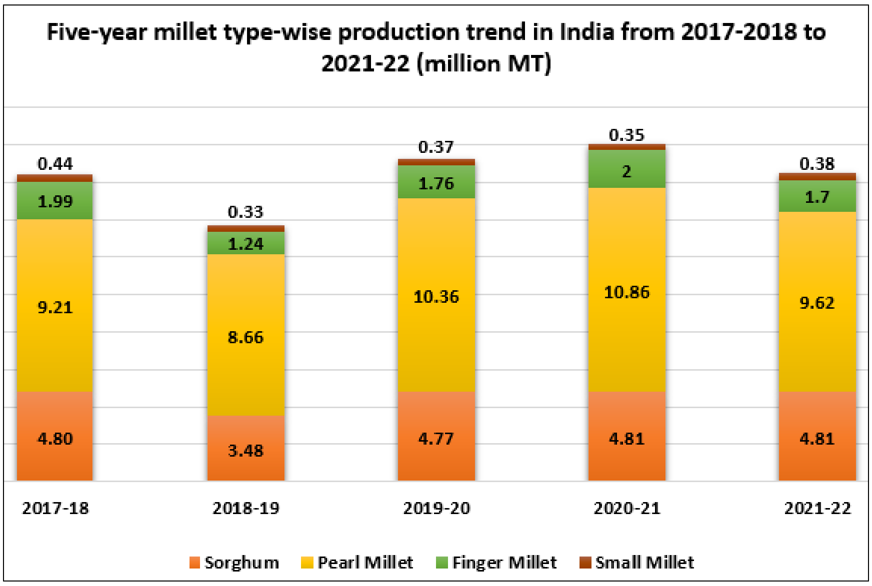


Fig 1: Top 10 countries in term of millets production and area under millets cultivation

India, a major millet producer, averages 16.39 million metric tons of millet production between 2017-18 and 2021-22. This includes 9.75 million MT of pearl millet, 4.54 million MT of sorghum, 1.74 million MT of finger millet, and 0.37 million MT of minor millets. The average millet cultivation area in the country during this period is 13.28 million hectares, with major shares under pearl millet (55%), sorghum (33%), finger millet (8%), and minor millets (4%) (Anonymous, 2023) [2]. The top 10 millet-growing states in 2021-22, such as Rajasthan, Maharashtra, Uttar Pradesh, Madhya Pradesh, Gujarat, Haryana, Jharkhand, Karnataka, Tamil Nadu, and Andhra Pradesh, collectively contribute over 95% of the production. India cultivates various millet crops, including sorghum, bajra (pearl millet), ragi or mandua (finger millet), and small millets like kutki, sanwa, kangni, cheena, kodo, and korale, known for their health advantages and nutritional worth. According to FAO, global millet production reached 89.17 million tonnes in 2019-20 from an area of 74 million hectares. India, a global leader, produced 17.9 million tonnes of millets in 2020-21, cultivated in 21 states across about 12.5 million hectares, contributing over 15% to the world's total production. Challenges in millet cultivation include low productivity, seed quality concerns, limited shelf-life, processing machinery shortages, market linkages absence, and issues related to uniformity, standards, and grades.

The share of small millets in the Gross Cropped Area has declined to 0.88% during 2014-19 (finger millet-0.56%, other small millets-0.32%), compared to 4.9% during 1956-61 (finger millet-1.6%, other small millets-3.3%). Similarly, the share in total food grains production decreased to 0.71% during 2016-21 (finger millet-0.58%, other small millets-0.13%), contrasting with 5.2% during 1956-61 (finger millet-2.5%, other small millets-2.7%). The period from 1951 to 2021 witnessed a substantial decline in small millet cultivation area (89.7% for small millets other than finger millet, 52% for finger millet). The area under finger millet remained stable at around 2.50 million hectares during the green revolution era, then gradually declined below 2.0 million hectares from the early 1980s, reaching 10% by 2020. In the case of other small millets, the average area remained around 5 million hectares till 1960, then gradually declined to above 4 million hectares till 1980, followed by a drastic fall to less than 25% in the next 25 years, reaching 10% by 2020 (Agricultural Statistics, 2022).

The overall production of small millets has declined by nearly 44%, although not consistently matching the rate of change in cultivation area. For instance, the production of finger millet gradually increased corresponding to the initial expansion in area, reaching its peak at 3.20 million tonnes in 1978-79, followed by a gradual decline. Despite a reduction in cultivation area by more than half during the same period, the total production has actually increased by 12.5% from the first 5-year plan to the 12th plan. This growth is attributed to improved yield levels resulting from farmers adopting high-yielding varieties and advanced production practices. In contrast, other small millets witnessed fluctuating production levels, plummeting by over 80%. However, productivity has marginally risen from 380 kg/ha in 1950-51 to 800 kg/ha in 2019-20 at the all-India level as shown in fig. 2. Notably, finger millet yields significantly increased from 649 kg/ha (1950-51) to 1747 kg/ha (2019-20) due to focused crop improvement initiatives and enhanced crop management practices. The distribution of individual millet cultivation is uneven, despite small millets being grown in nearly every state or region.



Source: State of Indian Agriculture - different years, Agricultural Statistics at a Glance 2020 [1]

Fig 2: Five-year millets production in India

Karnataka emerges as the major finger millet-producing state, contributing to 65% of both area and production in 2019-20, followed by Uttarakhand and Tamil Nadu. Interestingly, Tamil Nadu boasts the highest finger millet productivity at 3246 kg/ha, followed by Karnataka at 1726 kg/ha, surpassing the national average yield of 1697 kg/ha. In Madhya Pradesh, kodo and little millet dominate, while foxtail millet provides a significant contribution in Andhra Pradesh and Karnataka. The hills of Uttarakhand, the North-Eastern region, and the plains of North Bihar, western Uttar Pradesh, and Maharashtra witness significant cultivation of barnyard millet and proso millet. Browntop millet, known as Korale (Kannada) or Andakorra (Telugu), occupies limited hectares in the dryland tracts of the Karnataka-Andhra Pradesh border areas (Anonymous, 2023) [2]. The state-wise details of area, production, and yield of small millets are provided in Fig. 3. Karnataka leads as the largest small millet-producing state (56% of total production), followed distantly by Tamil Nadu (14.0%) and Uttarakhand (9.3%). The remaining states collectively contribute around one-fifth of the total production, with Karnataka having the highest proportion of cultivated area (48%), followed by Maharashtra (10.5%). Despite Madhya Pradesh having more area under other small millets, its contribution to total production is limited due to poor yield levels in predominantly grown kodo and little millet, resulting in high year-to-year fluctuations.

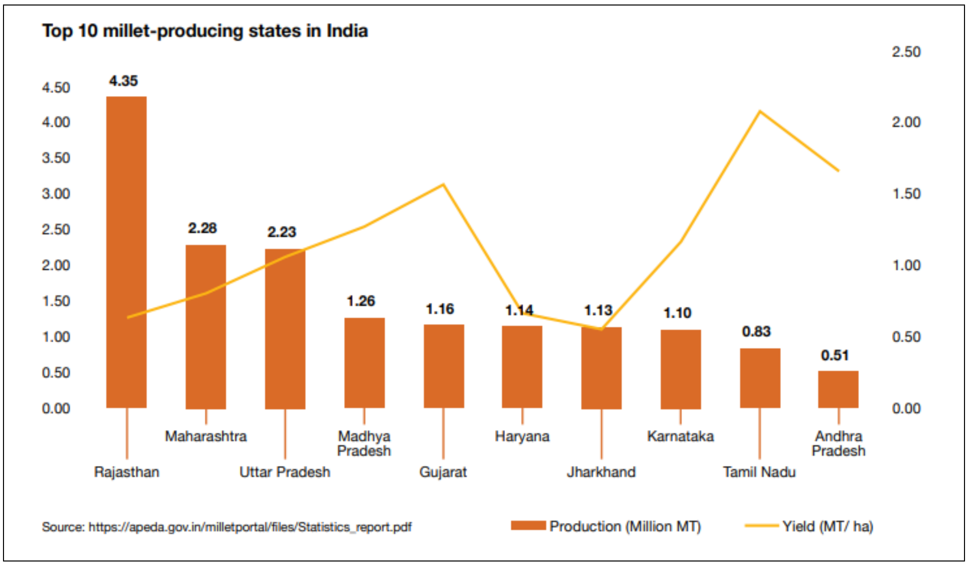


Fig 3: Top 10 millet producing states in India

Optimizing Millets Production: Mechanization and Enhanced Agronomic Practices

Agricultural mechanization provides the essential power and equipment for soil preparation, cultivation, storage, and processing of crops both in the field and on the farm. While its evolution has progressed from basic hand tools and animal-powered implements to sophisticated engine-powered equipment, the prevalence of hand tools and animal power in developing countries hinders agricultural productivity, adversely affecting the livelihoods of small-scale farmers. It is imperative to note that mechanization extends beyond tractorization, encompassing diverse operations in the crop production cycle and across the entire value chain. When appropriately applied, mechanization holds the potential to reduce labor requirements, optimize operational timing, increase crop yields, enhance the precision and efficiency of input application, and generate added value.

Approximately 52% of the total workforce in India is engaged in agriculture, contributing 15% to the GDP at constant prices for the year 2011-12. Remarkably, the soil in India, despite an average farm size of less than 1.08 hectares, sustains the food needs of a massive population of 1.3 billion. Small and marginal land holdings, constituting less than 2.0 hectares, make up 86% of total operational land holdings and encompass 47% of the total operated area (Anonymous, 2018) [5]. Agricultural mechanization in India is in its early stages, experiencing a growth rate of 7.5% annually, it faces challenges arising from small land holdings, cropping patterns, market prices of crops, minimum support prices (MSP), and governmental policies and legislations. Neglecting these challenges may exacerbate issues such as surplus labor, insufficient returns against input investment, and a gradual decline in agricultural enthusiasm. The farm mechanization levels assessed for major cereals, pulses, oil-seeds, millets and cash crops are illustrated in Fig. 1. The overall farm mechanization levels for rice, wheat, maize, sorghum and millets, pulses, oil-seeds, cotton and sugarcane crops are 45, 63, 40, 26, 34, 34, 26 and 24%, respectively. The overall farm mechanization level of the country is 40% which is lower than other developing countries such as China - 59.5% (Fang, 2017) [21] and Brazil - 75%.

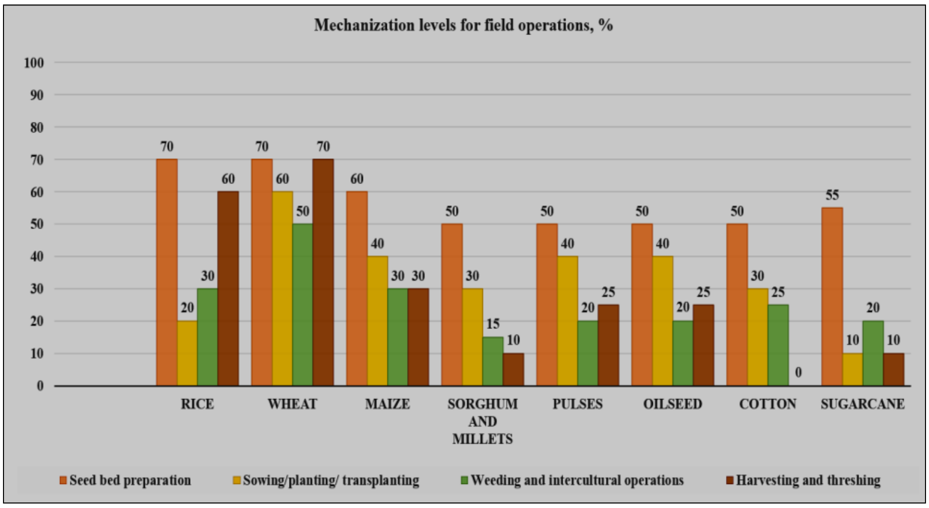


Fig 4: Level of mechanization as per crop-wise and operation-wise

Implementing improved agronomic practices is crucial for enhancing the productivity of small millets. This involves adopting advanced cultivation techniques, efficient water management, soil fertility enhancement, and pest control measures. Additionally, promoting the use of high-quality seeds, precision farming, and incorporating suitable crop rotation strategies can contribute to increased yields. Farmer training programs and extension services play a vital role in disseminating these improved practices, empowering farmers with the knowledge and skills needed to optimize small millet production. By embracing sustainable and innovative agronomic approaches, the agricultural sector can boost the productivity of small millets, ensuring food security and economic benefits for farmers. India holds a prominent position as a major millet producer globally, contributing to over 40% of the world's consumption. Small millets prove to be ideal crops adaptable to various soils, climates, and challenging conditions, demanding minimal inputs for cultivation.

Selection of improved varieties/cultivars

The selection of improved varieties or cultivars is a pivotal aspect in enhancing the overall productivity of small millets. It involves identifying and adopting varieties that exhibit desirable traits such as high yield, resistance to pests and diseases, adaptability to diverse agro-climatic conditions, and improved nutritional content.

Climate and soil requirement

Millets are resilient crops, exhibiting a robust ability to endure challenging environmental conditions, surpassing many other cereal varieties. Their cultivation is suitable for both tropical and sub-tropical regions. Millets showcase remarkable adaptability to various soil types, ranging from poor to fertile, and they demonstrate a level of tolerance to alkaline conditions. Optimal soils for millet cultivation include alluvial, loamy, and sandy soil, provided they ensure proper drainage.

Land preparation

Achieving a fine tilth is essential for the successful establishment of millet crops, facilitating optimal root and shoot development during the initial stages. To attain this, a recommended practice involves a single ploughing, followed by 2-3 harrowing sessions and cross plantings. It is crucial to level the fields effectively to ensure proper drainage and create favorable conditions for millet cultivation.

Seeds and Fertilizer: Techniques and Machinery

Millets are cultivated year-round, each crop having specific sowing times. The optimal period for kharif crop planting falls between the last week of June and the first week of July, contingent upon the monsoon onset. Rabi crops are typically sown in October-November, while summer crops are planted in January-February. In Bihar and Uttar Pradesh, these crops are cultivated as irrigated catch crops from mid-March to mid-May. To achieve peak millet yields, adherence to the recommended seed rate and spacing is crucial. The seed rate is affected by the sowing method and seed size, with Table 1, offering the suggested seed rate for a target plant population of approximately 4.0-5.0 lakh/ha for most millets. During sowing, maintaining a line-to-line distance of 20-30 cm and a plant-to-plant distance of 10-15 cm is advised for optimal results. Millets respond positively to fertilizer application, particularly nitrogen (N) and phosphorus (P), with recommended doses varying by state and season. The judicious use of organic and inorganic manures, as detailed in Table 2, can enhance fertilizer efficiency. For optimal outcomes, apply the entire P2O5 and K2O during sowing, while nitrogen is best applied in 2 or 3 split doses based on moisture availability.

Table 1: Optimum seed rate and fertilizer dose for higher yield in small millets

Seed Rate	Method of sowing		Finger Millet	Other small millets
		Line Sowing	**5-6 kg/ha**	**5-6 kg/ha**
		Transplanting	**4 kg/ha**	**8-10 kg/ha**
Fertilizer Dose	Season / Soil	Irrigated	60:30:30 kg NPK/ha	40:20:20 kg NPK/ha
		Rainfed	40:20:20 kg NPK/ha	20:20:00 kg NPK/ha

In regions with sufficient rainfall, apply 50% of the recommended nitrogen during sowing and the remaining 50% in two equal splits at 25-30 and 40-45 days after sowing (DAS). In areas with unpredictable rainfall, it is advisable to apply 50% of nitrogen during sowing and the remaining 50% around 35 DAS.

Adaptation of modern machinery for sowing and fertilizer application not only increases efficiency but also contributes to sustainable agriculture practices by optimizing resource use and minimizing environmental impact. Recently developed machineries, as outlined in Table 3, are instrumental in elevating the mechanization levels of millet cultivation operations. Farmers can choose equipment based on the scale of their operations, specific millet varieties, and local agro-climatic conditions.

Seed-sowing robots offer an efficient solution for precise seed placement, leading to time and cost savings for farmers. Various functional seeding robots have been developed and widely implemented. Lin *et al.*, (2015) [41] introduced a precision seeding robot for wheat equipped with four wheels, servo motors, and stepper motors. Trial results indicated a seeding rate exceeding 93% at typical sowing speeds. In 2019 [56], Raj *et al.*, presented a seeding robot capable of soil excavation, seed planting, and soil covering, with additional features such as fertilizing and watering. Bhimanpallewar *et al.*, (2020) [11] designed and tested an automatic robot for seeding and microdose fertilizing, demonstrating excellent prototype performance in planting various seeds. Kumar *et al.*, (2021) developed an intelligent seed-sowing robot controlled by an IoT system, achieving complete seeding automation through the use of stepper motors and DC motors.

Fig 4: Sowing machineries for different millets crop

Irrigation/water management

Millets are typically cultivated as rainfed crops and generally do not require irrigation. However, if water is available, one life-saving irrigation along with 3-4 irrigations during crucial growth phases-such as tillering, flowering, and grain development-is recommended. For summer crops, 2-5 irrigations may be necessary, depending on the soil type and prevailing climatic conditions

Weed management

Mechanical weed management stands out as an effective practice in the cultivation of millet crops, encompassing a range of techniques from handheld tools to advanced vision-guided hoes (Hussain *et al.*, 2018). Despite the availability of various methods, hand weeding and inter-row cultivation remain the predominant practices in millet cultivation.

Table 3: Different seed cum fertilizer drills for millets crops

References	Nandede *et al.*, 2018 [46]	Sawant *et al.*, 2018 [61]	Thiyagarajan*et al.*, 2024	Deogirikar *et al.*, 2021 [17]	Hapadgara *et al.*, 2020 [29]	Senthilkumar *et al.*, 2023	Nandede *et al.*; 2018 [47]
Crop	Kodo, little millet	Pearl millet	Ragi	Finger millet	Multi-millets	Multi-millets	Kodo and little millet
Working row	Single row	Four rows	11 furrow openers	24 orifices drum	18 gauges	Single row	Three row
Metering mechanism	Vertical rotor plate	Two oyjord metering mechanisms	Seed metering shaft to	Vertical	--	Vertical plate	--
Cost and seed saving (%)	51	--	Rs. 239/ha	--	Rs.2597/ ha	139%	47%
Efficiency (%)	69	80	92.7	--	65.90%	68%	55%-59%
Field Capacity (ha/h)	0.048 ha/h	0.17 ha/h	0.77 ha/h	1.5 km h	0.069 ha/h	0.05 ha/h	0.09 ha/h
Power Source	Manually	Tractor	Tractor	Manually operated	Animal drawn	Manually operated	Manually operated
Machinery developed	Different seed cum fertilizer drills for millets crops	Seed-cum-fertilizer plot drill	Seed cum fertilizer drill	Drum seeder cum fertilizer	Multi crop seed-cum-fertilizer drill	Single row millet planter cum fertilizer drill	Manual drawn pull type three row planter
Sr No.	1.	2.	3.	4.	5.	6.	7.

of all the operations involved in millet cultivation, weeding and inter-cultivation emerge as the most energy-intensive and laborious, as highlighted by Gowda *et al.*, (1999) [27]. Typically, inter-cultivation is carried out two to three times at intervals of 10 to 15 days, depending on field conditions and weed pressure. Notably, the combination of inter-cultivation followed by hand weeding has proven to be effective in weed control (Gowda and Dhananjaya, 2000) [25].

Various studies have explored the efficacy of mechanical weed management practices in millet cultivation. Cuerrier *et al.*, (2009) [16] utilized mechanical harrowing with a tine harrow to manage weeds in both forage and grain pearl millet at the 3 to 5 leaf stage, while Shamina *et al.*, (2019) [65] demonstrated the effectiveness of a combination of mechanical and hand weeding in barnyard millet under rain-fed conditions. Gowda and Dhananjaya (2000) [25] compared traditional hoes with improved blade hoes and bent-type sweep hoes in finger millet cultivation, highlighting the superior weed control and soil moisture conservation achieved by the improved tools. Additionally, a blade-type engine-operated mechanical weeder for finger millet showed promising results, covering multiple rows with high efficiency (Shrinivasa *et al.*, 2017) [66]. Pandey *et al.*, (2023) [51] designed an electric-powered inter-row weeder, indicating significant impacts of operating speed and weeding drum diameter on power utilization and weeding efficiency. This weeder demonstrated superior field capacity compared to a wheel hoe, reducing manpower requirements and operational costs.

Fig 5: Intercultural machineries for different millets crop

Crops require protection not only from weeds but also from pests and diseases. To address this, various low-cost, hand-operated sprayers and dusters have been developed and are commercially available for the application of plant protection chemicals. Sangeetha Jebalin *et al.* (2024) conducted a study to optimize herbicide dosage and spray volume for drone-assisted weed management in irrigated barnyard millet and the findings indicated that the application of pretilachlor at 500 g/ha combined with a spray volume of 40 L/ha using drone technology achieved a weed control efficiency of 91.9% at 15 days after treatment (DAT) and resulted in a grain yield of 2195 kg/ha.".

Beyond traditional methods, advancements in agricultural robotics are also evident. Deshmukh *et al.*, (2023) developed an intelligent robotic system for automated pesticide spraying, enhancing precision and minimizing health risks associated with manual application. In a similar vein, research by Deshmukh *et al.*, (2023) focused on a multi-purpose pesticide spraying robotic system employing a fuzzy control system for targeted pesticide application based on plant infection. Collectively, these studies underscore the evolving landscape of mechanized and robotic technologies in millet cultivation, aiming to optimize efficiency, reduce labour-intensive tasks, and address environmental concerns associated with traditional practices.

Harvesting and Threshing: Techniques and Machinery

The harvesting and threshing processes of millet crops are critical stages in their cultivation. Millets, being small-seeded grains, require specific methods to efficiently separate the grains from the mature plants. Harvesting is typically done when the millet plants reach maturity, and the seeds have ripened. Traditional methods involve cutting the plants manually with sickles, while more modern approaches utilize combine harvesters for larger-scale operations. With advancement in technologies in millets cultivation operations different harvesting machineries being developed as mentioned in table 4. Nisha *et al.* (2022) [48] developed a prototype finger millet harvester and evaluated the machine with various levels of reel rotational speed (30, 35, and 40 revolutions per minute), reel mounting height (35, 40, and 45 cm), and forward speed (1.6, 2.68, and 3.48 km/h). Among the different combinations tested, the minimum header loss of 1.25% was recorded at a reel rotational speed of 30 rpm, a mounting height of 40 cm, and a forward speed of 2.68 km/h.

Once harvested, the next step is threshing, where the grains are separated from the stalks and husks. Threshing can be achieved through manual beating, mechanical threshers, or even through innovative technologies as mentioned in table 5. The choice of method often depends on the scale of cultivation and the available resources. Efficient harvesting and threshing are crucial for preserving the quality of millet grains and ensuring a successful yield for this important cereal crop.

Fig 7: Harvesting machineries available for different millets crop

Table 4: Machinery available for harvesting of millets

References	**Li *et al.*, (2019).**	**Liang *et al.*, 2015 [40]**	**Ryadnov *et al.*, 2023; kassie *et al.*, 2021; He *et al.*, 2023 [57, 34]**	**Qiu *et al.*, 2024 [55]**	**Maganda (2017) [42].**	**Ghimire *et al.*, 2019 [24]**	**Donny *et al.*, 2012 [20]**
Loss Rate %	6.89	6.89%,	2.01%	Grain loss rate of 0.55% and header loss rate, 3.12%	-		
Crop	Multi-millets	Millet	Sorghum	All millets	Finger millet	Finger millet	Ragi millet
Working row	Six	2.0 m cutting width		0.30 m,	-		-
Harvesting mechanism	Cutter bar	Header with cutter bar	Cutter bar	Double-chain millet harvester header	Cutter bar	Cutter bar	Cutting blade
Efficiency	85-94	95	-	-	50.6	60	-
Field Capacity	0.4	0.23-0.45	0.46	-	0.041 ha/hr	0.045 ha/hr	-
Power Source	Combine	55 kw engine		Self-propelled	Engine powered		Self-propelled
Machinery	Combine harvester for millet	4lzg-1.5 small self-propelled millet harvester	Sorghum harvester	Millet combines harvester header	Engine powered millet harvester	Finger-millet harvesting machine	Ragi harvesting and threshing operation
Sr No.	1.	2.	3.	4.	5.	6	7.

Table 5: Different threshing machineries for millet crops

Sr No.	Machinery	Output capacity (kg/h)	Threshing Efficiency (%)	Broken grain percent (%)	Reference
1.	Multi millet thresher	80-120	96	2	Singh *et al.*, 2015
2.	Finger millet thresher cum pearler	30-35	86-92	3-5	Singh, *et al.*, 2010
3.	Multi millet crop thresher	1500-2500	91-96	4-7	Kumawat *et al.*, 1997 [38]
4.	Millet thresher	45-50	63.2	--	Gbabo *et al.*, 2013 [23]
5.	Axial flow motorized sorghum thresher	400-450	74.7	5.57-8.86	Simonyan *et al.*, 2008 [68]

Fig 8: Machineries for threshing operation of different millet crops

Post-harvest mechanization

Millet processing presents significant challenges, whether performed manually by tribal women in rural communities or through mechanized systems by commercial processors. The small grain size of millets complicates cleaning operations, while their unique morphological characteristics-particularly the externally positioned germ beneath the husk-make them exceptionally sensitive to processing (Sokhansanj & Patil, 2003) [74]. Excessive polishing or improper dehusking can expose the germ to oxidative damage, compromising grain quality and storage stability.

While traditional manual processing persists in rural communities, mechanized solutions have emerged to address these challenges through various force applications including impact, compression, abrasion, and shear. Modern motor-operated dehulling equipment has demonstrated substantial improvements, reducing processing time by 93%, labor requirements by 60%, and overall costs by 17% compared to traditional methods (Priyadarshi *et al.*, 2020) [54]. The Bureau of Indian Standards (BIS) has recently certified specialized millet processing machines including cleaners-cum-graders (IS 19039:2023), dehuskers (IS 19040:2023), and destoners (IS 19041:2023). A notable advancement is the CIAE-Millet Mill (Balasubramanian *et al.*, 2020) [7], an integrated system featuring pneumatic suction that achieves 70-85% dehulling efficiency across millet varieties while processing 100 kg/h at optimal moisture levels, representing a significant leap in preserving grain quality and processing efficiency. Concurrently, Sachdev *et al.* (2021) [59] conducted comprehensive analyses of foxtail millet's distinctive protein architecture, elucidating its potential applications across agricultural, nutritional, pharmaceutical, and biomaterial sectors. In the domain of underutilized millets, Sahoo *et al.* (2020) systematically investigated processing enhancements for little millet (Panicum sumatrense), a nutritionally dense but commercially marginal crop. Their research demonstrated that pretreatment protocols significantly influence processing outcomes, with samples subjected to 4-hour hydration followed by convective drying at 45°C achieving peak performance metrics: 96.72% dehulling efficiency, 70.21% milling efficiency, and 53.32% head yield, with additional recoverable fractions of 16.88% coarse and 3.25% fine particulates when processed through an abrasive roller system. These technological developments mark critical progress in overcoming the inherent challenges of millet processing while maintaining the nutritional integrity essential for long-term storage, developed machineries are presented in Table.6.

Table 6: Different post-harvest machineries for millet crops

Sr No.	Machinery	Output capacity (kg/h)	Dehulling Efficiency (%)	Broken grain percent (%)	References
	Millet mill dehusker	100	90	6-9	Bhandari *et al.*, 2021 [9]
	Foxtail millet Dehuller	100-300	82.2%	3-5	Chikkaballapur Krishnappa *et al.*, 2022 [15]
	Table Top Centrifugal Dehuller for small millets	6-8	92.7%, 91%, and 93.5% for foxtail, little and proso millets, respectively	fox-tail, little, proso, kodo and barnyardwas 2.4, 5.7, 2.3, 14.2 and 18.1%, respectively.	Gowda *et al.*, 2020 [25]
	Finger millet thresher-cum-pearler	32	Threshing efficiency, pearling efficiency, and cleaning efficiency, were 99.51 ± 0.11, 98.22 ± 0.31, and 96.51 ± 0.25 respectively.	2.35 ± 0.07%,	Powar, *et al.*, 2019 [53]
	Minor millet dehusker, Kodo and little millet	9-15	kodo millet was 48.5 and for little millet 52.0%	--	Patil *et al.*,2018 [52]
	Dehusking machine for foxtail and proso millet	-	61.6% for Cheeno and 44.55% for Kaguno.	--	Basnet *et al.*, 2020 [8]
	Compact foxtail millet deshelling machine (batch type)	50-80	Approx. 80%.	Damaged millets 8.472 ± 2.144%, shelled millets 13.812 ± 2.728,	Ullegaddi *et al.* 2020 [78]
	Barnyard millet dehuller	40-50	88.3	6.1±1.1% broken grain	Singh *et al.*, 2011
	Double stage dehuller	103-108	--	--	Kaleemullah *et al.*, 2023 [36]

Future prospects of mechanization in millet

The increasing global interest in millets driven by their resilience, low input requirements, and nutritional value has created momentum for advancing mechanization across the cultivation lifecycle. While significant progress has been made in post-harvest processing, mechanization in the cultivation phase remains underdeveloped, particularly in seeding, weeding, irrigation, and precision input management. Bridging this gap is essential for improving productivity, reducing labour dependency, and enabling millet farming to scale sustainably.

Future research and development must target on millet-specific agronomic characteristics, such as seed size variability, crop spacing, and soil adaptability, to guide the innovation of cultivation machinery. This includes the design of low-cost, regionally adaptable equipment for smallholder farmers, as well as scalable solutions for larger farms. Mechanization gaps currently reach from seedbed preparation to crop monitoring and nutrient delivery. Integrated mechanized solutions for these stages will be critical to enabling climate-resilient and commercially viable millet production systems. Moreover, localized machinery that accommodates intercropping and mixed cropping common practices in millet farming must be prioritized.

The United Nations' designation of 2023 as the International Year of Millets has significantly boosted global policy support and research investment, creating favourable conditions for advancing mechanization in millet cultivation. Future prospects lie in developing precision planting technologies that ensure optimal seed placement based on soil and varietal needs, and introducing energy-efficient intercultural tools such as solar-powered or manually operated weeders suitable for small farms and uneven terrains. Additionally, the integration of IoT-based sensors and AI-driven systems can optimize irrigation and input management, while climate-resilient machinery tailored for dryland and rain-fed conditions can enhance productivity and sustainability.

Conclusions

In conclusion, millets are cultivated through a dynamic interplay between conventional wisdom and contemporary inventions that bridge the gap between traditional farming methods and cutting-edge technologies. Particularly in arid and semi-arid regions, millets play a vital role in sustainable agriculture because to their resilience and adaptability. As the world's leading producer of millet, India plays a crucial role in providing food security for an expanding population. Modern machinery drives agricultural mechanization, which is essential to millet cultivation optimization since it provides accuracy, efficiency, and sustainable farming methods. Millet productivity is greatly increased by using improved agronomic methods, such as appropriate variety selection, effective water management, and accurate fertilizer application. With mechanical techniques and robotic technology, weed management which has historically involved a lot of labor-undergoes a revolutionary transformation that ensures effective weed control while eliminating tedious work. During the crucial phases of harvesting and threshing, conventional and contemporary techniques coexist harmoniously, with the latter increasing productivity and lowering labor requirements. Robots that plant seeds and clever pesticide delivery systems are examples of how technology is revolutionizing millet farming and increasing yield while adhering to environmental standards. Dwindling productivity and cultivation areas in tiny millets are among the challenges that require strategic interventions, with a focus on farmer training, extension services, and the promotion of premium seeds. To shape millet agriculture's future, cooperation between farmers, researchers, and politicians is essential. Millet farming is a journey that combines agricultural tradition and technical promise, providing a means of overcoming obstacles and making a substantial contribution to sustainable agriculture and global food security. Millets demonstrate their ability to lead the way toward a more resilient and sustainable future for global agriculture, as well as to sustain traditional agricultural practices, as we traverse this junction of tradition and innovation.

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