International Journal of Agriculture and Food Science 2025; 7(11): 598-601

ISSN Print: 2664-844X
ISSN Online: 2664-8458
NAAS Rating (2025): 4.97
IJAFS 2025; 7(11): 598-601
www.agriculturaljournals.com
Received: 21-08-2025
Accepted: 24-09-2025

Muskan Jain
Department of Post-Harvest Process and Food Engineering, College of Agricultural Engineering, JNKVV, Jabalpur, Madhya Pradesh, India

Priti Jain
Department of Post-Harvest Process and Food Engineering, College of Agricultural Engineering, JNKVV, Jabalpur, Madhya Pradesh, India

Mohan Singh
Department of Post-Harvest Process and Food Engineering, College of Agricultural Engineering, JNKVV, Jabalpur, Madhya Pradesh, India

Corresponding Author:
Muskan Jain
Department of Post-Harvest Process and Food Engineering, College of Agricultural Engineering, JNKVV, Jabalpur, Madhya Pradesh, India

Post-harvest processing of millets: Challenges, technological advances, and nutritional outcomes - a comprehensive review

Muskan Jain, Priti Jain and Mohan Singh

DOI: https://www.doi.org/10.33545/2664844X.2025.v7.i11h.1010

Abstract
Millets are nutrient-dense, climate-adaptable grains that hold significant promise for sustainable food systems and nutrition security. However, their adoption is hindered by persistent limitations in post-harvest processing, which influence yield, efficiency, and food quality. This review synthesizes developments ranging from traditional hand-operated methods to technologically advanced processing systems tailored specifically for millets. Innovations such as customized dehullers, cleaner-cum-pearlers, compact milling modules, and modern value-addition processes like extrusion and puffing are systematically discussed. Particular emphasis is given to how processing affects millet nutrient profiles. The review highlights the urgent need for affordable, millet-specific, and scalable technologies that empower farmers, small processors, and industries while improving product quality and market potential.

Keywords: Millets, Post-harvest Engineering, Abrasive milling, Nutritional Retention, Dehulling Efficiency, Value addition, Climate-resilient grains

Introduction

Millets, respectfully referred to as *"Shree-Anna"* in India, are small-seeded cereal grains belonging to the Poaceae (grass) family. This group includes sorghum, pearl millet, little millet, finger millet, teff millet, proso millet, kodo millet, browntop millet, fonio millet, and foxtail millet (Paliwal *et al*., 2023) [16]. Nutritionally, millets contain approximately 65-75% carbohydrates, 2-5% fat, 8-15% dietary fiber, and 7-12% protein (Vikaspedia, 2025). In India, they play a vital role in food security due to their ability to thrive under minimal inputs and challenging agro-climatic conditions such as drought, high temperatures, poor soil fertility, and pest pressure. Their short growing period further enhances their importance in sustainable agriculture, especially in semi-arid and rainfed ecosystems (Chapke *et al*., 2020; Food and Agriculture Organization of the United Nations, 2025; Ashoka *et al*., 2023) [4, 5, 1].

Millets have recently regained national and global attention. India's millet production increased from 15.38 million tonnes in the fiscal year 2023-2024 (FY24) to 18.015 million tonnes in 2024-2025, indicating a rising trend in cultivation and productivity. Further recognition came when the United Nations General Assembly declared 2023 as the International Year of Millets (IYM 2023), following a proposal by the Government of India supported by 72 countries. The FAO led the global celebrations, emphasizing sustainable production, enhanced consumption, and expansion of millet-based market opportunities.

Nevertheless, despite these positive developments, the commercial presence of millets remains limited. A major constraint is the challenge associated with post-harvest processing. Millet grains possess tightly bound husks and diverse grain shapes, making dehusking and milling far more complex than crops like rice or wheat. Attempts to adapt rice milling machines have achieved limited success due to differences in grain morphology and hardness, often leading to high breakage, reduced yields, and nutrient loss (Kate *et al*., 2021) [11].

This review discusses the existing challenges in millet processing and refinement, largely driven by the lack of millet-specific technologies. It also traces the evolution from traditional manual tools to modern processing equipment such as abrasive dehullers and compact multifunctional units. Additionally, it highlights recent advancements in cleaning, dehulling, and value-addition technologies. Understanding these developments is crucial for integrating millets into both rural and urban food systems and for supporting their broader commercialization and utilization (Kaleemullah *et al*., 2023) [10].

Traditional Millet Processing Practices

Traditional millet processing in rural regions relied heavily on manual labor and rudimentary tools, forming an integral part of household-level food preparation systems for generations. After harvesting, millet panicles or whole plants were typically sun-dried until the grains reached a moisture level of about 12-14%, which ensured safe storage and facilitated subsequent processing. Threshing and decortication were carried out using bullocks or tractors to trample the harvested crop, or through hand-operated devices such as stone grinders, wooden pounders, mortars and pestles, or simple pounding sticks on mud yards or tarred surfaces. These methods, although laborious, allowed dehusking with minimal grain breakage and helped maintain nutritional quality due to the gentle, low-impact nature of manual operations.

Drying formed another essential step. Millets are generally harvested at a moisture content of 15-20%, which is too high for safe storage. Therefore, extensive open-field or sun drying was practiced to reduce moisture to the stable range of 12-14%. Although effective, this method exposed grains to pests, insects, and unpredictable weather conditions, often resulting in contamination or partial spoilage. Cleaning and grading were also conducted using simple indigenous techniques. Winnowing was the primary means of removing lighter impurities such as chaff, dust, and small debris, but the process was highly labor-intensive and inconsistent. Grading relied on traditional hand-held sieves whose pore sizes were not standardized, leading to non-uniform separation of millet grains that naturally vary in size and shape.

Puffing and sand roasting represented another important traditional technique, especially for preparing ready-to-eat millet products. Sand roasting, a high-temperature short-time dry-heat process, used pre-heated sand to induce rapid expansion of the starchy endosperm. While it enhanced palatability, traditional sand roasting also introduced risks of contamination, inconsistent heating, and unhygienic working conditions. Despite these limitations, traditional processing methods were gentle, maintained most of the grain's inherent nutrients, and required minimal external energy inputs. However, these techniques could not meet the growing demands for large-scale processing and uniform product quality in modern food systems.

Current Millet Processing Practices

The adoption of mechanized technologies marked a major shift in millet processing, allowing rural and semi-urban units to handle larger quantities more efficiently. Devices such as hammer mills, disc mills, and abrasive dehullers gradually replaced manual tools, offering improved speed and throughput. Nevertheless, millets continue to pose substantial challenges owing to their small grain size, variable morphology, and tightly bound husk. Unlike rice or wheat, millet husks adhere firmly to the kernel, making their removal difficult without causing grain breakage or nutrient loss. Studies such as Shobana *et al*. (2013) [24] have noted that the structural composition of millets renders them more vulnerable to mechanical damage during milling, which complicates the use of generic equipment.

To overcome these challenges, millet-specific machines have been developed. Patil *et al*. designed a dehusker targeted at minor millets and demonstrated dehulling efficiencies of up to 52.21% for little millet and 48.74% for kodo millet, depending on feed rate and operational adjustments. Their results underscored the critical role of grain moisture, with optimal dehusking achieved at specific moisture levels. Further advancement was seen in the foxtail millet dehuller developed by Krishnappa *et al*. (2022), which performed best at 12% moisture and achieved efficiencies as high as 82.24%. Even so, these machines still leave a notable portion of grains either partially hulled or broken, resulting in average efficiencies of around 70-80%. Processor challenges extend beyond dehulling, as separating hulled from unhulled grains remains labor-intensive and equipment-dependent. Machine compatibility across millet types is also a major concern, given differences in shape, hardness, and husk thickness, as emphasized by Rao *et al*. (2017). These constraints highlight the pressing need for adaptable, millet-specific technologies capable of handling the diversity present in millet varieties cultivated across different regions.

Challenges in Millet Processing

Despite progress in the development of millet processing technologies, several persistent challenges restrict widespread adoption and efficiency across processing units. One of the most critical issues involves the removal of hard-to-detach husks. Millet varieties differ widely in their grain size, structural hardness, and husk adhesion. Small-grained varieties such as kodo and foxtail millet require precise moisture conditioning and specialized abrasive mechanisms to achieve effective dehulling, as demonstrated by Patil *et al*. (2018), Krishnappa *et al*. (2022), and Rao *et al*. (2017). A single machine with universal applicability remains impractical, making species-specific or adjustable technologies necessary.

Nutrient loss poses another significant challenge. The bran and germ layers contain a substantial portion of the grain's vitamins, minerals, dietary fiber, and antioxidant compounds. Common milling practices that prioritize appearance and texture often strip away these nutrient-rich layers, leading to diminished nutritional value. Maurya *et al*. (2023) [14] reported that polishing results in marked reductions in micronutrients such as iron, zinc, and B-complex vitamins, and also decreases antioxidant levels that are essential for managing metabolic disorders. The authors argue that preservation of the bran and germ is vital, particularly in populations vulnerable to micronutrient deficiencies. Kate *et al*. (2021) [11] similarly advocate for the adoption of sensor-based milling systems that prevent over-polishing and allow processors to tailor polishing intensity according to product requirements, thereby maximizing nutrient retention.

The limited availability of millet-specific machines further constrains efficient processing. As highlighted by Chapke *et al*. (2020) [4], the lack of standardization in grain properties makes it difficult to design universal equipment. While modifications of rice milling machines are common, they often cause excessive grain breakage, increased wastage, and reduced milling yields (Kaleemullah *et al*., 2023) [10].

Innovations such as the finger millet thresher-cum-pearler developed by Powar *et al.* (2021) [18] demonstrate the benefits of integrating multiple operations in a single unit, reducing labor and improving processing efficiency. Millet-specific machines improve profitability by minimizing losses, enhancing yield, and reducing operational costs.

Storage-related limitations also continue to hinder millet utilization. Millets are more prone to rancidity after milling due to higher lipid content, which oxidizes rapidly when exposed to air. Hadimani and Malleshi noted that improper storage leads to off-flavors, nutrient loss, and short shelf life. Stabilization techniques such as dry roasting, steaming, infrared heating, and blanching have been suggested by Maurya *et al.* (2023) [14] and Rathore *et al.* (2022) [20] as effective methods to slow lipid oxidation and extend shelf stability. Packaging also plays an essential role, with Kate *et al.* (2021) [11] emphasizing the importance of vacuum sealing, multilayer packaging materials, and modified-atmosphere packaging in preserving quality and reducing spoilage. These measures highlight the interconnectedness of processing, stabilization, packaging, and storage in ensuring commercially viable millet products.

Nutritional Implications of Millet Processing

Millet processing significantly influences the nutritional outcomes of the final product. Excessive polishing removes the bran and germ layers, reducing fiber, minerals, and essential vitamins. Chapke *et al.* (2020) [4] emphasize the importance of minimizing polishing to retain intrinsic nutritional benefits, particularly dietary fiber and B-vitamins. Pre-processing methods such as soaking, germination, and parboiling enhance nutrient availability and reduce anti-nutritional factors such as phytates and tannins. Germination, in particular, increases the bioavailability of iron and calcium, making millets more suitable for combating micronutrient deficiencies.

Whole and semi-polished millets offer significant health advantages. Products derived from whole grains retain higher levels of fiber and antioxidants, supporting digestive health, glycemic control, and cardiovascular function. Saleh *et al.* note that whole-grain millet consumption aligns with the requirements of therapeutic diets and nutrition-centered interventions. These findings affirm the importance of adopting processing methods that preserve grain integrity and nutritional density.

Innovations in Equipment and Processing Techniques

Recent advancements in millet processing technologies have improved efficiency, grain quality, and scalability. Cleaning remains a crucial first step because the presence of stones, chaff, and dust affects dehulling and polishing efficiency. Modern cleaning systems equipped with vibratory sieves, aspirators, and magnetic separators can process 1000-1200 kg per hour, providing high-throughput solutions suitable for commercial operations (Kunkari *et al.*, 2023) [13]. Integrating size grading and density separation, as noted by Maurya *et al.* (2023) [14], further enhances downstream processing. Machines adapted from rice milling, such as gravity separators and destoners, have also proved effective for millet cleaning (Balasubramanian *et al.*, 2012) [2]. Tejaswini *et al.* (2020) [25] developed a cleaner-cum-pearler that integrates cleaning and dehusking, achieving a pearling efficiency of 78.2% while minimizing breakage—demonstrating the potential of multi-functional equipment in small-scale processing units.

Abrasive dehullers equipped with emery rollers remain central to modern millet milling. Their adjustable pressure and rotational speed allow fine-tuning for different millet types (Kate *et al.*, 2021) [11]. The Vivek Thresher-cum-Pearler, developed by VPKAS Almora in collaboration with RuTAG-IIT Delhi, provides low-cost dehulling and polishing solutions suitable for rural and tribal contexts with limited power availability (Prasad, 2013) [19]. Powar *et al.* (2021) [18] developed a finger millet thresher-cum-pearler capable of achieving more than 78% pearling efficiency, significantly reducing grain breakage. These integrated machines support high-throughput processing and contribute to improved profitability for small and medium enterprises.

Compact milling units that combine dehulling, grinding, and sieving have gained prominence, especially within community-operated rural processing centers. Projects implemented by organizations such as the DHAN Foundation have demonstrated the viability of small-scale millet processing units with investments of ₹1.5-2 lakhs, processing capacities of 50-60 kg per hour, and favorable profit margins. These models often involve women-led self-help groups that manage operations, contributing to economic empowerment and improved local availability of processed millets (DHAN Foundation, 2023). Such developments underscore the potential of decentralized processing infrastructures to strengthen millet value chains.

Value addition processes—including puffing, roasting, flaking, malting, and extrusion—play an increasingly important role in the millet industry. New technologies such as microwave heating, infrared roasting, and high-pressure puffing enhance texture, flavor, and shelf life while preserving nutrients (Mariotti *et al.*, 2006; Kumar *et al.*, 2021) [15, 12]. Radhakrishnan *et al.* (2021) [21] highlight that value-added products not only improve convenience and sensory appeal but also expand millet's applications in modern food markets. Adoption of innovations from rice milling, including optical sorting and controlled pre-steaming, has also benefited millet processing by improving grain uniformity and processing consistency (Balasubramanian *et al.*, 2012) [2]. Emerging smart milling technologies incorporate sensors capable of monitoring temperature, moisture, and pressure in real time, thereby reducing wastage and maintaining product quality. Such automated systems provide operational flexibility, allowing processors to produce a variety of millet-based flours and specialty products with consistent quality.

Conclusion

Strengthening post-harvest processing is essential for promoting millets as mainstream nutritious grains. While traditional methods retain nutrients, they are not scalable. Modern technologies offer speed and capacity but need millet-specific refinement to reduce losses and improve efficiency.

Emerging solutions such as multi-stage cleaner-cum-pearlers, compact integrated mills, and advanced value-addition technologies show strong potential to boost the millet sector. Supporting these innovations with appropriate training, local manufacturing, and policy incentives can significantly improve processing efficiency, farmer income, and nutritional security.

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