Deep Learning Approaches for the Automated Classification of Millet Varieties: Current Trends and Future Directions

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ABSTRACT

Millet is a significant ancient cereal crop which is known for its nutritional value. For thousands of years, it has been a staple food in many cultures, providing a wealth of vitamins, minerals, fiber, protein, and carbohydrates. Millet grains can be processed into a variety of food products because they are small, round, and have a hard outer layer. In addition to being used in fermented foods like beer and sourdough, they are frequently ground into flour or grits for use in porridge, bread, and crackers. The importance of millet in maintaining food security is growing in light of climate change, water scarcity, and population growth worldwide. Millet is gaining popularity among food scientists, technologists, and nutritionists because of its potential health benefits and marital benefits. The goal of this review paper is to improve millet processing techniques so that a large and growing population can consume it.

***Keywords*:** Deep learning, AI, Functional characteristics, Millet, Nutritional value, Classification.

Introduction

Millets, a type of grain that belongs to the Poaceae grass family, are an ancient crop that was grown on a carly basis. They are round seeds that have the potential to become a worldwide sensation. Millets have been rebranded as "nutricereals" to emphasize their significance and nutritional worth. Millets are a nutrient-dense food that may help address the rising incidence of metabolic and gut-related illnesses. Known as "superfoods," these grains are renowned for their remarkable nutrient density and health advantages.

In the modern diet, rice and wheat have largely supplanted millets, which were once a mainstay of traditional Indian cuisine. Protective polyphenols such as hydroxycinnamic acid, luteolin, orientin, apigenin, isoorientin, catechin, and quercetin are abundant in them. These polyphenols have anti-inflammatory and antioxidant qualities by scavenging free radicals. While foxtail millet, pearl millet, and proso millet are distinguished by their high phenolic acid content, finger millet is distinguished by its high flavonoid content.

Millets are especially rich in ferulic acid, a form of hydroxycinnamic acid that is well-known for its strong antioxidant properties [1]

Small-seeded grains known as millets have been grown for thousands of years, mostly in Asia and Africa. They are renowned for their high nutritional content, ability to thrive in unfavorable soil conditions, and resistance to extreme weather. Millets, which are regarded as ancient grains, are becoming more and more well-liked globally because of their sustainability and health advantages.

Because of their drought-tolerant qualities and climate resilience, millets are simple to grow and can withstand high temperatures. They have a good shelf life and can be grown during both the rabi and kharif seasons. Compared to rice and wheat, which need 26 times as much water for irrigation, it uses a lot less. They grow 50% faster than wheat and consume 70% less water than rice. Because millets are naturally pest-resistant, fewer pesticides are needed. Millets can adapt to a variety of ecological conditions, are less susceptible to environmental stressors, require little irrigation, and grow and produce at their best with few inputs. Despite being disregarded in the past, millets are becoming more and more important in the modern world [2]. In fact, the biodiversity of millets gives researchers access to possible candidate genes that they can use to further improve crops. Millets, particularly improved small millets, may therefore hold great promise for overcoming the limitations of natural resources and climate uncertainty.

1.1 International Year of Millets 2023: Initiatives and Proposed Activities:

The United Nations received a proposal from the Indian government to designate 2023 as the International Year of Millets (IYOM). On March 5, 2021, the United Nations General Assembly (UNGA) formally adopted this proposal, which was backed by 72 other nations, and declared 2023 to be the International Year of Millets [3]. The Indian government is promoting awareness of the nutritional advantages of millet and the value addition of millet products to increase their acceptance both domestically and internationally as part of its celebration of IYOM 2023. Thus, the International Year of Millets presents a fantastic chance to:

-Preserve and uphold millets' contribution to food security.

-Boost millets' production worldwide

-Increase the effectiveness of millet processing, transportation, storage, and consumption.

Encourage environmentally friendly production methods while assuring stakeholders of high-quality millet.

1.2 History of Millets:

Millets date back approximately 10,000 years, making them one of the first grains to be cultivated. Since ancient times, they have been grown in Africa and Asia, where they were a mainstay of many early societies [4].

1.2.1 Origin in History

China (Neolithic Period, circa 8000 BCE): Foxtail and broomcorn millets were grown in northern China, primarily in Dunhuang, and possibly as far as the Yellow River Valley, according to archeological evidence.

Interest in pearl millet, which is widely grown in Africa and then transported to the Indian subcontinent to be a part of traditional diets, dates back to around 3,000 BCE.

Africa (~3,000 BCE): The modern countries of Sudan, Ethiopia, and West Africa began growing finger and pearl millet.

1.2.2 Ancient Civilizations' Use of Millets

China: Before rice even gained prominence, it was a staple crop in early Chinese civilizations.
India: Millets were traditional crops that were included in the ancient Ayurvedic prescriptions.
Greece and Rome: Before wheat and barley replaced millets as a staple grain, the Greeks and Romans used them.
Colonial and Medieval Eras
During the Middle Ages, millets were consumed by many people in Europe, particularly by the lower classes.
As wheat and rice emerged as the primary crops under the trade and economic policies for this area, millets were unable to counteract declines in preference during the colonial expansions.
Modernity and Revival
Due to industrial farming policies that promoted wheat, rice, and maize while opposing millet, millet consumption has decreased in many parts of the world in the 20th and 21st centuries. But recently, they have become a part of many health-conscious diets due to the growing popularity of the nutrient powerhouse that is gluten-free and climate-friendly. The United Nations designated 2023 as the "International Year of Millets" in an effort to highlight the benefits and inspire...

1.2.3 Types of Millets :

Millets are small-seeded grains that are members of the grass family, Poaceae. Many varieties of millets exist, and they are frequently divided into major and minor varieties according to how they are grown and consumed [5].
Major Millets (Cultivated Widely)
1. Pearl millet, also known as bajra, is a common crop in Africa and India that is high in iron and fiber.
2. Kangni/Korra foxtail millet: Rich in dietary fiber and protein, it helps control diabetes.
3. Sorghum (Jowar): Often used in roti and porridge, this grain is free of gluten and high in antioxidants.
4. Finger Millet (Ragi): Good for bones, high in calcium and amino acids.
5. Proso Millet (Chena/Barri): Low in carbs and high in protein, this grain is used for human consumption and as bird feed. Minor millets are nutrient-dense but less cultivated.
6. Barnyard Millet (Sanwa/Sawa): Excellent for fasting diets and high in iron.
7. Kodo Millet (Kodon): Easy to digest and high in fiber
8. Little Millet (Kutki/Samai): Rich in fiber and minerals, this grain is a good substitute for rice.

Table 1: Types of millets

S.No	Common Name	Botanical Name	Type	Key Characteristics
1	Pearl Millet	*Pennisetum glaucum*	Major Millet	Rich in iron; drought-tolerant; widely grown in India.
2	Finger Millet	*Eleusine coracana*	Major Millet	High in calcium; commonly used in South India.
3	Foxtail Millet	*Setaria italica*	Major Millet	High in dietary fiber and low glycemic index.
4	Little Millet	*Panicum sumatrense*	Minor Millet	Rich in B-vitamins and minerals.
5	Kodo Millet	*Paspalum scrobiculatum*	Minor Millet	High in antioxidants and easy to digest.
6	Barnyard Millet	*Echinochloa frumentacea*	Minor Millet	High in iron and fiber; good for diabetic diets.
7	Proso Millet	*Panicum miliaceum*	Minor Millet	High in protein and low in gluten.
8	Browntop Millet	*Brachiaria ramosa*	Minor Millet	Contains iron, calcium, and magnesium.
9	Guinea Millet	*Brachiaria deflexa*	Minor Millet	Grown in West Africa; drought-resistant.
10	Teff	*Eragrostis tef*	Minor Millet	Native to Ethiopia; gluten-free and iron-rich.

2. Production status :

Millets are one of the main cereal grains consumed worldwide, especially in arid and semi-arid parts of Asia and Africa, especially China and India. They are prized for their agro-industrial importance and high nutritional content [6].

Global millet production Millet is the sixth most productive grain in the world. An estimated 31,019,370 mes of millet were produced worldwide, with India leading the pack, followed by Niger, China, and nations (FAO, 2020). In 2023/2024, millet production is expected to reach 30.802 million metric tons.
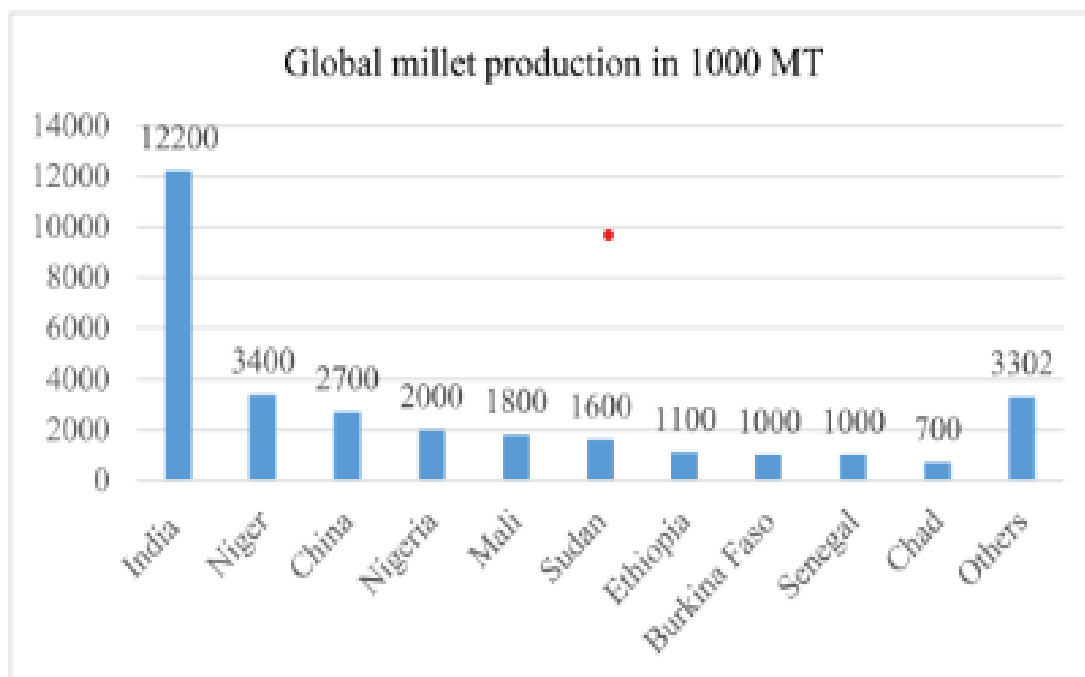

Figure 1: Global millet production [3]

With a projected output of 28 million metric tons in 2023, millet production has been steady in recent years. Africa produces the most millet, followed by Asia, where India is the biggest producer, followed by Niger and China. Other important millet-producing nations include Senegal, Mali, and Burkina Faso. Many people in developing countries rely heavily on millet in their diets, despite it not being a major food crop in developed countries (APEDA, 2023).

3. Indian millets production

India has been steadily increasing its millet production in recent years. India is one of the world's top producers of millets, and because of their resistance to drought, Indian farmers are growing their crop more and more. Through programs like the National Food Security Mission, the Indian government has aggressively encouraged the production of millet. As a result, it is anticipated that India's millet production will keep growing. 17.32 million tonnes of millets were produced nationwide in 2022–2023 (APEDA, 2023).
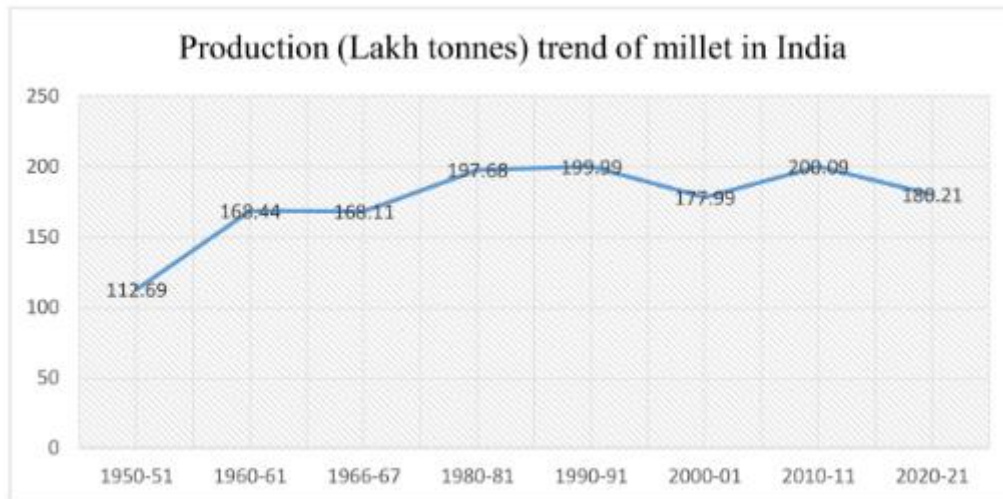
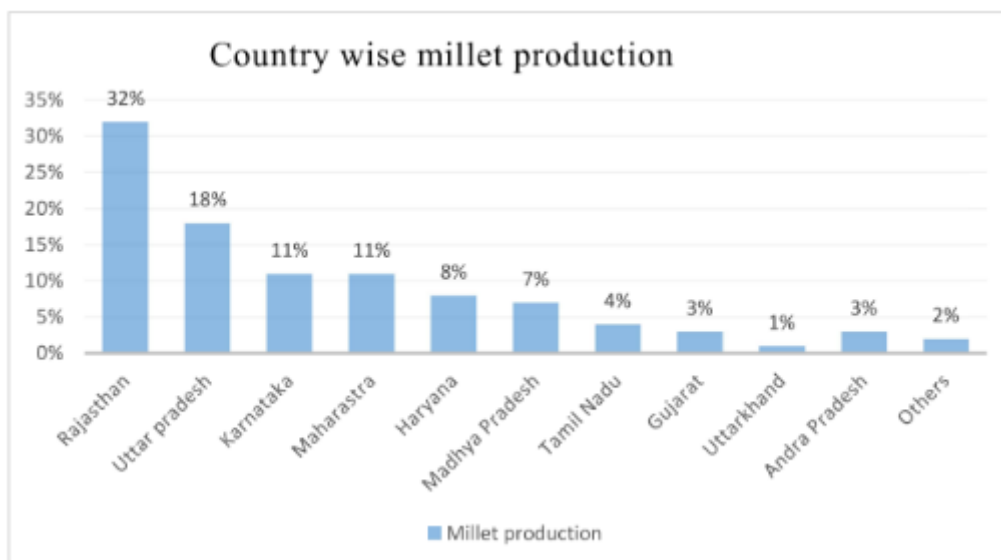**Figure 2:** Production trend of millets in India (APEDA, 2022) [7]

Figure 3: State wise production of millets (APEDA, 2023) [8]

Figure 2,3 [4,5] As a varied group of small-grained cereals, millets have unique physical traits that can differ slightly among varieties. The general physical characteristics of millets are broken down as follows:

1. Seed Dimensions and Form

Millets are small grains that range in shape from round to oval. Although they can differ in size among varieties, they are typically smaller than wheat and rice grains.

• Size Range: Depending on the millet variety, the seeds have a diameter of 1-2 mm.

2. Color

• Diverse Colors: Depending on the type and variety, millets can be anything from white to yellow to red to brown to even black.

For instance, Finger Millet (Ragi) is reddish-brown or dark brown, whereas Pearl Millet is usually light grayish or pale yellow.

The color of foxtail millet is typically golden yellow.

3. Texture

• Compact and Hard: Millets have a compact and dense grain due to their hard outer shell. Before eating, this outer husk must be removed.

• Smooth Inner Texture: The inner seed is firm, round, and smooth after the outer husk is removed.

4. Hull or Seed Coat: Millets, like other cereals, have a hard, indigestible hull or seed coat that shields the edible grain within. With a few exceptions, such as foxtail millet, which can be eaten with its hull still in place, these hulls must be removed before the grain is consumed.

5. Plant Structure and Height

Millets are generally short to medium-height grasses, with a typical height of 30 cm (12 inches) to 1.5 meters (5 feet), depending on the variety and growing environment.

• Robust Stalks: They are resistant to wind and other adverse conditions because of their robust, fibrous stalks, which support the plant during growth.

• Leaves: Millets typically have lance-shaped, long, narrow leaves with parallel veins.

6. The inflorescence

• Spike-like or pannular: Millet plants have different inflorescences, or flower clusters. While some millets, like Foxtail Millet, have more open, loose clusters, others, like Pearl Millet, have big, dense panicles.

• Flower Color: Before developing into seeds, the tiny flowers are frequently green or yellow in hue.

7. Root System

• Fibrous Roots: Millets are drought-tolerant due to their fibrous root system, which facilitates effective water access in arid, nutrient-poor soils.

• Shallow Roots: Millets can grow in soil that might not be able to support crops with deeper roots because of their generally shallow root system.

8. Drought-Resistant Characteristics

• Heat and Dry Conditions Tolerant: Millets are extremely resilient in arid climates due to their thick leaves and waxy coating, which helps to prevent water loss.

9. Mature Grain Form

• Firm and Hardy: Millet seeds are hard once they reach maturity and frequently require processing (popping, cracking, or milling) before being eaten.

4. Physical characteristics of millets

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3. Texture

• Compact and Hard: Millets have a compact and thick grain due to their hard outer shell. Before eating, this outer husk must be removed.

• Smooth inside Texture: The inside seed is solid, spherical, and smooth after the outer husk is removed.

4. Hull or Seed Coat:

Millets, like other cereals, have a hard, indigestible hull or seed coat that shields the edible grain within. With a few exceptions, such as foxtail millet, which can be eaten with its hull still in place, these hulls must be removed before the grain is consumed

• Fiber Content: When eaten, the grain's high fiber content adds to its overall nutritional worth.

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Millets are generally short to medium-height grasses, with an average height of 30 cm (12 inches) to 1.5 meters (5 feet), depending on the variety and growing area.

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• Leaves: Millets typically have lance-shaped, long, narrow leaves with parallel veins.

6. Panicle or spike-like inflorescence: Millet plants have different inflorescences, or flower clusters. While some millets, like Foxtail Millet, have more open, loose clusters, others, like Pearl Millet, have big, dense panicles.

• Flower Color: Before developing into seeds, the tiny blooms are frequently green or yellow in hue.

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5. Nutritional quality of millets

In addition to promoting long-term health and development and optimizing human genetic potential, food's nutritional value is essential for preserving human physical well-being. Thus, an emphasis on dietary quality is necessary to combat ingrained food insecurity and malnutrition. In addition to their many health benefits, whole foods and plant-based diets have been linked to a lower risk of heart disease, diabetes, cancer, and obesity [8].

Millets provide many health advantages, such as a high antioxidant content, substantial fiber content, low glycemic index, and gluten-free protein. They are also rich in physiologically

active chemicals. Millets' nutritional makeup makes them a great source of nutrients, protein, and energy. They include vital vitamins like riboflavin, thiamine, folic acid, and niacin (B3). Carbohydrates, mostly soluble carbohydrates and dietary fiber, make up about 70% of millet grains. Between 70 and 80 percent of millet polysaccharides are made up of amylose and armylopectin. Furthermore, millets are rich in tannins, phytates, and polyphenols (0.2-0.5%), all of which make a substantial contribution.

due to their antioxidant properties and contribute to the regulation of the aging process. Particularly noteworthy is finger millet, which has the greatest calcium concentration of any grain at 344 mg/100 g (Tripathi et al., 2023)

Biologically active chemicals with antioxidant potential have been found in millets and their dietary products [9] Both whole grain and flour versions of millet-based products, such as millet porridge, millet wine, and millet nutrition powder, are becoming more and more common in people's daily life. A starch is considered resistant if it can withstand enzymatic hydrolysis in the stomach and small intestine for at least 120 minutes after consumption. (OECD/FAO, 2019). A starch is considered resistant if it can withstand enzymatic hydrolysis in the stomach and small intestine for at least 120 minutes after consumption. Like other non-starch polysaccharides (NSP), RS is categorized as a dietary fiber (DF) and has comparable health [10] due to its excellent cost-economics and negligible impact on sensory qualities, it is seen as a possible replacement for conventional dietary fibers including cellulose, B-glucan, and inulin (Charalampopoulos et al., 2002). Cereals are the primary source of starch. A FAO analysis projects that by 2028, the world's grain consumption would have grown to 3036 million tons (OECD/FAO, 2019).

6. Merits of millets

1. Rich in Nutrients: Millets are a great source of fiber, vitamins (such as B vitamins), minerals (particularly calcium, iron, and magnesium), and antioxidants. They are therefore a fantastic complement to a well-balanced diet [11].

2. Gluten-Free: Millets are a wonderful choice for those who have celiac disease or gluten sensitivity because they are naturally gluten-free.

3. Beneficial for Digestion: Millets' high fiber content promotes healthy digestion and wards off constipation. Millets are a wonderful option for people with diabetes since fiber also helps control blood sugar levels.

4. Low Glycemic Index: Millets help control blood sugar levels and avoid energy crashes because of their low glycemic index, which means that sugar is released into the bloodstream gradually.

5. Heart Health: Because millets are high in unsaturated fats, they can help lower cholesterol and lower the risk of heart disease.

6. Sustainable Crop: Millets are a more environmentally friendly choice than other grains like rice and wheat since they can withstand drought and need less water. Additionally, they may grow in a variety of conditions, making them a more sustainable food source.

7. Weight Control: Millets' high fiber content helps you feel fuller for longer, which can help you control your weight and avoid overeating.

7. Demerits of millets

1. Availability: Compared to other grains like rice or wheat, millets are less frequently seen in large supermarkets. In some areas, this may make them more difficult to locate [12].

2. Taste and Texture: Compared to more recognizable grains like rice or quinoa, millets may not taste or feel as good to certain individuals. It has a little earthy flavor that may take some getting used to.

3. Rich in Phytic Acid: Phytic acid, a "anti-nutrient" found in millets, can bind to minerals including calcium, iron, and zinc, reducing their absorption potential. Those who depend heavily on millets for their diet may find this concerning.

4. Allergies: Although uncommon, millet allergies can occur in certain people. It is best to speak with a healthcare professional if you are worried about possible allergic reactions.

5. Limited Selection of Processed Products: Millet is used to make less processed goods, such flour and snacks, than wheat or rice. Its adaptability to certain cuisines may be limited as a result.

6. Millets have a slightly acidic character, which might be uncomfortable for people who have acid reflux or other digestive problems.

8. How deep learning applied to classify different millet varieties

Deep learning, particularly Convolutional Neural Networks (CNNs), offers a powerful approach for classifying different millet varieties based on images of seeds, leaves, or panicles. CNNs automatically extract and learn hierarchical features—such as texture, shape, and color—that are essential for distinguishing between millet types. This eliminates the need for manual feature engineering, enabling more accurate and scalable classification. In practical applications, high-resolution images of millet samples are fed into CNN architectures, which process and classify them through a series of convolutional and pooling layers. Data augmentation techniques like rotation, zooming, and flipping are often used to increase dataset diversity and improve model robustness. Transfer Learning further enhances this approach, especially when labeled millet datasets are limited. Pre-trained models like ResNet, VGG, or EfficientNet—originally trained on large image datasets—can be fine-tuned on millet-specific images. This allows the model to leverage general visual patterns learned from other domains while adapting to the nuances of millet classification. The integration of deep learning in millet variety classification can significantly aid researchers, breeders, and farmers by automating identification, improving accuracy, and accelerating the crop selection process.

9. Examples of input data (images of millet seeds, or sensor-collected grain morphology data)

Examples of input data for deep learning-based millet variety classification include high-resolution images of millet seeds captured under consistent lighting conditions, which help in identifying variations in shape, size, and color. Additionally, close-up images of leaves and panicles can be used to extract morphological features unique to each variety. Beyond images, sensor-collected data—such as grain morphology measurements from digital calipers or 3D scanners—can also serve as valuable input. These may include parameters like grain length,

width, thickness, and surface texture, which provide quantitative traits for model training and enhance classification accuracy when combined with image data.

10. Model Performance and Challenges

Model	Accuracy (%)	Data Used
CNN (from scratch)	82	Seed images
ResNet (Transfer Learning)	90	Seed + leaf images
EfficientNet (Fine-tuned)	93	Multimodal (images + morphology)

Challenges include limited annotated datasets, variations in image resolution, and high inter-class similarity, as many millet varieties share subtle visual traits. These factors hinder generalization. Future work should focus on creating open, standardized millet datasets and improving model explainability. Techniques like attention maps or Grad-CAM can highlight key features influencing classification decisions, making AI more interpretable for agricultural experts.

8. Literature Review

Millets are minor cereal crops in the Poaceae family that are underutilized. These tiny, nutrient-dense, seeded grains are non-acid-forming, gluten-free, and drought-resistant. They can be divided into two main groups: major millets and minor millets. Sorghum and pearl millet are categorized as main millets [13]. Foxtail millet, proso millet, finger millet, kodo millet, barnyard millet, and small millet are all included in the minor millet category.They are abundant in phytochemicals that have therapeutic qualities, such as antioxidant activities, which help prevent a variety of illnesses.They include a lot of fiber, polyunsaturated fatty acids (PUFA), and a low glycemic index. Protein, carbohydrates, fat, minerals, vitamins, and other bioactive compounds are among its many beneficial biological activities. These include antioxidant, anti-hyperglycemic, anti-cholesterol, anti-hypertensive, anthropometric effects, and the regulation of gut microbiota composition [14]. Along with staple crops like rice and wheat, millets are also very healthy and helpful, and they have the potential to significantly reduce the food insecurity that many nations currently confront.This review's objective is to gather as much information as possible from the body of literature regarding millet's nutritional value and health benefits while attempting to provide the material in a way that is simple to understand [15].

9. Conclusion

Technological developments in post-harvest processing and value addition have made it possible to produce processed millet products that appeal to both urban and rural consumers. In product development, millet processing is essential for enhancing nutrition and quality. Despite its acknowledged health advantages and potential as a cereal substitute, millet's complete range of uses is still unknown. Deep learning presents a promising approach for

accurate classification of millet varieties, addressing limitations in manual identification. CNNs and Transfer Learning models effectively extract key features from images and morphology data, improving classification performance. Despite this, challenges such as limited annotated datasets, inter-varietal visual similarity, and image variability persist. Building standardized, open-access datasets and employing model explainability tools will be crucial in advancing this field. Integrating AI into millet classification can significantly benefit crop monitoring, breeding programs, and digital agriculture, offering a practical step toward precision farming in underutilized yet vital cereal crops. To evaluate the bioavailability of micronutrients like minerals, more investigation employing cutting-edge methods is required. Increasing millet intake can help fight global malnutrition and provide a balanced diet. Consequently, increasing millet consumption and improving processing technologies are crucial stages in optimizing its advantages.

Author contributions

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Mayank Goyal: Writing

Komal Sharma: Proofreading, Reference

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