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Shelf-life extension of millets: A comprehensive overview of various preservation technique

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Abstract
Millets are a group of small-seeded, extremely varied plant species that are native to many parts of the world. Millets are full of nutrients and play a significant role in many people's diets. Although millets are more nutritious than cereals, they are still primarily used as food by traditional consumers and people in lower socioeconomic strata. However, millets have low shelf life because of its high content of fat and lipase activity, which causes rapid formation of rancidity and off- odors. Its preserving quality is significantly influenced by the various pre-treatments used and the storage environment. The effect of various processing methods, including mechanical processing, thermal processing, fermentation, germination, the addition of preservatives, and some novel techniques, including gamma irradiation, microwave processing, infrared heating, and high- pressure processing, on the storage stability and other nutritional properties of various millet flours, was reviewed in the current review. As millets regain popularity and become a staple food for many health-conscious consumers, these techniques are still being researched. This review summarizes such main traditional or industrial methods that increase the storage stability of millet flour.

Keywords: Microwave processing, infrared heating, and high- pressure processing

1. Introduction
The major constituent in the food we eat is grains. It includes a significant portion of our diet. Cereals account for about 60 to 70 percent of calories. According to recent research, there are an estimated 2210 million tonnes of grains produced globally, and 2216 million tonnes of grains are consumed (International Grains Council, 2021) [19]. Yet, the production of grains requires a significant water supply, which is what is mostly responsible for the depletion of groundwater. There is a growing need to switch to an alternative source of cereals that provides our daily calorie needs in order to address this worrying situation. Millets are one of the best substitutes for the traditional cereal ingredients. Millets are a group of small-seeded, extremely varied plant species that are native to many parts of the world. They are more likely to grow in settings with poor soil fertility, low moisture content, and a warm climate. The Food and Agricultural Organization (FAO) estimates that the production of millet on a global scale was 28.33 million tonnes in 2019 and will rise to 30.08 million metric tonnes in 2021. According to the Ministry of Agriculture and Farmers Welfare, the production of millets in India has increased from 14.52 million tonnes (2015-16) to 17.96 million metric tons (2020-21). Millets also include a large amount of nutrients, including protein, dietary fiber, essential fatty acids, B vitamins, and minerals including iron, calcium, magnesium, potassium, and zinc. Beyond its basic nourishment, they also offer additional health benefits like lowering blood sugar levels, controlling blood pressure, and preventing thyroid, cardiovascular, and celiac disease. Millets are an excellent gluten-free alternative to grains for persons with chronic celiac disease. Despite various benefits, millet has a short shelf life due to the presence of an active enzyme called lipase, which poses numerous storage and shelf-life issues. By producing rancidity and off-odors, this enzyme activity shortens the shelf life of millets.

2. Millets
Millets are a group of small-seeded grains that have been cultivated for thousands of years around the world, especially in arid and semi-arid regions. There are several types of millets which are mentioned in table 1.

Table 1: Description of various types of millets.

Types of millets	Botanical names	Description	Morphology	References
Foxtail millet	*Setaria italica*	Also known as Italian millet, this type of millet is one of the oldest cultivated crops in the world. It is a staple food in many parts of Asia and is known for its high protein and fiber content.	**Plant height:** Foxtail millet is a small, annual grass that typically grows to a height of 60-120 cm. **Leaves:** The leaves of foxtail millet are long and narrow, with pointed tips. They grow alternately on the stem and have a rough texture. **Inflorescence:** The inflorescence of foxtail millet is a cylindrical or oblong-shaped panicle that is densely packed with spikelets. The panicle can be up to 30 cm long and 2-3 cm wide. **Flowers:** The flowers of foxtail millet are small and inconspicuous, with both male and female reproductive organs. They are pollinated by wind. **Seeds:** The seeds of foxtail millet are small and round, with a diameter of about 2-3 mm. They are typically yellow or brown in color, and are rich in carbohydrates, protein, and fiber.	Singh, *et al*., 2019[38]
Pearl millet	*Pennisetum glaucum*	Pearl millet is an important food source in Africa and India. It is highly drought-resistant and is known for its high nutritional value, including its protein, fiber, and iron content.	**Plant height:** Pearl millet is a tall, annual grass that can grow up to 4 meters in height, although cultivated varieties are typically shorter, ranging from 1-2 meters**.** **Leaves:** The leaves of pearl millet are long and narrow, with a pointed tip. They grow alternately on the stem and have a rough texture**.** **Inflorescence:** The inflorescence of pearl millet is a dense, cylindrical or oblong- shaped panicle that can be up to 50 cm long and 20 cm wide. The panicle is composed of numerous spikelets that contain the flowers and seeds**.** **Flowers:** The flowers of pearl millet are small and inconspicuous, with both male and female reproductive organs. They are pollinated by wind. **Seeds:** The seeds of pearl millet are small and round, with a diameter of about 2-4 mm. They are typically beige or light brown in color, and are rich in carbohydrates, protein, and fiber.	Yadav, *et al*., 2012[41]
Finger millet	*Eleusine coracanaa*	Finger millet, also known as ragi, is a staple food in many parts of India and Africa. It is rich in calcium, iron, and protein, making it an important food for vegetarians and people with iron-deficiency anemia.	**Plant height:** Finger millet is a short, annual grass that typically grows to a height of 1-2 meters. **Leaves:** The leaves of finger millet are long and narrow, with a pointed tip. They grow alternately on the stem and have a smooth texture. **Inflorescence:** The inflorescence of finger millet is a compact, spiky-shaped panicle that is about 10-15 cm long. The panicle is composed of numerous spikelets that contain the flowers and seeds. **Flowers:** The flowers of finger millet are small and inconspicuous, with both male and female reproductive organs. They are pollinated by wind. **Seeds:** The seeds of finger millet are small and round, with a diameter of about 1-2 mm. They are typically brown or dark red in color, and are rich in carbohydrates, protein, and fiber.	Chethan, *et al*., 2007 [12]
Proso millet	*Panicum miliaceum*	Proso millet is grown in many parts of the world, including Asia, Europe, and North America. It is used as a feed grain for livestock and as a food source.	**Plant height:** Proso millet is a small, annual grass that typically grows to a height of 30-150 cm. **Leaves:** The leaves of proso millet are long and narrow, with a pointed tip. They grow alternately on the stem and have a smooth texture. **Inflorescence:** The inflorescence of proso millet is a cylindrical or oblong-shaped panicle that is typically 5-30 cm long. The panicle is composed of numerous spikelets that contain the flowers and seeds. **Flowers:** The flowers of proso millet are small and inconspicuous, with both male and female reproductive organs. They are pollinated by wind. **Seeds:** The seeds of proso millet are small and round, with a diameter of about 2-3 mm. They are typically yellow or white in color, and are rich in carbohydrates, protein, and fiber.	Muthukrishnan, *et al*., 2018[27]

2.1 Nutritional composition and health benefits of millets

Millet has many cultivating benefits in addition to having a high nutritional content when compared to other major grains like wheat and rice (Singh P, *et al*., 2012) [37]. Iron (2.2-17.7 mg/100 g), calcium (10-348 mg/100 g), phosphorus (200-339 mg/100 g), zinc (32.7-60.6 mg/100 g), and vitamins like niacin (0.09-1.11 mg/100 g), riboflavin (0.28-1.65 mg/100 g), and thiamine (0.15-0.60 mg/100 g) are all abundant in millets (Kumar, Tomer, *et al*., 2018) [23]. Moreover, millets are high in vitamins and phytochemicals (Bwai, *et al*., 2014) [10]. The millets mainly contain 1.2–9.8% crude fiber 60.9–72.6% carbs, 1.1–5.0% fat, and 6.2–12.5% protein (Gopalan *et al*., 2007) [17]. Several possible health advantages of finger millet have been associated to its polyphenol content (Mahmoud, *et al*., 2016) [25]. Compared to other cereals and millets, finger millet has more carbohydrates (81.5%), protein (9.8%), crude fiber (4.3%), and minerals (2.7%) (Bora, *et al*., 2019) [9]. With various health advantages, finger millet was discovered to be rich in tannins, steroids, phenols, alkaloids, and other phytochemical elements (Bwai, *et al*., 2014) [10]. For those with celiac disease and gluten intolerance, sorghum is one of the ancient cereal grains that is fully gluten-free and is regarded as a safe grain replacement (OSK Reddy, *et al*., 2017) [29]. Pearl millet was discovered to be full of starch, minerals, antioxidants, and soluble and insoluble dietary fibers. It has a dry matter content of 92.5%, ash at 2.1%, crude fiber at 2.8%, crude fat at 7.8%, crude protein at 13.6%, and starch at 63.2%. (Devi, *et al*., 2014) [14] as shown in table 2 according to IIMR (Indian Institution of Millets Research).

Table 2: Nutritional Composition of millets (for 100 g of each millet)

Millets	CHO (g)	Protein (g)	Fat (g)	Fiber (g)	Minerals (g)	Iron (mg)	Calcium (mg)
Sorghum	72.6	10	1.9	4	1.6	2.6	54
Pearl millet	67.5	10.6	5.0	1.3	2.3	16.9	38
Finger millet	72.0	7.3	1.3	3.6	2.7	3.9	344
Foxtail millet	60.9	12.3	4.3	8	3.3	2.8	31
Proso millet	70.4	12.5	1.1	2.2	1.9	0.8	14
Kodo millet	65.9	8.3	1.4	9	2.6	0.5	27
Little millet	67.0	7.7	4.7	7.6	1.5	9.3	17
Barnyard millet	65.5	11.2	2.2	10.1	4.4	15.2	11

Latest research demonstrates that eating plenty of dietary fibre reduces the prevalence of obesity (Amadou, *et al*., 2011) [3]. Dietary fiber-rich foods enhance intestinal function and lower the risk of developing chronic illnesses (Amadou and Gounga *et al*., 2014) [4]. Millets are a good source of dietary fibre; they have about 22% of it, which is more than other cereals like wheat, which has 12.6%, rice, which has 4.6%, and maize, which has 13.4% (Chethan, *et al*., 2007) [12]. Because they contain a significant amount of magnesium, millets aid in the prevention of Type -2 Diabetes. By producing a significant amount of carbohydrate-digesting enzymes that regulate insulin action, magnesium is a crucial mineral that aids in improving the efficacy of insulin and glucose receptors (OSK Reddy and colleagues, 2017) [29]. By lowering plasma triglycerides, millets, which are known to be high in phytochemicals and contain phytic acid, can lower cholesterol and prevent cardiovascular disease (Bora, *et al*., 2019) [9]. According to studies, regularly consuming whole millet grains lowers the incidence of Cardiovascular Disease (CVD). Millets are high in phenolic acids, phytates, and tannins, which are antinutrients that lower the risk of colon and breast cancer. Millets contain phenolics that are useful at inhibiting the development and spread of cancer (Chandrasekara A, *et al*., 2011) [11]. Sorghum contains polyphenols and tannins that contains both anti-mutagenic and anti- carcinogenic properties (Gowthamraj, *et al*., 2020) [18]. As the millets are gluten free, they are helping in reducing the celiac disease by reducing the irritation caused by the common cereal grains which contain gluten. (Bwai, *et al*., 2014) [10].

Fig 1: Health benefits of millets

3. Shelf-life problems of millets or millet flour

In comparison to cereals, millets or millet flour has storage issues, according to several studies. The millets have good storage qualities if kept as whole grains. According to traditional methods, millets are kept in aerial storage for long-term storage in tied bundles, earthen pots, underground pits, mud rhombuses, etc. (Mobolade, *et al*., 2019) [26]. All of these traditional methods for preserving whole grain millet are inexpensive, composed of eco-friendly materials, and help extend the shelf life of millet grains by lowering insect infestation and moisture development. Fresh neem leaves and dried red chillies can be used in the storage bins and containers to control insect infestation. By doing this, millets' shelf-life can be increased by up to 4-5 years (Kaced & Hoseney, 1984) [20].

The shelf-life of millets can, however, be reduced when they are milled into flour because, after milling, the seed structure is weakened and the cell wall cracks, making them more vulnerable to attack by various enzymes, microorganisms, and environmental influences like moisture accumulation. According to studies, pearl millet flour with a greater fat content begins to spoil after around 10 to 15 days when stored under normal environmental conditions (Tiwari, *et al*., 2014) [40]. All the elements that cause millet flour to deteriorate or spoil must be removed or replaced in order to extend its shelf life and storage.

4. Treatments for improving storage stability of millet flour

Using a range of processing techniques will extend the shelf life of millet flours. In order to prevent spoilage, these methods either try to inactivate the enzymes through various processing procedures or damage fungal or microbial DNA. These methods also induce alterations in millets' functional characteristics, which affects the grain's or the subsequent products' nutritional value. The following sections provide a detailed review of some of these widely used methods for improving the shelf life of millets are classified in figure 2.

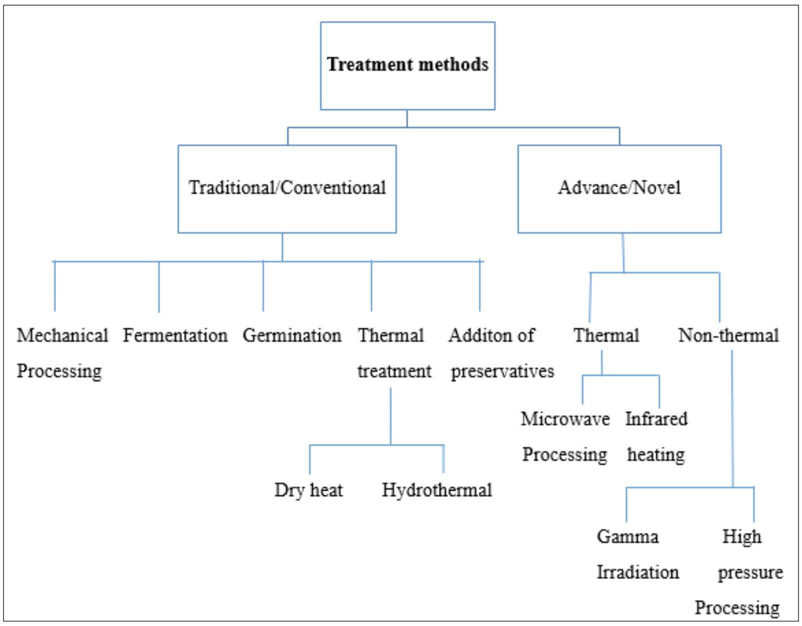

Fig 2: Classification of treatment methods for increasing shelf life of millet flour

4.1 Traditional processing

Traditional processing techniques and methods are the widely accepted and established method that are followed at the household level to improve the bioavailability and storage stability of plant-based diets. These processes include malting, fermentation, soaking, mechanical processing, and so forth.

4.1.1 Mechanical processing techniques

Before storage and consumption, millet grains are mechanically decorticated, which involves pericarp removal from the endosperm totally or partially, in order to improve their functional qualities and maintain high storage quality. Sorghum, pearl millet, and finger millets do not have a husk layer, but minor millets have. Husk is a stiff cellulose coating that is difficult for humans to digest (Patil, *et al*., 2016) [30]. Decortication is the first step in millet processing, which removes the husk to increase the storage stability of millets. Millets' nutritional value significantly changes as a result of decortication.Pearl millet includes a good amount of triglycerides, which are rich in unsaturated FFA, due to the greater pericarp or germ size than other grains (Sandhu, *et al*., 2018) [33]. Because dry milling partially separates the pericarp from the grain, it is also used to extend the storage or shelf life of millet flour. Recent research on pearl millet grain found that decortication considerably decreased the fat content, and that after 60 days of storage, the fat concentration was significantly lower (Babiker, *et al*., 2018) [6]. In order to demonstrate this, a study was carried out to determine the impact of various milling processes on the stability of pearl millet flour. It was discovered that FFAs in polished pearl millet flour remained below 1% up to the sixth day of storage (Tiwari *et al*., 2014) [40]. If kept at ambient temperatures for 50 days in polyethylene bags, pearl millet flours were found to have no lipase activity (LA) and good physical and functional pasty qualities.

4.1.2 Fermentation

The process of fermentation causes several biochemical changes that ultimately result in a changed ratio of nutritive and anti-nutritive components in the grains, which in turn impacts the storage properties of grains (Singh, Rehal, *et al*., 2015) [35]. Products that have been fermented utilizing yeast and lactic acid bacteria (LAB) in a symbiotic relationship have been proven to have longer shelf lives (Belz *et al*., 2019) [7]. In a recent study, the impact of fermentation on several characteristics of sorghum and pearl millet was examined. It was discovered that as fermentation duration increases, the total titrable acidity in the flour sample increases and the pH decreases (Onyango, *et al*., 2013) [28]. Fermentation influences the nutritional, functional, and sensory qualities of millet flour in addition to altering its biochemical and microbiological characteristics, which has a big effect on the finished product's quality. The shelf life and functional qualities of millet flour can thus be improved overall by fermenting under ideal conditions, and the procedure is particularly favorable when the finished flour will be utilized in various food preparations.

4.1.3 Germination

Due to the breakdown of carbohydrates during grain germination in foxtail millet, specific organic acids were produced. This led to an increase in titratable acidity and a drop in flour pH, both of which are unfavorable condition for microbial development (Coulibaly, *et al*., 2011) [13]. As a result of the oxidation of fatty acids to carbon dioxide and water to produce energy needed for seedling growth, one study discovered a decline in the crude lipid content of flour during the germination of foxtail and barnyard millet grains. The findings also demonstrated a significant increase in antioxidant activity, total phenolic content, and flavonoid content with increasing germination temperature and germination duration. The taste, color, and shelf-life of foods are all improved by antioxidants, which also help keep them edible for extended periods of time. Also, it has been discovered that sprouting millet flour enhances some of its nutritional and functional qualities (Sharma, *et al*., 2018) [34]. The largest phenolic content and powerful antioxidant activity can be found in flours made from sprouted foxtail, proso millet, and barnyard (Pradeep, *et al*., 2015) [31]. Germination is generally regarded as an efficient pre-treatment to enhance the nutritional and functional qualities of wheat flour without losing its storage stability.

4.1.4 Addition of preservatives

The majority of preservatives come from acids, and their main method of action is to make food more acidic, which is detrimental for microbes. Acid treatment can also degrade the grain's intrinsic lipase and decrease the amount of FFA produced. For instance, when pearl millet grains were treated for varied time periods with 0.2 N HCl, the amount of FFA in the flour at 25–30 °C was reduced by 73.9% after 24 hours and by 62.5% after 18 hours (Bhati, *et al*.,

2016) [8]. Antioxidants, both synthetic and natural, are another common chemical technique used to prevent cell damage by decreasing the autoxidation of triglycerides. For instance, 0.02% butylated hydroxytoluene (BHT) was added to the flour of two cultivars of pearl millet and stored for 90 days at room temperature in comparison to an untreated control sample (Abdalgader, *et al*., 2019) [1]. The efficiency of employing *Gaultheria fragrantissima* Wall essential oil and its primary constituents as a preservative for pearl millet during storage was evaluated by Kumar *et al*. (2018) [23]. The essential oil of *Artemisia nilagirica* (Clarke) Pamp was employed as a herbal agent to extend the shelf life of finger millet against microbial contamination and lipid peroxidation in a recent study of a similar nature by Kumar *et al*. (2018) [23]. Moreover, the addition of preservatives also results in certain changes in the physico-chemical properties of the flour, which alter the nutritional quality.

4.1.5 Conventional thermal treatments
Pasteurization and sterilization are the conventional thermal treatment and mostly used for inactivating microorganisms and enzymes activity in the food. There are several methods for conventional heat treatment, including hydrothermal and dry heat treatments.

In a recent study, the impact of dry heat treatment on the overall bacterial population of different millets was examined. It was discovered that heat treatment of sorghum, fox millet, and pearl millet grains at 150–170 C for 1.5 minutes significantly reduced the overall microbial population by 48, 23% during the primary treatment, and the number subsequently declined for a maximum of sixty days of storage (Kumar, *et al*., 2018) [23]. The bad flavor in flour that results in degradation is caused by FFA, which is found in food grains. Because the lipase enzyme is inhibited at higher temperatures, heat treatment is also known to decrease the FFA level of cereal flour, according to various researchers (Gili, *et al*., 2018) [16]. Heat treatment affects various physicochemical and functional aspects of flour significantly, along with the decreasing of microbial load and FFA.

As a common pretreatment for cereals, the hydrothermal treatment also includes dry heat parboiling, low-moisture parboiling, etc. By suppressing the lipase enzyme, the water heating process prevents the release of lipase from the association or modification of the adsorbed globular membranes of fat molecules. According to the methods adopted, the final grain quality varies, and hydrothermal processing significantly alters the flour's functional and nutritional characteristics. For instance, when finger millet was soaked in extra water for 10 hours at 30 degrees Celsius and then autoclaved for 30 minutes at atmospheric pressure, the amount of fat in the flour barely changed, with linoleic and palmitic acids increasing by 18% while decreasing by 12% (Dharmaraj & Malleshi, 2011) [15]. In a recent study, millet grains were hydrothermally treated at various moisture content and temperature levels to assess the impact on the shelf life of the flour. It was discovered that the rate of lipase inactivation risen with grain moisture content as well as temperature, with the highest inactivation rate being noted at 20% moisture content and 110 ℃ temperature (Kashaninejad, 2019) [22].

4.2 Novel thermal processing techniques
At the moment, electromagnetic technologies are regarded as trustworthy, reliable, and extensively examined substitutes for established, conventional procedures. These methods, which precisely direct thermal energy into the sample, include microwave processing and infrared heating. This type of heat distribution system provides a shorter treatment period, effectively improves the nutritional value and quality of millet flour, and prolongs the shelf life of the product.

4.2.1 Microwave processing
Cereal flours have been microwave heated in order to somewhat extend their shelf life and inactivate lipase activity. For instance, when the microwave power was kept constant at 900 W during a study to evaluate the effectiveness of microwave treatment to neutralize lipase in pearl millet grain, it was discovered that there was a 92.9% reduction in flour LA at a grain moisture content of 18% and a treatment time of 100 s. (Yadav, Anand, *et al*., 2012) [42]. With only a minimal increase in free fatty acid, the modified flour was determined to be acceptable up to 30 days of storage, but the raw flour was only found to be suitable for 10 days. Also, the grains were heated for varying amounts of time and moisture content at a continuous power of 900 W to evaluate the efficiency of microwave treatment for enhancing the storage qualities of millet flour (Kashaninejad, 2019) [22].

4.2.2 Infrared heating
By blocking lipid breakdown, infrared heating efficiently disables the action of lipase, lowering the production of free fatty acids in the sample (Li *et al*., 2016) [24]. Several foods have been found to respond well to infrared stabilization in the management of hydrolytic rancidity, and optimal levels of these operational parameters can boost the acceptance of conventional food products while extending shelf life. For instance, storage stability characteristics like FFA and LA were assessed in an infrared heating parameter optimization study of sorghum flour, and a processing temperature of 120 C for 8.5 min was discovered to be ideal for the lowest FFA and LA content (Swaminathan *et al*., 2015) [39]. Also, it has been demonstrated that millet flour's physico- chemical and nutritional characteristics change as a result of infrared heating. The innovative methods covered here have a number of significant advantages over conventional heat treatments.

The primary benefit of these techniques is their rapid heating rates, which drastically reduce processing times, minimize exposure, and minimize quality losses (Kalla & Devaraju, 2017) [21].

4.3 Novel Non- thermal processing techniques
Contemporary non-thermal processing techniques for food products include gamma irradiation, high-pressure processing (HPP), ultrasound processing, ozone processing, etc.

4.3.1 Gamma irradiation
Gamma radiation is utilized as a preservation technique for millet grain quality and fungus development (Mahmoud, *et al*., 2016) [25]. An investigation by Reddy and Viswanath (2019) [32] into the impact of gamma-irradiation on the physicochemical characteristics, LOX activity, and antioxidant activity of finger millet revealed that the radiation considerably decreased the flour's moisture content (Reddy Viswanath, *et al*.,2019) [32]. Yet, it was discovered that the combined effect of gamma radiation and heat therapy had a greater impact on lowering microbial burden than treatment alone (Kumar, Hymavathi, *et al*., 2018) [23]. Gamma ray irradiation is generally accepted as an efficient processing technique to increase millet flour's storage stability.

4.3.2 High-pressure processing
It was discovered that high pressure processing (HHP) can prevent flour spoiling by keeping nutritious qualities. Sharma *et al*. (2018) [34] attempted high-pressure steeping of foxtail millet grains that had already sprouted and those that hadn't, and they found that the percentage of bound water decreased as the temperature increases in the flour produced from the unsprouted millet. This supports the finding that the flour's overall sorption capacity has decreased, and it is commonly accepted upon that HPP has greatly enhanced the functional aspects of the flour that are related to storage stability. In a similar manner, raising pressure, temperature, and steeping duration in foxtail flour resulted in an increase in total phenolic content, antioxidant activities, and a decrease in tannins and phytic acid, improving the flour's nutritional value (Sharma, *et al*., 2018) [34].

5. Conclusion
Millet has a low shelf life due to its high fat content and lipase

activity as compared to other cereals. Several pretreatments that either mechanically remove the fat-containing component or restrict lipase activity while simultaneously ensuring microbiological stability can control the degradation of triglycerides. The main conventional or modern techniques that improve millet flour's storage stability are covered in this article. These techniques have been shown to extend millet's shelf life, but they also result in the loss of the majority of the grain's micro and macronutrients. The traditional processes such as fermentation and germination considerably improve the nutritional value of millet grains and also lengthen the shelf life of the flour. When the flour is utilized to create other food formulations, these alterations can be seen as advantageous. To inactivate lipase and lengthen the shelf life of millet, thermal treatments like dry heat and hydrothermal are frequently utilized. However, these methods are reported to cause certain physical and functional changes in the flour that may reduce its acceptance by consumers, thus it is important to introduce advanced thermal and non-thermal techniques in millet processing. It has been demonstrated that these treatments improve food safety while having superior nutritional and sensory qualities.

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