NOVEL TECHNOLOGIES ON THE STORAGE OF PEARL MILLET GRAIN AND FLOUR

INTRODUCTION:

The Pearl millet (Bajra) is a nutricereal and traditional crop and grown widely in Asian and African countries. It has the capability to survive under drought and high temperature conditions. Among all the millet varieties, greater than 29 million hectare area is occupied by pearl millet; however, its distribution is restricted geographically mainly in Africa (15 million) and Asia (11 million), as being the largest producer **(Rathore *et al.,* 2016)**.

More than 95 per cent pearl millet production comes from developing countries, and India as the largest producer. It covers an area of 9.8 million hectares out of total world production. This Pearl millet commonly used for food, feed, and forages purpose. It has higher carbohydrate (67.5 per cent), protein (14.0 per cent), fat (5.7 per cent), fiber (2.0 per cent) and ash (2.1 percent) content **(Ran *et al.,* 2018)**.

Despite its nutritional superiority, the utilization of pearl millet grain and flour is limited to few specific pockets and regions all-round the world due to the poor keeping quality of the grain and flour and development of off odour during storage **(Kumar *et al.,* 2018)**. The poor keeping quality of pearl millet grain and flour is due to the oxidative and hydrolytic rancidity caused by Lipase (LA), Lipoxygenase (LOX), Free fatty acids (FFA), Peroxide value (PV), Acid value (AV), Water activity (aw). So, the innovation of novel technologies in storage of millets i.e., especially for pearl millet is necessary **(Jukanti *et al.,* 2016)**.

WHY NOVEL TECHNOLOGIES?

- ❖ Contrary to conventional technologies minimal loss of heat-sensitive nutrients present in the food.
- ❖ Good preservation effect induced by
- ✓ Killing of microorganisms
- ✓ Arrest of enzymatic activities
- ❖ Suitable for In-package processing
- ❖ Processing of food at low temperature or in less time, so there is no damage to:
- ✓ Bioactive compounds
- ✓ Nutrients
- ✓ Flavors
- ❖ The need for novel processing technologies in the food industry is a direct result of consumer demand for fresh, high quality and healthy products that are free from chemical preservatives and yet are safe **(Rathore *et al.,* 2016)**.

PROCESSING TECHNOLOGIES FOR PEARL MILLET:

Conventional methods

- ❖ Mechanical processing
- ❖ Malting
- ❖ Germination
- ❖ Fermentation
- ❖ Blanching
- ❖ Conventional thermal treatments
- ❖ Addition of preservatives

Novel technologies

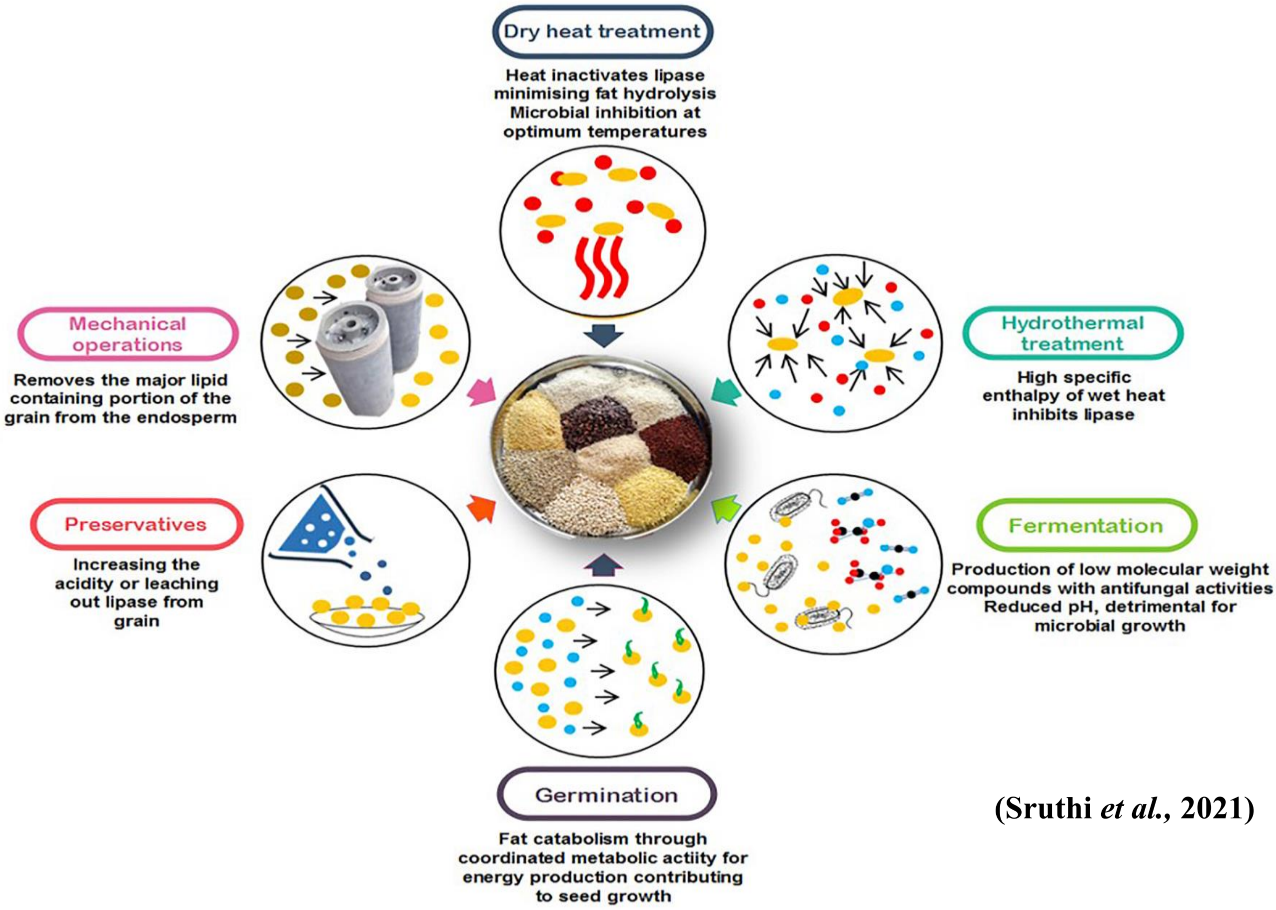
- ❖ Microwave processing
- ❖ Infrared heating
- ❖ Radiofrequency processing
- ❖ Ohmic heating
- ❖ Gamma irradiation
- ❖ High-pressure processing
- ❖ Pulsed light processing
- ❖ Pulsed electric field
- ❖ Ultrasound processing
- ❖ Cold plasma treatment
- ❖ Ozone processing

CONVENTIONAL / TRADITIONAL PROCESSING TECHNOLOGIES:

Traditional treatments and preparation methods are the conventional widely accepted and established practices that are accustomed at the household level to improve the bioavailability and storage properties of plant-based diets **(Ranasalva, N and Visvanathan, 2014)**. Such treatments include mechanical processing, fermentation, soaking, germination, malting, etc **(Akinola *et al.*, 2017)**. The conventional methods to be discussed in this section are broadly categorized into;

- ❖ Mechanical processing
- ❖ Malting
- ❖ Germination
- ❖ Fermentation
- ❖ Blanching
- ❖ Conventional thermal treatments
- ❖ Addition of preservatives

Malting Process



(Sruthi *et al.*, 2021)

Mechanism of conventional thermal and traditional processing methods to increase the shelf-life of pearl millet.

(a) Mechanical processing:

Pearl Millet grains are mechanically decorticated and undergo different processing treatments before storage and consumption to enhance their functional properties and called naked grains, as they do not have a husk layer. They are pearled and ground to flour or into grits, making them ready for cooking. Decortication-induced reduction in crude lipid content can in a way contribute to better storage properties because of lesser availability of fat for oxidation that can cause rancidity **(Suma *et al.*, 2011)**.

(b) Malting:

Malting is the process accompanied by restricted sprouting of cereals in humid atmosphere along with controlled set of conditions. Although protein content of the grains reduced significantly after malting, yet features such as improved protein quality and higher protein efficiency ratio make this one very popular method of processing and enhancement of shelf-life **(Pawase *et al.*, 2019)**.

(c) Germination:

Germination combines those events that begin with the absorption of water by the dormant dry seeds and terminate with the elongation of the radicle, which extends to make a way through the structures that surround it. It also commences a coordinated metabolic activity, which mobilizes the triacylglycerols from oil bodies present in the grain leading to the net conversion of oil to sugars. This happens because of the degradation of released FFA through β-oxidation and glyoxylate cycles **(Owheruo *et al.,* 2019)**.

(d) Fermentation:

Fermentation is necessary mainly for food preservation, flavor development and for enhancement of nutritional quality of raw products. Fermentation process is done by malting and souring with mixed cultures of yeast and Lactobacilli. Starch and soluble sugar present in millet get degraded by the enzymes present in grains and fermentation media **(Saleh *et al.*, 2013)**.

(e) Blanching:

One of the most effective techniques for enhancing the shelf life of pearl millet flour is blanching, which slows down the enzymatic activity without having any significant effect on its nutritional composition. It is done by boiling water at 98°C, followed by immersing of the grains in the boiling water (1:5 ratio of seeds to boiling water) for 30 s and drying at 50°C for 60 min **(Bhati *et al.*, 2016)**.

(f) Conventional thermal treatments:

There are several methods for conventional heat treatment, including hydrothermal and dry heat treatments. Dry heating can be done by heating the grains in hot air oven maintained at 100 6 2°C for 60 to 120 min, followed by rapid cooling and finally milling to obtain whole meal **(Jalgaonkar *et al.,* 2016)**. Combination of acid treatment (18 h) and dry heat (120 min) also showed significant reduction of fat acidity, free fatty acid, and lipase activity of pearl millet flour throughout a storage period of 28 days. Hydrothermal processing or parboiling is a widely applied pre-treatment for cereals, which is known to toughen the grains and subsequently improve their milling efficiency **(Singh and Saini, 2012)**.

(g) Addition of preservatives:

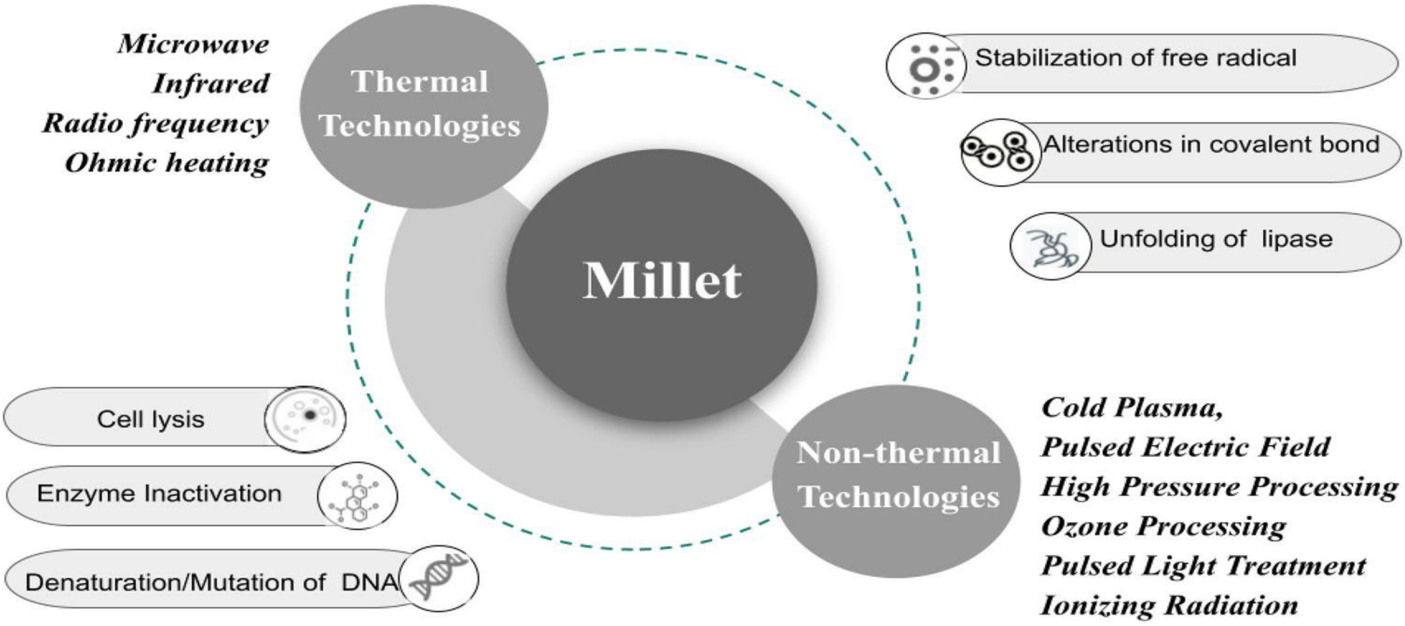
Preservatives are substances that are added to food products and other biological samples, to prevent microbial contamination and other undesirable chemical changes that might result in spoilage **(Doblado-Maldonado *et al.,* 2013)**. Chemical substances or artificial preservatives are largely exploited to prolong the shelf life of food grains and their by-products by inhibiting microbial contamination and decomposition **(Abdalgader *et al.,* 2019)**.

Advantages and disadvantages of conventional storage methods:

Advantages	**Disadvantages**
1.Cost-effectiveness	1. Loss of color, flavor, freshness, and some nutritional aspects and difficulty in maintaining quality
2. Simple technologies and do not require advanced equipment or infrastructure, making them easy to implement and maintain.	2. Increased costs of facilities and labor
3. Suitable for smallholder farmers	3. More power requirement and high capital costs

4. Preservation of nutritional quality	4. Potential difficulties in uniformity of heating
5. Low energy requirements	5. Formation of toxins on high temperature application
6. Cultural relevance	6. More time-consuming processes
	7. Risk of contamination
	8. Limited shelf life

2. NOVEL THERMAL AND NON-THERMAL TECHNOLOGIES:



Overview of thermal and non-thermal techniques in processing and its mechanism

(Joshi *et al.,* 2023)

1. NOVEL THERMAL TECHNOLOGIES:

Novel thermal treatments have been demonstrated to reduce the action of the enzymes lipoxygenase and lipase, extending the shelf life of Pearl millet grains. Thermal processing of grains has also been linked to denaturation of proteins, modified flavor, aroma, and starch granule structure, as well as a decrease in the microbial load. Presently, electromagnetic technologies are pondered to be reliable and thoroughly tested alternatives to the conventional established processes. These techniques include microwave processing, infrared heating, ohmic heating, radiofrequency heating/processing, etc. Where volumetric heating occurs and thermal energy is generated precisely into the sample. Such a pattern of heat distribution ensures reduced treatment times and contributes bluntly in improving the quality and nutritional characteristics of pearl millet flour and maintain its shelf life **(Joshi *et al.,* 2023)**. The novel technologies to be discussed in this section are broadly categorized into;

- Microwave processing
- Infrared heating

- ❖ Radiofrequency processing
- ❖ Ohmic heating
- ❖ Gamma irradiation
- ❖ High-pressure processing
- ❖ Pulsed light processing
- ❖ Pulsed electric field
- ❖ Ultrasound processing
- ❖ Cold plasma treatment
- ❖ Ozone processing

(a)Microwave processing:

Microwave (MW) processing is based on the principles of dipole rotation and ionic polarization, and it employs electromagnetic (EM) radiation in the wavelength range of 0.3 –300 GHz or 3MHz to 300GHz. In this, a part of the energy is absorbed while the rest is transmitted and reflected. The dielectric constant and dielectric loss factor influence microwave interactions with the food system. Microwave processing lowers antinutritional components in pearl millet and pearl millet-based products. The antinutrient inactivation is induced by the hydrolysis of peptide bonds, the dissociation of covalent bonds, and the alteration of disulfide bonds. Free radicals produced during MW processing reduce the amounts of inositol and inositol phosphate, and thus lowers the phytic acid concentration. The deactivation of trypsin inhibitors is aided by the denaturation of thermally unstable proteins. MW treatment (900 W for 40 – 100 s) reduced tannins in pearl millet by 45.53 respectively **(Sruthi *et al.,* 2021)**.

Microwave heating has been sketchily used to inactivate lipase in grain flours and in a way, increase their shelf life. There still exists a dispute to ascertain whether a thermal effect or electromagnetic field effect is the mechanism of microwave inactivation of enzymes. Polar water molecules will rotate according to the alternating electromagnetic field. The water molecule is a “dipole.” "Dipoles" will orient themselves when they are subject to electromagnetic field. Rotate at about 24 billion times per second. Ionic compounds in food can also be accelerated by the electromagnetic field. This orientation of water molecule causes huge friction inside the product and hence generation of heat take place inside the product **(Hithamani *et al.,* 2014)**.

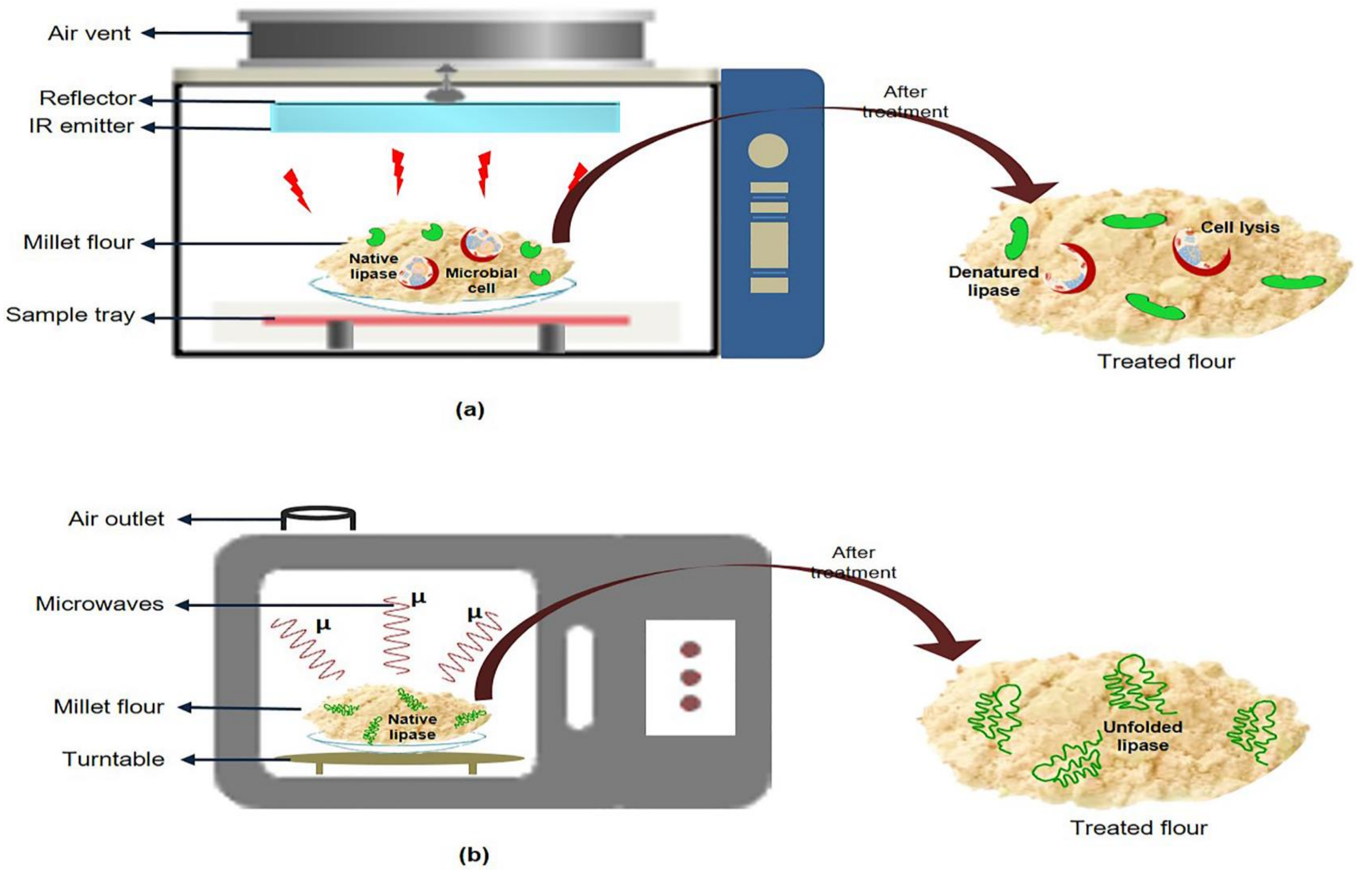
It was discovered that microwave heating of pearl millet grains significantly reduced lipase activity. They also conducted a subjective assessment of the overall acceptability of flour samples. The results showed that microwave-treated flour could be stored at room temperature for up to 30 days, whereas control flour had an unpleasant off-odour and bitter taste by the tenth day **(Yadav *et al.,* 2012b)**.

Microwave heating has been sketchily used to inactivate lipase in grain flours and in a way, increase their shelf life. There still exists a dispute to ascertain whether a thermal effect or electromagnetic field effect is the mechanism of microwave inactivation of enzymes. There is only a little evidence that non-thermal effects also exist, but the cause of enzyme inactivation by microwaves is generally been attributed to the thermal effects. A proficient way to cognize this is through understanding the inactivation kinetics of enzymes. It is well testified that the enzyme inactivation process is typically explained by the first-order reaction kinetics **(Sruthi *et al.,* 2021)**.

Microwave treatment inactivates lipase in pearl millet grain, it was found that, at a grain moisture content of 18% and treatment time of 100 s, there occurred 92.9% reduction in LA of the flour when the microwave power was kept constant at 900 W. The decreased LA of flour may be attributable to the high temperature attained by the sample during the treatment. An optimum grain moisture content ensures better availability of polar water molecules which might have facilitated the transformation of microwave energy into thermal energy. Whereas at lower moisture content, the availability of polar water molecules is less, and higher moisture content can cause evaporative cooling of the grains reducing temperature rise **(Joshi *et al.,* 2023)**.

The microwave treated flour was found satisfactory up to 30 days of storage with only a marginal increase in FFA, whereas the raw flour remained acceptable only up to 10 days. Furthermore, in a work to evaluate the efficiency of microwave treatment for improving the storage properties of millet flour, the grains were treated with different levels of moisture content and heating times at a constant power of 900 W. The inactivation rate of lipase was found to increase with an increase in microwave treatment time, and the highest inactivation was achieved at 90 s. A similar trend was observed for the FFA during 30 days of storage **(Yadav *et al.,* 2012b)**.

Schematic representation of novel thermal techniques to improve storage stability of millet flour (a) Infrared heating (b) Microwave processing.



The pearl millet (*Pennisetum glaucum*) was evaluated for polyphenolic content and their bioaccessibility. Significant reduction of total polyphenols and there was a 20% increase in the bioaccessible polyphenols observed in microwave-heated pearl millet grains and increase in shelf-life for 60 days **(Hithamani *et al.,* 2014)**.

Effect of microwave heating of pearl millet grains decreased lipase activity significantly with an increase in moisture level from 12 to 18 % and maximum reduction (92.9 %) was observed at 18 % moisture level for 100 s. Based on lipase inactivation and pasting properties, 80-s duration of microwave exposure at 18 % grain moisture was considered optimum. Significantly lower change in free fatty acid value (20.80–22.25) during storage up to 30 days was observed in flour of grains treated for 80 s at 18 % moisture level as compared to control flour (20.11–32.43). Subjective evaluation of overall acceptability of flour samples showed that microwave-treated flour (18 % moisture level, 80 s) was acceptable up to 30 days of storage at ambient conditions, while control flour had unpleasant off odor and bitter taste at the 10th day of storage **(Yadav *et al.,* 2012b)**.

Applications: Pasteurization, sterilization, dehydration, tempering, blanching, baking, cooking. thawing, boiling etc.

Advantages and disadvantages of Microwave Heating:

Advantages	**Disadvantages**
1.Rapid and uniform heating	1. Low penetration depth
2. High heating efficiency (80% or higher efficiency can be achieved)	2. High initial cost
3. Reduce energy and time of processing	3. Non uniform heating when using large size product
4. Reduced loss of nutrients than conventional heating	4. Less energy efficient than ohmic heating
5. Minimum fouling depositions, because of the elimination of the hot heat transfer surfaces	
6. Suitable for heat-sensitive, high-viscous, and multiphase fluids	
7. Does not generate exhaust gas therefore no contamination of foods by products of combustion	
8. Equipment is small, compact, clean in. operation	
9. Surface of the food does not overheat	
10. Automatic process control	
11. Rough estimate for industrial or commercial-grade microwave equipment could range from ₹50,000 to ₹5,00,000.	

(b) Infrared heating:

Infrared (IR) radiation lies between the wavelength of visible light and MW. It is classified into three wavelength regions: near IR (0.78–1.4 m), mid-IR (1.4–3.0 m), and far-IR (3.0–1000 m). The penetration of IR radiation causes vibrating motion in the water molecules, which results in the generation of heat. Reduced heating periods, uniform heating, less energy consumption, a high rate of heat transfer, and enhanced product quality are some of the advantages of IR technology. The thermal energy generated by IR radiation can cause microbial cell damage, contraction of cytoplasmic membranes, mesosome disintegration, and leaking of intracellular constituents. IR heating has also been shown to inactivate lipase by interfering with the lipid hydrolysis process, lowering free fatty acid production **(Yadav *et al.,* 2012a)**.

Principle of IR heating:

Principal food components or the radiation-absorbing molecules, including water, organic compounds, and biological polymers, absorb IR radiant energy efficiently in the wavelength range of 2.5 µm to 10 µm through changes in molecular vibration, chemical bonding, electronic excitation corresponding to the medium- and far-IR regions to generate heat. The efficiency of converting absorbed energy into heat is great at high wavelengths in IR radiation. Infrared radiation is absorbed by organic matter at separate frequencies that correspond to the transport of internal molecules between energy levels. Such transition within the range of infrared energy is expressed regarding the rotational movement and the vibrational (stretching) movement of internal atomic bonds **(Li *et al.,* 2016)**.

Infrared rays comprise the fraction of the electromagnetic spectrum that margins on visible light and microwaves with wavelength ranging from 0.78 to 1000 µm. Recently, infrared radiation has been extensively used in different thermal processing tasks in the food industry, which includes drying, pasteurization, frying, dehydration, etc. Exposure of any substance to infrared radiation instigates severe heating of both the surface as well as the inner layers, thus increasing the rates of heat and mass transfer as contrasted to other heating techniques. It offers numerous other advantages such as uniform heating, a high scale of controllability and most of the food constituents absorb irradiative energy in the infrared region **(Yadav *et al.,* 2012a)**.

Moreover, the heat energy of infrared gets directly absorbed by the food materials which guarantees short heating times and precise or targeted application. The efficient absorption of infrared energy by food substances is by means of modifications in the molecular vibrational state, leading to radiative heating. This thermal energy can cause both external and internal damage to the microbial cells including cell wall damage, contraction of cytoplasmic membranes, the disintegration of mesosomes, and leakage of internal cellular. Infrared stabilization was found effective in terms of checking hydrolytic rancidity in different foods and optimized levels of these operational parameters can extend the storage-life and enhances the acceptability of conventional food products **(Swaminathan *et al.,* 2015)**.

To optimize the infrared heating parameters of sorghum flour, storage stability parameters such as FFA and LA were evaluated, and a processing temperature of 130 ◦C for 7.5 min was found optimal for the lowest FFA and LA content. The reduced LA and consequent decrease of FFA can be comprehended because of water desorption phenomena as there is a significant positive correlation between enzyme activity and water activity. Infrared irradiation caused extensive loss of moisture content in sorghum samples. Water serves as both reactant and solvent in lipid rancidity reactions and thus plays a pro-oxidative role in lipid oxidation. It was found in previous studies that irreversible destruction of lipase and LOX cannot be achieved by infrared and these regenerate after water adsorption during storage. However, the water monolayer is also assumed to be essential to conceal the surface of lipids in certain foods, preventing lipids from getting directly exposed to oxygen **(Li *et al.*, 2016)**.

Infrared heating efficiently disables the action of lipase, lowering the production of free fatty acids in the sample. 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. Also, it has been demonstrated that millet flour's physico- chemical and nutritional characteristics change because of infrared heating. The innovative methods covered here have several 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 **(Swaminathan *et al.*, 2015)**.

This study demonstrated that the Infrared heating (0.78 – 1000 µm) is used as potential technology to regulate the activity of lipase. It was reported that infrared treatment at 130°C for 7.5 min was best suited for reduction of lipase activity in pearl millet processed products **(Yadav *et al.*, 2012a)**.

Advantages and disadvantages of Infrared heating:

Advantages	**Disadvantages**
1.Less drying time	1. Low penetration power of infrared radiation
2. Highly energy efficient	2. Prolonged exposure may cause fracturing tissue causing rupture in biological materials.
3. Uniformity in drying	3. Insensitivity to the reflective properties of the coating
4. Homogeneity of heating	
5. High heat transfer rate	
6. Improves the quality of the treated product	
7. Improves the safety of treated food.	
8. High controllability	
9. Reduces the consumption of chemicals and water and increases manufacturing efficiency	
10. Does not produce volatile organic compounds, carbon monoxide or nitrogen oxides	

11. It does not need heat recycling and does not need an isolated system.	
12. Preserves vitamins and has very little flavor loss, and the temperature of the surrounding air is not affected.	
13. Industrial-grade infrared equipment can range from ₹1,00,000 to ₹10,00,000.	

(C) Radiofrequency processing:

Radiofrequency heating, that generates heat volumetrically within dielectric materials because of rotation-induced polarization mechanism by the dipole molecule and direct conduction effect. Radio frequency (RF) or high frequency dielectric heating refer to the heating of dielectric material (water) with electromagnetic energy at frequency between 1 to 300 MHz. Through ionic polarization or dipole rotation, RF waves can penetrate dielectric materials and generate heat volumetrically. Because of their greater wavelength or higher penetration power, RF waves penetrate deeper than MW **(Jasmeen *et al.,* 2023)**.

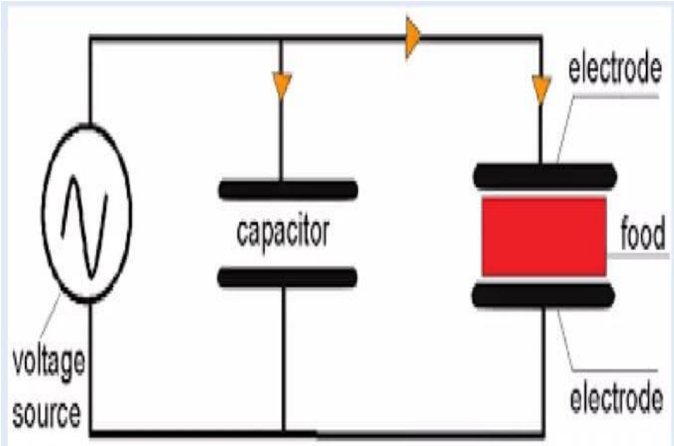
RF treatment has been reported to be used for insect control, microbial inactivation, enzyme inactivation, protein modification, drying, roasting, and other applications in grains. Prime goal of this technology is food preservation by ensuring its safety and quality **(Yarrakula *et al.,* 2022)**.

Radiofrequency processing (RF) with hot air improves treatment efficiency and heating uniformity It was studied the physicochemical and functional parameters of pearl millet using hot air-assisted RF technology. When compared to raw pearl millet, the WAC of hot air-assisted RF-treated pearl millets increased slightly. The treatment for 5 min retained the maximum WAC (8.66 g/g). Higher WAC values are required to improve the processing qualities of dough and pastes. RF treated samples are reported to have increased protein solubility, antioxidant potential, and total phenolic content (TPC). They also showed improved emulsifying and foaming characteristics as well as a brighter color than steam treated samples. However, more research is required to validate the effects of RF heating on the physicochemical and functional parameters of millet and millet-based products **(Joshi *et al.,* 2023).**

Principle of RF Heating:

- ✓ Molecular reorientation and friction occurs due to continuous realignment (action of changing different position or state) of the molecules.
- ✓ Ionic movement towards oppositely charge electrode
- ✓ Rapid change in polarity causes heat generation

General radio frequency heating process:



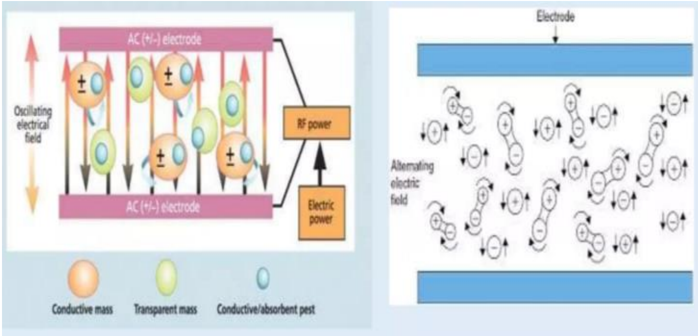


Figure:- Space charge and dipolar polarization in an alternating electric field at radio frequencies (Orsat and Raghavan, 2005)

The study indicated that physicochemical and functional parameters of pearl millet using hot air-assisted RF technology. When compared to raw pearl millet, the WAC of hot air-assisted RF-treated pearl millets increased slightly. The treatment for 5 min retained the maximum WAC (8.66 g/g). Higher WAC values are required to improve the processing qualities of dough and pastes. RF treated samples are reported to have increased protein solubility, antioxidant potential, and total phenolic content (TPC). They also showed improved emulsifying and foaming characteristics as well as a brighter color than steam treated samples and increases shelf-life up to 2 months **(Yadav *et al.*, 2012a)**.

Studied the effect of hot air assisted radio frequency (HARF) treatment at different exposure periods (5, 8, 11 &14 min) on physical (moisture, colour, water activity, bulk density, tapped density) and functional (WAC, OAC, WSI) properties of pearl millet. As the exposure time increased, the moisture content and water activity were reduced significantly while the colour values and bulk density changed insignificantly. The functional properties such as WAC and WSI decreased insignificantly while the OAC was insignificantly increased as the exposure time increased also increases shelf-life up to 65 days **(Yarrakula *et al.*, 2022)**.

Advantages and disadvantages of Radio Frequency Processing:

Advantages	**Disadvantages**
1.It is rapid heating technique compare to conventional heating. Hence it requires less time to attain desired temperature.	1. Equipment and operating cost
2. More uniform heating and drying and Self-limiting during drying	2. For an equivalent power output, RF heating equipment is more expensive than conventional convection, radiation, or steam heating systems.
3. Moisture leveling and profiling	3. It is also more expensive than an equivalent ohmic heating system.

4. Selective heating and it offers greater heat penetration depth and uniform heat distribution.	4. Different products will require different heating process time due to their shape, size, dielectric material, position etc.
5. Shorter process lines.	5. Industrial-grade RF equipment suitable for can range from ₹5,00,000 to ₹50,00,000.
6. Contactless heating and it does not require any direct contact between food product and its electrodes unlike ohmic heating.	
7. Energy efficiency and it targets food product and not air surrounding the product during heating.	
8. It reduces moisture from the food item under heating.	
9. It avoids overheating and dehydration of the product surface.	

(d) Ohmic heating:

Ohmic heating is a technique in which an alternating electrical current flow through a conductor, causing the temperature to rise in accordance with Joule's law. During ohmic heating, heat is created volumetrically inside the material, allowing the process to raise the temperature at a faster pace. Ohmic heating is an advanced terminal processing method wherein the food material which serves as an electrical resistor, is heated by passing electricity through resulting in rapid & uniform heating. Also known as electrical resistance heating or joule heating or electro-heating / Green technology **(Yang *et al.,* 2016)**.

Ohmic heating, where heating occurs because of internal heat generation when alternating electrical current passes through the food, are also gaining popularity in the food industry. Ohmic heating resulted in decreased water solubility and absorption indices and yielded a harder and brighter product of cooked pearl millet flour as compared to conventionally cooked ones **(Dias-Martins *et al.,* 2019)**.

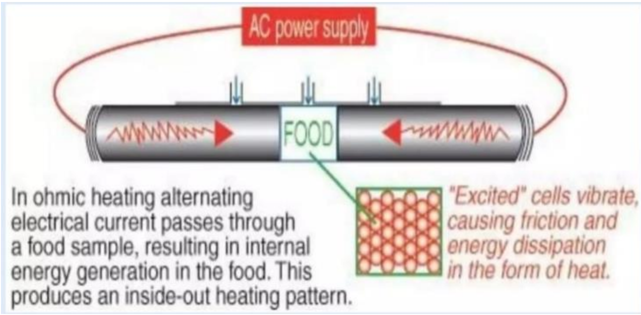
The electrical energy is dissipated into heat, which results in rapid and uniform heating. The heating occurs in the form of internal energy generation within the material. The ohmic heating instrument is equipped with titanium electrodes and enclosed on a Teflon tee. Samples are placed between the electrodes with an alternating current of 50 Hz with three different levels of electrical field strengths (EFS) (75, 150, and 225 V/m). A 1.5 KW capacity dielectric heater operating at 13.56 MHz can be used. Developed by United Kingdom Electricity Research and Development Center Licensed to APV Baker Ltd for commercial exploitation **(Jasmeen *et al.,* 2023)**.

Ohmic heating has been reported to be a viable method for cooking grains such as rice and maize because of its high energy efficiency, rapid cooking time, low energy consumption, and renewability. But their applications in the processing of millets have not been explored much. The uniformity and rate of heating are closely linked to the electric field and the electrical conductivity of the sample being processed. Depending on the process condition and composition of treated material, temperature increase during the ohmic heating results in moisture migration, protein denaturation, and starch gelatinization. It was investigated the effects of ohmic cooking on the cooking yield, texture, color, WAC, water solubility index (WSI), and pasting characteristics of pearl millet. They observed that ohmic-heated samples had a lower cooking yield than conventionally cooked samples. This is because the pericarp layer will act as a barrier to electrical conductivity. This reduces the flow of electrons, reducing the effect of ohmic heating on the grain endosperm. The ohmic cooking method also resulted in harder grains **(Joshi *et al.,* 2023)**.

Ohmic cooking resulted in higher softening rates than conventional techniques. This is because volumetric heating evenly distributes heat throughout the rice-water mixture. As a result, starch gelatinization occurs across the rice grains at the same time. It was reported that ohmic-cooked rice exhibited higher starch gelatinization than conventional grain. The authors also reported that ohmic-cooked rice grains showed a more porous microstructure as compared to normally cooked grains. This is due to electroporation induced structural changes during ohmic heating **(Sruthi *et al.,* 2021)**.

Whole and decorticated pearl millet grains were cooked for 30 and 20 min, respectively, by the conventional open pan and ohmic methods. Ohmic heating (OH) did not result in softer grain texture than the conventional method. Whole pearl millet grain cooked by both methods did not present significant differences in color and texture, but decorticated millet grains cooked by the ohmic method resulted in harder grains with greater lightness than the conventionally cooked decorticated millet grains. Overall, OH could be a promising technology for cooking pearl millet grains, as it did not cause any negative effects on the quality attributes of the grains, and it increases shelf-life up to 40 days and is an environmentally friendly technology and has high energy efficiency **(Dias-Martins *et al.,* 2018)**.

The study reported that ohmic-cooked pearl millet grains exhibited higher starch gelatinization than conventional grain. It was found that ohmic-cooked pearl millet grains showed a more porous microstructure as compared to normally cooked grains. This is due to electroporation induced structural changes during ohmic heating thus increased shelf-life 45 days **(Yang *et al.,* 2016)**.



Applications: Rice bran stabilization, blanching, sterilization, juice extraction, oil extraction, pasteurization, evaporation, dehydration, fermentation, peeling, thawing etc.

Advantages and disadvantages of Ohmic Heating:

Advantages	**Disadvantages**
1. High energy efficiency because 90% of the electrical energy is converted into.	1. Only suitable for liquids or particles in liquids.
2. Reducing risks of fouling on heat transfer 2 surface and burning of the food product.	2. Lack of generalized information.
3. Higher temperature that required for HTST processes can be achieved.	3. Requested adjustment according to the conductivity of the dairy liquid.

4. Suitable for batch as well as continuous operation.	4. Narrow frequency band.
5. Uniform heating of particulate food with faster heating rates.	5. Industrial-grade ohmic heating equipment can range from ₹3,00,000 to ₹30,00,000.
6. Keep product quality basically intact.	
7. Easy to operate and no residual heat transfer after the current is shut off.	
8. Environmentally-friendly system.	
9. Ease of process control with instant switch-on and shut-down.	

2. NOVEL NON-THERMAL TECHNOLOGIES:

Heat treatment causes loss of organoleptic properties and consumer acceptance because of various chemical and physical changes in foods under intense conditions. Under these circumstances, a finest product with zero bacterial load, superior storage properties, and enriched functionalities is a top priority, which paves way for a methodical application of non-thermal techniques in cereal processing. These techniques come under non-conventional food processing practices that are aimed at improving the sustainability of food processing operations, and are, based on specific physical or chemical constraints, having the peculiarity to be effective at mild temperatures in contrast to conventional food processing operations **(Sruthi *et al.,* 2021)**.

Non-thermal processing techniques for food products include gamma irradiation, high-pressure processing (HPP), pulsed light (PL) processing, pulsed electric field (PEF), ultrasound processing, ozone processing, cold plasma, etc. However, these techniques are not considerably put into application for augmenting the shelf life of millets and other under-utilized cereals, though most are well established and few are even on the verge of commercialization **(Joshi *et al.,* 2023)**.

(a) Gamma irradiation:

Gamma radiation inactivates microorganisms by breaking the covalent bonds in bacterial and viral DNA. The radioactive isotopes Co-60 and Cs-137 are the sources of this radiation. Gamma-ray, X-ray, and electron beam are ionizing radiations. Ionizing radiation technologies used for food applications. Gamma radiation sources are (cobalt-60 with emission energy levels of 1.17 and 1.33 Mev and cesium-137 with emission energy of 0.66 MeV). They are the ionizing part of the electromagnetic spectrum that has been used to increase the shelf life and safety of several foods, reducing losses and the occurrence of foodborne illnesses. The Food and Agriculture Organization, International Atomic Energy Agency, and World Health Organization have ascertained after several experiments that irradiation dosages not exceeding 10 kGy on average will not cause toxicity and nutrition loss problems while guaranteeing microbial safety of food. The international unit for the radiation dose is the Gray (Gy) **(Jasmeen *et al.,* 2023)**.

It was studied the applicability of gamma radiation as a preserving method on storage and quality characteristics of pearl millet grains. The study revealed that at a dose level above 0.5 kGy, a weighty reduction in the percentage of fungal incidence as well as FFA was obtained. The decrease in FFA can be accredited to the diminution of lipase in the grain, which can contribute to the stabilization and shelf-life extension of the flour **(Singh *et al.,* 2023)**.

Gamma radiation is utilized as a preservation technique for millet grain quality and fungus development. The impact of gamma-irradiation on the physicochemical characteristics, LOX activity, and antioxidant activity of pearl millet revealed that the radiation considerably decreased the flour's moisture content. Yet, it was discovered that the combined effect of gamma radiation and heat therapy had a greater impact on lowering microbial burden. Gamma ray irradiation is generally accepted as an efficient processing technique to increase millet flour's storage stability **(Mahmoud, *et al*., 2016)**.

Gamma rays are the ionizing part of the electromagnetic spectrum that has been used to increase the shelf life and safety of several foods, reducing losses and the occurrence of foodborne illnesses. The Food and Agriculture Organization, International Atomic Energy Agency, and World Health Organization have ascertained after several experiments that irradiation dosages not exceeding 10 kGy on average will not cause toxicity and nutrition loss problems while guaranteeing microbial safety of food **(Sruthi *et al.,* 2021)**.

Food irradiated to any dose, apposite to achieve the intended technological purpose, is both safe to consume and nutritionally acceptable. There are many means by which radiation treatments improve the storage stability of millet flour. For instance, radiation can cause both direct and indirect damage to the DNA or protein, making it more sensitive to the treatment causing its inactivation. They also generate free radicals, such as hydrogen peroxide, hydroxyl radicals, and hydrogen atoms, because of the radiolysis of water, which can damage cellular metabolic pathways, leading to bacterial death and preventing spoilage without having any toxicological effects on the food. Free radicals also interact with certain macronutrients and with minerals, modifying physico-chemical and sensory attributes of the food **(Singh *et al.,* 2023)**.

To demonstrate, in a study to evaluate the potential of gamma irradiation in decontaminating the microbial load in pearl millet flour, it was found that total aerobic plate count (TAPC) and total yeast and mold count (TYM) decreased at a sufficient radiation dose of 5 kGy. Furthermore, after storage for about one month, there was a 1.2 log CFU/mL decrease in TAPC and 0.3 log CFU/mL decrease in TYM owing to radiation treatment of 5 kGy. The irradiation treatment also stabilized the water content at an average value of 10.7% **(Sujatha *et al.,* 2018)**.

It was studied the applicability of gamma radiation as a preserving method on fungal growth and quality characteristics of pearl millet flour. The study revealed that at a dose level above 0.5 kGy, a weighty reduction in the percentage of fungal incidence as well as FFA was obtained. The decrease in FFA can be accredited to the diminution of lipase in the grain, which can contribute to the stabilization and shelf-life extension of the flour. The occurrence of lipoxygenase activity is another major concern in the food industry. The hydroperoxides, which are produced because of the LOX reaction, act as a substrate for the downstream enzymes in the production of volatile compounds like hexanal associated with undesirable flavors **(Mahmoud *et al.,* 2016)**.

The effect of γ-irradiation on the physico-chemical properties, LOX activity, and antioxidant activity of pearl millet. The study showed that irradiation significantly lowered the moisture content of the flour. Besides, the radical scavenging activity, catalase, and superoxide dismutase activities intensified, and the LOX activity and malondialdehyde (MDA) content decreased because of the treatment. Malondialdehydes are secondary products of lipid oxidation that are highly reactive and serve as a convenient index for establishing the degree of the peroxidation reaction and subsequently, the shelf life. It can destruct the integrity as well as diminish the fluidity of cell membranes. A reduced LOX activity in the irradiated samples was explained because of degradation, damage, or conformational changes in the protein, and the possible impact of mutations on the active site domain of the LOX protein. However, a combined effect of heat treatment and gamma irradiation was found to have a more significant impact on microbial load reduction than the treatments conducted alone. Irradiation is also comprehended to improve the functionality and quality characteristics of millet flour as demonstrated by many studies **(Jasmeen *et al.,* 2023)**.

Mahmoud *et al.* (2016) observed a dose-dependent decrease in the contents of anti-nutrients such as tannin and phytic acid in irradiated pearl millet, with the reason being their chemical degradation by the action of free radicals. With this, the *in vitro* protein digestibility showed a minor increment owing to the irradiation-induced changes in the protein structure causing its denaturation and thus improving the digestibility. Gamma irradiation treatment causes decrease in both fungal infection and FFA was achieved at treatment levels higher than 0.5 kGy. The reduction in lipase in pearl millet can be attributed to the decline in FFA, which may help in the stabilization and extension of the shelf life of flour.

It was investigated the effect of gamma irradiation on pearl millet. They found that at dosages of 10, 15, 20, 25, and 30 kGy, the phytate content of electron-irradiated sorghum was reduced by 39, 49, 66, 79, and 90%, respectively, as compared to control. This decrease in phytic acid level will be due to the chemical degradation of phytate to lower inositol and inositol phosphates by the action of free radicals generated by irradiation **(Jasmeen *et al.,* 2023)**.

The present investigation was conducted to find out the effects of heat or irradiation combined with heat on *in vitro* starch digestibility (IVSD). Whole (WC) and dehulled (DC) pearl millet grains were treated either with heat (170°C) or irradiation at 1.0kGy / 2.5kGy and stored for 90 days. The mean IVSD in untreated grains was 66.99 and 70.6 percent in WC and DC, which were improved by 6 and 4 percent due to irradiation treatment. The percent increase from 1.0 kGy to 2.5 kGy was 5.27 in DC and 3.23 percent in WC grains. Storage of both untreated and treated grains affected the IVSD ($p<0.05$) with a significant reduction (1.54%) **(Sujatha *et al.,* 2018)**.

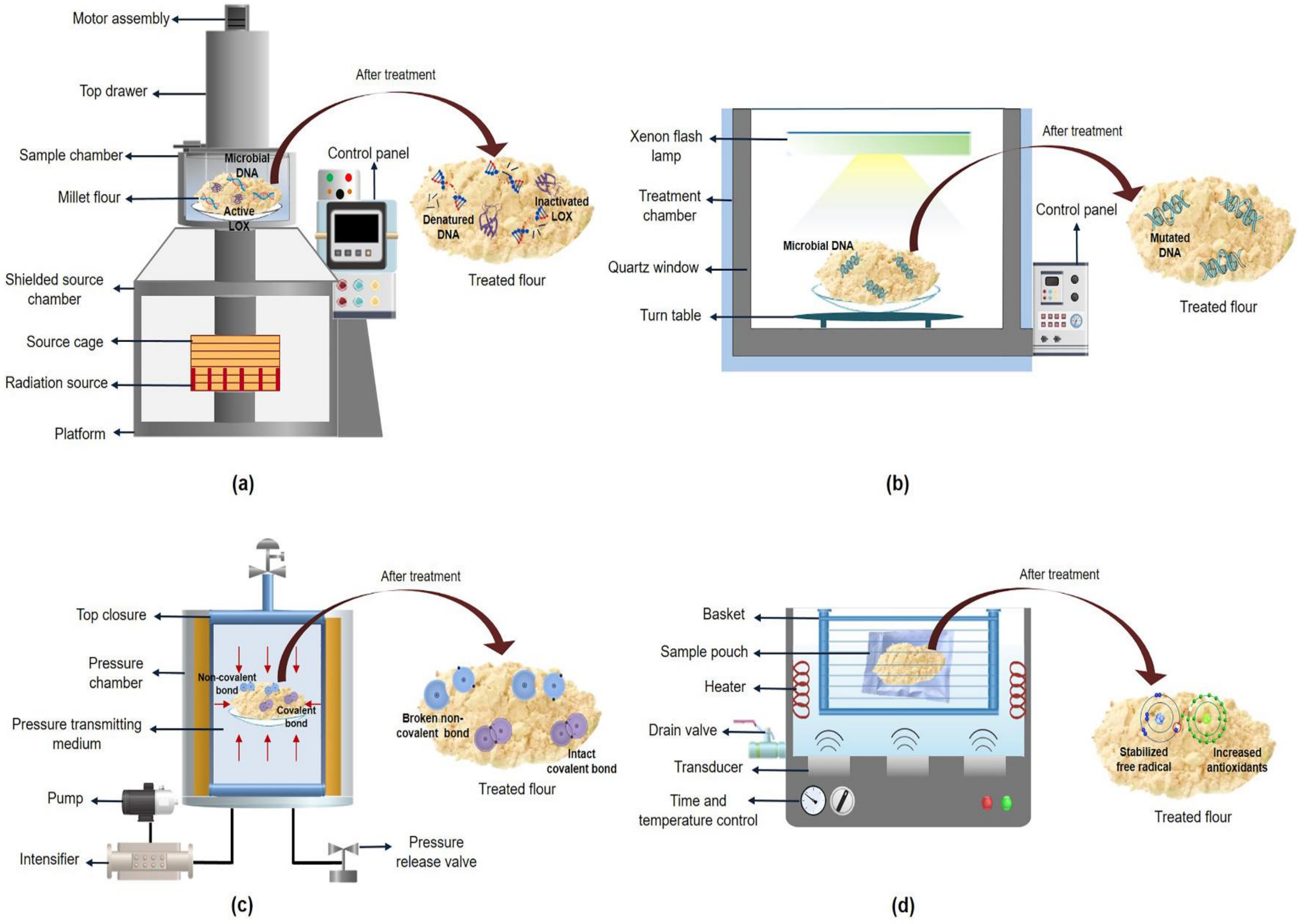
In this study the effect of gamma irradiation in inhibiting these enzymes for increasing the shelf life of pearl millet. we have analyzed a large variation in the activities of polyphenol oxidase (0.08-0.23 U/mg protein) and peroxidase (47-121 nM DMAP/min/mg protein) enzymes in fresh flour of genotypes under study. Additionally, we found that gamma irradiated grains caused reduction in PPO activity by 13-15% and POX activity by 53-55%.

This help in selection and optimization of gamma treatment for improving the shelf life up to 3 months and nutritional properties of pearl millet flour **(Singh *et al.*, 2023)**.

Applications:

- ✓ 0.2-1.0 Gy are used for disinfestation of fruits and vegetables.
- ✓ 1-5 kGy can be used to inactivate vegetative bacteria.
- ✓ >10 kGy are used for sterilization of dry foods such as spices, herbs.

Illustration of non-thermal processing techniques to improve storage stability of millet flour (a) Gamma irradiation (b) Pulsed light processing (c) High-pressure processing (d) Ultrasound processing.



Advantages and disadvantages of Gamma irradiation:

Advantages	**Disadvantages**
1.Irradiation leaves no radioactivity or toxic residues on the treated product.	1. It reduces small amount content of several key nutrients.
2. Irradiation is an efficient, continuous, automated process requiring less treatment time.	2. It is ineffective against viruses.

3. Irradiation will not contaminate the environment while chemical vapour from fumigation will.	3. Capital cost is more.
4. Irradiation delivers a superior product to the consumer because the efficacy of the process.	4. Industrial-grade gamma radiation can range from ₹5,00,000 to ₹50,00,000.
5. Disease causing germs are reduced or eliminated.	
6. Decrease incidence of food borne illness.	
7. Increase level of quality assurance in international trade of food products.	
8. Nutritional value of food is preserved	

(b) High-pressure processing:

High-pressure processing (HPP) is a technique in which the sample is under equally distributed pressure, irrespective of shape and size, which ranges from 100 to 800 MPa at or below ambient conditions or even more than 100 °C. Both solid and liquid foods (with or without packaging) can be treated in this method, and the high-pressure causes microbial death in the food materials. It involves the application of high pressures ranging from 100 to 1000 MPa in batch or semi-continuous manner from a millisecond pulse to over 20 mins at temperatures as low as 0°C to above 100 °C. Also known as "High Hydrostatic Pressure" or "Ultra High Pressure" processing **(Wang *et al.,* 2018)**.

High pressures, up to 1000 MPa are applied to food packages submerged in a liquid. Pressure causes destruction of micro-organisms. Bacteria in the log phase of growth are more sensitive than cells in the stationary, dormant or death phases. High pressure is applied in an "isostatic" manner such that all regions of food experience a uniform pressure. The combination of high pressure together with mild heat treatment can destruct the non-covalent bonds present within the microbial cells such as proteins, nucleic acid, and lipids occasioning inactivation of microorganisms and leave the covalent bonds as such, and thus, retaining the color, aroma, flavor, and nutrition of foods **(Sharma *et al.,* 2018)**.

HPP is a promising substitute for thermal processing for the inactivation of food-borne microorganisms and enzymes without the addition of chemical preservatives and additives at considerably lower temperatures than established thermal processes. The combination of high pressure together with mild heat treatment can destruct the non-covalent bonds present within the microbial cells such as proteins, nucleic acid, and lipids occasioning inactivation of microorganisms and leave the covalent bonds as such, and thus, retaining the color, aroma, flavor, and nutrition of foods. The secondary oxidation of lipid always produces volatile low molecular compounds like aldehydes and ketones **(Jasmeen *et al.,* 2023)**.

HPP has the potential by increasing the cell permeability, HPP promotes the extraction efficiency of MDA and thereby reducing the 2-Thiobarbituric acid (TBA) value. TBA is a measure of oxidative rancidity in fats and quantifies the products formed in the termination phase of lipid oxidation. High-pressure soaking was also found to cause the removal or destruction of outer bran layers of grain, especially the hydrophobic lipid layer, and can thus assist in increasing the shelf life of pearl millet flour. However, HPP has not been applied in pearl millet processing to inactivate lipase and other triggering enzymes and thereby preventing flour rancidity. The findings reported here confirm ample potential of this technique in arresting flour deterioration by controlling the deciding factors **(Joshi *et al.,* 2023)**.

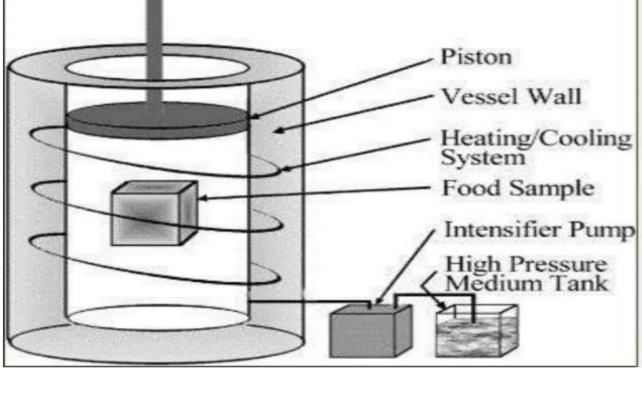
The impact of HPP on the pearl millet grains. The treatment at 400 MPa for 10 min at ambient conditions resulted in the inactivation of yeast and lactic acid bacteria. The complete sterilization was obtained at 400 MPa for 60 min at 66 °C and 600 MPa for 10 min at 66 °C. The α-amylase activity and glucoamylase activity was reduced by 59.7% and 20.5%, respectively, at 400 MPa treatment for 10 min at 66 °C. It was investigated the effect of high-pressure soaking on pearl millet grains. The treatment increased the degree of gelatinization from 0.51 to 64.93% in germinated grains and from 0.32 to 55.21% in control samples. The highest effective diffusion coefficient for germinated grains was reported to be 6.77. 10–9 m2/s at 200 MPa at 60 °C and for non-germinated grains was5.67. 10–9 m2/s at 400 MPa at 80 °C. They also found that the treatment reduced phytic acid and tannin content of both grain samples **(Sruthi *et al.,* 2021)**.

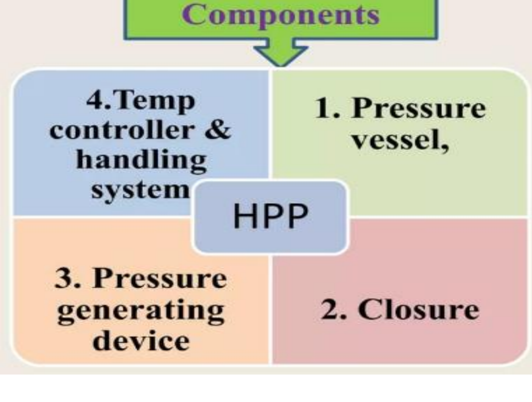
This study demonstrated that the high pressure processed flours of germinated (GPMF) and non-germinated (NGPMF) pearl grains were studied for its functional properties and shelf-life enhancement. Germination and high-pressure processing of pearl millet grains significantly improved the functional properties of the flour and the values of spreading pressures lied in the range of 0 – 0.078 J m-2 for NGPMF and 0 – 24 0.124 J m-2 for GPMF, while, the glass transition temperatures ranged between 82.25 to 28.67oC for NGPMF and from 51.11 to 11.83 oC for GPMF at all three temperatures and its increases shelf-life up to 60 days **(Sharma *et al.,* 2018)**.

Hydrolytic and oxidative rancidity are the main cause of pearl millet quality deterioration during storage. Pearl millet grains was soaked in water and treated with high pressure (HP) at 100-400 MPa, for 0-10 min. The effect of HP treatment on moisture content, fat acidity value during 3 months storage at room temperature, was evaluated and compared with soaked (0.1 MPa) pearl millet grains and untreated pearl millet grains. After storage, moisture content of HP treated grains were significantly higher than the untreated but lower than the soaked, apart from the grains treated at 400 MPa – 0 min, which was the lowest in moisture content. HP treatment at 400 MPa enhanced the fat acidity immediately after the treatment, while samples treated at 200 MPa – 0 min showed lower level of hydrolytic rancidity during storage **(Wang *et al.,* 2018)**.

Applications:

- ✓ Pasteurization and sterilization of fruits and fruit products, sauces, pickles, yoghurt, meat and vegetables.
- ✓ Sterilization of heat sensitive ingredients like shellfish, flavourings, and vitamins.





Advantages and disadvantages of High-pressure processing:

Advantages	**Disadvantages**
1.High pressure is not dependent of size and shape of the food.	1. High capital cost of equipment.
2. HPP retains food quality, maintains natural freshness, and extends microbiological shelf life.	2. Food enzymes and bacterial spores are very resistant to pressure and require very high pressure for their inactivation.
3. HPP results in foods with better taste, appearance, texture and nutrition.	3. The residual enzyme activity and dissolved oxygen results in enzymatic and oxidative degradation of certain food components.
4. It can be applied at room temperature thus reducing the amount of thermal energy needed for food products during conventional processing.	4. Most of the pressure-processed foods need low temperature storage and distribution to retain their sensory and nutritional qualities.
5. High pressure processing is isostatic (uniform throughout the food); the food is preserved evenly throughout, without any particles escaping the treatment.	5. Industrial-grade HPP equipment can range from ₹50 lakh to ₹5 crore.
6. The process is environment friendly since, it requires only electric energy and there are no waste products.	

(c) Pulsed light processing:

Pulsed light or High Intensity Light is a recent innovative method of non-thermal processing where short-duration penetrating pulses (1 μs - 0.1 s) of intense broad-spectra electromagnetic radiation (200–1100 nm) are repetitively and quickly discharged on to the food surface. A PL system comprises a power supply, a treatment chamber, and a xenon lamp. The electrical energy accrued in the power supply is supplied to the lamp filled with xenon gas, generating an intense light with a wavelength range of 200–1100 nm **(Hwang *et al.*, 2018)**.

PL is known to interact with various food constituents thus causing modifications in the storage stability and quality attributes of the food. Contains a broad spectrum of 'white' light, from UV wavelengths of 200 nm to NIR wavelengths of 1000 nm. Peak emissions between 400-500 nm. Emit 1-20 flashes per second of electromagnetic energy. The antimicrobial effects of UV wavelengths are due to absorption of the energy by highly conjugated double carbon bonds in proteins and nucleic acids. Which attributed to structural changes in the DNA, as well as abnormal ion flow, increased cell membrane permeability and depolarization of the cell membrane. decontamination or sterilization technology **(Jeon *et al.* 2018)**.

The effectiveness of PL is affected by factors such as applied voltage, flashes, treatment time, sample-to-light source distance, the spectral range of flashes, sample characteristics, microbial activity, and degree of contamination. Fluence is the most crucial element in defining a PL treatment. Decontamination of surfaces, microbiological inactivation, and enzymatic inactivation have all been achieved using PL treatment. PL can be successfully applied for improving the storage stability of pearl millet flour as it can induce desired modifications to the factors that instigate lipid oxidation and rancidity **(Sruthi *et al.,* 2021)**.

The photothermal and photochemical effects of PL are evidenced to be the plausible mechanism that results in lipase inactivation in food products and pulse fluence is a dominant factor. Deactivation can also be from the site-sensitive fragmentation of lipase because of changes in its tertiary structure than the secondary structure. Similar mechanisms can be explained for LOX deactivation as well. Thus, PL can be successfully applied for improving the storage stability of pearl millet flour as it can induce desired modifications to the factors that instigate lipid oxidation and rancidity. There still exists an anomaly in the mechanism of microbial inactivation by PL and it is usually consented that PL stimulates pyrimidine dimers, cross-linking of strands, and other sorts of DNA lesions. The emitted ultraviolet radiation gets absorbed by the microbial DNA which is trailed by the formation of cross-linked pyrimidine nucleoside bases, initiating a mutation in the DNA **(Joshi *et al.,* 2023)**.

Thus, the technique is contemplated to be the DNA damage in the microorganisms and the subsequent destruction of cellular structure in consequence of the absorption of energy by intensely conjugated double bonded carbons in nucleic acid and proteins of microorganisms. An energy level of at least 35 J/cm2 is sufficient for microbial inactivation, however, exposure time, applied voltage, microorganism species, and properties of the food matrix add to the treatment efficiency. The performance of PL for disinfecting various types of food has been investigated by many studies, with microbial inactivation being specifically applicable in transparent liquid foods **(Jasmeen *et al.,* 2023)**.

It was evaluated the bactericidal effect of pulsed light treatment on glutinous millet and found that at a total fluence of 54.43 J/cm2, 0.66 log/g reduction in microbial load. It is to be mentioned that the site of microorganisms conferring to the surface characteristics of food stimulates the bactericidal effects, and a rough surface can shield the microorganisms from the radiation. Also, the design of the treatment compartment and initial bacterial populations showed an evident imperative consequence on the bactericidal effect for granular foods. Explicitly, samples with a high initial load of microbes exhibited elevated bactericidal effects since more microorganisms were exposed to PL **(Sruthi *et al.,* 2021)**.

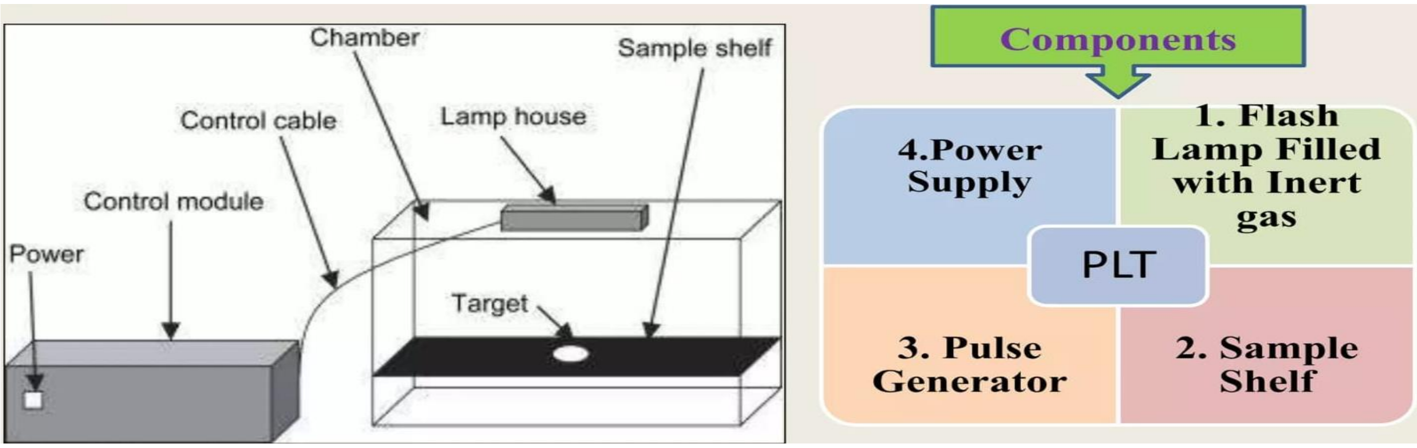
PL is reported to result in minimal changes in the functional and nutritional properties of the pearl millet. where insignificant changes in the water activity, moisture content, and color properties were observed in PL treated millet samples. Several experiments performed over the past years revealed that PL processing showed high effectiveness for transparent liquid foods whereas they failed to penetrate opaque liquid foods. This hindrance to the radiation can drastically reduce the bactericidal effect **(Jeon *et al.* 2018)**.

This study demonstrated the bactericidal effect of two types of pilot-scale intense pulsed light (IPL) Devices. Pearl millet grains with initial microbial loads of 2.04×104 and 5.03×103 CFU/g, respectively, were treated by cyclone-type and belt-type IPL devices at total fluences of 3.89–54.43 J/cm2. The maximum microbial reductions of the pearl millet were 0.74, and 0.66 log/g, respectively, when using the cyclone-type IPL, and 2.63 and 0.55 log/g when using the belt-type IPL device. The pearl millet has a greater bactericidal effect and increased shelf-life 45 days when treated with the belt-type device. Therefore, the design of the treatment chamber can have an improved bactericidal effect on pearl millet grains, demonstrating the importance of selecting a suitable IPL device according to the size of the sample to be treated **(Hwang *et al.*, 2018)**.

Effect of Intense pulsed light (IPL) irradiation on pearl millet lipase. During IPL irradiation, lipase activity decreased significantly with increasing exposure time. From the results found that IPL-induced deactivation was caused by fragmentation, leading to lipase tertiary structural changes. Furthermore, it indicated that the internal sensitive bonds of lipase were cleaved preferentially by IPL and increased its shelf-life up to 45 days is seen in pearl millet **(Jeon *et al.*, 2019)**.

Applications:

- ✓ Used in decontamination of vegetables, dairy products, baked products, fresh fruit, meats, seafood and vegetables.
- ✓ Microbial inactivation of water, and sanitation of packaging materials and disinfection of equipment surfaces.



Advantages and disadvantages of Pulsed Light Technology:

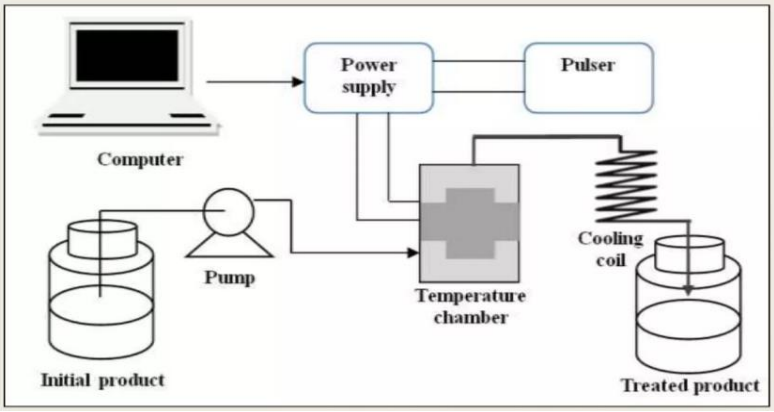
Advantages	**Disadvantages**
1.Effective against vegetative cells, spores and enzymes.	1. Complex mode of action.
2. Reduction of process times and temperatures.	2. Depth of penetration affected by solids and air in product.
3. Little adaptation required of existing processing plant.	3. Possible damage by free radicals.
4. Heat transfer increased.	4. Sometimes need to be used in combination with another process (e.g. heating).
5. Possible modification of food structure and texture.	5. Potential problems with scaling- up plant.
6. Batch or continuous operation	6. Only surface effects and difficult to use with complex surfaces
7. Medium cost	7. Not proven effective against spores

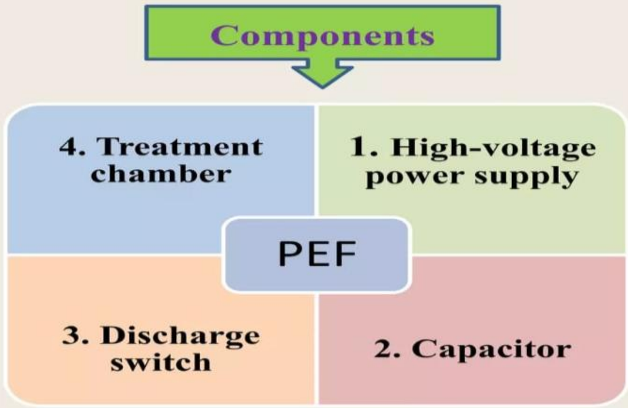
8. Very rapid process	8. Possible resistance in some microorganisms
9. Little or no changes to food	9. Reliability of equipment to be established
10. Low energy input	10. Lower penetration depth
11. Mostly suitable for dry foods	11. Industrial-grade pulsed light technology equipment can range from ₹5 lakh to ₹50 lakh.

(d) Pulsed electric field:

Pulsed electric field (PEF) technology uses a short burst of electric field pulses of high intensity in the range of 10–80 kV/cm over the food material for a couple of microseconds, which is kept in between the two electrodes. This technology inactivates the enzymes and the pathogens, and thus results in an increment of shelf life while retaining nutritional and organoleptic properties. PEF could be employed to enhance the hydration characteristics and extraction bioactive constituents and oils from grains **(Umesh *et al.*, 2016)**.

It is also called as High Intensity Pulsed Electric Field. Mainly used to inactivate the deteriorative microorganisms Pulses of high voltage (20-80 kV/cm) passed over the product placed between a pair of electrodes for an extremely short period of time (1-100 µs). Resistance heating, electrolysis and disruption of cell membranes (electroporation) can occur contributing to the inactivation of microorganisms. The gap between two electrodes is called as the treatment gap **(Almeida *et al.*, 2022)**.





PEF could be employed to enhance the hydration characteristics and extraction bioactive constituents and oils from grains. The fermented pearl millet flour with PEF at different treatment durations, electric field intensities and flour-to-water ratio. The research revealed that treating the flour for 875 µs at an electric field intensity of 2 kV/cm and flour–water ratio of 45 % (w/v) resulted in total phenolic content of 24.8 % and antioxidant activity of 33.9 %, which was higher than the control sorghum flour sample. The electroporation increased the porosity of cellular membrane of the samples. Starch granule disruption was higher in the PEF-treated sample than in the control sample. As a result, the surface area of granules increased, resulting in the release of more phenolic compounds that were bound to the protein–carbohydrate matrix **(Joshi *et al.*, 2023)**.

The study reported that the application of pulsed electric field (PEF) and effects of drying temperature on the thermal properties of pearl millet grains. The grains underwent extraction process using 0.5% of sodium metabisulfite, the pastes were pretreated with application of PEF (10 and 30 kV/cm) and the pulse frequency was 600 Hz. 6 µs wide, and 90-s residence time. The pretreated pastes were subjected to temperatures of 40, 50, and 60°C with an air velocity of 1.0 m/s. PEF showed maximum reduction in the time process of 180 min (46.15%) for the PEF 30KV/cm at a temperature of 60°C. The different intensities of PEF resulted in greater moisture transport presenting a uniform drying process. Therefore, PEF can reduce the costs of the drying and gelatinization and increases shelf-life up to 2 months **(Almeida *et al.,* 2022)**.

The study reported that Mild intensity pulsed electric field (PEF) was studied on pearl millet flour. The pearl millet flour naturally fermented at optimized conditions, were treated at the different flour to water ratio (FWR) of 10, 27.5, 45% (w/v) and 5, 8.75, 12.5% (w/v). In addition, three levels of PEF electric field intensity (EFI) as 1, 2 and 3 kV/cm were used to treat the pearl millet flour for the treatment time of 500, 875 and 1250 µs. The treated samples were analyzed for the total phenolic content (TPC), antioxidant activity (AA) and phenolic characterization. For pearl millet flour optimized conditions were determined as 45% (w/v) FWR, 2 kV/cm EFI and 875 µs treatment time. TPC and AA of pearl millet flour were 24.8% and 33.9%, respectively and it also increased shelf-life for 40 days **(Umesh *et al.,* 2016)**.

Applications: Used for preservation of pumpable fluid or semi-fluid foods.

- ✓ Pasteurisation of fruit juices, soups, liquid egg and milk, thawing, decontamination of heat sensitive foods.

Advantages and disadvantages of Pulsed Electric Field:

Advantages	**Disadvantages**
1.Kills vegetative bacteria (and spores at higher temperatures)	1. Little effect on food enzyme activity
2. No evidence of toxicity	2. Some microbial survival
3. Preserve nutritional quality of food	3. Expensive equipment
4. Reduced processing times	4. Foods should have approx. 40% free water for anti-microbial effect
5. Uniformity of treatment throughout food	5. Batch processing
6. Desirable texture changes possible	6. Limited packaging options
7. In-package processing possible	7. Only effective in combination with heat
8. Potential for reduction or elimination of chemical preservatives	8. Industrial-grade PEF equipment can range from ₹10 lakh to ₹1 crore.
9. Positive consumer appeal	

(e) Ultrasound processing:

Ultrasonication is one of the emerging technologies with extensive potential in the food industry that was developed to processing, maximize quality, and safeguard the safety of food products. Ultrasound generates high-energy sound waves (20–100 kHz) with energies greater than 1 W/cm2 that are conducted through food improving the mass transfer rates, extraction efficiencies, and functional properties of different nutrients. It is also called as Ultrasonication. Sound is vibration that transmitted in a medium (air), and can hear by human ear. The frequency of sound waves audible to human ear ranges from 20Hz to 20 kHz. Frequencies <20 Hz are "Infrasounds" and Frequencies >20 kHz are "Ultrasounds" **(Vidhyalakshmi *et al.,* 2023).**

When ultrasound waves meet a medium, it creates regions of alternating compression and expansion. These compression and expansion cause cavitations i.e. formation of bubbles in the medium. These bubbles are larger in size during the expansion cycle, which increases gas diffusion, causing the bubble to expand. When the ultrasonic energy is insufficient to retain the vapour phase in the bubbles then rapid condensation occurs. The condensed molecules collide and create shock waves which create regions of high temperature and pressure **(Balasubramaniam *et al.,* (2019)**.

The transmission of high-energy waves through the food medium results in a series of rarefaction and compression cycles that disturb the molecules present within the liquid causing such modifications in the food matrix. The process by which energy gets transferred to samples is termed acoustic cavitation, where generation, growth, and rapid collapse of gas bubbles occur. The cavitation process initiates micro-streaming, enhancing the transfer of heat and mass, and the collapse of cavitation bubbles is rapid and rigorous leading to drastic changes in pressures (>1000 atm) and temperatures (up to 500 ◦C) in the encircling region. This phenomenon leads to the disintegration of cell membranes, inactivation of enzymes, formation of micro-channels, and generation of free radicals. The potential mechanisms that prevent pearl millet flour deterioration can be described by the increased antioxidant activity of the pearl millet flour, improved functional and nutritional attributes, and ultrasound-induced enzyme denaturation **(Jasmeen *et al.,* 2023)**.

Types of Ultrasounds:

1. Low energy ultrasounds:

- Frequencies 100 kHz, low power and low- intensity (<1 W/cm²).
- Non-destructive, Provide information such as physicochemical properties of food.

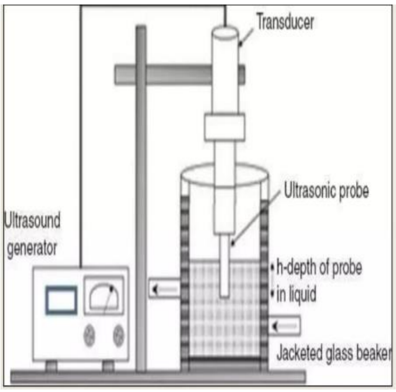
2. High energy ultrasounds:

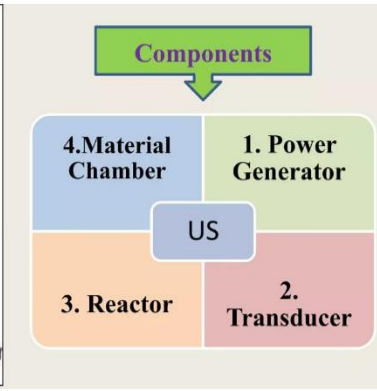
- Frequencies 18-100 kHz, high power, high- intensity (1 W/cm²).
- Used for physical disruption and acceleration of chemical reactions.

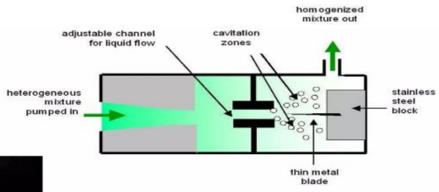
US treatment on pearl millet grains increases the capacity for water absorption and speeds up the binding of water molecules to the amylose and amylopectin chains. The decline in the stability of the starch and swelling power was due to the increased damage to the crystalline and amorphous areas of the starch structure. The yield of polyphenols is positively correlated with US power. The release of phenolic compounds is facilitated by the collision of molecules as US power increases. Similar increases in yield (about 30%) were reported when power increased from 250 to 500 W under optimal circumstances in samples of US-treated pearl millet **(Joshi *et al.*, 2023)**.

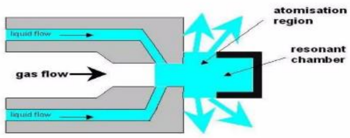
Yadav *et al.* (2012a) reported a decreasing trend in the TPC values of the pearl millet grains as US amplitude and time increased. Higher amplitude and time increase the cavitation in cellular structure. This results in increased solvent penetration, which could have been attributed to the reduction in phenolic components. The US assists in converting hydrolysable tannic acid to gallic acid, lowering the total tannin level in the sample. Additionally, it also causes the leaching out of condensed tannin. Furthermore, ultrasound treatment has been shown to significantly reduce the amount of phytate in finger millet. The sample produces heat at higher US amplitudes, raising the temperature of the sample. The mechanism of the reduction of phytates is the heat-induced chemical breakdown of phytate into inositol phosphate.

The effect of ultrasonication on pearl millet flour were evaluated for thermal, pasting, crystalline, and in-vitro starch digestibility properties. It was indicated that ultrasonication for 10 and 20 mins increased gelatinization enthalpy and peak viscosity and ultrasonication for 20 mins increased resistant starch content (14.49–31.69%) and decreased glycaemic index (58.25–48.49) and increases shelf-life up to 3 months. It can be used to modify the starch properties to enhance resistant starch content and storage for 45 days in pearl millet flours. This modified flour could be incorporated in food products with low glycaemic index **(Vidhyalakshmi *et al.*, 2023)**.









Two eco-friendly methods namely ultrasonication (UA) and enzyme treatment followed by ultrasonication (EUA) were compared with the conventional heat reflux method (HR). The polyphenolic profile and content along with the antioxidant potential of the extract were evaluated. Phenolic yield increased 2.3fold using EUA with xylanase (XUA) compared to heat reflux extraction (HR). However, yield with UA was equivalent to the conventional method. Total flavonoids increased 1.4fold in UA and 1.3fold in XUA, similarly, tannins also showed a significant increase (1.1fold in UA and 1.2fold in XUA). It is reported on enhanced extraction of polyphenols from pearl millet using a combination of enzyme treatment and ultrasonication, providing a green technology for utilization of polyphenols in nutraceuticals and functional foods and for shelf-life enhancement up to 2 months **(Balasubramaniam *et al.*, (2019)**.

Applications: Crystallization, foams destruction, tenderization of meat, extraction, degassing, filtration, drying, freezing, mixing, homogenization, effluent treatment, growth modification of living cells, alteration of enzyme activity, sterilization of equipments.

Advantages and disadvantages of Ultrasound processing:

Advantages	**Disadvantages**
1.Minimizing of flavor loss	1. Ultrasound application needs more input of energy which makes industrialists to think over while using this technique on commercial scale.
2. Non-destructive and non-invasive	2. Ultrasound induces physicochemical effects which may be responsible for quality impairment of food products by development of off-flavors, alterations in physical properties and, degradation of components.
3. Greater homogeneity	3. Ultrasonic power is responsible for change in materials based on characteristics of medium. So, this power needs to be minimized in food industry to achieve maximum results.
4. Significant energy savings	4. Increased free radical formation.
5. The reduction of pathogens at lower temperatures	5. Effect on color & antioxidants has been reported in some sonicated samples due to degradation of pigments (anthocyanin, ascorbic acid. lycopene & carotenoid) at high energy levels.
6. Higher product yields	6. However, during emulsification and processing of vegetable oils, a metallic and rancid odor has been detected only for insonated oil and foods.
7. Reduced operating and maintenance costs	7. Formation of undesirable biochemical and nutritional changes.
8. Shorter processing times	8. Industrial-grade ultrasound processing equipment can range from ₹5 lakh to ₹50 lakh.

(f) Cold plasma treatment:

Cold plasma (CP) is a relatively novel technology emerged as an alternative source for surface sterilization and disinfection, for ensuring the quality and safety of minimally processed food and the novelty lies with its non-thermal, economical, versatile, and environmentally friendly nature. The term ‘plasma’ refers to a quasi-neutral ionized gas, primarily composed of electrons, ions and reactive neutral species in their fundamental or excited states. Cold plasma is generated at 30-60 °C under atmospheric or reduced pressure (vacuum), requires less power, exhibits electron temperatures much higher than the corresponding gas (macroscopic temperature), and does not present a local thermodynamic equilibrium **(Tavakoli *et al.,* 2022)**.

The cold plasma technique was originally applied to enhance the antimicrobial activity in surface engineering, bio-medical field and polymer industries. Plasma: ionized gas containing reactive oxygen species (0, 0, 0, & OH), reactive nitrogen species (NO, NO, & NO, J, UV, free radicals, and charged particles. Plasma is generated when electrical energy is applied to a gas present between two electrodes. CP: ionized gas is formed by relatively low energy (1-10 eV) and gases used in food applications are argon (Ar), helium (He) and air Electrode material are steel, aluminum, brass, iron, and copper **(Lokeswari *et al.,* 2021).**

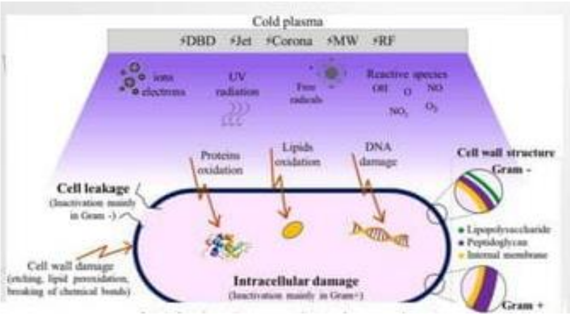
Pearl millet grains treated with cold plasma technology at 180 V with a 0.01 m3/h airflow rate. The study concluded that the phytic acid content was reduced by 60.66 and 39.27% when the treatment was operated on for 1 and 2 h, respectively. They also investigated the phytic acid reduction by a combination of cold plasma treatment with conventional soaking and found that 21.6% of phytic acid was reduced compared to the control sample. It was reported that the crystallinity of the pearl millet flour reduces due to the depolymerization of starch during the cold plasma treatment. They also showed that the treatment breaks down the microstructure of the starch granules of the flour. The treatment increased the WAC, OAC, swelling capacity, and solubility index of the flour, while dispersibility and viscosity decreased. The presence of non-polar amino acids and other protein structures can be the source of the increase in oil retention capacity, while the damage to the starch granules following plasma treatment can be the cause of the increase in WAC **(Sruthi *et al.,* 2021)**.

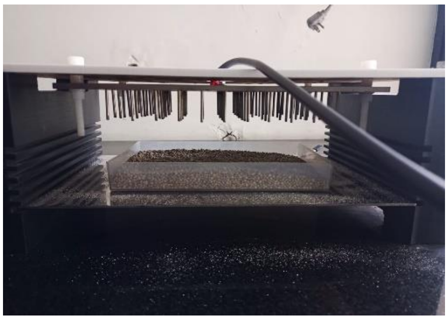
The impacts of ultra-high pressure coupled with CP treatment on physical, chemical, and digestive qualities are investigated in another research on pearl millet grains. Due to non-penetrative damage caused by plasma etching, slight changes were reported on the starch granule surface. The fluorescence intensity of the treated samples weakened with the increase in CP treatment time. This indicates that CP treatment increased the mobility of double helices and caused a loss of radial orientation, which has resulted in poor birefringence. They also observed a lower relative crystallinity in CP-treated samples than in native samples. This might be attributed to the depolymerization of starch molecules by reactive oxygen species **(Joshi *et al.,* 2023).**

The cold plasma treatment on pearl millet (*Pennisetum glaucum*) with an input voltage of 40 and 45 kV for 5, 10, and 15-min exposure time was studied. The influence of cold plasma on the physical, nutritional, hydration, and pasting properties of pearl millet was assessed. There was no significant difference in loose and tapped bulk density, whereas the color intensity has significantly differed with the treatment. The nutritional properties, such as crude fat (3.46% to 4.71%) was increased, whereas crude fiber, protein, and moisture had significantly diminished. The results of hydration properties, such as swelling capacity, solubility and water absorption have shown significant increment with treatment time and voltage. Besides, the pasting properties of the treated millet were significantly improved and shelf-life increased up to 60 days **(Lokeswari *et al.,* (2021)**.

Effect of nonthermal cold plasma Gas type (air and oxygen), voltage (22 and 25 volts), and time (0, 2, 4, 6, 8, and 10 min). The results show that with increasing voltage and time of plasma treatment, the pH decreased significantly and brightness parameter, yellow–blue parameter, water-solubility, water absorption, oil absorption, and swelling power increased significantly, the duration of plasma treatment, voltage, and change in input gas from air to oxygen did not significantly change the particle size, and noticed that increased shelf-life up to 60 days **(Tavakoli *et al.,* 2022)**.

Applications: In food industry particularly, current cold plasma research are focused on its applications for food decontamination, enzyme inactivation, toxin degradation, waste water treatment and packaging modifications. Specifically for food processing, cold plasma has proven to be effective for inactivation of food-borne pathogens and spoilage microorganisms. Recently the different inactivation mechanisms for Gram positive and Gram-negative bacteria by cold plasma has been reported.





Advantages and disadvantages of Cold plasma treatment:

Advantages	Disadvantages
1.This technique is applicable for both solid as well as liquid food products.	1. Plasma technique is not suitable for high fat products
2. This method reduces the use of preservatives.	2. Cost of the plasma processing is large.
3. It does not require water or other chemical solvent, thus it is also considered environmentally friendly.	3. Cold plasma is not used for inactivation of endogenous enzymes which are present intact in the whole grains because plasma effect is a surface phenomenon.
4. Cold plasma does not leave any residue.	4. Industrial-grade cold plasma treatment equipment can range from ₹10 lakh to ₹1 crore.
5. It doesn't affect nutrients and vitamins within the food.	
6. This process operates at ambient temperature (ideal for thermo labile products)	
7. It is a novel, ultra-fast sterilization /preservation process (sterilization takes place in few minutes).	
8. It is possible to inactivate all types of pathogens.	
9. Low running cost (cost of natural gas and electricity).	
10. It has minimal heat affected zone.	
11. It's welding speed is high	

(g) Ozone processing:

Ozone is a powerful oxidant with numerous applications in food processing. Ozone treatment is an eco-friendly and economical method of food processing. Ozone is generated when free oxygen radicals interact with diatomic oxygen to form triatomic oxygen molecule. The free oxygen radical is generated by breaking O–O bonds, which demands a significant amount of energy. Ozone (03) is a powerful gas molecule consists of three oxygen atoms. Formed by dissociating oxygen molecule. Ozone has extremely great oxidative power and very ready to react to germs, viruses, and a host of microbes **(Yan *et al.*, 2012)**.

Ozone is an unstable molecule that rapidly decays to Oxygen (02), releasing a single oxygen atom which is extremely reactive. This atom reacts with the cell membrane of the bacteria or virus, attacking the cellular components and interrupting the normal cell activity, which rapidly destroys those microorganisms. If the ozone is brought into contact with the volatile substance, the free oxygen atom reacts with them, removing characteristic odors of these compounds. In numerous food items, the use of ozone, either gaseous or liquid, has been used to inactivate pathogens and spoilage germs. Ozone treatment can efficiently remove pests and mycotoxins from food products. The main advantage of the treatment is that it does not leave any residue in the food product. The main advantage of the treatment is that it does not leave any residue in the food product **(Marston *et al.*, 2014)**.

HOW OZONE IS PRODUCED?

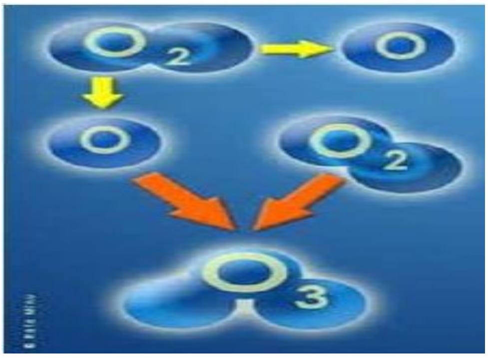
There are two methods of producing ozone. They are;

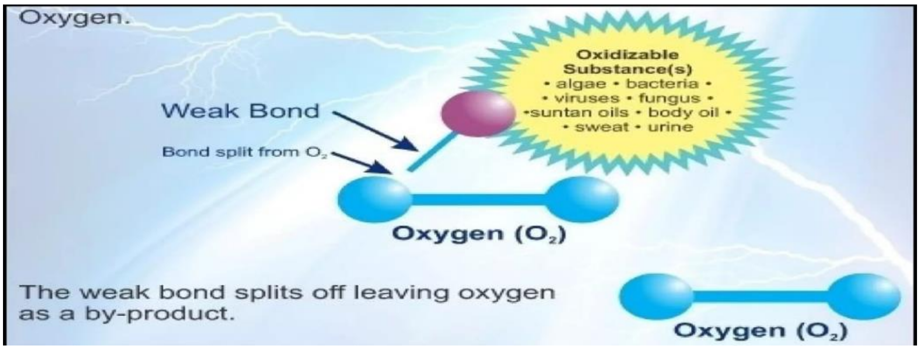
1) Ultra-violet method:

- Ultra-violet light creates ozone when a wavelength > 254nm hits an oxygen atom.

2) Corona discharge method:

- Corona discharge creates ozone by applying high voltage to a metallic grid sandwiched between two dielectrics.
- Splitting of oxygen molecules into single oxygen atom & combine with another oxygen molecule (02) to form ozone (03).





This study demonstrated that pearl millet flour was subjected to ozone at the rate of 0.06 L/min for 15, 30, and 45 min. The pH of ozone-treated flour decreased as exposure time increased. The L* (lightness) values of Pearl millet flour significantly increased, while the b* (yellowness) values significantly decreased as ozone exposure time increased. Peak viscosity significantly increased as time of ozonation increased from 0 to 45 min. Additionally, longer ozonation exposure times increased cells per slice area, lightness, and slice brightness values pearl millet cakes while reducing crumb firmness. While ozonation improved the volume and texture in cakes and bread made from ozonated pearl millet flour. In both applications, the increased brightness and lightness values due to ozone exposure is recommended to acceptability of pearl millet products by enhancement of shelf life up to 2 months **(Marston *et al.*, 2014)**.

Effect of ozone treatment may also inactivate tannin activity and increase fermentation efficiency in grains. The physicochemical properties of ozone-treated whole tannin grain and its fermentation. The fermentation efficiency of ozone-treated tannin grain pearl millet was approximately 90%, which was 8–14% higher than that of untreated samples at the 36th hr of fermentation. At the end of 72 hr of fermentation, the efficiencies of ozone-treated pearl millet flour were 2–5% higher than those of untreated samples. Measured tannin levels of ozone-treated samples decreased significantly from 3.8 to 2.7% and enhancement of shelf-life 50 days **(Yan *et al.*, 2012)**.

Advantages and disadvantages of Ozone processing:

Advantages	**Disadvantages**
1.Ozone oxidation is nature friendly process.	1. Installation of ozone technology unit is complicated.
2. Highly effective in cold water, which saves energy & cost.	2. May produce undesirable aldehydes and ketones by reacting with certain organics.
3. Significant reduction in processing time.	3. Less soluble in water than chlorine; thus, special mixing devices are necessary.
4. Effective against wide range of harmful microorganisms.	4. In light, it may degrade the material.
5. Dissolves metallic substances like iron and manganese.	5. The initial investment is more as compared to other chemicals.
6. Removes unwanted color, taste, and odor of product.	6. Industrial-grade ozone processing equipment can range from ₹1 lakh to ₹50 lakh.

CURRENT STATUS OF UTILIZATION OF NOVEL TECHNOLOGIES FOR PEARL MILLET STORAGE:

The current status of utilizing novel technologies for pearl millet storage offers promising avenues for improving food security, reducing post-harvest losses, and enhancing the overall value chain of pearl millet production **(Kadlag *et al.*, 2012)**.

Trends in the emergence of novel non-thermal processing technology with improved quality and safety resulted in innovations in processing techniques. Research and development in response to consumer preferences gave rise to: Microwave processing, Infrared heating, Radiofrequency processing, Ohmic heating, Gamma irradiation, High-pressure processing, Pulsed light processing, Pulsed electric field, Ultrasound processing, Cold plasma treatment, Ozone processing etc. food processing techniques that are purely innovative **(Ranjeet *et al.*, 2021)**.

These innovative processing technologies contributed toward the enhancement of food quality, safety, feasibility, and bioactivity of functional components. Applicability of novel and innovative processing techniques is growing widely because of their health impact and thus resulted in reduced consumer complaints. In future traditional thermal processing will be completely replaced by innovative food processing techniques as these techniques are rapidly making their way into the global market **(Dahiya *et al.*, 2018)**.

In summary, the outlook for utilizing novel technologies in pearl millet storage is promising, with opportunities for innovation, collaboration, and sustainable development. By leveraging emerging technologies and adopting a holistic approach to storage management, stakeholders can enhance food security, reduce post-harvest losses, and improve the livelihoods of smallholder farmers in pearl millet-producing regions **(Adewale *et al.*, 2017)**.

CONCLUSION:

Novel technologies have shown the potential in achieving industrial application in pearl millet storage. Nonthermal processing has minimal effects on the colour, aroma, taste and nutritional value of pearl millet-based products. Combinations of technologies can be designed to enhance safety and quality, and minimize food loss.

Novel technologies for pearl millet storage offer promising solutions to mitigate post-harvest losses and ensure food security. Innovations such as hermetic storage, moisture control systems, and improved packaging materials can significantly prolong shelf life, preserve nutritional quality, and reduce susceptibility to pests and fungal contamination. By implementing these advancements, farmers and stakeholders can enhance the efficiency and sustainability of pearl millet storage practices, ultimately contributing to the resilience of food supply chains and the livelihoods of communities dependent on this essential crop.

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