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Review

Nutritional benefits, post-harvest challenges, and innovative preservation strategies of onions (*Allium cepa* L.): A comprehensive review

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Abstract Onions (*Allium cepa* L.), one of the most widely grown and consumed vegetables worldwide, are prized for their distinct flavor, health advantages, and active ingredients. The significance of onions in the Allium family and their use in various cuisines are examined in detail in this review. Along with potential drawbacks, it also discusses the benefits found in onions, such as essential vitamins, minerals, and antioxidants. The difficulties of cultivating onions and managing them after harvest are covered in the review, with particular attention paid to spoiling, microbes, and the negative social and economic impacts of onion waste. It also looks at contemporary processing techniques that assist cut waste and increase the shelf life of onions, such as drying, freezing, and producing value-added products. A variety of preservation procedures, ranging from more recent ones like cold plasma treatment and nanotechnology to more conventional ones like pickling and drying, are also examined. Lastly, the study examines both traditional and modern onion storage techniques. To increase onion output, decrease waste, and create a more sustainable global supply chain, it emphasizes the necessity of integrating old and new technologies.

Keywords onion, innovative technology, spoilage, preservation, packaging

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1. Introduction

1.1. Global significance of onions (Allium cepa L.)

In the *Alliaceae* family, onions (*Allium cepa* L.) are the most cultivated species. The *Allium* genus comprises over 700 plant species, many of which possess underground rhizomes or bulbs. These plants are native to North Africa, Europe, Asia, and North America which is shown in Fig 1. However, Fig. 2 reveals their consumption by countries. Among the primary species in this family, *Allium sativum* (garlic) and *Allium cepa* (onion) are particularly well known for their strong flavors and their tendency to induce tears when chopped (Borborah et al., 2014). With more than 800 species, the *Allium* genus is one of the largest families of monocot plants (Huo et al., 2019). Onions are annual plants that produce small white or purple flowers and develop a fleshy bulb underground. As they grow, their green cylindrical leaves thicken at the base to form the bulb, while their short, hollow, thickened stem can reach up to one meter in height (Ashwini and Sathishkumar, 2014). This review aims to explore the global significance of onions, with a focus on innovations to minimize losses and improve quality. It examines their nutritional value, health benefits, cultivation challenges, post-harvest issues, processing methods, preservation techniques, and packaging solutions.

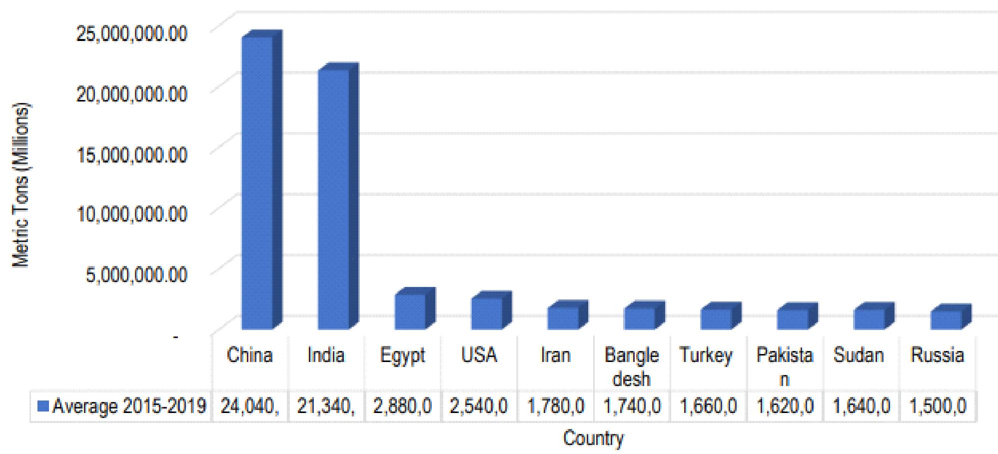

Fig. 1. Top 10 onions producing countries in the world (FAOSTAT, 2021). Data from Namibian Agronomy Board (2021).

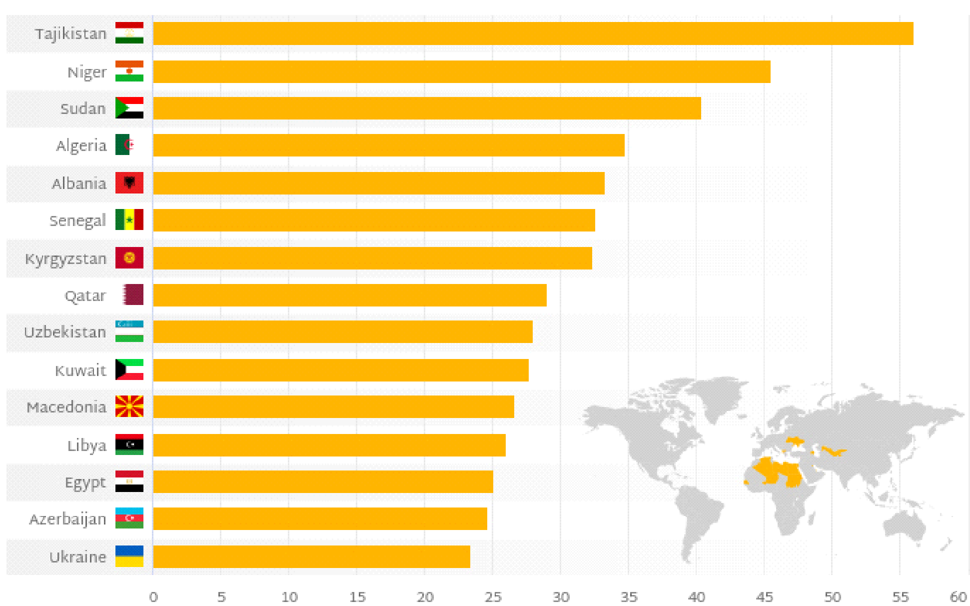

Fig. 2. Onions consumption by country. Data from FAOSTAT (2021).

1.2. Global onions production and consumption trends

Global onion production has increased by over 25% in the past decade, reaching 93.2 million tons annually (FAOSTAT, 2021). As the second most important horticultural crop, onions are widely traded due to their long shelf life and resilience in transport. In 2020, China led production with 23.9 million tons, followed by India at 21.4 million tons (FAOSTAT, 2021). Other major producers include Iran, the United States, and Egypt. Despite challenges, the Netherlands recorded an 11% growth in production (Hanci, 2018). Onion is actively expanding its market, particularly in Africa. Onion consumption is also rising globally, with Tajikistan consuming 62.5 kg per person in 2018 (FAOSTAT, 2021). The global average consumption has increased by 13.5% over the last decade, driven by the growing use of dried onions in cooking. Onions, cultivated for over 5,000 years, originated in Central Asia and continue to contribute to global food security and economic growth (Pareek et al., 2017).

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2. Nutritional and health benefits of onions

Onions (*Allium cepa*) are not only valued for their flavor but also for their significant nutritional and medicinal benefits. They are rich in essential nutrients such as water, carbohydrates, proteins, vitamins, minerals, flavonoids, sulphur compounds, and phenolics (Benmalek et al., 2013). The nutritional composition of onions varies depending on the type, growing conditions, and farming practices (Agnieszka et al., 2017). As shown in Tables 1 and 2, onions are low in calories (40 kcal per 100 g) but provide a range of beneficial nutrients, including 9.3 g of carbohydrates, 1.7 g of fiber, and essential minerals like potassium, calcium, magnesium, and phosphorus, which support metabolism and bone health (Benmalek et al., 2013; Marefati et al., 2021). Furthermore, onions contain significant amounts of vitamin C, which boosts immunity and promotes skin health (Nile and Park, 2014), as well as B vitamins (thiamine, pyridoxine, and folate) that contribute to overall well-being (Ashwini and Sathishkumar, 2014).

Onions' health benefits are largely attributed to their high antioxidant content, particularly flavonoids such as quercetin and anthocyanins. Quercetin, which accounts for approximately 80% of the flavanol content in onions, is a powerful antioxidant that helps reduce inflammation and oxidative stress by neutralizing free radicals (Fredotović et al., 2017). Other bioactive compounds, including terpenes, carotenoids, polyphenols, and sulphur compounds, further enhance onions' antioxidant properties (Bilal et al., 2016). These compounds contribute to various health benefits, including heart protection, cancer prevention, and inflammation reduction. For example, onion extracts rich in quercetin reduce oxidative stress in diabetic animal models (Jakaria et al., 2019), while polyphenols have been found to inhibit cancer cell proliferation (Tsuboki et al., 2016).

In addition to their antioxidant properties, onions possess antibacterial qualities, with studies indicating that onion fiber can combat harmful bacteria such as *E. coli* and *Staphylococcus*

Table 2. Nutritional composition of white onions and red onions

Nutrient	White onions	Red onions
Moisture (%)	89.62	88.48
Ash (%)	3.33	3.17
Crude protein (%)	3.22	3.02
Fat (%)	2.17	6.50
Crude fiber (%)	3.83	2.83
Carbohydrate (%)	87.44	84.48
Sodium (mg/100 g)	0.40	0.37
Calcium (mg/100 g)	1.36	1.32
Iron (mg/100 g)	0.09	0.12
Phosphorous (mg/100 g)	3.09	3.68
Potassium (mg/100 g)	14.29	16.02
Zinc (mg/100 g)	0.026	0.03
Manganese (mg/100 g)	0.01	0.01
Magnesium (mg/100 g)	0.86	0.97
Vitamin C (mg/100 g)	14.67	18.00

Data from Lawal and Matazu (2015).

Table 1. Major Nutrients in onions

Major nutrients	References
Water	Nile and Park (2014)
Protein	Ashwini and Sathishkumar (2014)
Carbohydrates	Nile and Park (2014)
Steroids	Benmalek et al. (2013)
Vitamins A, B, C, and E	Ashwini and Sathishkumar (2014); Benmalek et al. (2013)
Minerals (selenium, phosphorus, iron, chromium, calcium)	Ashwini and Sathishkumar (2014); Benmalek et al. (2013)
Fiber	Marefati et al. (2021)
Flavonoid (quercetin, apigenin, rutin, myricetin, kaempferol, catechin, resveratrol etc.)	Rodriguez et al. (2017)
Allicin	Nile and Park (2014)

Data from Benmalek et al. (2013).

aureus (Cheng et al., 2015). Onions also contain sulfur and quercetin compounds (shown in Fig. 3) that help regulate blood pressure (Karna et al., 2019), and their prebiotic fiber promotes the growth of beneficial gut bacteria, aiding digestion (Pareek et al., 2017; Rashid et al., 2021). Onion essential oil has also been found to exhibit anti-biofilm properties against *Listeria monocytogenes* (Somrani et al., 2020).

Onions have long been recognized for their potential cancer-fighting properties. Studies suggest that onions' sulfur compounds may have anticancer effects (Savitha et al., 2021), and a novel sulfur molecule, "Onionin A," has been identified as having potential anti-tumor properties (Bilal et al., 2016). Some other studies on the health benefits of bioactive ingredients in Onion are detailed in Table 3. Consuming onions may also help prevent tumor growth (Nicastro et al., 2015), and research by Shrivastava and Ganesh (2010) suggested that onions might be more beneficial than garlic in preventing cancer. Furthermore, the anti-inflammatory and anticancer effects of onions have been emphasized in recent studies (Jakaria et al., 2019; Savitha et al., 2021).

3. Challenges in onions cultivation

Despite the growing demand and health benefits, growing onions presents a few obstacles. Onion flies (*Delia antiqua*) and onion thrips (*Thrips tabaci*) are two pests that can seriously harm crops, lowering their production and quality. Serious risks include diseases like white rot and downy mildew, which reduce the amount and quality of onions (Mishra et al., 2014). Unpredictable weather, severe temperatures, and water shortages brought on by climate change exacerbate the situation and negatively impact onion quality and production (FAO, 2021). Sustainable agricultural practices that lessen dependency on pesticides, preserve soil health, and guarantee long-term onion production are crucial in addressing these

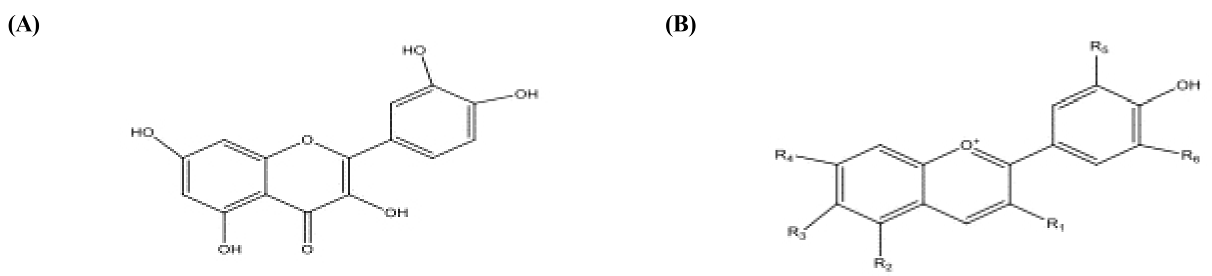

Fig. 3. **Structures of some antioxidant in onions quercetin (A) anthocyanin (B).**

Table 3. **Health benefits of bioactive ingredients in onions**

Health benefits of the bioactive ingredients	References
Preventing cardiovascular diseases	Lamson et al. (2000)
Antioxidant	Ashwin and Sathishkumar, (2014); Sidiq et al. (2013)
Anti-inflammatory	Dawud et al., (2016), Hanahan and Weinberg, (2000)
Immunomodulatory effects	Savitha et al. (2021)
Tumor promoting inflammation	Fuentes et al. (2020)
Reducing the risk of death from coronary heart disease	Arshad et al. (2017)
Against arteriosclerosis	Kleemann (2011)
Antimicrobial activity against fungal, bacterial and viral infections	Cheng et al. (2015)
Anticarcinogenic and antimutagenic activities	Shrivastava and Ganesh (2010)
Anti-hypertensive effect and reduce blood pressure	Karna et al. (2019)
Anti-hyperglycemic or anti-diabetic potential	Baragob et al. (2015)

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problems (Kumar et al., 2021).

3.1. Post-harvest handling and storage issues

Since onions are highly perishable, treating them after harvest poses significant difficulties that impact their quality, shelf life, and marketability. Food loss occurs at several phases, including after harvest, according to the Food and Agriculture Organization (FAO, 2011). Due to their high moisture content and vulnerability to microbial infection, onions are particularly vulnerable to spoilage during this period, which can result in financial losses, especially in developing nations. Among the things that make these difficulties worse are poor sorting, packaging, and storage. Physical damage, improper handling, microbiological contamination, deteriorating during harvest, transportation, and even environmental factors like temperature, humidity, and storage conditions can all reduce the market value and shelf life of onions (Mishra et al., 2014).

In addition to providing recommendations on how to avoid these problems and increase shelf life while maintaining quality during storage and distribution, this review examines onion spoilage, the bacteria involved, and how decay occurs.

3.1.1. Spoilage of onions

Onions spoil when they start to break down, which affects their safety, taste, texture, and appearance. This happens mainly due to bacteria or enzymes, causing bad smells, color changes, softness, and off flavors as shown in Table 4. Several factors contribute to spoilage, including physical damage, temperature changes, humidity, and the release of ethylene gas (Petropoulos et al., 2016). Storing onions above 18°C encourages bacteria growth, while storing them below 4°C can cause freezing damage, making them weaker and more vulnerable to pathogens (Palta et al., 1977). High humidity promotes mold and softness, while low humidity causes onions to dry out and lose flavor (Qiu et al., 2022). Physical damage speeds up spoilage, and improper storage can lead to sprouting (Shekhawat et al., 2022).

3.1.2. Spoilage micro-organisms of onions

Humidity plays a significant role in the spoiling of onions. High humidity promotes microbial growth, leading to mold formation and softening of the onions, while low humidity causes moisture loss, resulting in shriveling and flavor loss (Qiu et al., 2022). Physical damage, such as punctures or bruises, provides entry points for microbes, accelerating the spoilage process (Mishra et al., 2014). Improper storage can also lead to sprouting, as the production of ethylene triggers ripening, which causes loss of texture and the development of undesirable compounds, further diminishing the quality of the onions (Shekhawat et al., 2022).

Microorganisms such as *Erwinia carotovora* contribute to soft rot in onions by producing enzymes that break down cell walls, leading to mushy, discolored tissue and unpleasant odors (Doyle, 2007). Similarly, *Enterobacter* species, which thrive in high humidity and temperatures, can ferment onions, causing off-flavors and hastening decomposition (Salem et al., 2006). Fungal pathogens, including *Aspergillus* species, *Penicillium* species, and *Botrytis cinerea*, are also major contributors to onion rot (Gruber-Dorninger et al., 2017). *Aspergillus* species are responsible for mold rot and aflatoxin production, a carcinogenic mycotoxin (Alina, 2022). Furthermore, yeasts like *Saccharomyces cerevisiae* also contribute to spoilage by fermenting sugars and producing off-flavors under anaerobic conditions (Parapouli et al., 2020).

According to Orpin et al. (2017), various bacteria, including *Escherichia coli* and *Pseudomonas* species, as well as fungi like *Aspergillus*, are linked to onion rotting. Microbial growth is exacerbated by environmental factors such as temperature, humidity, and physical damage (Tang et al., 2015). Therefore,

Table 4. Microorganisms that affect onions

Micro-organisms	Action on Onion Spoilage	References
Aspergillus niger	Black discoloration of tissue near neck. Causing black mold rot	Srinivasan and Shanmugam (2006)
Pseudomonas aeruginosa	Causing soft rot on Onion. Pale yellow to light brown tissues. Water-soaked appearance	Sinha et al. (2018)
Penicillium expansum	Causing a blue mold, puncture and bruises	Nassarawa and Sulaiman (2019)
Botylis cinerea	Causing a gray mold and drying of bulb	Ji et al. (2018)
Fusarium oxysporum F. sp. *Cepae*	Causing a bacterial brown rot and a dark brown discoloration	Ji et al. (2018)

proper handling, storage, and cleanliness are essential to reduce contamination and extend onion shelf life (Ehuwa et al., 2020).

3.1.3. Spoilage mechanism of onions

Several biological, chemical, and environmental factors contribute to onion spoilage, reducing both quality and shelf life (Qiu et al., 2020). A primary cause of spoiling is enzymatic breakdown, where enzymes like cellulases and amylases degrade cellulose and starch in the cell walls, weakening the onion’s structure (Araji et al., 2014; de Souza and Kwaguti, 2021). This makes the onion softer, making it more vulnerable to microbial invasion and accelerating spoilage (Mishra et al., 2014). Another enzyme, polyphenol oxidase (PPO), is linked to enzymatic browning, which makes onions brown when exposed to air, diminishing their appearance and marketability (Zhang, 2023). Polyphenols contribute to both enzymatic and non-enzymatic browning, leading to undesirable tissue discoloration when the onion’s cellular structure is damaged (Singh et al., 2018).

Dehydration is another significant factor in spoilage. Onions shrink under low humidity, affecting their flavor and texture, and making them more prone to contamination and damage (Gorrepati et al., 2017). Improper storage conditions further decrease firmness and increase bruising risks (Tournas and Katsoudas, 2015). Additionally, gas exchange and respiration after harvesting deplete nutrients and accelerate aging, especially at high temperatures (Sun et al., 2023). The production of ethylene during storage causes sprouting and enzymatic alterations, further deteriorating onion quality (Julianti et al., 2013).

3.2. Solutions and future directions for onions post-harvest management

To address the post-harvest challenges in onion production, a diversified strategy is needed, incorporating better handling and storage practices, improved market accessibility, farmer education, and infrastructure development (Khandagale and Gawande, 2019). Research by Falola et al. (2022) identifies rot, pests, infections, improper storage, and poor transportation as major causes of post-harvest losses. Socioeconomic factors, including farmer income and market accessibility, also play a significant role, and addressing these issues is crucial for reducing losses (Affognon et al., 2015).

Focusing on key areas such as disease management, pest control, and climate change adaptation is essential to ensure the sustainability and availability of onions in the global market. Advancements in post-harvest management, such as improved transportation and storage technology, can significantly reduce spoilage and waste (Shee et al., 2019). By tackling these issues through coordinated efforts and innovations, the onion industry can become more sustainable, ensuring a steady supply of onions, increasing farmer incomes, and improving food security.

Onion processing technology offers an effective solution to post-harvest losses by converting excess onions into value-added products such as pickles, dried flakes, powder, paste, and oil (Soni et al., 2022). This not only extends the shelf life of onions but also preserves their nutrients, reducing waste and increasing food security (Gnanasundari et al., 2023).

4. Drying and freezing technologies in onion processing: Traditional methods, innovations, and applications

4.1. Drying technology of onions

Drying is an effective method for preserving onions, extending their shelf life, and preventing spoilage. It also enables the production of widely used food industry products such as onion powder, flakes, and other dehydrated ingredients (Kumari et al., 2021). According to Ao et al. (2024), increasing drying temperatures accelerates the process. Arslan and Ozcan (2010) note that dehydrated onions are commonly used to enhance the flavor of meats, soups, snacks, and sauces. Various drying techniques including vacuum drying, spray drying, sun drying, tray drying, and freeze-drying help maintain the quality of onions while ensuring longer preservation (Fitzpatrick et al., 2016).

4.1.1. Traditional drying methods

Sun drying is one of the oldest and most energy-efficient methods of preserving onions, particularly in regions with abundant sunlight (Misha et al., 2013). However, it is weather-dependent, time-consuming, and exposes onions to environmental contaminants. This method remains common in resource-limited rural and developing areas (Ahmed et al., 2013). Sontakke and Salve (2015) observed that while sun-

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dried onions retain some nutritional value, they may lose part of their flavor and aroma compared to modern drying techniques.

Anbukkarasi et al. (2013) found that using the windrow method sun drying onions for four days followed by a 21-day curing period in sheds reduced sugar content while enhancing storage life and minimizing losses. A faster alternative is air drying, or hot-air drying, which involves exposing onions to warm air at controlled temperatures. However, improper execution can lead to flavor and nutrient loss. To preserve essential minerals and antioxidants while maintaining flavor.

4.1.2. Advanced drying methods

Sophisticated drying methods, including vacuum, infrared, microwave, and freeze-drying, have improved the preservation of fruits and vegetables, including onions (Hasan et al., 2019). Freeze-drying, or lyophilization, maintains the onion's natural nutrients, flavor, and structure by freezing the onions and then applying low pressure, causing the ice to sublimate. Hamed and Foda (1966) found that onions freeze-dried at -30℃ for 7-8 h under 6.1 mm Hg pressure retained superior color, flavor, and nutritional content compared to conventionally dried onions.

Microwave-vacuum-freeze drying is a rapid and cost-effective method for drying onions (Abbasi and Azari, 2009). Reis et al. (2022) reported that freeze-drying and multi-flash drying techniques effectively preserve the color, texture, and rehydration qualities of vegetables, including onions. Microwave drying, which uses electromagnetic waves, is more efficient than hot air drying, retaining more nutrients and bioactive compounds (Mitra et al., 2010). Hoover drying, often combined with freeze or microwave drying, operates at lower pressure, reducing oxidative damage and preserving essential nutrients (Parikh, 2015). Additionally, vacuum drying has been shown to be particularly effective in maintaining the color and bioactive components of onions (Calin-Sánchez et al., 2020).

4.1.3. Hybrid and novel drying techniques

Solar-assisted drying is becoming an increasingly popular and sustainable method for drying onions, particularly in regions with abundant sunlight. By combining solar energy with mechanical systems like fans and heaters, the drying process becomes faster, more efficient, and consistent, while also reducing environmental impact. Solar-assisted drying can be achieved using direct or indirect drying methods as shown in Fig. 4. Nwankwor et al. (2021) found that solar-assisted systems, when used alongside traditional methods like air or hoover drying, significantly reduce drying times without compromising product quality.

Another advanced technique is superheated steam drying shown in Fig. 5, which uses steam at temperatures higher than boiling to extract moisture from onions. This method enhances rehydration, accelerates drying, and helps retain the onion's nutrients, color, and aroma. Sehrawat et al. (2016) demonstrated that superheated steam drying preserved the flavor and aroma of onions while using less energy and reducing drying time compared to traditional techniques.

Hot air-assisted infrared drying is an energy-efficient method that heats the onion's surface using infrared radiation (Askari et al., 2013). This technique, which exposes onions to electromagnetic radiation with wavelengths from 0.8 to 1,000 μm, is faster and uses less energy than conventional hot-air

(A) (B)

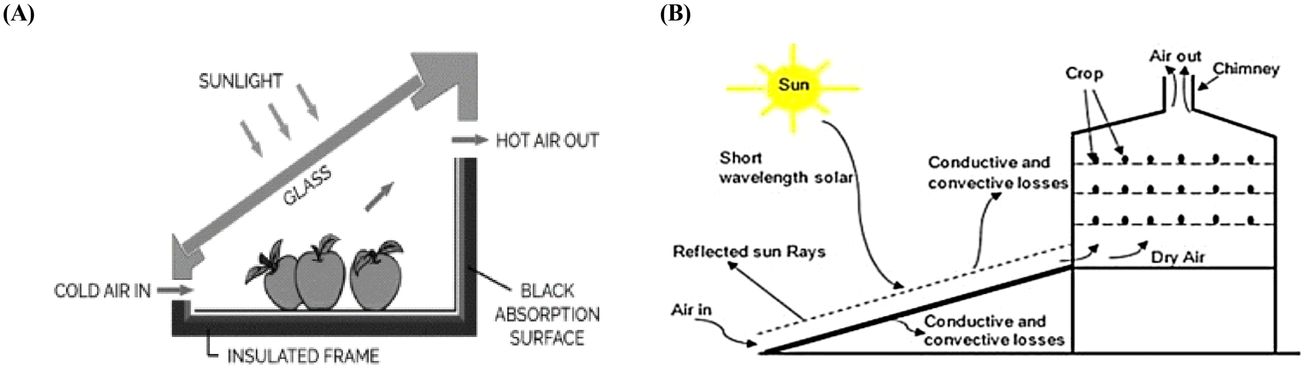

Fig. 4. Direct and indirect solar drying- direct solar drying (A) and indirect solar drying (B). Adapted from Abhay et al. (2017) and Nwankwor et al. (2021).

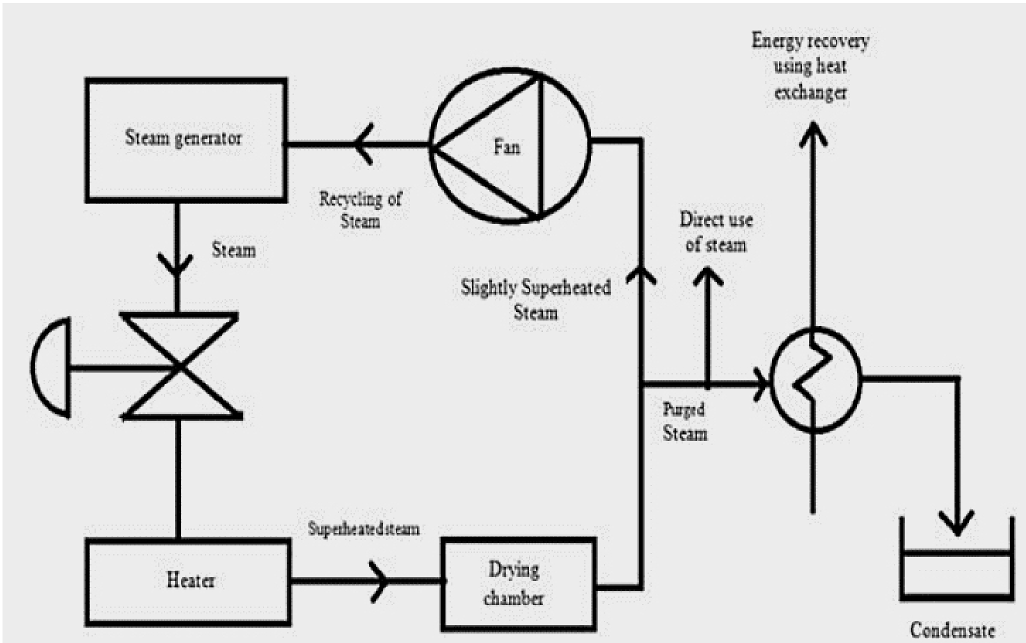

Fig. 5. Superheated steam drying setup. Adapted from Nwankwo et al. (2021) and Sehrawat et al. (2016).

drying. Boudhrioua et al. (2009) found that infrared drying preserves flavor and texture while removing moisture quickly, ensuring the retention of nutritional value.

4.2. Freezing technology in onion processing

Onions can be preserved by freezing them, which helps maintain their texture, flavour, and nutritional content over time (Kumar et al., 2020). By bringing onions' temperature below freezing, the method inhibits the growth of microorganisms and slows down the enzymes that cause spoiling (Liu et al., 2020; Van der Sman, 2020). How much super cooling is done during freezing determines how many ice crystals develop; the more super cooling, the more ice crystals form (Kaur and Kumar, 2020). Dalvi-Isfahan et al. (2019) discovered that freezing onions may alter their flavor and texture, thereby compromising their quality when thaw.

4.2.1. Traditional freezing methods

The most popular technique in industry for freezing onions is air-blast freezing. In a blast freezer, the onions are exposed to cold air, usually at a temperature of -18°C to -30°C (Dempsey et al., 2012). By preventing big ice crystals from accumulating inside the cells, this rapid freezing method helps maintain the texture and flavor of the onion. Uneven freezing, however, may occur if not properly managed. According to Jung et al. (2015), air-blast freezing produced the tiniest ice crystals, caused the least amount of cell damage, and lost the least amount of organic acids, sugar, and vitamin C.

Onions can be frozen using liquid nitrogen using a process called cryogenic freezing, which is becoming more popular since it can increase quality and prolong shelf life. The controlled environment established by liquid nitrogen prevents microbial growth (Mascheroni, 2000; Wande and Shinde, 2013). However, cryogenic freezing is usually reserved for high-value products like seafood or specific fruits and is not cost-effective for most crops. Additionally, issues like product cracking and recrystallisation may arise. Agnelli and Mascheroni (2002) discovered that by shielding the cell walls from harm, cryogenic freezing aids in maintaining the food's shape.

4.2.2. Innovations in freezing technologies

When vegetables freeze, ice crystals form because of points created by heat and mass transfer. The size and structure of these crystals depend on how long freezing takes and how much the temperature drops below freezing (You et al., 2021). Larger ice crystals can damage the food's texture and quality.

Recent freezing technology advancements aim to improve food quality and efficiency. One of these is high-pressure

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freezing (HPF), which lowers the freezing point of water by applying pressure up to 210 MPa. This promotes faster freezing and smaller, more uniform ice crystals, reducing damage to the food (Li et al., 2018). HPF improves the texture and structure of frozen fruits and vegetables. It includes techniques like High Pressure Induced Freezing (HPIF), High Pressure Shift Freezing (HPSF), and High Pressure Assisted Freezing (HPAF) (Cheng et al., 2017).

Freezing alone does not always improve food texture (Chaudhary, 2021). However, combining high-pressure freezing with ultrasound technology, which operates between 20-100 kHz, enhances freezing. Ultrasound speeds up the process by promoting ice formation, improving heat transfer, and creating bubbles that speed up freezing (Zheng and Sun, 2006). Kiani et al. (2015) found that this process improves food preservation. Additionally, Roldán-María et al. (2009) discovered that low temperatures and specific pressures increase the antioxidant levels in onions.

5. Impacts of processing on nutritional, antioxidant, and sensory properties of onions

Onions (Allium cepa) are rich in minerals like potassium and magnesium, vitamins like C and B6, and bioactive compounds such as flavonoids and sulphur. These nutrients offer antibacterial, anti-inflammatory, and antioxidant benefits. Processing methods like drying and heat treatment can affect onions' antioxidant levels, nutritional value, and sensory qualities. While some nutrients, like vitamin C, may degrade, others, such as sulphur compounds, may become more bioavailable (*Allium cepa*).

5.1. Effects of thermal processing on onions nutrients and bioactive ingredients

Onions are often processed using methods like boiling, roasting, and heating, which can affect their nutritional value. For instance, water-soluble vitamins such as vitamin C are sensitive to heat and can be reduced during cooking. Boiling, for example, can lead to a loss of up to 35% of vitamin C (Benzie et al., 2017). Although boiling might cause some mineral loss if the water is thrown away, minerals like potassium and magnesium stay relatively stable during cooking. Roasting, however, increases the availability of sulfur compounds, such as diallyl disulfide, which may enhance their anti-inflammatory and anticancer properties (Gao et al., 2016).

Drying methods like oven drying, freeze drying, and air drying concentrate the nutrients and flavor of onions. Freeze-drying, especially, does a great job of preserving nutrients like vitamin C compared to hot-air drying (Hassan et al., 2020). Drying also helps maintain onions' fiber, which aids digestion, and freeze drying is the best at keeping the fiber intact.

When onion juice is extracted for supplements, some nutrients may be lost. Cold-press juicing tends to preserve more nutrients than centrifugal juicing (Khaksar et al., 2019). However, juicing increases sugar concentration, which can raise the glycemic index, a concern for diabetics, while removing fiber, reducing its digestive benefits.

Onions are rich in antioxidants like sulfur compounds, flavonoids, and phenolic acids, which offer health benefits. Heat processing, though, can either increase or decrease these antioxidants. While cooking can degrade certain antioxidants, sulfur compounds can become more potent (Roldán-Marín et al., 2009). Freeze-drying, however, preserves antioxidants better than hot-air drying (Rui et al., 2018) and cold-press juicing retains more antioxidants than other juicing methods (Tiwari et al., 2019). Lastly, processing methods also affect the taste, texture, and color of onions, with roasting enhancing their sweetness and color.

5.2. Impact of freezing on nutritional and antioxidant composition of onions

Onions' texture, nutritional value, and antioxidant content are all significantly impacted by freezing as shown in Table 5. Ice crystals that form when onions are frozen have the potential to harm the cells and decrease the availability of vital elements like vitamins and minerals. Rapid freezing techniques, on the other hand, minimize cell damage and produce smaller, more uniformly distributed ice crystals, which aid in preserving nutrients. According to Grova and Negik (2023), rapid freezing helps preserve antioxidant quality by cutting down on freezing duration and tissue damage.

To maintain antioxidant activity, onions must be frozen quickly. Larger ice crystals created by sluggish freezing cause more cell damage and a higher loss of antioxidants

Table 5. Effects of freezing conditions on quality parameters in allium vegetables

Vegetable type	Vegetable	Pretreatment	Freezing method	Freezing temp	Nutritional results	References
Allium vegetables	Onion	None	Deep chest freezer (-20℃)	-20℃	Antioxidant capacity: 30.39% decrease Total phenolic content: 37.32% decrease	Çubukçu et al. (2019)

upon thawing, as Table 5 illustrates. However, fruits and vegetables retain their antioxidant activity better when frozen quickly, which results in fewer ice crystals (Vicent et al., 2017). In their comparison of several drying techniques for onion powder, Gutam et al. (2021) discovered that freeze-drying retained the nutritional and sensory characteristics of onions better, retaining their color, texture, and rehydration capabilities while minimizing the loss of volatile chemicals.

Rapid freezing has advantages, but depending on the size and kind of ice crystals generated, it might also result in various textural and nutrient release modifications. Quick freezing may nevertheless result in certain textural alterations and a decrease in nutritional availability, according to Kobayashi and Suzuki (2019). Onions frozen at -20℃ exhibited a reduction in phenolic content and antioxidant capacity, according to Cubukcu et al. (2019). This highlights how crucial it is to properly regulate freezing temperatures to reduce nutritional loss and maintain onions' sensory appeal.

6. Preservation techniques of onions

6.1. Traditional preservation methods of onions

Commonly used in cooking, onions (*Allium cepa*) have a short shelf life due to their high moisture content and propensity to deteriorate. Particularly in areas with restricted access to cutting-edge technologies, traditional preservation techniques help to keep their flavor and nutritional value, prolong their freshness, and lower post-harvest losses. They are also easy, inexpensive, and readily available.

6.1.1. Drying

By lowering the moisture content of onions, drying is a common and traditional way of preservation that helps stop the growth of bacteria and enzymes that cause spoiling (Pandiselvam et al., 2021). Drying increases onions' storage stability by bringing their moisture content down to less than 10%. A variety of drying techniques are frequently employed, including hoover, air and freeze drying (Ahmed et al., 2013). However, dehydrating whole onions or onion fragments results in significant flavor component losses, according to Freeman and Whenham (1975). As was covered before in this review, more recently, sophisticated drying methods such as microwave, infrared, and radiofrequency drying have drawn interest due to their quicker heating times and superior food preservation capabilities.

6.1.2. Storage in cool, dry, and well-ventilated areas

Conventional onion storage typically depends on ambient factors such as dry, cool, and well-ventilated spaces. To keep moisture from building up, onions are sometimes stored in bags, baskets or bins that let air circulate. Onions must be stored properly to prevent sprouting and maintain freshness; the ideal range is 4-10℃ with a humidity of 65-70% to minimize moisture absorption and spoiling. To increase airflow, onions can be braided or kept in mesh bags or hanging bundles in homes or rural areas. This approach is straightforward and economical, but it is only appropriate for temporary storage and is dependent on the ambient conditions. Sprouting or rotting may result from excessive heat or humidity (Sharma et al., 2021).

6.1.3. Pickling

Onions are preserved using an age-old technique called pickling, which involves submerging them in a solution of vinegar, salt, and occasionally sugar or spices to create an acidic environment that inhibits the growth of bacteria. Usually kept in jars, pickled onions add a tart flavor and can be consumed within a few days or weeks. They become a popular addition to salads, sandwiches, and side dishes because of this process, which also improves their flavor and prolongs their shelf life for months. Pickling onions increases their health advantages by preserving antioxidants like flavonoids, according to research (Irmak et al., 2017; Soni et al., 2022). Kark (2017) also discovered that pickled onions

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contained more pyruvic acid.

6.1.4. Smoking

Onions are preserved using the classic smoking method, which involves exposing them to smoke from burning wood or other organic materials. In addition to drying the onions and adding antimicrobial elements that aid in their preservation, this method gives them a distinctly smokey flavor. The onions can keep their freshness for long periods of time since the gradual drying process keeps them from spoiling. Onions could be hung in smokehouses or smoked over wood chips. The smoke's antibacterial and antioxidant qualities extend the onions' shelf life and keep them fresh for several months. In rural places where refrigeration is scarce, this method is particularly helpful (Alba et al., 2020).

6.1.5. Fermentation

Fermentation is a well-established preservation method that leverages the activity of beneficial microbes, like lactic acid bacteria, to produce acids that prevent spoilage. Onions are typically left to ferment for several days or weeks after being submerged in a brine or saltwater solution. During this process, lactic acid is produced, which helps preserve the onions and imparts a distinct sour, acidic flavor. Ramadevi et al. (2010) investigated the preservation of onions through lactic acid fermentation using varieties such as Arka Niketan, Arka Bindu, and White Onion. They found that when lactic acid bacteria were combined with 25% cider vinegar, the Arka Bindu variety had the lowest pH and the highest acidity. Fermented onions, rich in probiotics, offer additional health benefits, particularly for gut health (Khorasani et al., 2019). This natural preservation method not only extends shelf life but also enhances the nutritional value of onions by enriching them with beneficial microorganisms.

6.1.6. Oil or vinegar preservation

Onions can be preserved easily and successfully by storing them in vinegar or oil. By peeling, cutting, and submerging onions in vinegar or oil, this method creates an anaerobic environment that inhibits the growth of dangerous germs, such as *Clostridium botulinum*. This method is frequently employed in Middle Eastern and Mediterranean cooking, where onions are frequently marinated in olive oil and spiced with different herbs. Although this technique can greatly increase the onions' shelf life for weeks or even months, it is crucial to adhere to appropriate storage and hygiene procedures to avoid infection (Irmak et al., 2017).

6.2. Innovative preservation techniques of onions

6.2.1. Controlled atmosphere storage (CAS)

An innovative preservation technique called Controlled Atmosphere Storage (CAS) maximizes the storage conditions to preserve onions' quality for extended periods of time. CAS extends shelf life by modifying atmospheric conditions, such as preserving 3 kPa O_2 and 5 kPa CO_2, which slows respiration, postpones senescence, prevents pathogen growth, and lowers ethylene production (Chávez-Mendoza et al., 2016; Chope et al., 2007b). By allowing onions to be sold during off-seasons, CAS provides financial advantages while being more costly than traditional refrigeration.

While higher temperatures (24℃ or 30℃) are unsuitable for commercial usage, CAS storage at circumstances such 1% O_2 and 99% N_2 at 5℃ can retain onion quality with little flavour changes (Yoo et al., 2012). According to Praeger et al. (2003), onions exhibit a 2.8% weight loss after 36 weeks at 1% O_2, which is much less than the 1% loss every 9 weeks under ambient storage conditions. It has also been noted that different varieties react differently to CAS. According to Bansal et al. (2015), the 'Carlos' variety exhibits decreased Total Soluble Solids (TSS) under CAS, whereas the 'Caramelo' variety maintains its best marketability under controlled refrigeration. In areas like Southern India, where it helps lower postharvest losses during the monsoon season, CAS has shown benefits (Gomathy et al., 2019).

6.2.2. Cold plasma treatment

A cutting-edge and eco-friendly technology, cold plasma has been popular in the agri-food sector since it is affordable and can enhance food quality and safety (Pankaj et al., 2018). Microorganisms are successfully rendered inactive by cold plasma, which operates at moderate temperatures and produces a variety of vaporous species with high-energy electrons that can reach temperatures of up to 20,000 K (Misra et al., 2011). This method keeps food's nutritional value and flavor intact while extending its shelf life.

According to Misra et al. (2016), cold plasma treatment has shown great promise in preserving food integrity and getting rid of dangerous microbes. Terebun's 2021 study on plasma treatment of onion seeds revealed no discernible surface alterations under a microscope, indicating that the method may successfully maintain the seeds' properties. This demonstrates the potential of cold plasma as a non-invasive, sustainable food preservation method without sacrificing quality.

6.2.3. Essential oil coatings

In the food business, essential oils are becoming more and more recognized as creative and sustainable preservatives that provide a greener substitute for conventional preservation techniques (Ju et al., 2019). Thyme, oregano, and clove oils have potent antibacterial qualities and can be applied as coatings to onions to prolong their shelf life. These coatings create a barrier that keeps bacteria from growing, lessens dehydration, and keeps onions fresher longer. Onions are also a good preservation option since essential oils help maintain their nutritional content and flavor. According to Esmaeili et al. (2023), essential oils have strong antibacterial properties and have been shown to be effective against pathogens such as *Listeria monocytogenes*, *Escherichia coli*, and *Staphylococcus aureus*.

6.2.4. Irradiation technology

According to a study by Kumar et al. (2021), gamma irradiation effectively preserved onions by reducing contamination and delaying sprouting, while also maintaining their quality. Despite safety concerns, research suggests that controlled doses of irradiation are a safe and effective method for preserving onions. Irradiation is a technique that exposes food to ionizing radiation to eliminate bacteria, pests, and spoilage microorganisms. This method has been thoroughly studied for extending the shelf life of various produce, including onions.

6.2.5. Ultrasound treatment

Using high-frequency, high-intensity sound waves that can penetrate food materials, ultrasound treatment provides a straightforward, affordable, and effective substitute for other cutting-edge technologies. By creating disruptions in solid particles in a solution, the technique breaks them apart and allows them to diffuse into the solvent (Cares et al., 2010). The extraction of bioactive substances and the preparation of fruit and vegetable pastes and juices are only two of the many foods' processing uses for ultrasound. The total phenolic content of spices has also been measured more recently using ultrasound (Teng et al., 2019).

6.2.6. Nanotechnology in preservation

Nanotechnology has become a promising approach for food preservation, employing nanoparticles and nanomaterials to interact with food at the molecular level (He et al., 2019). Advances in nano emulsions, nanocomposites, and nanocoating have improved the antimicrobial and antioxidant properties of food coatings, significantly extending the shelf life of onions. Natural polymers such as chitosan, known for their antimicrobial and antioxidant benefits, are also being explored for preservation purposes (Yuan et al., 2016).

Research by Younes (2020) found that incorporating nano-silver into carboxymethyl cellulose effectively preserved fresh and dried onions by inhibiting microbial growth, enhancing pungency, and maintaining color. Additionally, mild heat treatments and edible alginate-based coatings have been shown to slow respiration rates and delay onion deterioration (Medino-Jaramillo et al., 2022). However, the high cost of silver nanoparticles limits their large-scale application. To address this, researchers are exploring alternative nanomaterials. Copper nanoparticles offer a cost-effective antimicrobial solution, while zinc oxide nanoparticles, known for their broad-spectrum antimicrobial properties, provide an affordable and effective option for preserving perishable foods (Jin and Jin, 2021; Solangi et al., 2024). These innovations in nanotechnology offer sustainable alternatives to conventional preservation methods, ensuring better onion storage without compromising quality.

6.2.7. Irradiation

Postharvest losses in onions, caused by factors such as rotting, sprouting, and physiological weight loss, drastically limit their shelf life and diminish their quality. Elevated temperatures and high humidity exacerbate these problems, particularly during the rainy season. One promising approach to addressing these issues is gamma irradiation. Different gamma irradiation dosages (0 Gy, 10 Gy, 60 Gy, 100 Gy, and 200 Gy) were examined on onion bulbs kept at room temperature in a study by Sharma et al. (2020). According to the results, irradiation at 120 Gy successfully decreased weight loss, rotting, and sprouting, prolonging the onions'

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shelf life for up to three months.

Additionally, irradiation onions maintained their freshness and firmness while exhibiting little decline in their levels of pyruvic acid, ascorbic acid, and total soluble solids. Onion quality was best preserved by radiation at 120 Gy, which provided a workable way to lower postharvest losses and guarantee longer storage.

6.3. Chemical preservation methods of onions

Chemical preservation techniques are frequently employed to overcome these issues and increase shelf life. These methods help maintain onions' flavor, texture, and nutritional value in addition to preventing microbial infection and spoiling.

6.3.1. Use of chemical fungicides and antimicrobials

Onions are chemically preserved using fungicides and antimicrobial chemicals to stop the growth of bacteria, yeasts, and fungus that can cause rot and reduce quality. Onions can be effectively protected from fungal diseases such as *Botrytis* alli-induced neck rot and postharvest spoilage from fungi like *Penicillium* and *Fusarium* by using fungicides like thiabendazole, prochloraz, and fluazinam. Onions are also sanitized using peracetic acid, a mixture of acetic acid and hydrogen peroxide, which increases food safety and prolongs their shelf life. Along with carbendazim, acetic acid and sulphur dioxide fumigation also aids in lowering fungal infestation.

Studies have demonstrated that plant extracts, especially those derived from Moringa oleifera and other spices, have antifungal properties that can reduce spoiling (Arowora and Adetunji, 2014; Kumar et al., 2015). These techniques offer practical ways to maintain the quality of onions and guarantee food safety while they are being stored and transported.

6.3.2. Application of ethylene inhibitors

Onions' ripening and aging are influenced by ethylene, a plant hormone that accelerates premature sprouting, leading to waste and quality degradation. To address this, ethylene inhibitors are used to prevent sprouting and extend shelf life. The effectiveness of ethylene scavengers depends on factors such as the surface area of the substrate and potassium permanganate content (Taylor et al., 2012). 1-Methylcyclopropene (1-MCP), a common ethylene inhibitor, blocks ethylene receptors, preventing the plant's response to the hormone. Studies show that 1-MCP helps maintain flavor, texture, and overall quality while delaying sprouting (Downes et al., 2010). Additionally, fungicidal treatments like thymol can reduce spoilage by up to 96% (Ji et al., 2018). Maleic hydrazide, once commonly used to inhibit sprouting, was banned in 2009 due to health concerns, prompting research into safer alternatives, such as combining it with carbendazim to control fungal infections and rotting (Kumar et al., 2015). These approaches help preserve onion quality during storage.

6.3.3. Preservation with salts and sugars

Salt and sugar have been traditional preservatives for food, including onions, by creating conditions that prevent microbial growth through osmosis, which removes moisture. Salting reduces water content, inhibiting microorganism growth (Albarracin et al., 2011). High salt concentrations disrupt microbial cell membranes and enzymatic reactions, making the environment unsuitable for spoilage. To further enhance preservation, salting is often combined with boiling or drying. It also improves the flavor, texture, and aroma of onions. In brine preservation, onions are submerged in saline solutions, which dehydrate them and prevent bacterial growth (Sebranek, 2009).

Another classic preservation method is dipping onions in sugar or syrup to encourage dehydration. Osmotic dehydration pretreatments significantly affect drying rates, water loss, solid gain, and the retention of vitamins and minerals. According to Alabi et al. (2016), osmotic treatment with a 20% w/w solution at 50℃ for 120 min, followed by drying at 60℃, maximized solid gain and iron content, improving the quality of preserved onions.

7. Packaging solutions for onions

Due to their high perishability, onions require appropriate packaging to maintain their quality while being stored and transported. Avoiding microbiological contamination, moisture loss, and physical damage, packaging plays a crucial part in prolonging the shelf life of onions while also preserving their freshness, flavor, and nutritional content.

7.1. Traditional packaging solutions for onions

Shelf life of onions can be prolonged with the right storage facilities. Research on conventional storage practices highlights how important it is to use the right ways to prevent quality deterioration. For example, Deka et al. (1995) discovered that the best method to reduce weight loss, sprouting, and rotting was to store onions in dry sand on a solid floor. Iordachescu and Nihailescu (1979) discovered that onions kept in bags for 180 days lost 17.2% of their weight, they brought attention to the importance of the right circumstances. Likewise, Singh and Singh (1973) observed that onions preserved better in tats on brick foundations than with other local methods. These results highlight how crucial it is to choose the best storage options to preserve onion quality, lower postharvest losses, increase shelf life, and ultimately cut down on food waste.

7.1.1. Mesh bags

Onions are frequently packaged in mesh bags composed of materials like nylon, kenaf, or polypropylene. These bags provide adequate ventilation, which lowers the chance of decay and helps avoid moisture accumulation. They are a popular option for retail packaging since they are affordable, long-lasting, and simple to use (Murumkam et al., 2018). In contrast to other packaging techniques, mesh bags do not provide protection against physical damage, dust, or pests, all of which can reduce the shelf life of onions.

Shehu et al. (2023) investigated how postharvest losses from onions were affected by both conventional and improved storage methods. They discovered that onions kept in jute bags sprouted at a significantly lower rate (22%) than onions kept in mesh bags, suggesting that jute bags may be useful for lowering sprouting and enhancing storage quality.

7.1.2. Paper and burlap sacks

Onions are traditionally packaged in paper and burlap bags, which offer a ventilated environment that preserves flavor and texture. Eco-friendly and biodegradable materials like wood, plants, or recycled paper are frequently used to make these sacks. Paper packaging is a common option in the food business because of its mechanical strength, recyclability, and affordability (Deshwal et al., 2019; Otto et al., 2021). The shelf life and quality of onions stored in paper and hessian sacks may be impacted since they are more likely to rupture than mesh bags and provide less defense against moisture or pests. Notwithstanding these disadvantages, paper and burlap sacks are an attractive and sustainable alternative for packing onions due to their cost-effectiveness and environmental advantages.

7.2. Modern packaging solutions for onions

7.2.1. Plastic film packaging

Onions are frequently packaged in plastic film due to its flexibility, resistance to punctures, and capacity for secure sealing, particularly in consumer markets. In packaging, materials like high-density polyethylene (HDPE) and low-density polyethylene (LDPE) are commonly utilized, especially in Modified Atmosphere Packaging (MAP), which controls the air conditions surrounding onions to prolong their shelf life. These films come in flexible, semi-rigid, and rigid forms, and they are also utilized for comparable purposes with other materials as polyester (PET), polypropylene (PP), and polyvinyl chloride (PVC).

Although plastic films are useful for keeping perishables fresh and preventing spoiling, their non-biodegradability raises environmental issues and contributes to the accumulation of trash over time (Salame, 1986; Van Willige et al., 2002). As a result, there is growing interest in packaging alternatives that are more environmentally friendly.

7.2.2. Edible coatings

As an eco-friendly and efficient way to package onions, edible coatings are growing in popularity. These coatings, which are made from natural materials like carnauba wax, beeswax, and chitosan, provide a thin, biodegradable layer that guards against microbial contamination and helps stop moisture loss. The antibacterial qualities of chitosan-based coatings are very noteworthy, and they are crucial in prolonging the onions' shelf life. Packaging materials made of nanocomposite materials are becoming more popular in addition to edible coatings. By adding nanoparticles to conventional packaging, these materials improve mechanical strength, antibacterial qualities, and the capacity to identify foodborne pathogens and other important analytes. Food packaging solutions that are more efficient and sustainable are being developed because of these advances (Donglu et al., 2016; Iduma and Obele, 2021; Sharma et al., 2017).

7.3. Advanced packaging technologies for onions

7.3.1. Active packaging

Active packaging is a cutting-edge technique that enhances food preservation by incorporating elements within the packaging to actively interact with the contents. In contrast to traditional packaging, active packaging carries out specialized tasks such

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scavenging hazardous gases, managing moisture, releasing advantageous substances, and controlling temperature to enhance food quality and safety. Active packaging for onions can include oxygen scavengers, moisture absorbers, or antimicrobials, all of which help to prolong shelf life. Examples include moisture control, which maintains ideal humidity and minimizes spoiling, and oxygen scavengers, which inhibit the growth of mold and sprouting. The quality of onions is further preserved by this method, which also aids in preventing microbial contamination (Kuswandi et al., 2020; Lee et al., 2019; Singh et al., 2019).

7.3.2. Intelligent packaging

An inventive method for tracking and providing real-time information on the state of packed goods is intelligent packaging, which incorporates sensors or indications. Intelligent packaging helps minimize food waste, guarantee consumer safety, and boost the general effectiveness of the food sector by identifying changes in the product's environment. Numerous parts of this technology, including data carriers, sensors, and indicators, improve supply chain management and offer insightful information on product quality. To ensure optimal quality from production to consumption, time-temperature indicators help track exposure to unfavorable conditions, while ethylene gas sensors can identify sprouting in onions (Kalpana et al., 2019; Müller and Schmid, 2019). Throughout the supply chain, these developments are essential to preserving the safety and freshness of onions.

8. Conclusions

Because of their high nutritional value and bioactive components, onions (*Allium cepa* L.) are essential to world agriculture, food, and nutrition. Onions confront several difficulties despite their significance, including spoiling, handling problems after harvest, and financial losses. To overcome these obstacles, this analysis highlights the necessity of cutting-edge technology in onion processing, preservation, and packaging. Innovations that have the potential to increase shelf life, decrease waste, and maintain quality include cold plasma treatment, controlled atmosphere storage, and environmentally friendly packaging options. Understanding how different processing methods influence nutritional and antioxidant characteristics is also necessary to maximize health advantages. By combining state-of-the-art technology with traditional processes, we can create a more sustainable and efficient onion supply chain that benefits producers and consumers worldwide.

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