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LONG-TERM STORAGE TECHNOLOGIES FOR DATE FRUITS AND PHYSIOLOGICAL CHANGES DURING STORAGE: A REVIEW

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Abstract. Date fruits (*Phoenix dactylifera* L.) are highly perishable due to their elevated sugar and moisture content, resulting in substantial postharvest losses that compromise both economic value and nutritional quality. This review synthesizes current knowledge on long-term storage technologies for date fruits and the physiological transformations they undergo during storage. Traditional preservation methods, including sun drying and convective drying, remain widely practiced but face limitations in scalability and quality retention. Advanced physical technologies—modified atmosphere storage (MAP), controlled atmosphere storage (CAS), cold storage, high-pressure processing, pulsed electric fields, cold plasma, and irradiation—have demonstrated significant potential for extending shelf life while preserving sensory and nutritional attributes. Physiological changes during storage encompass respiration and ethylene evolution, moisture migration and weight loss, textural softening through cell wall polysaccharide degradation, enzymatic and non-enzymatic browning, and alterations in bioactive compounds including phenolics, flavonoids, and antioxidant capacity. The integration of emerging technologies within hurdle-based frameworks offers a promising pathway toward sustainable, clean-label preservation systems that reduce postharvest waste and enhance market competitiveness.

Keywords: date palm, postharvest preservation, modified atmosphere packaging, physiological changes, storage technologies, hurdle technology.

Introduction. Date palm (*Phoenix dactylifera* L.) cultivation spans tropical and subtropical regions across the Middle East, North Africa, South Asia, and parts of the Americas, with the fruit serving as a staple food and significant export commodity . The nutritional profile of dates—characterized by high carbohydrate content (44–88% of dry weight), dietary fiber (6.4–11.5%), essential minerals, and bioactive phytochemicals—positions them as a valuable functional food ingredient . However, the same attributes that confer nutritional value, particularly elevated sugar and moisture levels, render dates highly susceptible to postharvest deterioration. Depending on cultivar and maturity stage at harvest, date fruits may lose marketability within weeks under ambient conditions, creating urgent imperatives for effective preservation strategies.

The physiological complexity of date fruits derives from their unique ripening progression, which proceeds through distinct stages: Kimri (unripe green), Khalal (mature, crisp, and colored), Rutab (ripe, softened), and Tamer (fully ripened, dried) . Each stage presents distinct storage challenges. Khalal-stage fruits, prized for their fresh crisp texture, are particularly perishable and require immediate cooling and careful handling . The economic consequences of inadequate storage are substantial: in regions where preservation infrastructure is limited, farmers may be forced to sell at depressed prices or abandon orchards entirely .

This review addresses two interconnected dimensions of date fruit postharvest management: the technologies available for long-term storage and the physiological changes that occur during storage,

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which collectively determine quality outcomes. By examining both traditional and emerging preservation approaches alongside the biochemical and physiological transformations they aim to mitigate, this synthesis provides a framework for developing integrated, science-based storage protocols.

Traditional Storage and Preservation Techniques. Convective Drying

Convective drying, which employs heated air streams to evaporate moisture from fruit tissue, remains among the most widely adopted industrial preservation methods for dates. The process typically involves fruit selection, washing, optional peeling, slicing (4–6 mm thickness), blanching to inhibit enzymatic browning, and drying at 55–65°C with air velocity of 1–2 m/s for 8–12 hours until moisture content reaches 15–18% . This moisture reduction effectively inhibits microbial proliferation while concentrating sugars and preserving much of the fruit's nutritional value.

The method's principal advantages include technological simplicity, established industrial scalability, and precise control over temperature, humidity, and airflow parameters . Controlled drying conditions minimize mold risk and ensure product uniformity. However, limitations persist: natural sun-drying variants require several days to weeks, creating bottlenecks in processing capacity and exposing fruit to inconsistent drying rates that promote uneven quality and microbial hazards . Hybrid approaches combining microwave pre-treatment with tunnel drying have demonstrated improved efficiency without compromising sweetness or texture .

Freezing-Based Preservation. Freezing technologies offer an alternative pathway for long-term preservation, particularly for Khalal-stage fruits intended for fresh-like consumption. Individual quick freezing (IQF) and cryogenic freezing have demonstrated superior retention of color, texture, and nutritional quality compared to conventional slow freezing over nine months of storage at –20°C and –40°C . Rapid freezing minimizes ice crystal formation and cellular damage, preserving fresh-like hardness, chewiness, and enzyme activity. Pre-treatments including steaming and partial dehydration prior to freezing further enhance sensory and physicochemical attributes, achieving the highest overall acceptability scores in comparative evaluations .

Freeze-drying extends storage stability to twelve months, though color changes—decreased lightness and increased redness—follow first-order kinetics at elevated storage temperatures, suggesting the utility of predictive modeling for quality forecasting . Thermal sterilization (100°C for 10 minutes) provides a shelf-stable ambient storage option for up to ten months while unexpectedly increasing total phenolic content .

Advanced Physical Storage Technologies. Modified and Controlled Atmosphere Storage. Modified atmosphere storage (MAP) and controlled atmosphere storage (CAS) manipulate the gaseous environment surrounding fruit to retard physiological processes and microbial growth. For date fruits, elevated carbon dioxide concentrations have proven particularly effective. Barhi dates stored at 0°C under 20% CO_2 maintained quality for 173 days, compared with only 60 days under normal air composition at the same temperature . The treatment prevented fruit darkening, maintained firmness, preserved total soluble solids and sugar content, and retarded degradation of caffeoylshikimic acid, a dominant phenolic antioxidant .

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The efficacy of CO_2 enrichment appears concentration-dependent: 20% CO_2 substantially outperformed 5% and 10% treatments, extending storage from 17 weeks to 26 weeks while maintaining superior color and firmness . Importantly, no chilling or CO_2 injury symptoms were observed at 0°C, indicating the compatibility of these treatments for sensitive cultivars . The mechanism appears to involve suppression of respiratory activity and ethylene-mediated ripening processes, alongside direct antimicrobial effects.

Cold Storage and Humidity Management. Temperature reduction remains the foundational intervention for date fruit preservation. Cold storage at 0°C significantly extends storage life by suppressing respiration rates, ethylene emission, and catabolic enzyme activities while minimizing microbial proliferation and insect infestation . Optimal relative humidity for Khalal dates ranges from 85–95%, preventing excessive water loss that leads to shriveling and hardness .

Relative humidity exerts complex effects on quality attributes. Studies on Mejhoul and Boufeggous cultivars demonstrated that higher relative humidity (65%) promoted greater softening compared to 55% RH, attributed to cell wall polysaccharide degradation and pectin depolymerization . Conversely, high humidity under certain conditions promoted weight gain in low-water-activity fruits and increased browning index values for both cultivars, reflecting the interplay between moisture migration, enzymatic activity, and Maillard reactions . These findings underscore the necessity of cultivar-specific humidity optimization rather than uniform recommendations.

Preharvest Elicitor Applications. Emerging evidence supports the integration of preharvest treatments with natural elicitors to enhance postharvest storage outcomes. Chitosan (1%) applied alone or in combination with salicylic acid (2 mM) and calcium chloride (3%) significantly delayed ripening and decay in Barhi dates during two months of cold storage . The combination treatments reduced weight loss, maintained lower total soluble solids, and prevented rotten fruit incidence after 60 days. At the end of storage, calcium-based treatments exhibited the highest total phenolic, flavonoid, and tannin contents, with corresponding elevations in antioxidant and antimicrobial activities . These findings suggest that elicitor-mediated enhancement of fruit defense systems represents a viable complementary strategy.

Emerging Nonthermal Technologies. A comprehensive review of advanced physical techniques identifies high-pressure processing (HPP), pulsed electric fields (PEF), cold plasma, and irradiation as promising nonthermal approaches for date preservation . These technologies offer the potential for microbial inactivation and quality preservation without chemical preservatives, aligning with consumer demand for clean-label products. The "hurdle" concept—combining multiple preservation interventions at sub-lethal levels—has been proposed as a framework for integrating these emerging technologies with established methods to achieve comprehensive protection against diverse spoilage mechanisms .

Physiological Changes During Storage. Respiration and Ethylene Evolution. Date fruit ripening is characterized by a climacteric respiratory pattern, with a marked increase in respiration rate coinciding with the transition to the Rutab stage . Ethylene production peaks approximately seven days before the rapid increase in respiration, indicating that ethylene serves as the trigger for ripening-associated metabolic shifts . Storage temperatures above optimal levels accelerate these processes,

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motivating ethylene emission and catalyzing conversion of Khalal fruits to the softer Rutab stage . The effectiveness of cold storage and modified atmospheres derives substantially from their suppression of these respiratory and hormonal dynamics.

Moisture Migration and Weight Loss. Weight loss during storage results primarily from transpiration, driven by vapor pressure deficits between fruit tissue and the surrounding atmosphere . More than 97% of weight loss in stored fruits is attributable to transpiration, with structural characteristics of the skin—including micro-crack density, size, and morphology—modulating water loss rates . Storage at low relative humidity (55%) exacerbates weight loss in high-water-activity cultivars, while high humidity (65%) can promote weight gain in low-water-activity fruits, potentially creating conditions conducive to microbial proliferation . Moisture content changes follow complex patterns dependent on cultivar, initial water activity, and storage conditions, with implications for both textural quality and microbial stability.

Textural Changes and Cell Wall Modifications. Softening during storage results from degradation of cell wall polysaccharides, including depolymerization of water-soluble and acid-soluble pectins and soluble hemicellulose . The activities of invertase and cellulase enzymes increase significantly at the end of the Khalal stage and the beginning of the Rutab stage, contributing to cell wall disassembly . Modified atmosphere storage with elevated CO_2 has demonstrated efficacy in preventing fruit softening, with sensory panelists rating 20% CO_2-treated fruits as firmer and more similar to freshly harvested fruit than controls or lower-CO_2 treatments .

Color Deterioration and Browning Reactions. Color changes during storage involve both enzymatic and non-enzymatic mechanisms. Polyphenol oxidase and peroxidase catalyze oxidation of phenolic hydroxyl groups to quinones, which subsequently polymerize to form melanin pigments, producing undesirable darkening . Concurrently, Maillard reactions between amino acids and reducing sugars (glucose, fructose) generate brown pigments, particularly at elevated temperatures. The browning index increases significantly under high relative humidity conditions, compromising consumer acceptability . Modified atmosphere storage with 20% CO_2 effectively prevented darkening, maintaining bright yellow color in Barhi dates over extended storage .

Bioactive Compound Alterations. Date fruits contain significant quantities of phenolic compounds (approximately 7 mg/g), flavonoids (0.697 mg/g), and tannins with established antioxidant, antimicrobial, and anti-inflammatory properties . Storage conditions profoundly influence the retention of these bioactive constituents. High CO_2 modified atmosphere treatments maintained total phenolic content, total tannins, and antioxidant activity over 173 days of storage, whereas conventional cold storage resulted in progressive losses . Interestingly, storage temperature effects on phenolics vary by cultivar: total phenol content was highest at 25°C for Khalas, Ruzeiz, and Sukkari cultivars, followed by 5°C and –18°C in decreasing order . This counterintuitive finding may reflect enhanced extractability or stress-induced phenolic synthesis at higher temperatures, though the implications for nutritional quality require further elucidation.

Integration and Future Directions. The diverse array of preservation technologies and the complex physiological processes they target argue against reliance on any single intervention. The hurdle technology framework—which combines multiple sub-lethal preservation stresses to achieve

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synergistic protection—offers a systematic approach for integrating cold storage, modified atmospheres, preharvest elicitors, and emerging nonthermal technologies . Such integration must be tailored to cultivar-specific physiology, maturity stage at harvest, intended market (fresh vs. processed), and available infrastructure.

Critical research gaps remain. Systematic comparison of advanced technologies across cultivars, maturity stages, and storage durations is limited, impeding evidence-based selection and optimization . The mechanisms underlying cultivar-specific responses to storage conditions—particularly regarding phenolic metabolism and humidity tolerance—require further investigation. Cost-effectiveness analyses of emerging technologies within diverse production contexts are needed to guide adoption decisions, particularly for smallholder operations in developing regions.

Conclusion. Long-term storage of date fruits requires a sophisticated understanding of both preservation technologies and the physiological processes they modulate. Traditional convective drying and freezing methods remain relevant, while modified atmosphere storage, particularly with elevated CO_2 combined with cold storage, has demonstrated remarkable efficacy in extending storage life beyond six months while preserving quality. Physiological changes during storage—encompassing respiratory metabolism, moisture dynamics, textural degradation, browning reactions, and bioactive compound alterations—dictate the effectiveness of any preservation strategy. Future progress depends on integrating emerging nonthermal technologies within hurdle-based frameworks, tailoring interventions to cultivar-specific physiology, and developing cost-effective solutions adaptable to diverse production scales and market requirements.

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