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Quality preservation of date palm (*Phoenix dactylifera* L.) fruits at the Khalal stage: a review on current challenges, preservation methods, and future trends

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Date palm fruits have great commercial value and spiritual and cultural significance in multiple countries due to their high nutritional value and various health benefits. Some popular date varieties such as Barhi, Hayani, Samany, and Zaghlol are harvested at the Khalal stage due to their unique organoleptic properties, including crunchy texture, delicious taste, and attractive color; therefore, they have a great consumer demand and significant market relevance. However, dates at the Khalal stage are facing three issues: (1) they are perishable due to the higher moisture and sugar content, (2) they are rapidly converted from the Khalal to Rutab stage (ripening), and (3) the short picking season, where huge quantities of the fruits reach the horticultural ripening during a short time. Therefore, delaying ripening, maintaining freshness, preventing spoilage, and extending the shelf-life represent the major challenges at the Khalal stage. Accordingly, this review discussed the main factors responsible for quality loss and shelf-life shortening of Khalal dates. Preservation methods, research needs, and future trends were also discussed.

KEYWORDS

date palm, post-harvest changes, Khalal stage, ripening, preservation

1 Introduction

Date palm (*Phoenix dactylifera* L.), a famous fruit crop belonging to the *Arecaceae* family, is considered to be the oldest tree planted by humans and is mainly cultivated in northern Africa, the Arabian Peninsula, and Iran, where a tough climate is predominant (Sarraf et al., 2021; Alqahtani, 2024). Dates have great commercial value and play important roles in the diet and social life, particularly for the populations of the Middle East, with spiritual and cultural significance (Jaradat, 2013). Due to their high nutritional and economic value, besides their importance in agroecosystems, dates have gained great importance in the global economy; consequently, the cultivated area and global production have significantly increased in the last few years (Singh et al., 2022). The FAO statistics for the year 2023 showed that the total planted area of date reached 1.29 million ha, and the total global production was 9.66 million tons per annum; among the top five producers, Saudi Arabia ranked second (Figure 1), with 1.64 million tons per annum (FAO, 2024).

Date fruits have five maturity stages, namely Hababouk, Kimri, Khalal (sometimes called Bisr, Bisir, or Balah), Rutab, and Tamar (also written Tamer or Tamr); generally, fruits are consumable at Khalal, Rutab, and Tamar stages (Siddiq and Greiby, 2013; Abdelkarim et al., 2022). However, numerous important and popular date palm varieties such as Barhi, Hayani,

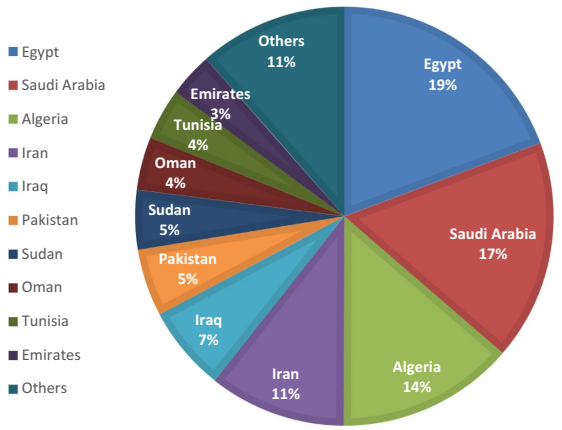

FIGURE 1
Top ten date palm-producing countries based on FAO statistics (FAO, 2024).

Samany, and Zaghlol are picked at the Khalal maturity stage, at which the fruits have distinct organoleptic qualities with a crunchy texture, delicious taste, and attractive yellow/red color according to the variety (Lobo et al., 2013; Alhamdan et al., 2019; Abu-Shama et al., 2020). Accordingly, dates at the Khalal stage have a great consumer demand and significant market relevance. Generally, Khalal dates are mainly consumed as fresh fruits due to their unique sensory properties; however, few applications of Khalal dates were mentioned in the literature such as pickles, chutney (an Indian thick sauce contains fruits, vinegar, sugar, and spices, and is used as an appetizer), and meat products (Ghnimi et al., 2017). In addition, the farmers in some rural regions in Egypt use date fruits at the Khalal stage to prepare jams, particularly from the Samany/Samani variety. In Saudi Arabia, additional applications of Khalal dates, besides their direct consumption as fresh fruits, were recorded including (1) jams, which are processed from high-sweet types such as Barhi, (2) pickles, which are prepared from low-sweet types, low quality, and unripe Khalal fruits, (3) fruit salad, (4) bakery products, (5) cake, (6) Salooq, a traditional date palm product in Saudi Arabia, is prepared by blanching Khalal date fruits and drying them at room temperature in the shadow to be consumed as whole fruits like dried Tamr varieties.

One of the challenges facing Khalal dates marketing is the short picking season, where huge quantities of the fruits reach the horticultural ripening within a short time; accordingly, the farmers harvest their crop at this stage to achieve high market prices (Al-Qurashi and Awad, 2011; Alhamdan and Atia, 2017). In contrast, the huge production of Khalal dates causes a significant amount of losses and increases the quantity offered in the market, which in turn results in a severe decrease in price and profitability (Alhamdan and Atia, 2017; Noutfia et al., 2019). As a climacteric crop, dates are rapidly transformed from Khalal to the Rutab stage, at which the texture becomes soft, the color turns to brown, and the taste changes to more sweety; additionally, the fruits become more susceptible to deterioration, and the shelf-life decreases which in turn results in a significant decline in consumer demand and market value (Alsawmahi et al., 2018; Abu-Shama et al., 2020; Ghafoor et al., 2022). Inappropriate agricultural practices, particularly during harvest, can affect Khalal dates' quality and storage stability and may accelerate the ripening process. Moreover, microbial contamination, aflatoxins formation, and insect infestation represent great threats to the quality and safety of Khalal dates after harvest (Sarraf et al., 2021). Therefore, it is necessary to prevent or minimize the impacts of such quality degradation factors through applying appropriate agricultural practices and effective decontamination and preservation methods. Also, it is important to find effective and appropriate techniques to slow down the ripening process of Khalal dates and keep their freshness for a longer period after picking and during handling, marketing, and storage.

Accordingly, numerous studies investigated the impact of preservation methods on Khalal dates' quality and storage stability after harvesting, e.g., refrigeration (Ghafoor et al., 2022), modified atmosphere packaging (Aleid and AL Saikhan, 2017), ripening inhibitors (Al-Qurashi and Awad, 2011), edible coatings developed by dipping (Ghafoor et al., 2022) or ultrasonication method (Mohammed et al., 2024), natural plant extracts (Ghafoor et al., 2022; Alqahtani et al., 2023a,b), lactic acid (Alqahtani et al., 2023a,b), salicylic acid (Atia et al., 2020), calcium chloride (Atia et al., 2020), and ultrasound treatment (Abdelkarim et al., 2022). Therefore, the current review targets to: (1) discuss the physicochemical, mechanical, and biological factors that have been confirmed to have a deteriorating effect on the quality of stored Khalal date palm fruits; (2) explore the past and recent techniques to preserve the quality and improve storage stability of date fruits at Khalal stage; (3) specify the research needs and future vision to make the Khalal date palm a promised industry and profitable trade.

2 Quality degradation factors of Khalal date fruits

2.1 Metabolic and physiological changes during ripening

Due to their climacteric nature, dates produce the ethylene hormone and pass through a series of physiological changes during the maturation process, leading to full ripeness (Al-Qurashi and Awad, 2011; Ghafoor et al., 2022). Generally, since fertilization till ripeness, date fruits development process has five stages (as mentioned in Figure 2), based on the Arabic naming, as follows: (1) Hababouk represents the first stage after fertilization and lasts 4–5 weeks where the fruits have a round shape, a small size as chickpea, and a light green color; (2) Kimri reflects immature fruits with oval shape, firm texture, and green color; also, the fruits have a rapid increase in weight and size with a high moisture content and tannin concentration; it continues for 9–14 weeks based on the cultivar., climate, and location; (3) Khalal/Bisr/Bisir/Balah represents the first maturity stage at which fruits become consumable and reach its maximum size and weight with firm and crunchy texture, yellow or red color, and sweet taste as Khalal has the highest sucrose content among maturity stages (Sidhu, 2006); also, Khalal stage takes about 3–5 weeks; (4) Rutab refers to soft, light brown, and ripe date fruit; however, moisture, protein, fat, and ash contents of dates decrease while sugar content increases at this stage which can be ascribed to the conversion of starch to sugar; it lasts about 2–4 weeks; (5) Tamr/Tamar/Tamer stage represents fully ripe fruits that have a softer texture, wrinkled shape, dark brown color with highest TSS, highest sweetness, and lowest astringency; it continues for 2–4 weeks (Siddiq and Greiby, 2013; Abdelkarim et al., 2022).

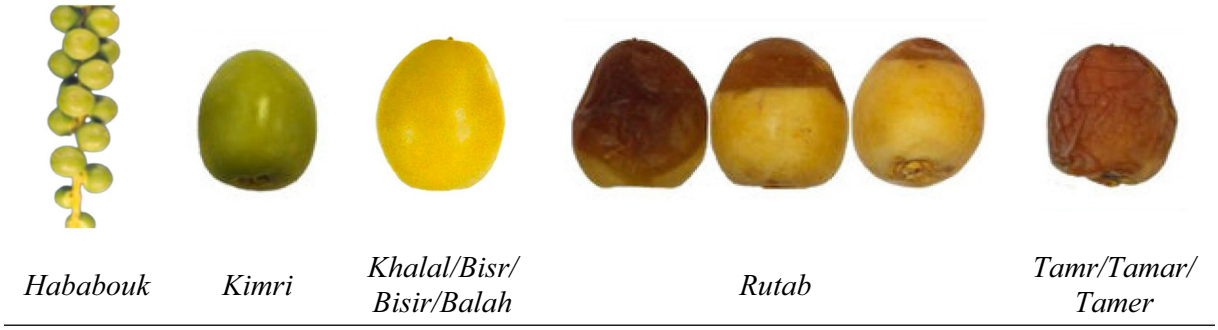

FIGURE 2
Maturity stages of dates. Adopted from Siddiq and Greiby (2013) and Alqahtani et al. (2023b).

As mentioned in Figure 3, date fruits are subjected to a series of sequenced metabolic and physiological changes during the ripening process which is controlled by several factors including the genotype, bunch size, ambient temperature, time of exposure to light, water, and carbohydrate supply, and hormonal levels, mainly gibberellin, auxin, and ethylene (El Hadrami and Al-Khayri, 2013).

The genetic system of the cell nucleus is considered the crucial factor affecting the ripening process of dates through the transcription of ripening-motivated genes and synthesis of specific proteins (Figure 3), such proteins (a) motivate ethylene synthesis and abscisic acid which in turn accelerates ripening and increases the mitochondrial respiration, (b) activate the formation of sugars, organic acids, and volatile compounds (improve taste and odor), (c) facilitate the production of enzymes responsible for the degradation of pigments (cause color changes), (d) motivate the production of enzymes that facilitate the degradation of pectin and cell wall (cause tissues softening) (El Hadrami and Al-Khayri, 2013). In addition, the ripening process (after harvesting) can be greatly affected by storage temperature, respiratory rate, moisture content, O_2, and ethylene levels (Sarraf et al., 2021). It is worth noting that respiration rate and ethylene emission were maximum at the Khalal compared to other ripening stages (Siddiq and Greiby, 2013). Water loss is a crucial factor affecting the dates' post-harvest quality; a previous study showed that the moisture content decreased markedly from 66% (at the Khalal) to 43% (at the Rutab stage) (Al-Shahib and Marshall, 2003).

Although no sufficient studies have been carried out on the hormones responsible for date ripening, auxins may be involved in the motivation of fruit development through the stimulation of ethylene synthesis. Gibberellins, in contrast, are expected to increase the length of fruit stalks within the bunches, consequently decreasing compaction and allowing dates to grow larger. Ethylene, the main ripening hormone, is produced from methionine and the intermediate S-adenosylmethionine through the aid of two main enzymes (1-aminocyclopropane-1-carboxylic acid synthase and oxidase); the oxygen level during storage is a critical factor affecting the activity of these enzymes and, accordingly, the ethylene synthesis process (El Hadrami and Al-Khayri, 2013).

Phytohormones (plant hormones) are a group of chemical compounds produced in plants in low concentrations to regulate their growth, development, reproductive processes, longevity, and even death (Dilworth et al., 2024). Generally, the common phytohormones are jasmonates, salicylic acid, cytokinins, gibberellins, brassinosteroids, abscisic acid, and ethylene (Arif et al., 2020). Jasmonates are produced from fatty acids, methyl jasmonates, and jasmonic acid and regulate plant growth, development, and reproduction. Jasmonates have multiple defense responses against pathogenic and environmental stresses, therefore, they represent an important member of the defense system (Wani et al., 2016). Moreover, jasmonic acid is expected to regulate ripening through transcription factors and ethylene synthesis genes but the mechanism requires verification (Kou et al., 2021). Salicylic acid, a natural phenolic, is another essential hormone of the defense system and has significant impacts on growth, development, ripening, and response to environmental stresses (Xiang et al., 2021). In addition, salicylic acid may play converse roles based on its concentration, i.e., the low concentration can improve the resistance to environmental stresses while high concentrations may motivate cell degradation (Wani et al., 2016). Cytokinins are a group of process regulators, mainly growth, in plants. Several authors confirmed that cytokinins can motivate cell division, bud growth, seed germination, and chloroplast formation and therefore it can delay ripening and senescence (Wani et al., 2016). The kinetin and 6-benzylaminopurine (types of cytokinins) have been approved by the USA Environment Protection Agency as safe plant growth regulators, accordingly, they have been widely used to prolong fruits' shelf life (Xu et al., 2012).

Similarly, gibberellins act as growth and development regulators; they can stimulate cell division and seed germination. Moreover, gibberellins have an antagonistic relationship with senescence-related hormones, mainly, ethylene and abscisic acid; accordingly, they are widely applied to extend the horticultural products' shelf life (Xiang et al., 2021). Brassinosteroids, sterolide compounds produced from mevalonic acid, are similar to cytokinins in biosynthesis and the roles in enhancing the plant tolerance to biotic and abiotic stresses and adaptation to environmental stresses (Xiang et al., 2021). Ethylene and abscisic acid are the two main senescence, maturity, and ripening hormones. Their concentration usually increases with the advancement of ripening and senescence of horticultural products; also, injured and senescent fruits have a high concentration of these hormones after harvest (Xiang et al., 2021). Accordingly, the control of synthesis and metabolism of these hormones is crucial to preserve fruit quality. Other phytohormones (discussed above) have direct or indirect impacts on the synthesis and metabolism of ethylene and abscisic acid and can be used to protect fruits from multiple postharvest disorders and diseases.

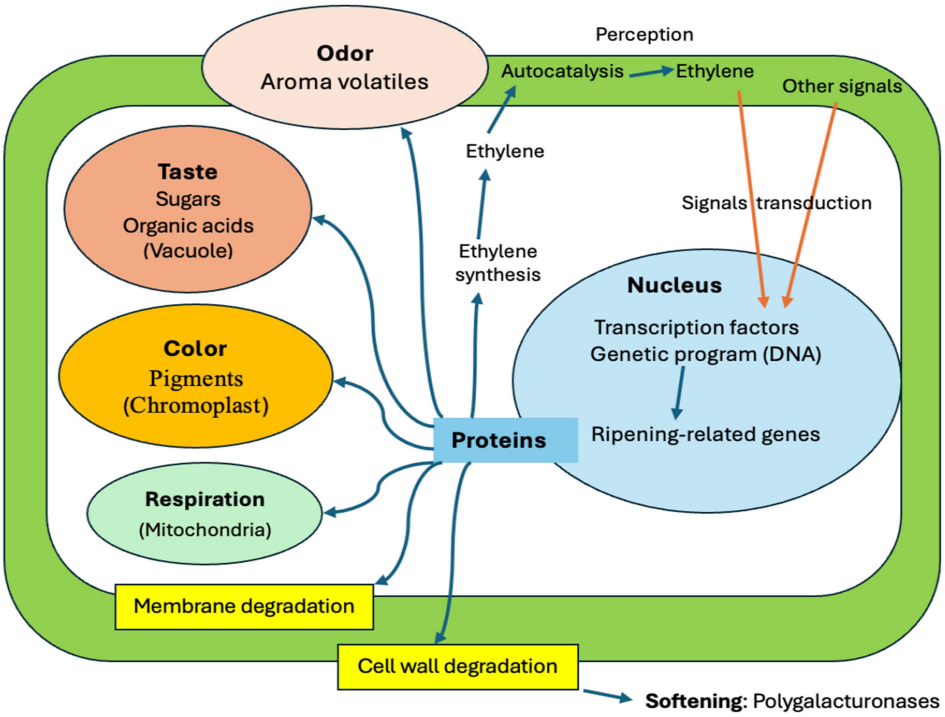

FIGURE 3
Diagram showing the series of metabolic changes that occur in dates during the ripening process. Adapted from El Hadrami and Al-Khayri (2013).

However, the decline of the post-harvest quality of the fruits mainly occurs due to over-ripening, senescence, pathogenic deterioration, physiological disorder, and mechanical injury. The plant cell has a defense system consisting of multiple compounds including phytohormones to face abiotic and biotic stresses through complex mechanisms; jasmonates and salicylic acid represent the main phytohormones that contribute to defense system which motivates defensive responses such as insect resistance (triggered by jasmonates) and disease resistance (induced by salicylic acid) (Xiang et al., 2021). Briefly, climacteric fruits, including date palm, are subjected to ripening and senescence after harvest; such processes could be controlled by promoting and inhibiting phytohormones (Figure 4), i.e., ethylene and abscisic acid (promoting factors) can be applied to accelerate ripening and senescence processes while cytokinins and gibberellins (inhibiting factors) can be applied to prevent or delay ripening and senescence processes through inhibition of the biosynthesis and/or sensitivity of senescence-related phytohormones. Accordingly, cytokinins and gibberellins pathways are crucial to extending the post-harvested shelf life of date fruits.

In addition, enzymes play a crucial role in the ripening process of dates and affect their quality and shelf-life. Under ambient conditions, enzymatic activity at the Khalal stage increases leading to significant changes in the physicochemical properties of the fruits as follows: (1) the fruits' skin color changes from yellow/red to brown due to the enzymatic degradation of the skin pigments besides the enzymatic browning through the oxidation of polyphenolic compounds (Sarraf et al., 2021); (2) the fruit's firmness decreases greatly due to the degradation of pectin by polygalacturonase and pectinesterase enzymes and the fruits are softened and the crunchy texture is lost; also, cellulose, hemicellulose, lignin, and total fiber contents reduces with ripening progression (Aleid, 2013); (3) fruit's sweetness increases due to starch conversion into sugars (Lobo et al., 2013); (4) fruit's astringency decreases significantly due to the polymerization of tannins, a group of phenolic compounds responsible for astringency in dates and other fruits, and this reduction stills with the progression of ripening which results in improving the taste (Lobo et al., 2013); (5) although the fruits weight increases to reach its maximum value at the Khalal stage, it decreases with the advanced ripening at Rutab stage, mainly, due to water lose (Lobo et al., 2013). Accordingly, there is an urgent need to decrease water loss, delay ripening, maintain the crunchy texture, and keep the desirable flavor and taste of dates by applying different preservation methods.

2.2 Inappropriate practices during harvest and post-harvest

The procedures applied during harvesting, transportation, handling, packaging, marketing, and storage affect Khalal dates' quality and storage stability. First, harvesting time should be determined carefully as it can directly affect dates post-harvest quality. Propper harvesting time protects dates from cracking, splitting, dehydration, and insect and microbial attack (Kader and Hussein, 2009). Generally, Khalal dates are mainly picked when their color becomes yellow or red, based on the variety (Lobo et al., 2013). Also, cultivar properties, such as moisture, sugar, and soluble tannins content (affect taste and texture), besides climatic conditions and market demand, should be considered to indicate the optimum harvesting time (Aleid, 2013). Too early picking should be avoided as the fruits are very immature and cannot respond to artificial ripening,

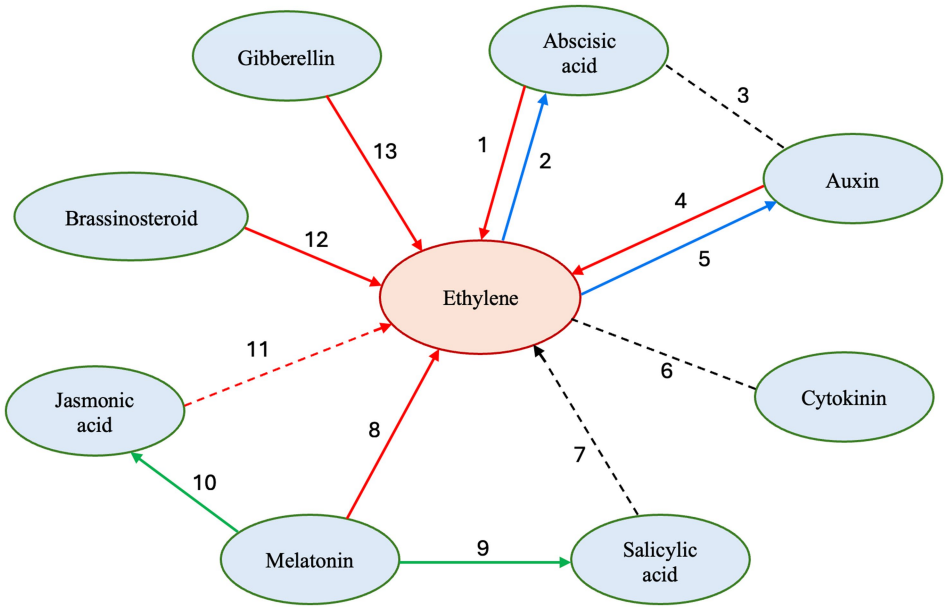

FIGURE 4
The regulatory relationship of phytohormones in climacteric fruits during ripening. Adapted from Kou et al. (2021). The numbers on the figure can be illustrated as follows: 1, abscisic acid promotes ethylene synthesis by regulating ethylene biosynthesis genes; 2, Abscisic acid has a synergistic effect with ethylene; 3, the signals of ethylene, auxin, and abscisic acid are regulated by auxin response factor (ARF) during fruit ripening; 4, auxin response factor is the core of auxin signaling; 5, ethylene affects the expression mechanisms of the genes producing proteins of auxin carriers and auxin response. 6, the relation between ethylene and cytokinin is not well known; other studies (Xiang et al., 2021) confirmed that cytokinins can motivate cell division, bud growth, chloroplast formation and may delay ripening and senescence; 7, salicylic acid inhibits the expression of the genes responsible for ethylene production; 8, melatonin contributes to the regulation of ethylene-related genes expression; 9 and 10, melatonin motivates the signaling pathways of salicylic acid and jasmonic acid (defense hormones); 11, jasmonic acid regulates ripening through transcription factors and ethylene synthesis genes but the mechanism stills to be verified; 12 and 13, regulate ethylene-related genes. The red arrow shows the regulating effect on the genes related to ethylene synthesis; the blue arrow reflects the impact of ethylene on other hormones; the green arrow refers to activation, and the dotted line reflects a regulatory relationship, but the mechanism is not verified.

resulting in poor quality (Lobo et al., 2013). Oppositely, late harvesting can cause over-ripening, where the fruits become soft and more susceptible to microbial spoilage and insect infestation.

Also, the harvesting method represents a critical factor that impacts the quality, safety, and shelf-life of Khalal dates. Dates at the Khalal stage are very perishable due to the higher moisture and sugar content. Therefore, inappropriate practices during the harvesting and post-harvest processes can negatively affect fruits' quality and marketability (Yahia et al., 2013). In general, date fruits are harvested manually; the harvesting laborers can access the tree's crown by climbing, ladders, picking platforms, and mechanical lifts (Yahia et al., 2013). However, using sharp tools like knives or sickles and applying excessive force during harvesting can cause injuries, bruises, punctures, and breakages of the fruits, which decreases quality, facilitates microbial attack, increases insect infestation, and accelerates spoilage.

In addition, handling and transportation of dates during post-harvest processing are crucial factors in keeping quality and improving storage stability as the fruits are firm and perishable. Freshly harvested dates should be cooled as soon as possible and transported under refrigerated conditions to retard or minimize water loss, quality degradation due to physiological changes (respiration and ripening), microbial attack, and insect infestation (Kader and Hussein, 2009). Hydrocooling is recommended for Khalal dates; an effective disinfectant should be added to the cooling water, and then excess moisture on the cooled fruit surface should be removed; therefore, forced air cooling could be a better option than hydrocooling (Kader and Hussein, 2009). The handling process includes sorting, grading, disinfection, dehydration, and packaging (Sarraf et al., 2021). Generally, rough handling, e.g., using high stacks or tightly packed containers, using tough containers with sharp edges, overloading, overcrowding, improper loading and unloading, and inappropriate transportation can cause physical damage such as injury, bruising, and crushing, which decreases the quality and shortens the fruits' shelf-life.

Furthermore, cleaning procedures may negatively affect fruits' quality and shelf-life if they are not properly carried out. It is well known that freshly harvested fruits may contain dust, dirt, or pesticide residues on their surfaces (Yahia et al., 2013). Washing (with water) is the most common cleaning method, but applying sanitizers is highly recommended for contaminant removal, microorganism disinfection, and cross-contamination prevention. However, improper washing and sanitizing may spread these contaminants and increase microbial contamination, which affects fruits' appearance, quality, and safety. Oppositely, over-washing may result in physical damage, removing the outer protective layer of the fruits, making them more susceptible to water loss and microbial infection.

Storage conditions, mainly temperature and humidity, of Khalal dates, play critical roles in keeping quality and prolonging the shelf-life. High temperature can increase the respiration rate, motivate ethylene emission, activate catabolic enzymes, and catalyze the ripening and conversion of fruits to the Rutab stage. Moreover, high temperatures during harvest and post-harvest processing can increase

water loss, which results in dry, hard, and shriveled fruits. Also, microbial growth can be multiplied under higher temperatures and humidity, causing deterioration and shortening the shelf-life. Therefore, cold storage is an indispensable option during the storage of Khalal dates to preserve quality, ensure safety, delay over-ripening, and minimize microbial growth and insect infestation (Sarraf et al., 2021). Generally, Khalal dates should be stored at 85 to 95% relative humidity to prevent water loss; additionally, dates should not be stored with products that have strong or undesirable odors, such as garlic, onion, and potato (Kader and Hussein, 2009).

However, for better quality and longer shelf-life of Khalal dates, the following recommendations should be applied:

1. The harvesting time should be determined accurately; too early and too late harvesting time should be avoided.
2. The harvesting process should be carried out carefully; injuries, bruises, punctures, and breakages of the fruits should be prevented or minimized.
3. Handling and transportation should be conducted correctly; tough containers, overloading, improper loading and unloading, and inappropriate transportation can cause physical damage.
4. Cleaning procedures should be conducted properly; insufficient sanitizing and overwashing should be avoided.
5. Storage conditions should be adjusted; low temperature, controlled humidity, and low oxygen levels are highly advisable. Products with undesirable odors should not be stored with dates.
6. Using a cold chain (Figure 5) during handling and marketing is highly recommended (Yahia et al., 2013).

2.3 Microorganisms

Microbial spoilage is the major factor causing quality deterioration of Khalal dates after harvesting, particularly at higher temperatures and relative humidity, e.g., when the crop is harvested during or after heavy rains (Lobo et al., 2013). Dates at the Khalal stage are susceptible to microbial attack with spoilage and pathogenic bacteria besides yeasts and fungi due to their higher moisture and sugar content; generally, *Escherichia coli, Staphylococcus aureus,* and *Bacillus cereus* are the main pathogenic bacteria that have been detected in Khalal dates (Sidhu, 2006). Similarly, the main fungal genera causing date spoilage are *Alternaria*, *Aspergillus*, *Cladosporium*, *Fusarium*, *Rhizopus*, and *Penicillium* (Sarraf et al., 2021). Generally, *Aspergillus* is the most abundant genus of fungi that can attack date fruits at all ripening stages, causing spoilage and aflatoxin contamination (Lobo et al., 2013). Aflatoxins are chemical substances developed by some

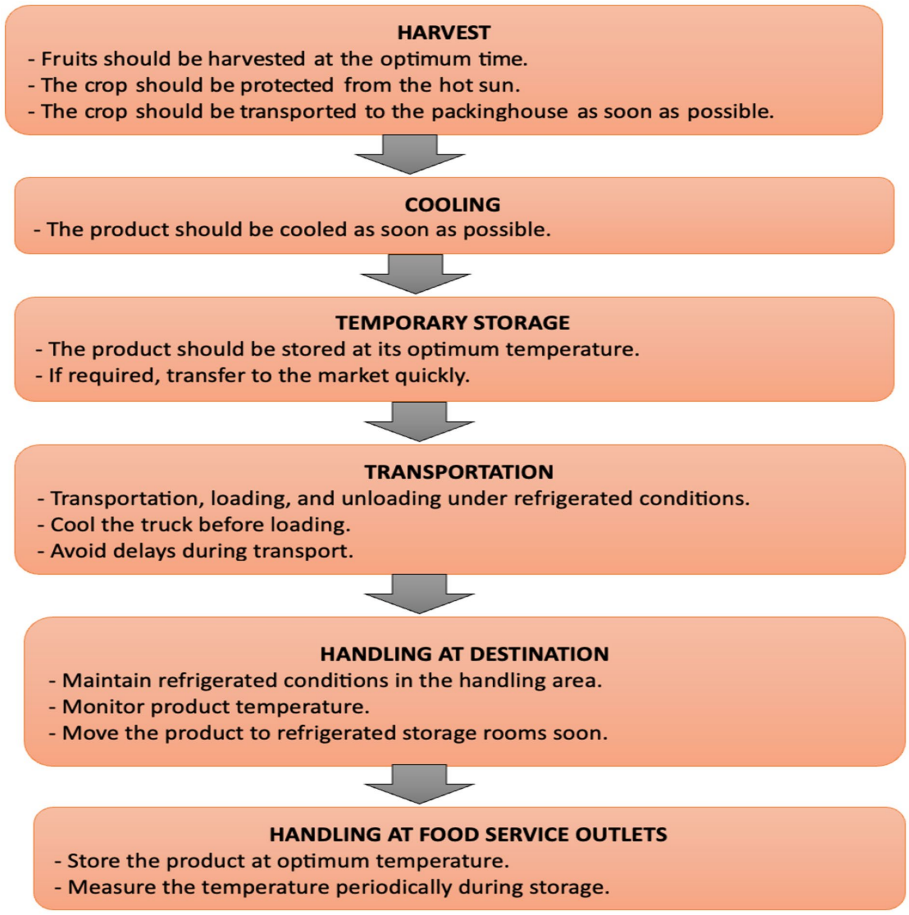

FIGURE 5
Maintaining cold chain for the Khalal dates. Adopted from Yahia et al. (2013).

toxigenic fungal strains, such as *Aspergillus flavus* and *Aspergillus parasiticus,* with carcinogenic, mutagenic, and teratogenic effects (Ahmed et al., 1997). A previous study (Ahmed and Robinson, 1998) confirmed the detection of aflatoxins (B1 and G1) in date samples infected with *Aspergillus parasiticus* at the Khalal stage. *Aspergillus flavus*, at advanced growth levels on dates, can cause aflatoxin contamination, making the fruits unsafe for human consumption (Yahia et al., 2013). Similarly, *Aspergillus parasiticus* can attack Khalal date fruits and produce aflatoxin within 10 days under storage at 28°C (Sidhu, 2006).

Moreover, *Fusarium oxysporum* f. sp. *albedinis* causes one of the most dangerous diseases of date palm known as Bayoudh; it invades the date palm tree through the roots, producing foliar withering and leading to the death of the seedlings and trees (El Modafar, 2010). The most important method to face Bayoudh was through the development and planting of resistant cultivars; unfortunately, Bayoudh-resistant date palm varieties usually produce low-quality fruits (Dihazi et al., 2012). However, biological control using microorganisms represents a promising trend to face Bayoudh (Dihazi et al., 2012). Due to its tolerance to the higher sugar content than other microorganisms, yeast species of *Zygosaccharomyces*, such as *Z. mellis,* commonly attack dates, causing fermentation with the development of an alcoholic odor (Lobo et al., 2013). Additionally, the alcohol may be converted to acetic acid by *Acetobacter* bacteria, leading to the souring of dates (Lobo et al., 2013). However, using efficient sanitation procedures in packinghouses and storage rooms can significantly decrease microbial contamination. Additionally, using a cold chain throughout the Khalal dates handling and marketing stages can significantly minimize microbial growth and, therefore, ensure safety, preserve quality, and prolong the shelf-life (Yahia et al., 2013). Other technologies applied to control microbial growth will be discussed below.

2.4 Insect infestation

Insects represent a principal factor responsible for the quality loss in all date maturity stages. Generally, the absence of insect infestation is a crucial index for date quality according to CODEX standards (Abo-El-Saad and El-Shafie, 2013). Date fruits are attacked by different types of insects; generally, beetles and weevils (Order: *Coleoptera*) and moths (belong to the order *Lepidoptera*) are the two major groups of insects that attack date fruits and cause severe loss in their quality and market value (Abo-El-Saad and El-Shafie, 2013). In addition, non-insect pests such as mites, mollusks, bats, rats, and birds sometimes attack dates, causing contamination and quality deterioration. Most of the published literature discussed insect infestation in the Rutab and Tamer stages, while very few studies covered the Khalal stage (Sidhu, 2006; Sarraf et al., 2021).

The carob moth (*Ectomyelois ceratoniae*), order *Lepidoptera*, represents one of the most dangerous pests attacking date palm fruits in the ripening stages, including Khalal, and remains in the infested fruits through the post-harvest processing and during storage (Perring et al., 2015). Fruits are damaged by the carob moth as follows: the larvae penetrate the fruits and feed on the internal component, causing severe deterioration with large quantities of frass, making the dates unsuitable for human consumption (Abo-El-Saad and El-Shafie, 2013; Negm et al., 2015). *Parlatoria blanchardi,* order *Hemiptera*, also known as the white date scale or the armored scale insect, is one of the most important insects that attack dates at Kimri and Khalal stages by sucking the sap from the dates resulting in small, stunted, shriveled, and distorted fruits which severely decrease their market value; also, the scale forms white filaments around the fruits which retard photosynthesis and therefore prevent maturity (Negm et al., 2015; Sarraf et al., 2021). Also, the larvae of *Batrachedra amydraula*, order *Lepidoptera*, called the lesser date moth, attack dates at various maturity stages, i.e., the larvae of the first generation penetrate the Hababouk dates and feed on the internal content of the fruit (Perring et al., 2015). Similarly, Kimri and Khalal fruits are attacked by the following generations of the lesser date moth larva; the infested fruits become reddish; after 4 weeks, the fruits become brown, dry out, and fall from the tree; moreover, the rot-causing microorganisms may enter the infested fruits and cause fruit decay and fermentation (Negm et al., 2015; Perring et al., 2015; Sarraf et al., 2021).

The dust mite (*Oligonychus afrasiaticus*), class *Arachnida*, also called old world date mite, is a serious pest invading date palm fruits at Hababouk, Kimri, and Khalal stages (Yahia et al., 2013; Negm et al., 2015). The dust mite feeds by injuring the fruits' surface and sucking the plant sap released from these wounds or scratches and produces gum-like exudates on the fruit surface (Negm et al., 2015). Also, the mites form a dense webbing onto which dust accumulates around the fruits, which negatively affects the physicochemical processes of the fruits, retards ripening, and reduces water and TSS content leading to fruits of poor quality with hard injuries and scratches (Chaaban and Chermiti, 2009; Negm et al., 2015). Spider mites (*Oligonychus pratensis*), class *Arachnida*, also known as New World date palm mites, or banks grass mites, are the main pests attacking date fruits at the Kimri and Khalal stages; it makes scratches and wounds on fruits' surfaces and sucks the bleeding sap from these injuries (Negm et al., 2015). Due to the necrosis of fruit tissues, the color of the infested area becomes grayish-white, and at severe infestation, fruits may turn brown or reddish-black with silky threads around the fruits; finally, the fruits become hard, shrivel with many cracks, and unripe properly, resulting in low-quality fruits that are unsuitable for fresh market consumption (Negm et al., 2015). Dried-fruit beetle (*Carpophilus hemipterus*), confused sap beetle (*Carpophilus mutilates*), pineapple beetle (*Urophorus humeralis*), and pineapple sap beetle (*Haptoncus luteolus*) all belong to the order *Coleoptera* and also attack date fruits at different maturity stages, causing serious damage to the fruits (Sarraf et al., 2021). Generally, various insect control programs should be applied during different maturation stages before harvesting; once the crop is harvested, infested fruits should be discarded during the sorting process.

3 Applications to extend the post-harvest shelf-life of Khalal dates

Based on the literature, various methods have been investigated to preserve the quality and stability of Khalal dates during storage (Tables 1, 2). More details about each method are discussed below.

3.1 Cold storage

Cold storage is the most common and effective preservation method for a wide sector of food products worldwide, particularly

TABLE 1 Advantages and disadvantages of preservation methods of Khalal date fruits.

Method	Advantages	Disadvantages	References
Cold storage	• Delayed ripening. • Extended the shelf-life. • Maintained the quality. • Retarded enzymatic reactions. • Inhibited microbial growth. • Slowed down insect activity.	• Chilling injuries. • Refrigerated temperature does not kill insects and psychrophilic microorganisms.	Siddiq and Greiby (2013); Sarraf et al. (2021); Ibrahim et al. (2024)
MAP	• Minimized respiration rate. • Delayed the ripening process. • Reduced microbial growth. • Decreased insect activity.	• It may affect fruit appearance, odor, and flavor. • Requires specific packages. • The gas combinations should be monitored during storage. • It should be accompanied by cold storage.	Kader et al. (1989); Exama et al. (1993); Chonhenchob et al. (2013); Ahmed et al. (2023)
Edible coatings	• Retarded water loss. • Decreased respiration rate. • Delayed ripening processes.	• It is a time-consuming technology. • It should be used along with cold storage. • It may affect fruit appearance, taste, and flavor.	Ncama et al. (2018); Senturk Parreidt et al. (2018)
Lactic acid	• Inhibited microbial growth. • Extended the shelf-life.	• The higher concentrations of LA negatively affect the sensory properties of stored fruits. • It should be used along with cold storage.	Seddiek et al. (2022); Alqahtani et al. (2023b)
Calcium chloride	• Prevented fruit softening. • Delayed ripening. • Decreased color changes.	• It should be accompanied by cold storage.	Irfan et al. (2013); Atia et al. (2020)
Natural plant extracts	• They have a higher antimicrobial and antioxidant activity. • Decreased moisture loss. • Minimized color changes. • Maintained fruits' firmness. • Inhibited fungal growth.	• It is a time-consuming method. • The high cost of extraction. • The effects on fruits appearance and odor. • It requires cold storage.	Seddiek et al. (2022); Alqahtani et al. (2023a); Alqahtani et al. (2023b)
Growth inhibitors	• Delayed fruit ripening. • Extended the shelf-life. • Maintained the quality of dates. • Maintained a higher content of vitamin C.	• This method is more effective if applied before harvesting. • It requires cold storage.	Mohammed and Shabana (1980); Hussein et al. (1993); Al-Qurashi and Awad (2011)
Ultrasonic	• Inhibited microbial growth. • Preserved fruit quality. • Extended the shelf-life of Khalal dates.	• It should be supported with cold storage.	Abdelkarim et al. (2022)

fruits and vegetables (Siddiq and Greiby, 2013; Mohammed et al., 2024). Generally, it depends on keeping the product at a controlled low temperature which markedly prevents or minimizes the growth of spoilage microorganisms, retards insect infestation, and decreases enzymatic activity; moreover, it delays post-harvest physiological changes, including respiration, water loss, ripening, and senescence which in turn can extend the shelf-life and maintain the quality and freshness of the fruits (Siddiq and Greiby, 2013; Sarraf et al., 2021; Ibrahim et al., 2024). Due to their climacteric nature, Khalal dates produce ethylene, the natural ripening hormone, and are subjected to post-harvest physiological changes leading to ripening (Al-Qurashi and Awad, 2011; Ghafoor et al., 2022). Therefore, cold storage is critical for decreasing post-harvest changes, delaying the ripening process, and preventing the conversion of Khalal dates to Rutab (Siddiq and Greiby, 2013).

Several reports confirmed that cold storage is an effective preservation method for maintaining the quality and extending the shelf-life of Khalal dates. Sarraf et al. (2021) stated that cold storage could significantly reduce undesirable changes in the quality of Khalal dates, mainly flavor and texture. These authors reported that Khalal dates should be kept at 0°C and 85%–95% RH to minimize water loss and delay over-ripening. In addition, maintaining low temperatures during transportation, delivery, distribution, handling, and marketing of dates is highly recommended to preserve quality, maintain safety, and extend the shelf-life as it minimizes color, flavor, and textural changes, retards microbial growth, prevents insect infestation, and decreases the incidence and severity of souring (Yahia et al., 2013; Ibrahim et al., 2024). Moreover, storage of date fruits at low temperatures (below 5°C) prevents the growth of pathogenic bacteria (Abdul Aly et al., 2018). As aflatoxin-producing fungi growth is directly affected by storage temperature (Mukherjee et al., 2018), cold storage of Khalal dates could be an effective option to avoid aflatoxin contamination. The efficiency of cold storage is mainly affected by (1) the fruits' initial quality, (2) the degree of microbial contamination and insect infestation, and (3) the temperature applied (Lallouche et al., 2017). Additionally, avoiding temperature fluctuations during cold storage is critical to control microbial growth (Sarraf et al., 2021).

TABLE 2 Comparison between the preservation methods of Khalal date fruits in terms of effectiveness and quality degradation indices.

Quality parameter	Preservation method							
	Cold storage	MAP	Edible coatings	Lactic acid	Calcium chloride	Natural plant extracts	Growth inhibitors	Ultrasonic
Shelf life	3 weeks	4 weeks	4 weeks	4 weeks	5.7 weeks	6 weeks	8.5 weeks	3 weeks
Moisture loss	8%	1%	9%	9%	29%	9%	5%	n.d
TSS	20%↑	19%↑	23%↑	18%↑	23%↑	15%↑	6%↓	10%↑
pH	22%↓	n.d*	9%↓	12%↓	n.d	15%↓	n.d	n.d
TTA	100%↑	n.d	42%↑	71%↑	n.d	92%↑	33%↑	n.d
Total phenolics	61%↓	n.d	25%↓	50%↓	n.d	58%↓	75%↓	25%↓
Antioxidant activity	46%↓	n.d	22%↓	44%↓	n.d	44%↓	n.d	17%↓
L* value	25%↓	29%↓	13%↓	22%↓	15%↓	17%↓	n.d	30%↓
Firmness	92%↓	50%↓	96%↓	92%↓	30%↓	92%↓	87%↓	90%↓
Sensory acceptance	20%↓	18%↓	8% ↓	16%↓	39%↓	17%↓	n.d	n.d
References	Alqahtani et al. (2023b)	Al-Eid et al. (2012)	Ghafoor et al. (2022)	Alqahtani et al. (2023b)	Atia et al. (2020)	Alqahtani et al. (2023b)	Al-Qurashi and Awad (2011)	Abdelkarim et al. (2022)

*n.d, not determined; ↑, means increase; ↓, means decrease.

Regarding the quality degradation indices, a previous study conducted by (Alqahtani et al., 2023b) showed that the quality of Khalal dates, stored under refrigerated conditions (4 ± 1°C), declined significantly with prolonged storage. The authors reported that the moisture loss was about 8% after 3 weeks (the end of the storage period). Matching with the decline in the moisture content, the authors recorded an increase in the TSS of Khalal dates by 20% after 3 weeks of cold storage. Similarly, the pH of refrigerated Khalal dates decreased by 22% while titratable acidity multiplied after 3 weeks of storage. Also, total phenolics decreased by 61% and antioxidant activity decreased by 46%. Firmness, a crucial indicator of ripening, decreased by 92% by the end of storage, indicating the loss of fruits' firmness and the conversion to Rutab. L* value, an indicator of color darkening, decreased by 25% due to the advancement of ripening. The sensory parameters (appearance, odor, taste, texture, and overall acceptability) of cold-stored Khalal dates decreased with the extended storage; however, the Khalal dates were sensorially acceptable up to 3 weeks of cold storage with an overall acceptability score of 6.71 (decreased by 20%) based on the nine-point hedonic scale. Although cold storage is the most common preservation method, particularly for fruits, postharvest changes, e.g., moisture loss, shrinking, overripening, softening, and flavor changes, are still high (Fawole et al., 2020). Besides, the growth of some low-temperature-tolerant microbial strains may affect the quality and safety of stored dates. Accordingly, additional preservation methods should be applied along with low-temperature storage to improve the preservation process efficacy (Mohammed et al., 2024).

3.2 Modified atmosphere packaging (MAP)

MAP is an effective technique that has been widely applied to prolong the shelf-life of fresh foods, particularly fruits, and vegetables; it depends on modifying the percentages of gases in the air surrounding the food product, namely decreasing O_2 and increasing CO_2 levels that can reduce oxidation reactions, retard microbial spoilage, delay shrinkage, decrease enzymatic browning, preserve the sensory quality of food product compared to the normal atmosphere (Ahmed et al., 2023). Modifying the air composition inside the stored fruit's package provides optimum conditions to maintain freshness and prolong the shelf-life for a longer time (Qu et al., 2022). Additionally, MAP can reduce respiration rate, decrease ethylene production, delay ripening, decrease metabolic heat production, minimize quality loss, and prolong fruits' shelf-life (Kader et al., 1989; Chonhenchob et al., 2013). The efficacy of MAP depends on the package's permeability, storage temperature, and respiration rate (Chonhenchob et al., 2013). A previous study (Al-Eid et al., 2012) investigated the effect of MAP on the quality and storage stability of Khalal dates under refrigerated conditions. These authors reported that dates stored in MAP (20% CO_2 in air), using packs sealed with a non-permeable film, minimized fruits' weight loss during storage, which was <1% after 4 weeks. The TSS of Khalal dates increased by 19%; however, the increase in TSS of dates stored in MAP (20% CO_2 in air) was lower than other treatments. Dates stored in 20% CO_2 in air revealed significant retention of fruit firmness, a principal indicator of ripening, with 50% compared to other treatments. Similarly, the L* value decreased by 29%; the decrease in the L* value for this treatment was lower compared to other treatments. Although sensory scores decreased during storage, dates stored in 20% CO_2 in air revealed better retention of sensory properties after 4 weeks of storage with an overall acceptability score of 5.3 (decreased by 18%) based on the 9-point hedonic scale that was higher than other treatments. MAP could be applied without adding gasses, known as passive MAP, where the fruits consume the O_2 and produce CO_2 through normal aerobic respiration; this results in higher levels of CO_2 and lower levels of O_2 inside the sealed package with the advancement of storage time (Mortazavi et al., 2007). A previous study conducted on the effect of passive MAP on the shelf-life of Barhee date fruits at the Khalal stage showed that passive MAP decreased metabolic activities, minimized weight loss, reduced

softening, delayed ripening, maintained sensory quality, and preserved the Khalal date shelf-life to 20 days under refrigerated storage (Mortazavi et al., 2007). However, inappropriate design of MAP may negatively affect sensory properties and shorten the shelf-life of the stored product (Exama et al., 1993).

3.3 Edible coatings (ECs)

ECs are natural polymers applied on food products, mainly fruits and vegetables, in a thin layer to preserve the quality and prolong the shelf-life by retarding water loss, decreasing respiration rate, and preventing gas exchange from fruits' surfaces (Senturk Parreidt et al., 2018). ECs could be prepared from (1) polysaccharides, e.g., starch, alginate, chitosan, and carrageenan; (2) proteins, e.g., gluten and collagen; and (3) Lipids, e.g., waxes and vegetable oils (Yaashikaa et al., 2023). ECs represent a safe, simple, non-thermal, and eco-friendly method to preserve fruit and vegetables, which is compatible with the global demand for healthy foods (Özden and Bayindirli, 2002). Additionally, several reports confirmed that ECs can be used to preserve fresh fruits and vegetables as they can delay ripening processes, decrease respiration rate, decrease moisture and weight loss, retard softening, minimize undesirable changes in taste and odor, delay browning and discoloration, and reduce nutrients' loss (Ncama et al., 2018). However, few studies were carried out on using ECs to preserve the quality and prolong Khalal dates' shelf-life. The effect of chitosan-based edible coating on the quality of fresh Khalal dates (Barhee variety) stored under refrigerated conditions was evaluated (Ghafoor et al., 2022). These authors reported that chitosan-based edible coatings enriched with natural extracts maintained hardness, preserved sensory properties, inhibited mold growth, maintained fruits' quality, and extended the shelf-life to 4 weeks. Dates coated with chitosan and orange peel extract showed the lowest changes in quality degradation parameters, i.e., the moisture loss was 9%, TSS increased by 23%, pH decreased by 9%, TTA increased by 42%, phenolics content decreased by 25%, antioxidant activity decreased by 22%, L* value decreased by 13%, hardness decreased by 96%, and sensorial acceptance decreased by 8% at the end of storage (4 weeks). A recent study investigated the effect of ECs prepared from gelatin, chitosan, and guar gum on the quality of cold-stored Khalal dates (Abu-Shama et al., 2020); the authors confirmed that the coating with guar, gelatin+guar+chitosan, and gelatin+guar were the most effective treatments in delaying ripening, reducing moisture loss, preserving vitamins and polyphenols content, maintaining sensory properties, inhibiting bacterial growth, and prolonging the Khalal dates' shelf-life (8 weeks). Similarly, the quality and storage stability of Khalal dates coated with pea starch, zein protein, or carnauba wax and stored at 3 or 25°C for 21 days were evaluated; the authors found that pea starch and zein protein were the most effective coatings in delaying ripeness, retarding texture deterioration, maintaining higher sensory scores, and extending the shelf-life of cold stored Khalal dates, while pea starch + carnauba wax, and zein protein + carnauba wax coatings were better in preventing fungal growth (Mehyar et al., 2014). Also, coating with gum Arabic using an ultrasonic method delayed the ripening process, minimized color changes and weight loss, maintained quality, and prolonged fruits' shelf-life to 8 weeks under cold storage (Mohammed et al., 2024). Despite the multiple benefits of ECs, it is still considered an assistant preservation method as it should be used along with cold storage; besides, it is a time-consuming technology and may affect fruit appearance.

3.4 Lactic acid (LA)

LA is a GRAS organic acid with a strong antimicrobial effect against a spread sector of microorganisms; accordingly, it could be applied successfully in food preservation (Seddiek et al., 2022). The use of LA in fruit and vegetable processing and preservation has also been approved by the National Organic Program in the USA (Chen et al., 2019). Several reports investigated the impact of LA on the quality parameters and shelf-life of fruits and vegetables (Chen et al., 2019; Seddiek et al., 2022). Dipping fresh-cut apple slices in LA (1%) preserved the quality and extended the self-life to 16 days compared to the control (8 days) (Seddiek et al., 2022). However, very few studies discussed the potential of using LA to preserve the shelf-life of Khalal dates. Recent research reported that dipping treatments with LA (1%) prolonged the shelf-life of Khalal dates (Barhi variety) to 4 weeks under refrigerated conditions; the authors stated that water loss, softening, and fungal growth of the treated samples were minimized (Alqahtani et al., 2023b). The study showed that moisture loss was 9%, TSS increased by 18%, pH decreased by 12%, TTA increased by 71%, total phenolic content decreased by 50%, antioxidant activity decreased by 44%, L* value decreased by 22%, hardness decreased by 92%, and sensorial acceptance decreased by 16% at the end of storage (4 weeks). Such findings indicate that LA could be a promised treatment to maintain quality, minimize deterioration, and delay the ripening of cold-stored Khalal dates. However, the higher concentrations of LA (> 1%) showed undesirable effects on the sensory properties, particularly appearance and odor, and shelf-life of stored fruits and vegetables.

3.5 Calcium chloride ($CaCl_2$) and salicylic acid (SA)

Dipping in $CaCl_2$ and SA solutions has been applied as a postharvest treatment to maintain quality and improve the storage stability of various fruit and vegetable crops (Gharezi et al., 2012; Irfan et al., 2013). Dipping in $CaCl_2$ solution significantly delayed ripening, decreased color changes, minimized texture breakdown, and prolonged the shelf-life of fig fruits (Irfan et al., 2013). Likewise, SA has been used as a dipping treatment to reduce postharvest losses of several types of horticultural products; previous reports confirmed the efficacy of SA in maintaining quality, minimizing post-harvest losses, and prolonging the shelf-life of kiwifruit and navel oranges (Zhang et al., 2003; Huang et al., 2008). Previous research investigated the impact of dipping in $CaCl_2$ and SA solutions on the quality of cold-stored Khalal dates; the authors observed that dipping in 2% of $CaCl_2$ solution was the best treatment as it significantly decreased weight loss, minimized fruit decay, reduced color changes, maintained crunchy texture, and prolonged the shelf-life of the fruits to 40 days (Atia et al., 2020). This study showed that weight loss was 29%, TSS increased by 23%, L* value decreased by 15%, hardness decreased by

30%, and sensorial acceptance decreased by 39% at the end of storage (5.7 weeks) for the dates treated with 2% $CaCl_2$ solution.

3.6 Natural plant extracts

Recently, more attention has been paid to using natural plant extracts in the food industry. These products can be extracted from agro-industrial by-products such as seeds, peel, leaves, pomace, and press cake; they have a higher antimicrobial and antioxidant activity due to their higher content of phenolic substances and phytonutrients. A recent study investigated the effect of guava leaf extract (GLE) and pomegranate peel extract (PPE) on the storage stability of cold-stored, minimally processed apples (Seddiek et al., 2022); treated samples maintained their quality up to 12 days, whereas control spoiled after 7 days. Also, the shelf-life of Khalal dates could be prolonged through dipping treatment in a solution containing PPE (Alqahtani et al., 2023b); the authors stated that treatment of cold-stored Khalal dates (Barhee variety) with PPE enhanced the quality and shelf-life (6 weeks) compared to the control (3 weeks), decreased moisture loss, minimized color changes, maintained fruits' firmness, and inhibited fungal growth (Alqahtani et al., 2023b). This study showed that moisture loss was 9%, TSS increased by 15%, pH decreased by 15%, TTA increased by 92%, total phenolic content decreased by 58%, antioxidant activity decreased by 44%, L* value decreased by 17%, hardness decreased by 92%, and sensorial acceptance decreased by 17% at the end of storage (6 weeks). Such findings show that PPE could be used as an effective preservation method along with cold storage to preserve the quality and delay the ripening of Khalal dates during storage. Similarly, the effect of GLE + lactic acid as a dipping treatment on the quality parameters of cold-stored Khalal dates was investigated (Alqahtani et al., 2023a); the authors confirmed that this treatment prolonged the shelf-life, prevented moisture loss, delayed color changes, preserved firmness, minimized microbial growth, and maintained sensory properties of cold-stored Khalal dates. In addition, coating Khalal dates with chitosan containing extracts of olive cake and/or orange peel improved storage stability, preserved quality, and extended the shelf-life of cold-stored Khalal dates (Ghafoor et al., 2022). However, natural plant extracts can not be used alone to extend the shelf-life of Khalal dates; they can be used as an assistant method besides cold storage; additionally, some plant extracts may affect the sensory properties of treated fruits.

3.7 Growth inhibitors

The application of growth regulators could be beneficial in delaying ripening and, therefore, extending the shelf-life of Khalal dates. Gibberellic acid, also known as gibberellin A3 or GA3, is a growth hormone formed naturally in plants and fungi and plays a crucial role in cell elongation, stem growth, germination, flowering, and fruit ripening. Preharvest application of GA3 and NAA (naphthyl acetic acid) on Zaghloul and Zahdi dates, respectively, during the Kimri stage increased the fruit's size, weight, and yield but postponed the ripening process (Mohammed and Shabana, 1980; Hussein et al., 1993). Applying growth regulators (NAA, GA3, and ethephone) on Khenazi dates at the Hababouk stage decreased dry matter, increased fruit weight and yield, and delayed fruit ripening for 1 month (Al-Juburi et al., 2001). The impact of postharvest treatment with GA3, benzyladenine (BA), and NAA, at concentrations of 50, 40, and 150 mg/L, respectively, on the quality parameters of Khalal dates (Barhee variety) during cold storage were evaluated; the authors found that dipping in the solutions of these growth regulators before cold storage delayed the ripening and maintained the quality of dates; also, the treated fruits maintained a higher content of vitamin C than the control (Al-Qurashi and Awad, 2011). These authors observed that weight loss was about 5%, TSS decreased by 6%, TTA increased by 33%, phenols decreased by 75%, and ripening was 87% at the end of storage (60 days at 1°C). Generally, the authors recommended that growth regulators should be applied as a preharvest treatment to be more effective in delaying date ripening instead of postharvest treatments; they ascribed this difference to the maturity stage of the fruit at the time of treatment. Also, treated fruits should be stored under refrigerated conditions.

3.8 Ultrasonication

The sound waves with frequencies greater than the human hearing range (> 20 kHz) are known as Ultrasound; they can be generated at various frequencies for multiple research, industrial, and medical applications. Ultrasonics is considered a non-thermal technique and is being adopted in numerous applications, including sonication processes, homogenization, extraction, and primary treatment before some food processing and preservation methods such as drying, microwaves, edible coating, and cold storage (Akhoundzadeh Yamchi et al., 2022). The potential of using ultrasonic techniques to improve the fruits' shelf-life was investigated; the authors stated that ultrasonic can be supported with other methods such as osmotic dehydration, advanced edible films, drying, microwave, and cold storage (Mohammed et al., 2024). Regarding Khalal dates, very few studies investigated the impact of ultrasonic on the fruits' post-harvest shelf-life. A recent study (Abdelkarim et al., 2022) showed that ultrasound treatment could be used to improve the storage stability of Barhi dates at the Khalal stage. These authors reported that operating conditions (intensity and exposure time) and storage temperature can markedly affect the physical, nutritional, and microbial quality of dates. They found that ultrasound treatment with the intensity of 140 W/cm^2 for 5.2 min and storage at 20°C preserved physical, microbial, and nutritional quality and prolonged the shelf-life of Khalal dates to 21 days. By the end of storage (3 weeks), the authors found that the TSS increased by 10%, total phenols decreased by 25%, antioxidant activity decreased by 17%, total color change decreased by 30%, and firmness decreased by 90% for Khalal dates treated with ultrasound and stored under refrigerated conditions.

4 Research needs and future vision

There is no doubt that cold storage represents the most common commercial preservation method of Khalal date fruits. However, due to the short marketing life of cold-stored Khalal dates and the increased consumer demand, it is necessary to use additional methods simultaneously with cold storage to extend the shelf-life and maintain the post-harvest quality. For this purpose, we propose a sustainable

approach to improving preservation techniques through an innovative strategy aligned with sustainability as follows:

1. Preserving fruits' quality should be started from the farm by selecting an accurate harvesting time, following appropriate harvesting procedures in which injuries, bruises, punctures, and breakages of the fruits should be prevented or minimized, using optimum handling and transportation methods (using a cold chain during handling and marketing), and applying optimum storage conditions.
2. Improving the current preservation methods through finding innovative solutions to the main present limitations, e.g., using intelligent systems to monitor gas-combination changes in the controlled atmosphere storage and finding transparent edible films to avoid undesirable appearance.
3. Advanced technologies such as UV-C light, pulsed light, electron beams, cold plasma, photosensitization, ionizing radiation, high-pressure carbon dioxide, hydrogen peroxide, ozone, electrolyzed water, and hurdle technology should be investigated for quality preservation of Khalal dates.
4. Finding low-cost, effective, and applicable methods to extend the post-harvest storage life of Khalal dates for the low-income populations who cannot provide a post-harvest cold chain.
5. Development of sustainable, biodegradable, effective, and eco-friendly materials for date fruit packaging.
6. Using solar energy to develop the power required for refrigeration instead of fossil-fuel-based energy. These systems keep dates at optimum storage temperatures which delay the ripening process and prevent deterioration with minimum cost and without environmental pollution.
7. Recycling systems can be applied such as the upcycling of secondary products raised from the Khalal date industry like seeds and low-quality fruits can be upcycled for other uses (e.g., animal feed or organic fertilizer), contributing to a circular economy.
8. Development of new date palm varieties that are more resistant to bacterial and fungal diseases, chilling injury, bruises, and punctures and have a longer post-harvest life.
9. Improving the storage conditions of Khalal dates, e.g., package properties and the composition of storage air.

By adopting the above-mentioned sustainable techniques, the preservation process of Khalal dates could be more efficient with lower waste and lower cost, and it can support local economies and the environment.

5 Conclusion

Dates have great commercial value and play important roles in the diet and social life of several populations with spiritual and cultural significance. Dates at the Khalal stage have a great consumer demand and significant market relevance due to their high nutritional value, various health benefits, and distinct organoleptic properties, including crunchy texture, delicious taste, and attractive color. However, improper pre-harvest and post-harvest practices and inappropriate storage conditions can cause physical damage, microbial contamination, and premature ripening, which can negatively affect the quality and shelf-life of Khalal dates. Also, post-harvest physiological processes, metabolic activity, ripening, microbial contamination, and insect attack can cause significant losses in dates' quality, shorten their shelf-life, and reduce their market value. This review screened the main quality deterioration factors and the current preservation methods applied for Khalal dates. Accordingly, it is important at this crucial stage to apply optimal harvest and post-harvest practices to maintain the firm texture, attractive color, and freshness of Khalal dates, which are critical for market appeal and consumer preference. However, further studies are required to minimize quality loss and prolong the dates' post-harvest shelf-life.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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