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INFLUENCE OF POSTHARVEST INCUBATION TEMPERATURES ON THE ARTIFICIAL RIPENING KINETICS AND QUALITY OF DATE PALM FRUITS AT BISIR STAGE

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Abstract

Climate change significantly delays the natural maturing process of the Bisir-stage date palm fruits on the tree. This problem causes high postharvest losses. In order to combat it, the unripe Bisir fruits are ripened using the traditional methods such as open-sun drying, curing and solar tunnel drying. These methods are however constrained by temperature and humidity variation. This study aimed to develop safe laboratory method for the artificial ripening of unripe Bisir fruits. An experiment was conducted to examine the effects of different incubation temperatures (40, 45, and 50°C) on the ripening of unripe Bisir fruits from five commercial date palm cultivars: Khalas, Helali, Barhi, Ruziez, and Sheshi. The results showed that fruits incubated at 45 and 50°C ripened within three days without loss of quality. Measurements of fruit and pulp weight, size, pH, color, firmness, moisture content, total soluble solids, sugar composition, phenol content, and tannin levels were comparable to those of naturally ripened Tamer fruits. Therefore, the findings suggest that incubation at 45 or 50°C provides an effective method for artificial ripening of unripe date palm Bisir fruits.

Key words: Date palm; Immature fruits; Artificial ripening; Incubation temperatures; Fruit ripening indices; Fruit quality

Introduction

The date palm (*Phoenix dactylifera* L.) is an important fruit crop in arid and semi-arid regions of the world, with large areas cultivated and high annual production, particularly in the Kingdom of Saudi Arabia and other Arab countries (Anon., 2023). It provides substantial economic and nutritional benefits, and its cultivation is concentrated in countries such as Egypt, Iraq, Saudi Arabia, Algeria, Morocco, Tunisia, the United Arab Emirates, and Iran (Abd-Rabou & Radwan, 2017; Al-Abdoulhadi *et al*., 2011). Optimal date palm production requires long, hot summers, mild winters without frost, the absence of rain during flowering and fruit set, low relative humidity, and abundant sunshine (Zaid & de Wet, 2002). Environmental factors such as temperature, relative humidity, rainfall, and others, have a strong impact on the growth and development of plants and climate change has turned into a great issue because it has a direct impact on agricultural systems (Lepetz *et al*., 2009). The alteration of temperature and rainfall patterns experienced in different places around the world over the past decades, as well as the increase in the global surface temperatures towards the end of this century, have been recorded and this could change the suitability of present and future date-growing areas (Jeffrey & Harold, 1999; Shabani *et al*., 2012).

Date palm is a climacteric fruit and its growth occurs in five stages during the post pollination and fertilization: Hababouk (pea size fruit undergoing active cell division with light green color), Kimri (immature green fruit with cell elongation), Khalal or Bisir (full fruit with active cell division and fully colored), Rutab (ripe fruit that is soft and brown), and Tamer (fully ripe fruit with moisture content less than 20%). The terms Khalal and Bisir are frequently used interchangeably due to the fact that the transition between them constitutes a biological continuum, not two discrete phases (Reuveni, 1986; Zaid & de Wet, 2002; Al-Shahib & Marshall, 2003; Fadel *et al*., 2006). The specific changes in physical and biochemical properties of fruits define each of the stages. Fruit ripening is a natural process that makes fruit edible and appealing. It is controlled by a series of synchronized chemical changes within the fruit (Ahmed *et al*., 1995). Such changes involve chlorophyll degradation and pigment synthesis, altering the skin color; breakdown of organic acids, therefore, changing the taste; and the process of hydrolyzing starch to sugars, thus, making

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food sweeter and more tasting (Al-Mazroui *et al*., 2007; Awad *et al*., 2011; Rastegar *et al*., 2012; Eid *et al*., 2013).

The date palm fruits in the same bunch not ripen at the same time, therefore, several pickings are needed to harvest them (Nixon, 1951; Mougheith *et al*., 1976). To obtain the maximum fruit yield and quality, it is necessary to determine the right time of harvesting using reliable indices of ripening (Sawaya *et al*., 1982a,b; Bacha *et al*., 1987; Chao & Krueger, 2007; Sarraf *et al*., 2021). The ripening season in Saudi Arabia occurs during the summer, when temperatures rise and relative humidity drop in July and August. Recently, many date palm cultivars ripened unevenly within a single bunch. In some cases, particularly with late-maturing cultivars, fruits remained in the Bisir stage and fail to enter into the Rutab and Tamer stages (Iqbal *et al*., 2025). These unripe fruits are highly vulnerable to insect pests and diseases and lead to significant losses (Saleem *et al*., 2010). Some cultivars, including Barhi, Helali, and Sukkary are also consumed at the Bisir stage, however, their oversupply to local markets increase their wastage due to limited availability of cold storage, transportation and preservation (Al-Abbad *et al*., 2011). As a result, many unripe fruits are harvested and used as animal feed.

To overcome these problems, date growers have adopted artificial ripening methods to accelerate the transition from early stages to Rutab or Tamer. Artificial ripening techniques for date palm fruits have attracted attention because they can be simple, environmentally friendly, and cost-effective (Awad, 2007; Mohammed *et al*., 2023). Several studies have evaluated chemicals such as brine, sodium chloride, and acetic acid as ripening promoters (Saleem *et al*., 2005, 2010). Other researchers have examined physical methods, including controlled temperature and humidity, freezing, microwave radiation, oven drying and solar dehydration (Baloch *et al*., 2003; Navarro, 2006; Yektankhodaei *et al*., 2007; Mohammed *et al*., 2021).

Most previous work on temperature effects has focused on ripe Tamer fruits, mainly for storage, transport, and postharvest pest and disease control (Rafaeli *et al*., 2006; Hazbavi *et al*., 2015; Ben-Amor *et al*., 2016, 2018; Mohamed & Mustapha, 2020). In contrast, there is very limited information on the influence of controlled postharvest incubation temperatures on the artificial ripening of unripe Bisir-stage fruits in different date palm cultivars. This gap is particularly important for cultivars such as Khalas, Helali, Barhi, Ruziez, and Sheshi, which can suffer high losses when fruits fail to ripen on the palm. Therefore, there is a need to develop non-hazardous laboratory-based incubation techniques that can induce ripening in Bisir fruits while maintaining acceptable quality. The current research was intended to examine the interaction between various postharvest incubation temperatures in the ripening kinetics and quality characteristics of Bisir-stage fruits of the selected date palm cultivars to minimize the postharvest wastage and maximize the utilization potential of the this important crop. The temperatures of 40, 45, and 50°C were selected to establish an effective, controlled alternative to variable traditional methods. The chosen range of 40, 45, and 50°C builds upon previous studies that have successfully used similar elevated temperatures to accelerate date ripening. This experiment aimed to refine the optimal threshold, confirming 45–50°C as the effective range for rapid, quality-preserving ripening within three days, whereas 40°C proved insufficient.

Materials and Methods

Collection and preparation of the fruit samples: Unripe Bisir fruits were collected from five date palm cultivars: Khalas, Helali, Barhi, Ruziez, and Sheshi. All sampled trees were twelve years old and grown at the Date Palm Research Center of Excellence, King Faisal University, Al-Ahsa, Saudi Arabia. Sodium benzoate solution was used to disinfect the fruits to reduce microbial activities. Naturally ripen Tamer and unripen Bisir fruits of each cultivar were graded, washed, packed in polyethylene film bags, and kept at 4°C before physicochemical analysis. To achieve artificial ripening, fifty fruits of each cultivar were incubated at 40, 45, and 50°C. All incubation chambers provided a stable and identical environment for their respective temperature settings, ensuring that temperature was the sole variable in the ripening process. Relative humidity was not actively controlled within the incubators, as the primary experimental variable was temperature. The fruits were observed on daily basis until they reached the ripe stage (brown color). The fruits were moved to Fruit Quality Assessment Laboratory for physicochemical analysis.

Physicochemical analysis: The parameters evaluated were: fruit size (length and diameter) and weight, pulp weight, color, firmness, moisture content, acidity, total soluble solids (TSS), total sugars, reducing sugars, non-reducing sugars, phenolic content and total tannins. A digital Vernier caliper was used to measure the fruit length and diameter. Fruit and pulp weight were determined using a Sartorius electronic balance. After peeling, the pulp and seed weights were recorded to calculate the pulp-to-seed ratio. Fruit firmness was measured with a texture analyzer (K95590 Digital Penetrometer, Koehler, USA), with the maximum penetration force recorded as an indicator of firmness.

Fruit color was measured using a HunterLab ColorQuest-45/0 LAV colorimeter (Hunter Associates Laboratory Inc., USA), recording the L*, a*, and b* values. Chroma (C*) and hue angle (h°) were calculated as described by Munir *et al*. (2024). Moisture content was determined by drying 10 g fruit samples in an oven at 70°C until a constant weight was achieved. Acidity (pH) was measured using a pH meter (Model HI-99121, Hanna Instruments, UK). TSS was determined from the juice of 10 fruits per treatment using a digital refractometer (Model HI96801, Hanna Instruments, UK) and expressed as Brix, following the method of Rehman *et al*., (2024). Total sugars, reducing sugars, and non-reducing sugars were quantified using the Anthrone method (Ali *et al*., 2025; Waseem *et al*., 2025). Total phenolic content was determined with the Folin-Ciocalteu micro method (Talaat *et al*., 2025), and total tannins were measured according to Abbas *et al*., (2025).

Statistical analysis

Two-way analysis of variance (ANOVA) was used to analyze the temperature and cultivars data (Genstat version 11, Lawes Agricultural Trust, UK). Treatment means of five replicated samples were separated using the least significant difference (LSD) test at a 5% probability level. Heatmap with hierarchical clustering and chord diagram were created using R and RStudio software.

Results

The results of this study revealed statistically significant differences ($p \leq 0.05$) in fruit weight, pulp weight, fruit length, fruit diameter, fruit pH, fruit color (L*, a*, b*, C*, and h°), fruit firmness, fruit moisture content, total soluble solids, total sugars, reducing sugars, non-reducing sugars, total phenol content, and total tannin content parameters between the five date palm cultivars (Khalas, Helali, Barhi, Ruziez, and Sheshi) when their unripe Bisir fruits were incubated at three different temperatures (40, 45, and 50°C) to enhance artificial ripening.

The data in Fig. 1 reveals that artificial ripening increased fruit weight compared to natural ripening. Among the five cultivars, unripe 'Bisir' stage Khalas fruits achieved the highest weight (11.51 g) when artificially ripened, followed by Sheshi (11.04 g), Helali (10.97 g), Barhi (8.58 g), and Ruziez (7.94 g). The incubation temperature was critical, with the maximum fruit weight observed at 40°C. In contrast, fruit weights at 45°C (9.17 g) and 50°C (9.04 g) were statistically similar to the weight of naturally ripened fruits (9.28 g). Furthermore, the interaction between cultivars and temperature showed that for all five cultivars, artificial ripening at 45°C and 50°C produced fruit weights comparable to those ripened naturally. Figure 2 presents the pulp weight for the same treatments. The cultivar ranking for pulp weight mirrored that of total fruit weight: Khalas had the highest pulp weight (10.34 g), followed by Sheshi (10.15 g), Helali (10.06 g), Barhi (7.76 g), and Ruziez (7.16 g). Regarding temperature, artificially ripened Bisir fruits had maximum pulp weight at 40°C (9.08 g), with lower weights at 45°C (8.44 g) and 50°C (8.29 g). The pulp weight of naturally ripened 'Tamer' stage fruits was 8.59 g. Consistent with the overall fruit weight results, the combined effect of cultivar and temperature indicated that the pulp weight of all cultivars artificially ripened at 45°C and 50°C was more or less equivalent to that of naturally ripened fruit.

The results for fruit dimensions and pH are shown in Figs. 3, 4, and 5. For fruit length (Fig. 3), the cultivar Khalas produced the longest fruits (40.01 mm), followed by Sheshi (36.78 mm), Helali (34.18 mm), Ruziez (31.81 mm), and Barhi (30.47 mm). Artificially ripened fruits were longest at 40°C (35.10 mm), while lengths at 45°C (33.36 mm) and 50°C (33.15 mm) were statistically similar to naturally ripened fruits (33.78 mm). The combination of Khalas fruit ripened at 40°C yielded the greatest length, whereas Barhi at 50°C resulted in the shortest. For fruit diameter (Fig. 4), the cultivars ranked as follows: Khalas and Helali (both 24.41 mm), Sheshi (23.96 mm), Barhi (23.01 mm), and Ruziez (21.48 mm). Diameter decreased with higher ripening temperatures, measuring 23.55 mm at 40°C, 22.88 mm at 45°C, and 22.79 mm at 50°C, compared to 23.09 mm for natural ripening. Finally, fruit pH (Fig. 5) also varied by cultivar, with Khalas being the least acidic (pH 5.94), followed by Helali (5.81), Ruziez (5.73), Barhi (5.59), and Sheshi (5.29). Higher incubation temperatures made fruits more acidic, with pH dropping from 5.62 at 40°C to 5.40 at 45°C and 5.37 at 50°C; naturally ripened fruits had a pH of 5.62.

The analysis of fruit color (Figs. 6-10) revealed significant differences based on both cultivar and ripening temperature. In terms of lightness (L*), cv. Helali had the lightest color (50.59), followed by Ruziez (49.30), Barhi (49.26), Sheshi (49.18), and Khalas (47.78). Lightness was highest when fruits were ripened at 40°C (50.43), decreased at 45°C (45.75), and was statistically similar at 50°C (42.85) to naturally ripened fruit (42.51), with a consistent decline as temperature rose. For the red/green component (a*), cv. Khalas scored highest (14.60), followed by Helali (13.37), Ruziez (13.31), Sheshi (12.80), and Barhi (12.15), with values also rising at 40°C (14.25) and dropping thereafter. The yellow/blue component (b*) was highest in cv. Khalas (22.36), followed by Sheshi (21.68), Barhi (21.63), Helali (21.53), and Ruziez (20.41), again being higher at 40°C (17.48). Color intensity or chroma (C*) followed the order: Khalas (26.97), Helali (25.67), Sheshi (25.42), Barhi (25.02), and Ruziez (24.58), and was also higher at 40°C (22.57). The hue angle (h°) was highest for cv. Helali (63.14), followed by Ruziez (62.38), Barhi (62.28), Sheshi (62.00), and Khalas (60.33), and was also maximum at 40°C (63.55). For all these color parameters, a*, b*, C*, and h°, the values for fruits ripened at 50°C were statistically similar to those of naturally ripened fruits, and a clear pattern emerged where increasing the incubation temperature linearly reduced all color values across every cultivar.

The measurements of fruit firmness, moisture, and total soluble solids are shown in Figs. 11, 12, and 13. For firmness (Fig. 11), cv. Ruziez was the firmest (4.60 kg cm^{-2}), followed by Helali (4.54 kg cm^{-2}), Khalas (4.40 kg cm^{-2}), Barhi (4.28 kg cm^{-2}), and Sheshi (4.03 kg cm^{-2}). Firmness was highest when fruits were ripened at 40°C (4.07 kg cm^{-2}), and decreased at higher temperatures; the firmness at 45°C (3.28 kg cm^{-2}) and 50°C (3.22 kg cm^{-2}) was statistically similar to that of naturally ripened fruit (3.32 kg cm^{-2}). For moisture content (Fig. 12), cv. Barhi retained the most moisture (26.80%), followed by Helali (26.35%), Khalas (24.93%), Ruziez (22.65%), and Sheshi (22.58%). Moisture was highest at 40°C (17.84%), and the lower levels at 45°C (14.99%) and 50°C (14.71%) matched the moisture in naturally ripened fruit (15.72%). The TSS (Fig. 13) was highest in cv. Barhi (46.76 Brix), followed by Helali (46.46 Brix), Khalas (42.73 Brix), Sheshi (42.22 Brix), and Ruziez (39.07 Brix). Artificially ripened fruits reached their peak TSS levels at 45°C and 50°C (52.07 Brix), which was statistically similar to natural ripening (51.85 Brix), while ripening at 40°C resulted in lower TSS (45.42 Brix). Across all cultivars, higher ripening temperatures consistently led to softer fruits losing moisture and becoming sweeter.

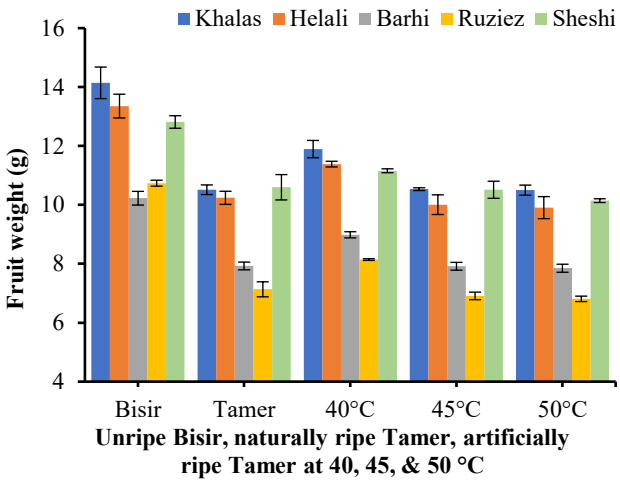

Fig. 1. Effect of different incubated temperatures on fruit weight of five date palm cultivars harvested at unripe Bisir stage for artificial ripening. Y-bars on each bar represent the variability (SE) within replicates.

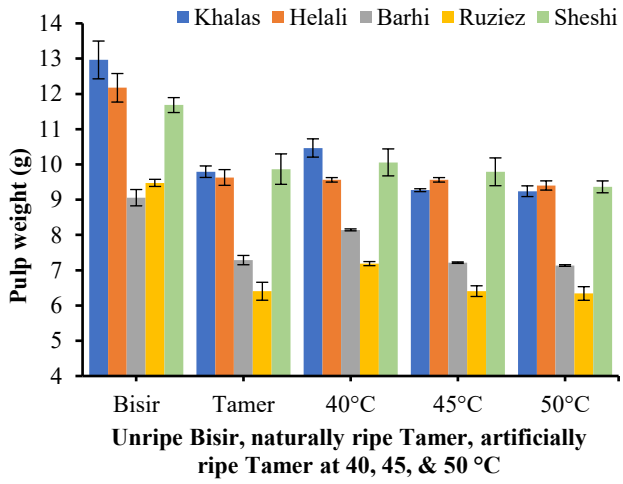

Fig. 2. Effect of different incubated temperatures on pulp weight of five date palm cultivars harvested at unripe Bisir stage for artificial ripening. Y-bars on each bar represent the variability (SE) within replicates.

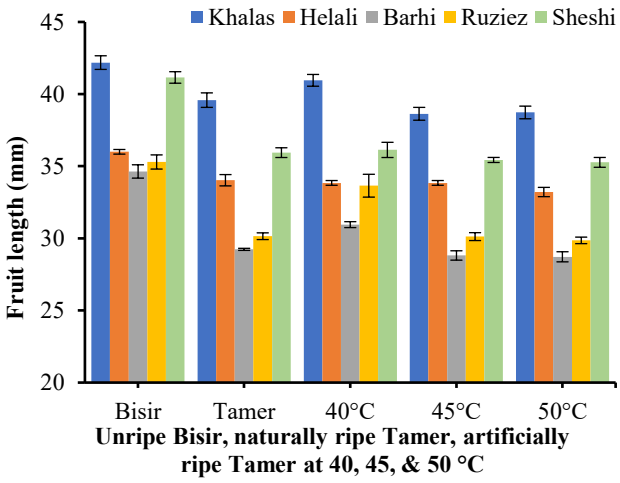

Fig. 3. Effect of different incubated temperatures on fruit length of five date palm cultivars harvested at unripe Bisir stage for artificial ripening. Y-bars on each bar represent the variability (SE) within replicates.

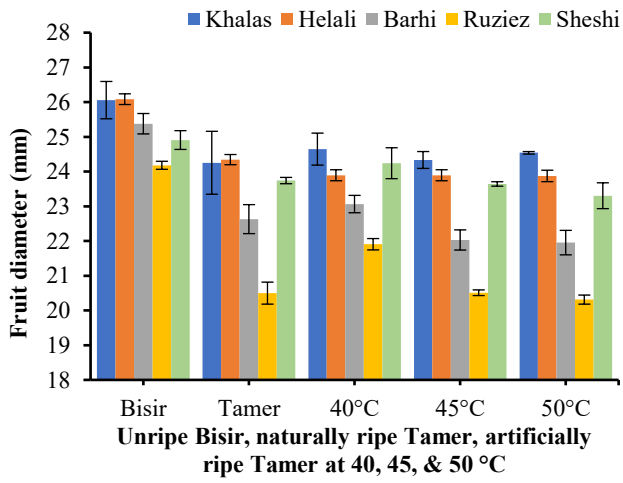

Fig. 4. Effect of different incubated temperatures on fruit diameter of five date palm cultivars harvested at unripe Bisir stage for artificial ripening. Y-bars on each bar represent the variability (SE) within replicates.

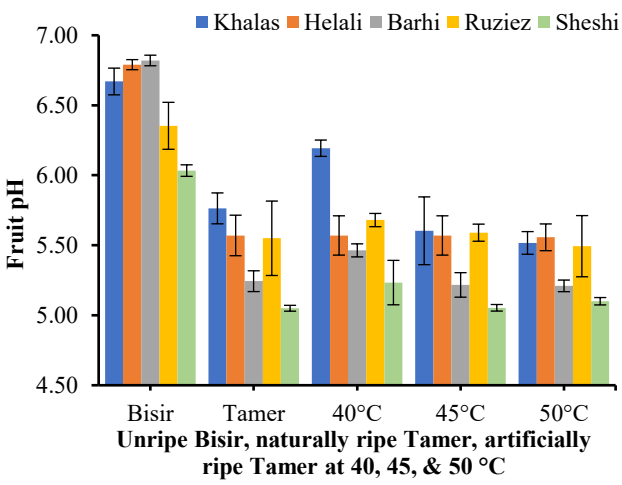

Fig. 5. Effect of different incubated temperatures on fruit pH of five date palm cultivars harvested at unripe Bisir stage for artificial ripening. Y-bars on each bar represent the variability (SE) within replicates.

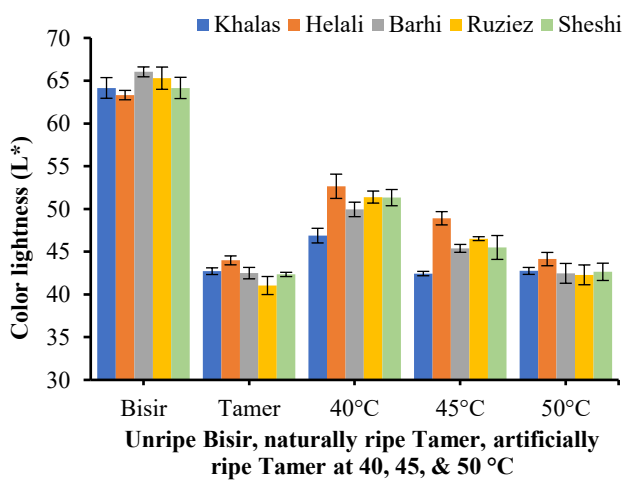

Fig. 6. Effect of different incubated temperatures on color lightness (L*) of five date palm cultivars harvested at unripe Bisir stage for artificial ripening. Y-bars on each bar represent the variability (SE) within replicates.

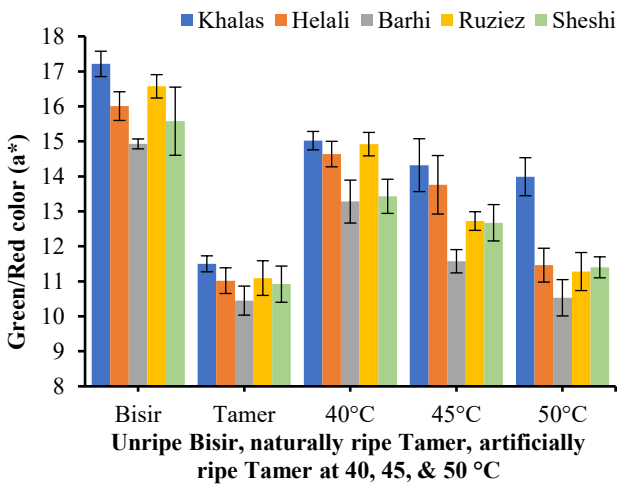

Fig. 7. Effect of different incubated temperatures on Green/Red color (a*) of five date palm cultivars harvested at unripe Bisir stage for artificial ripening. Y-bars on each bar represent the variability (SE) within replicates.

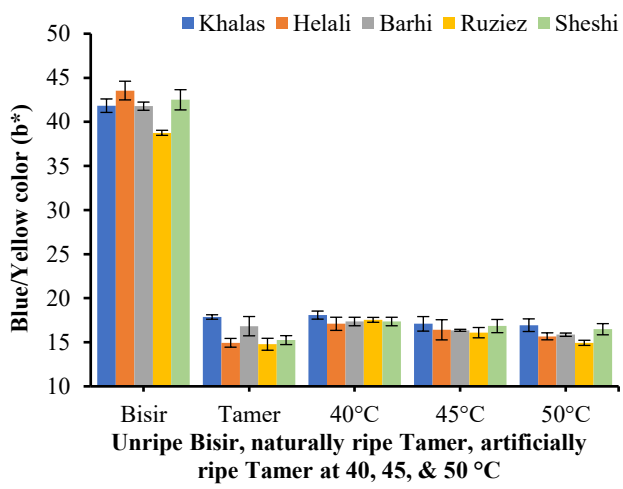

Fig. 8. Effect of different incubated temperatures on Blue/Yellow color (b*) of five date palm cultivars harvested at unripe Bisir stage for artificial ripening. Y-bars on each bar represent the variability (SE) within replicates.

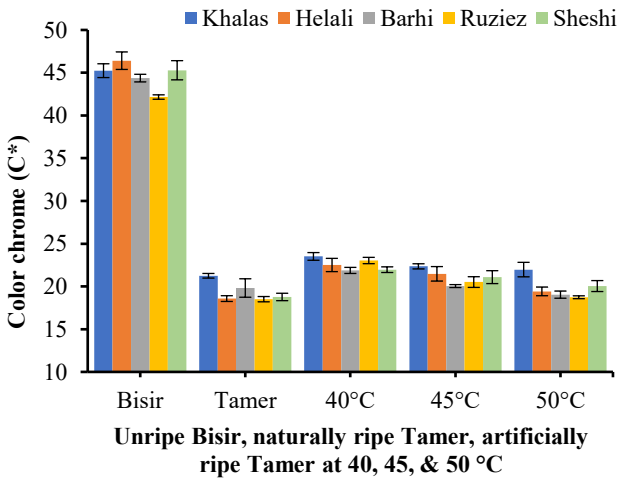

Fig. 9. Effect of different incubated temperatures on color chrome (C*) of five date palm cultivars harvested at unripe Bisir stage for artificial ripening. Y-bars on each bar represent the variability (SE) within replicates.

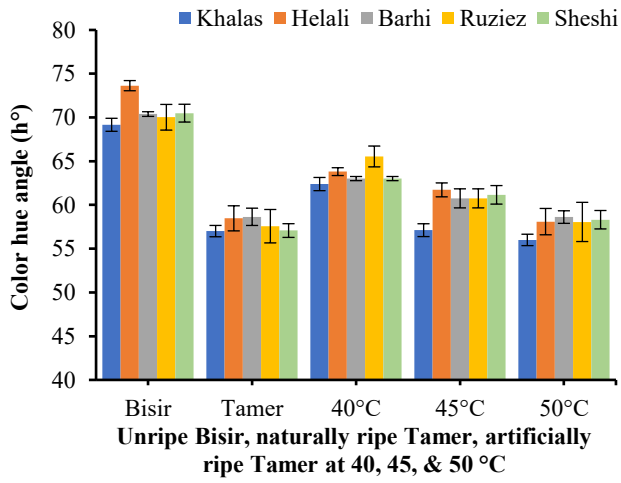

Fig. 10. Effect of different incubated temperatures on color hue angle (h°) of five date palm cultivars harvested at unripe Bisir stage for artificial ripening. Y-bars on each bar represent the variability (SE) within replicates.

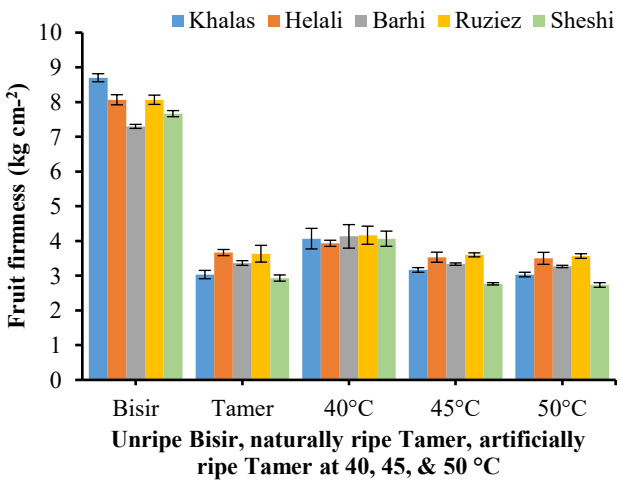

Fig. 11. Effect of different incubated temperatures on fruit firmness of five date palm cultivars harvested at unripe Bisir stage for artificial ripening. Y-bars on each bar represent the variability (SE) within replicates.

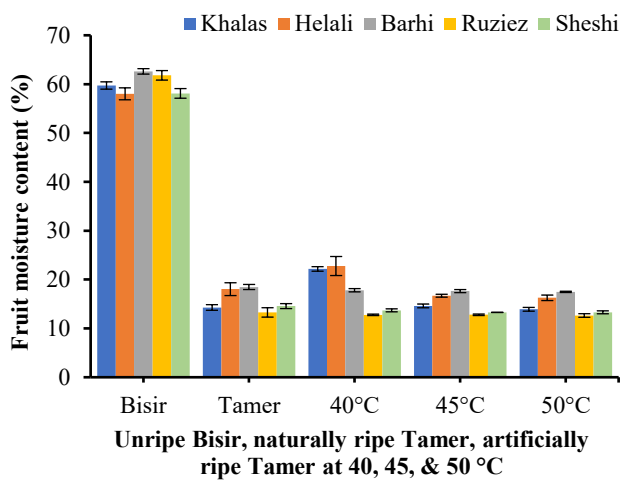

Fig. 12. Effect of different incubated temperatures on fruit moisture content of five date palm cultivars harvested at unripe Bisir stage for artificial ripening. Y-bars on each bar represent the variability (SE) within replicates.

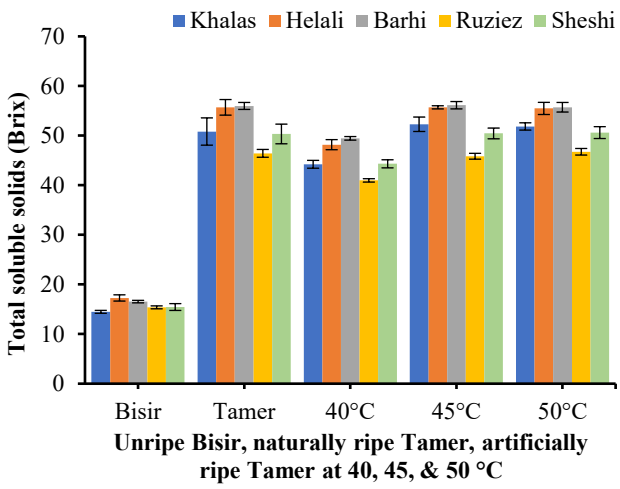

Fig. 13. Effect of different incubated temperatures on total soluble solids of five date palm cultivars harvested at unripe Bisir stage for artificial ripening. Y-bars on each bar represent the variability (SE) within replicates.

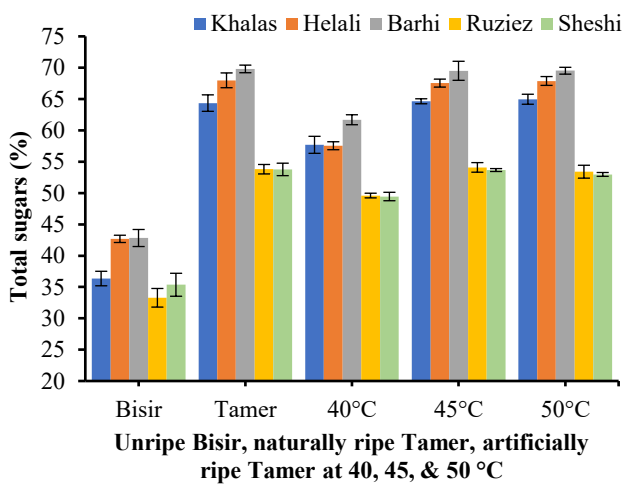

Fig. 14. Effect of different incubated temperatures on total sugars of five date palm cultivars harvested at unripe Bisir stage for artificial ripening. Y-bars on each bar represent the variability (SE) within replicates.

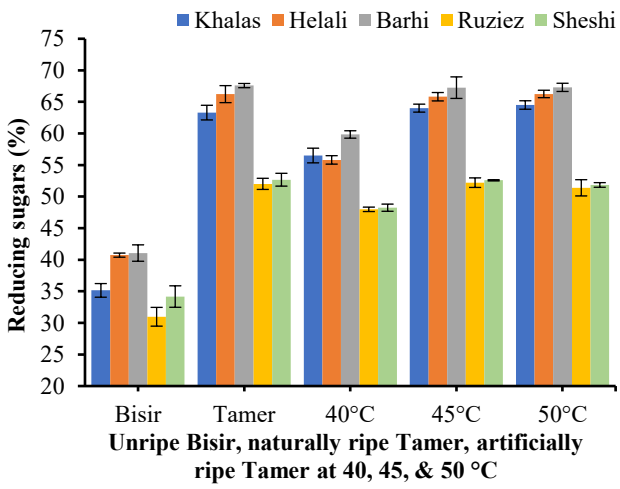

Fig. 15. Effect of different incubated temperatures on reducing sugars of five date palm cultivars harvested at unripe Bisir stage for artificial ripening. Y-bars on each bar represent the variability (SE) within replicates.

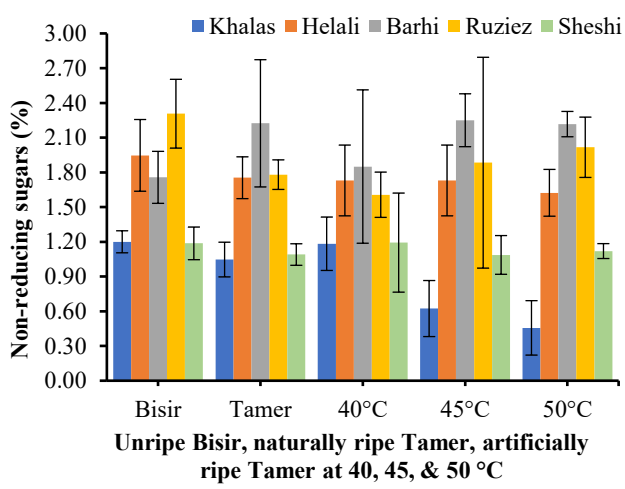

Fig. 16. Effect of different incubated temperatures on non-reducing sugars of five date palm cultivars harvested at unripe Bisir stage for artificial ripening. Y-bars on each bar represent the variability (SE) within replicates.

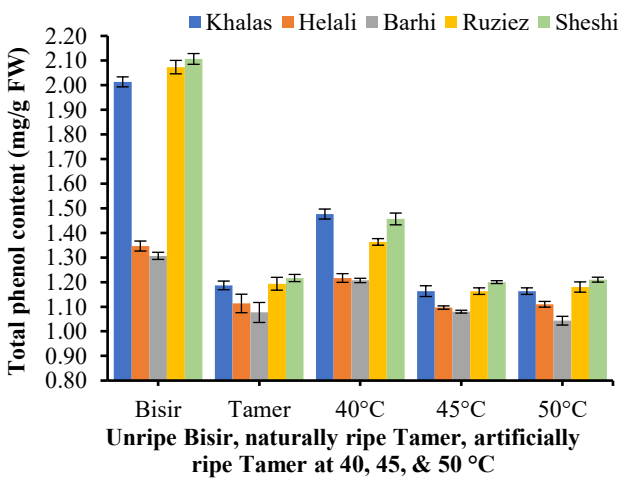

Fig. 17. Effect of different incubated temperatures on total phenol content of five date palm cultivars harvested at unripe Bisir stage for artificial ripening. Y-bars on each bar represent the variability (SE) within replicates.

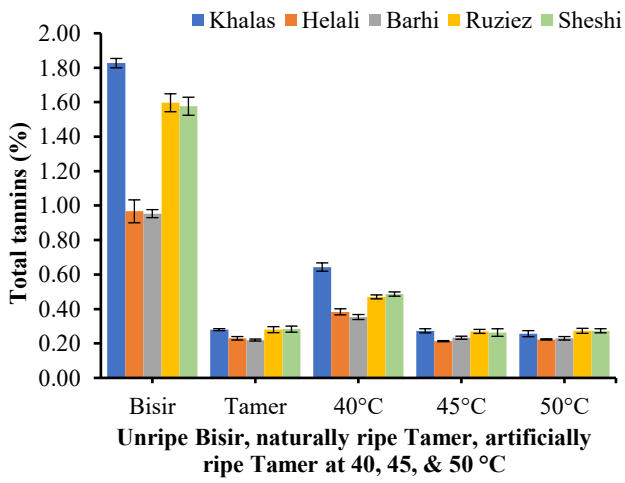

Fig. 18. Effect of different incubated temperatures on total tannins of five date palm cultivars harvested at unripe Bisir stage for artificial ripening. Y-bars on each bar represent the variability (SE) within replicates.

The sugar and phenolic compound profiles are depicted in Figs. 14-18. For total sugars (Fig. 14), cv. Barhi had the highest content (62.66%), followed by Helali (60.72%), Khalas (57.60%), Sheshi (49.04%), and Ruziez (48.83%). Natural ripening showed 61.94% total sugar, a level matched by artificial ripening at 45°C (61.89%) and 50°C (61.74%), while 40°C resulted in a lower value (55.19%). A similar pattern was observed for reducing sugars (Fig. 15), with the highest levels in cv. Barhi (60.61%), followed by Helali (58.97%), Khalas (56.69%), Sheshi (47.90%), and Ruziez (46.91%). Artificial ripening at 45°C (60.37%) and 50°C (60.26%) produced reducing sugar levels equivalent to natural ripening (60.36%), whereas 40°C was less effective (53.68%). Non-reducing sugars (Fig. 16) were a smaller fraction, with cv. Barhi again ranking highest (2.05%), followed by Ruziez (1.91%), Helali (1.75%), Sheshi (1.13%), and Khalas (0.90%); these levels did not change significantly with different ripening temperatures. In contrast, phenolic compounds decreased with higher heat. Total phenol content (Fig. 17) was highest in cv. Sheshi (1.43 mg/g FW), followed by Khalas (1.40 mg/g FW), Ruziez (1.39 mg/g FW), Helali (1.17 mg/g FW), and Barhi (1.14 mg/g FW). It was risen at 40°C (1.34 mg/g FW), but dropped to 1.14 mg/g FW at 45°C and 50°C matching natural ripening (1.15 mg/g FW). Similarly, total tannin content (Fig. 18) was highest in cv. Khalas (0.65%) and was also highest in unripe Bisir fruit (1.38%) and when ripened at 40°C (0.46%). However, tannins were lowest (0.25%) at 45°C and 50°C and were statistically similar to those in naturally ripened fruit (0.25%). Across all cultivars, higher ripening temperatures consistently increased sugar concentrations but decreased the content of phenolic compounds and tannins.

Heatmap with hierarchical clustering of fruit quality traits in five date palm cultivars under different postharvest incubation temperatures: The heatmap analysis presented in Fig. 19 reveals a clear and structured response of fruit quality traits to postharvest incubation temperatures (40, 45, and 50°C) across five date palm cultivars (Khalas-KH, Helali-HE, Barhi-BA, Ruziez-RU, and Sheshi-SH) at the Bisir stage. It exhibits a high positive temperature effect on sugar characteristics, where TSS, TS, RS, and NRS are significantly increased with the increase in temperatures, especially at 50°C, indicating that the high temperatures significantly increase the rate of saccharification and sweetness. On the other hand, physical characteristics such as FW, PW, FL and FD are negatively correlated to temperature, which shows a compromise between biochemical traits and fruit morphology and moisture content. The color parameters (L*, a*, b*, C*, and h°) tend to turn darker and more chromatic with rising temperature. Biochemical indices such as FpH and FMC decrease whereas FF and TPC and TT tend to be relatively more or less moderate when the temperature increased. Cultivar-specific differences were observed such as Barhi and Helali show highly thermal sensitivity in sugar accumulation and physical trait loss, whereas Khalas shows high resilience, maintaining physical attributes across the temperature range.

The hierarchical clustering of the traits organizes different parameters into different groups by the similarity of their response to temperature and cultivar. The sugar metrics, TSS, TS, RS, and NRS are clustered together in the primary cluster, which shows that these traits have a well-coordinated response pathway that is highly sensitive to incubation temperature, a fundamental ripening acceleration factor. A second large cluster is a combination of the fruit size and mass characteristics (FW, PW, FL, and FD), which shows that they are co-regulated and decrease with the increase of temperature, creating a structural integrity module, and is negatively correlated with the sugar cluster. Color parameters, such as L*, a*, b*, C*, and h°, are close to each other, as they play an interdependent role in the development of the pigments of the fruit skin during ripening, whereas biochemical properties (FpH and FMC) indicate a link between the color change, acidification and water loss. The secondary metabolites (TPC, TT) and the fruit firmness (FF) suggest that some texture and certain phytochemicals may be controlled by partially independent regulatory mechanisms that are not strongly affected by the thermal conditions. The cultivar-temperature combinations clustering shows temperature is more influential than cultivar, with cultivars grouping by their sensitivity to temperature. Cultivars differ according to sensitivity within temperature groups: Khalas and Sheshi form a stable, distinct group, whereas Barhi and Helali cluster closely together. This clustering shows that ripening involves distinct, temperature-sensitive trait networks, explaining why specific incubation protocols suit different cultivars.

Fruit quality traits relationship during artificial ripening of date palm fruits under varying postharvest incubation temperatures: Across the incubation range of 40–50°C, most parameters show a negative relationship with temperature, meaning their values decrease as temperature increases. FW (R^2 –0.83), PW (R^2 –0.89), FL (R^2 –0.83), FD (R^2 –0.83), FpH (R^2 –0.84), and the color attributes; L* (R^2 –0.98), a* (R^2 –1.00), b* (R^2 –0.98), C* (R^2 –1.00), and h° (R^2 –0.99) all decline steadily from 40 to 45 to 50°C, indicating that higher temperatures are associated with lower fruit size, acidity, and color intensity. Similarly, FF (R^2 –0.80), FMC (R^2 –0.82), NRS (R^2 –0.75), TPC (R^2 –0.75), and TT (R^2 –0.75) also decrease with increasing temperature, supporting the negative association (Fig. 20). The linear fits between temperature and these traits are generally strong negative coefficients of determination, supporting a consistent downward trend. In contrast, TSS (R^2 0.75), TS (R^2 –0.73), and RS (R^2 –0.74) exhibit a positive relationship with incubation temperatures (40–50°C). Their values at 45 and 50°C are higher than at 40°C, indicating that increasing temperature enhances the concentration of TSS, TS, and RS. Although the R^2 values for these sugar-related traits are slightly lower than for some physical and color traits, they still indicate a positive association between temperature and sugar related attributes.

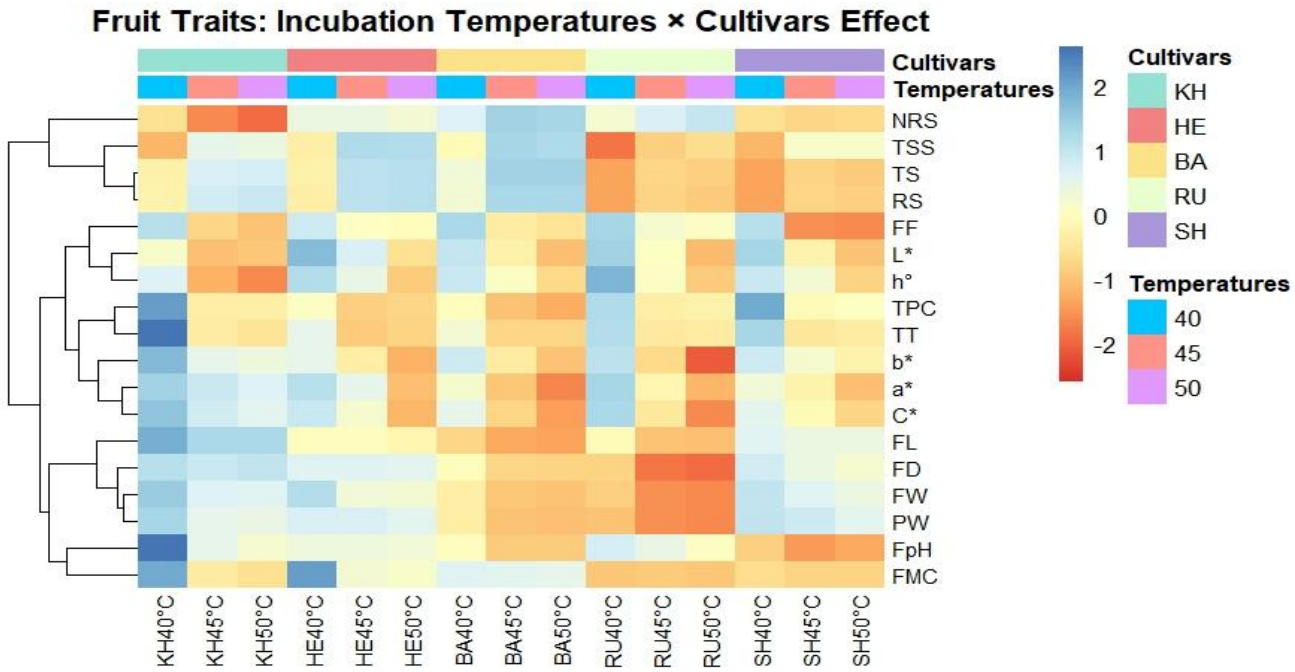

Fig. 19. Hierarchical clustering has been done by Euclidean distance and linkage technique by Ward. The heatmap shows the normalized value of the Z-scores in rows, wherein the traits were put into the mean = 0 and standard deviation = 1 to allow a comparison of the cross-traits. Dendrograms display similarity in the responses in traits (row clustering) and sample profiles (column clustering). Cultivar are abbreviated as KH (Khalas), HE (Helali), BA (Barhi), RU (Ruziez), and SH (Sheshi). Abbreviations of fruit traits: FW (Fruit weight), PW (Pulp weight), FL (Fruit length), FD (Fruit diameter), FpH (Fruit pH), L* (Lightness), a* (Green/Red), b* (Blue/Yellow), C* (Chrome), h° (hue angle), FF (Fruit firmness), FMC (Fruit moisture content), TSS (total soluble solids), TS (total sugars), RS (reducing sugars), NRS (non-reducing sugars), TPC (total phenol content), and TT (total tannins).

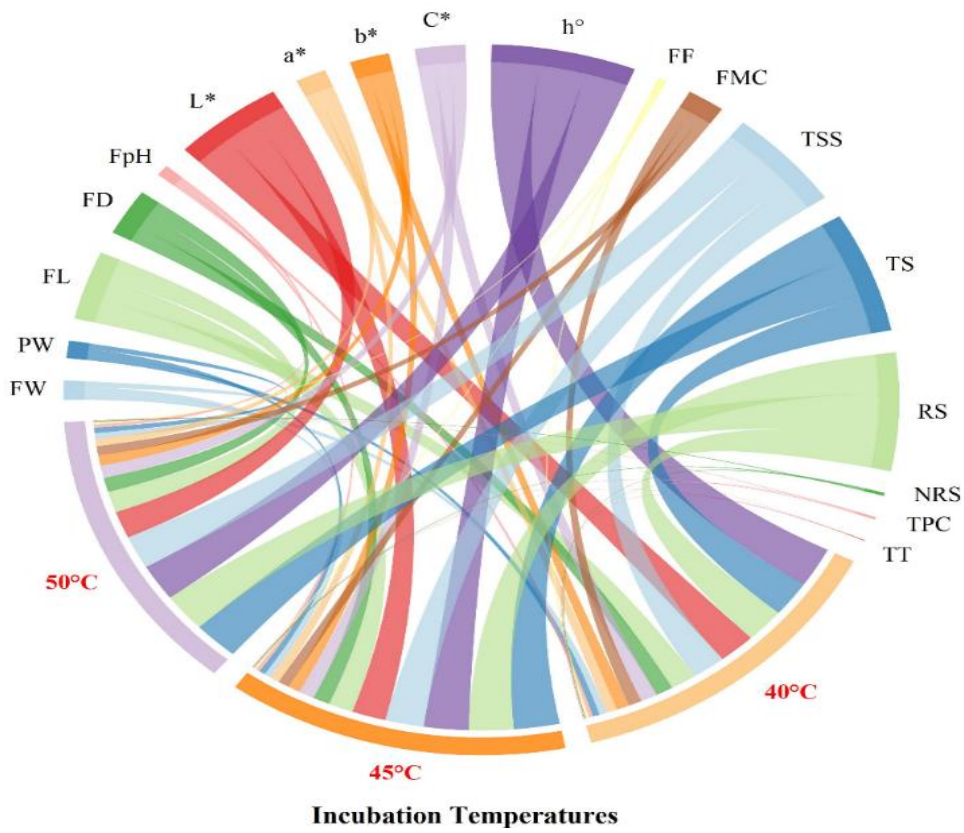

Fig. 20. Chord diagram illustrating the Pearson correlation network among fruit quality traits of Bisir date palm fruits incubated at 40, 45, and 50°C. Abbreviations of fruit traits: FW (Fruit weight), PW (Pulp weight), FL (Fruit length), FD (Fruit diameter), FpH (Fruit pH), L* (Lightness), a* (Green/Red), b* (Blue/Yellow), C* (Chrome), h° (hue angle), FF (Fruit firmness), FMC (Fruit moisture content), TSS (total soluble solids), TS (total sugars), RS (reducing sugars), NRS (non-reducing sugars), TPC (total phenol content), and TT (total tannins). Chord thickness corresponds to the absolute correlation coefficient ($R^2 \geq 0.90$).

Discussion

Saudi Arabia is facing a 'date fruit unripening syndrome' (DFUS), a disorder linked to climate change that prevents fruits from maturing to the Rutab and Tamer stages. DFUS has been reported at rates of 20-30% in the Eastern region, 10-15% in Riyadh, and 5-10% in Qassim. The syndrome threatens the livelihood of farmers and socio-economic stability of the communities that depend on date palm production (Iqbal *et al*., 2025). The current research is able to overcome this problem by explaining a scientifically-based, post-harvest incubation procedure that is capable of providing artificial ripening to Bisir-stage date palm fruits of five commercially-important cultivars. After three days at 45°C or 50°C incubation temperatures, the fruits developed qualities almost identical to naturally ripened Tamer fruits. This finding offers a powerful and reliable alternative to traditional methods. These findings are based on a fact that the date palm as being a climacteric fruit with its ripening is triggered by a natural, internal release of ethylene gas (Serrano *et al*., 2001). It is reckoned that the endogenous ethylene production is efficiently induced by the use of high temperatures, which is itself a potent abiotic stressor (Huang *et al*., 2023), that is otherwise suppressed by DFUS during the climacteric setup. The action of the key enzymes of the ethylene pathway, 1-aminocyclopropane-1-carboxylic acid (ACC) synthase and AACC oxidase are likely boosted by the heat shock which triggers a signal transduction cascade that stimulates the transcription of the ripening-related genes, resulting in a coordinated and accelerated transition to a stable Tamer-like fruit development state (Khan *et al*., 2024, Li *et al*., 2025). Fruit incubated at 40°C, did not regularly constantly achieve full similarity with natural ripening. This is therefore inferred that it operates at the threshold for activating the complete ethylene-mediated cascade, resulting in a slower and less active metabolic transition (Tipu & Sherif, 2024).

The observed morphological and textural changes indicate the ripening strategy under different temperature regimes. The reduction in the fruit weight, pulp weight, and fruit diameter with the rise of incubation temperature could be related to increased transpiration as a result of increased vapour pressure deficit at high temperature (Habibi *et al*., 2024). This controlled dehydration is a desirable process, which resembles the natural one of desiccating during the transition to the Tamer stage with the decrease in moisture content (Taain, 2013). A key indicator of successful artificial ripening was the significant softening (fruit firmness) of the fruit at 45 and 50°C, which corresponded to the texture of naturally ripened fruits. This is assumed that the decrease in firmness is mediated by the collaborative breakdown of the primary cell wall and middle lamella, and is guided by expression of a set of cell wall-modifying enzymes induced by ethylene (Tucker *et al*., 2017). Pectin methylesterase, polygalacturonase and cellulase are enzymes which work together to break down structural polysaccharides, e.g., pectin and cellulose. The loss of firmness is likely due to rapid degradation caused by high temperatures, which increase cell membrane viscosity and accelerate enzymatic reactions. The higher firmness retained by fruits at 40°C shows reduced cell wall disassembly activity, which hindered the ripening process (Anderson & Pelloux, 2025).

Along with physical changes, the fruit undergoes a major metabolic shift from acidic to sweet, improving its taste. As incubation temperature rises, fruit pH decreases steadily because organic acids like malic and citric acid are rapidly broken down in the Krebs cycle to supply energy and carbon for ripening (Walker & Famiani, 2018). In the present study, reaching the same pH values at 45 and 50°C as those of natural Tamer fruits confirms that this key metabolic shift is being effectively catalyzed. Total soluble solids and both total and reducing sugars increase sharply at higher temperatures due to two corresponding processes. First, heat acts as a catalyst, speeding up hydrolytic enzymes like α-amylase and β-amylase that convert insoluble starch into soluble sugars such as glucose and fructose. Second, increased water loss concentrates soluble solids within the fruit tissue (Du *et al*., 2024; Jayasooriya *et al*., 2025). The combined effects of biochemical activity and physical concentration produced very high Brix values, matching those of naturally ripened fruit. The sugar pattern, marked by a strong increase in reducing sugars and consistently low non-reducing sugars, reflects natural date ripening driven by high invertase activity (Rastegar *et al*., 2012; Kazem & Al-Asadi, 2024).

The colorimetric test indicates the visual changes during ripening, showing the shift from the yellow or red of the Bisir stage to the brown of the Tamer stage. It is supposed that the decrease in lightness and hue angle with rising temperature reflects chlorophyll breakdown, catalyzed by chlorophyllase and promoted by ethylene and heat (Gill *et al*., 2017; Chen *et al*., 2022). As green chlorophyll declines, old pigments appear, and enzymatic reactions involving polyphenol oxidase (PPO) and peroxidase (POD) cause further browning through oxidation and polymerization of phenolic compounds (Tilley *et al*., 2023). The incubation heat is therefore a dual role in which it inactivates the chlorophyll and actively facilitates the enzymatic browning reactions (PPO/POD) that differentiate the Tamer stage (Amiour & Hambaba, 2016). The color parameters at 50°C were closely corresponded natural Tamer fruits, suggesting this temperature best replicated the complete pigment transformation.

Changes in bioactive compounds during ripening are crucial for developing flavor and nutritional quality. The decline in total phenols and tannins, with higher incubation temperatures indicates successful de-astringency (Zhao *et al*., 2025). Tannins in Bisir-stage fruits cause astringency and poor taste, but during ripening, PPO oxidizes tannins, converting them into large insoluble compounds that no longer interact with salivary proteins (Morzel *et al*., 2022). High incubation temperatures catalyze these reactions, while the reduction of soluble tannins during both artificial and natural ripening of Tamer fruits eliminates astringency and creates a sweet, mellow flavor (Bar-Ya'akov *et al*., 2019). Similar decrease in the phenols indicates that the artificial process is based on the natural biochemical reaction, at which these compounds are produced or participated in the process of browning (Li *et al*., 2023).

There was a substantial genotypic diversity between the five cultivars, which was the inherent difference in fruit morphology and biochemistry. This supports the value of using multiple cultivars and indicates that while the 45–50°C protocol is broadly effective, it provides a basis for further cultivar-specific optimization. Incubation temperatures work as a controlled stimulus that activates the fruit's natural ripening program, increasing the activity of enzymes responsible for cell wall degradation, starch hydrolysis, and phenol oxidation. Similarly, high temperatures reduce moisture, increasing sugars and lowering water activity to enhance shelf stability. This study thus offers a reproducible, rapid, and high-quality DFUS solution that can save large crop quantities, strengthen food security, and provide a scientifically supported approach to mitigating climate change impacts on date palm cultivation.

Conclusion

The present study establishes a successful postharvest remedy to date fruit unripening syndrome (DFUS), where three days incubation of unripe Bisir-stage fruits in 45°C or 50°C significantly induces artificial ripening in fruits that have physicochemical qualities statistically equivalent to naturally ripened Tamer fruits, whereas Bisir fruits of almost all cultivars at 40°C proved less effective. This response could be due to high temperatures, which might trigger an endogenous ethylene-mediated climacteric pathway, organizing desirable softening, the rise of sweetness through the hydrolysis of starch and the decrease moisture content, the formation of desirable colors, and a vital de-astringency with the help of tannin polymerization. Although there was genotypic difference between cultivars, the incubation temperature strategy was generally successful, and was a fast, dependable, and non-hazardous substitute of the standard procedures. The study provides an effective approach to the reduction of postharvest losses, food security, and socio-economic stability by modifying unmarketable Bisir fruits into high quality and palatable products in response to climate change.

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