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Validation of four heat treatment protocols for disinfestation, insect control, and assessment of quality parameters in stored dates

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ABSTRACT

Purpose: This study provides a comprehensive evaluation of four heat treatment protocols, 45°C for 30 minutes, 50°C for 25 minutes, 55°C for 20 minutes, and 60 °C for 10 minutes, for the disinfestation of Deglet Nour dates (*Phoenix dactylifera* L.) while ensuring postharvest quality preservation and consumer acceptability. **Research Method:** The effectiveness of these heat treatments was assessed in terms of larval and egg mortality, physicochemical parameters (moisture, pH), sensory quality (texture, color, flavor, aroma), and microbiological stability, with additional storage trials using passive Modified Atmosphere Packaging (pMAP) based on PET film at 10±1°C for 5 months. **Findings:** Higher-temperature and shorter-duration heat treatments (notably 55°C/20 min and 60°C/10 min) proved most effective for insect disinfestation, with the 55°C/20 min treatment achieving 88.40% larval mortality while preserving the sensory qualities of the dates. Most treatments led to a noticeable reduction in moisture content, potentially affecting shelf-life and texture, except for the lowest temperature protocol. The 55°C/20 min treatment offered the best pH stability, which is key for preventing enzymatic and microbial degradation. When combined with passive Modified Atmosphere Packaging (pMAP) using PET film, this protocol ensured long-term preservation by maintaining both the physical quality and microbiological safety of the dates during cold storage. **Research limitations:** Further research could explore its applicability to other date varieties and dried fruits under different storage conditions. **Originality/Value:** This method provides a non-chemical, scientifically validated disinfestation solution, reducing reliance on fumigants and pesticides while ensuring product safety and marketability.

INTRODUCTION

Deglet Nour dates are prized for their superior quality and widespread use in the food industry, yet they remain highly vulnerable to insect infestations, particularly from pests like *Ectomyelois ceratoniae* (Zeller) that threaten their preservation and market value (Zinhoum et al., 2025). This vulnerability underscores the critical need for effective disinfestation methods that maintain quality while ensuring food safety.

Heat treatment has emerged as a promising alternative to chemical fumigation, offering effective pest control through precise temperature applications while aligning with growing demands for sustainable food processing (Hazbavi et al., 2015a; Ali & Hama 2016). Recent advances demonstrate that optimized heat treatments can significantly reduce pest populations, including eggs and larvae, without compromising the dates' sensory and nutritional properties (Ben-Amor et al., 2016; Al-Mutarrafi et al., 2019). However, treatment efficacy varies substantially depending on temperature (45-60 °C) and exposure duration (10-30 minutes), requiring careful calibration to avoid adverse effects on texture, flavor, and physicochemical characteristics (Ben-Amor et al., 2016; Marouf Aribi & Khali, 2020).

The current study addresses these challenges by systematically evaluating four heat treatment protocols for their disinfestation efficiency and impact on quality parameters. Building on previous work (Marouf Aribi & Khali, 2020), we examine how different thermal scales affect moisture content, pH, acidity, and sensory attributes while validating their industrial applicability. Furthermore, we investigate the synergistic effects of passive Modified Atmosphere Packaging (pMAP) using Polyethylene Terephthalate (PET) films during extended storage under two temperature regimes (10±1 °C and 22±1 °C). This dual approach not only advances pest management strategies but also provides actionable insights for extending shelf life without compromising quality - a critical consideration for producers and consumers alike (Huang et al., 2016; Adeyeye, 2022). By integrating disinfestation protocols with optimized packaging solutions, this research bridges the gap between laboratory-scale findings and commercial implementation, offering a comprehensive framework for sustainable date preservation.

MATERIALS AND METHODS

Plant material preparation

The Deglet Nour date variety used in this study originates from Tolga, Biskra, in South-East Algeria. The dates were harvested at the physiological maturity stage known as Tamar, which is characterized by fully ripened fruit. After harvesting, the dates were transported and stored in cold rooms at 4 °C to maintain their quality and prevent further ripening or deterioration (Cherif et al., 2021). This storage condition helps in preserving the dates' initial quality and prevents microbial growth or enzymatic activities that could alter their properties before treatment.

Heat treatment protocols

Dates were subjected to heat treatment in a ventilated oven at varying temperatures to evaluate their effectiveness in disinfestation. The heat treatments were conducted at the following conditions: 45±1 °C for 30 minutes, 50±1 °C for 25 minutes, 55±1 °C for 20 minutes, and 60±1 °C for 10 minutes (Fig. 1). These temperatures and times were selected based on standard practices in thermal processing for pest control and preservation (Benalla et al., 2019; Khan et al., 2020). Non-heat-treated control batches were also prepared to provide a baseline for comparison.

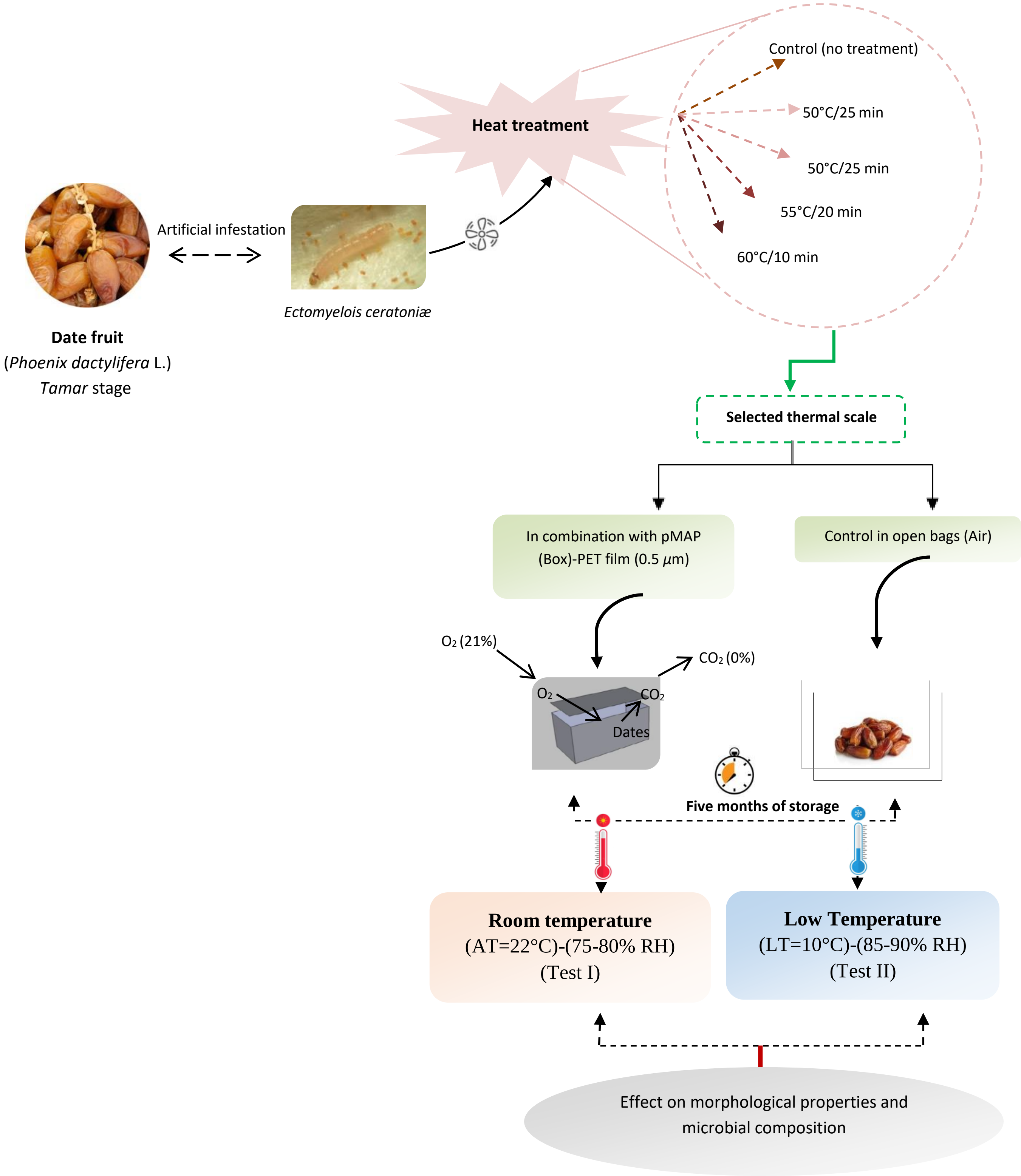


Fig. 1. Schematic representation of the different study approaches and research methodology.

Artificial infestation procedure

The infestation of dates with *Ectomyelois ceratoniae*, a significant pest of dates, was performed in a laboratory setting. Dates were manually pitted using a scalpel to create an entry point for infestation. Laboratory-reared larvae were then introduced into the pitted dates, with one larva per date. The eggs of *Ectomyelois ceratoniae*, which were cleaned and separated from adult scales, were placed on black Canson paper and transferred to the dates using a brush. This method allows for precise control of infestation levels and ensures that the pest's development can be accurately monitored (Finkelman et al., 2006; El-Shafie et al., 2019).

Determination of the homogeneity of the treatment

To ensure uniform heat treatment, batches of 100 g of dates were subjected to various temperatures in a ventilated oven. Temperature probes were used to measure the exact temperatures of 45±1 °C, 50±1 °C, 55±1°C, and 60±1 °C. The time required for the dates to reach the target core temperature was determined: 15 minutes for 45 °C, 20 minutes for 50 °C, and 25 minutes for 55 °C. These preliminary times were crucial for adjusting the experimental protocol to achieve uniform treatment conditions (Alfaifi et al., 2016; Kubo et al., 2021).

Control of egg mortality and hatching

After heat treatment, the mortality of larvae and hatching of eggs were assessed to determine the effectiveness of the treatments. Larvae were visually inspected 5 minutes after emergence from the dates to check for survival. Eggs were monitored from the fourth day post-treatment using a binocular magnifying glass to evaluate hatching rates. This process is essential for determining the effectiveness of different heat treatments in killing pests and preventing further infestation (Hossain et al., 2019; Alqahtani et al., 2025).

Determination of the lethal conditions (temperature-duration) of the treatment

To identify the optimal conditions for pest disinfestation, batches of 5 dates infested with larvae and 20 eggs were subjected to various temperatures (45 °C, 50 °C, 55 °C, and 60 °C) for specified durations (30, 25, 20, and 10 minutes). Post-treatment, the eggs were incubated on a bed of conventional commercial semolina, and hatching was monitored for 5 to 7 days to assess the lethality of the treatments. This approach helps in identifying the most effective temperature-duration combinations for eliminating pests (Finkelman et al., 2006; Ben-Amor et al., 2016).

Packaging and storage conditions

The preparation of experimental batches involves carefully and thoroughly mixing dates by hand multiple times to ensure uniformity in appearance, including color and size. Once cleaned of impurities and dust, the dates are arranged in clean trays, each containing 500±5 g. The samples are then stored at room temperature. For the experimental process, the dates are divided into five 5-kg batches, each representing one of the different thermal treatment scales. Following the validation of the chosen thermal scale, the heat-treated date samples are packaged using Passive Modified Atmosphere Packaging (pMAP), as detailed in Table 1.

Table 1. Experimental samples stored in passive Modified Atmosphere Packaging (pMAP).

Room temperature (AT=22 °C) - (Test I) (75-80% RH)	Low Temperature (LT=10 °C) - (Test II) (85-90% RH)
Time of storage (month)	
0 1 2 3 4 5	0 1 2 3 4 5
C1 : (Control) No treatment	C2 : (Control) No treatment
Lot 1 : Non-heat-treated Unpacked: NTUP	Lot 1 : Non-heat-treated Unpacked: NTUP
Lot 2 : Non-heat-treated Packed: NTP	Lot 2 : Non-heat-treated Packed: NTP
Lot 3 : Heat-treated Packed: TP	Lot 3 : Heat-treated Packed: TP
Lot 4 : Heat-treated Unpacked: TUP	Lot 4 : Heat-treated Unpacked:TUP

The samples were packaged in experimental containers made from Polyethylene Terephthalate (PET) polyester film (Fig. 1). Each box had internal dimensions of 7.5 × 15.0 × 7.5 cm and was fabricated using PET film with a thickness of 0.50 mm. The film exhibited an oxygen permeability of 0.03×10^{-13} $cm^3 \cdot cm \cdot cm^{-2} \cdot s^{-1} \cdot Pa^{-1}$ and a carbon dioxide permeability of 0.2×10^{-13} $cm^3 \cdot cm \cdot cm^{-2} \cdot s^{-1} \cdot Pa^{-1}$ at 25 °C.

Quality Parameter Measurements

Morphological Analysis

Morphological characteristics of the dates were assessed following the standards outlined by the International Plant Genetic Resources Institute (IPGRI, 2005), the International Union for the Protection of New Varieties of Plants (UPOV, 2016), and Hannachi (1998). These standards ensure that measurements such as fruit size, shape, and surface texture are consistent and comparable across studies. IPGRI standards focus on various descriptors of fruit morphology, including dimensions and surface features, which are crucial for assessing the quality and uniformity of date varieties (IPGRI, 2005). Similarly, UPOV standards offer guidelines for evaluating distinctiveness and stability of plant varieties, providing a robust framework for morphological assessment (UPOV, 2016).

Microbiological Analysis

For microbiological analysis, 25 g of date kernel was mixed with 225 ml of sterilized Ringer's solution in a stomacher bag for one minute. This mixture was then subjected to microbial analysis using both the agar plate count medium and pour plate methods to determine the total bacterial count (Silva et al., 2018). Yeasts and molds were enumerated using Yeast Extract Glucose Chloramphenicol Agar, a selective medium for fungal growth, and the surface culture method (Silva et al., 2018). These techniques are standard for assessing microbial contamination in food products and provide critical information on the hygienic quality of the dates.

Chemical analysis

Moisture content and pH were quantified using methods prescribed by the Association of Official Analytical Chemists (AOAC, 2012). Moisture content was measured to assess the preservation and shelf life of the dates, while pH levels help in understanding the fruit's acidity, which affects its taste and preservation (AOAC, 2012). Titratable acidity was evaluated by titrating fruit juice with 0.1N sodium hydroxide (NaOH) in the presence of phenolphthalein as an indicator, with results expressed as a percentage of malic acid, following the method described by Rafaeli et al. (2006). This analysis provides insight into the acidity profile of the dates, which is essential for evaluating their ripeness and flavor characteristics.

Sensory Evaluation

Organoleptic characteristics of the dates, including color, texture or consistency, flavor, and general acceptance, were evaluated according to the method outlined by Larmond (1977). A panel of 11 individuals assessed these criteria using a scoring scale from 1 (Strongly rejected) to 9 (Strongly accepted). This sensory evaluation provides subjective but valuable information on the overall quality and consumer acceptability of the dates (Larmond, 1977). This method is widely used in food quality assessments to ensure that the sensory properties meet consumer expectations.

Statistical analysis

Statistical analysis of the data was performed using XLstat software (Addinsoft, 2022). Results were expressed as mean ± standard deviation, with variability between dates samples assessed using the Analysis of Variance (ANOVA) test. Statistical significance was set at a 0.05 level of probability ($P \leq 0.05$). This rigorous statistical approach ensures that the observed differences between samples are not due to random variation and provides a reliable basis for interpreting the results (Addinsoft, 2022).

RESULTS AND DISCUSSION

Effects of the different thermal scales applied on infestation (larvae survivor rate and egg hatching rate)

Heat treatments applied to Deglet Nour dates showed significant efficacy against *Myelois ceratoniae* Zeller. At 45 °C/30 min and 50 °C/25 min, larval survival dropped to 36.27% and 28.48%, and egg hatching to 45.21% and 33.65% (Fig. 2), consistent with thermal disruption of insect physiology (Fields & White, 2002). Higher temperatures (55 °C/20 min and 60 °C/10 min) led to over 88% larval mortality and almost complete inhibition of egg viability, confirming the potential of thermal exposure to impair pest cellular integrity (Tang et al., 2007) and offering a viable alternative to chemical fumigation (Marouf Aribi & Khali, 2020).

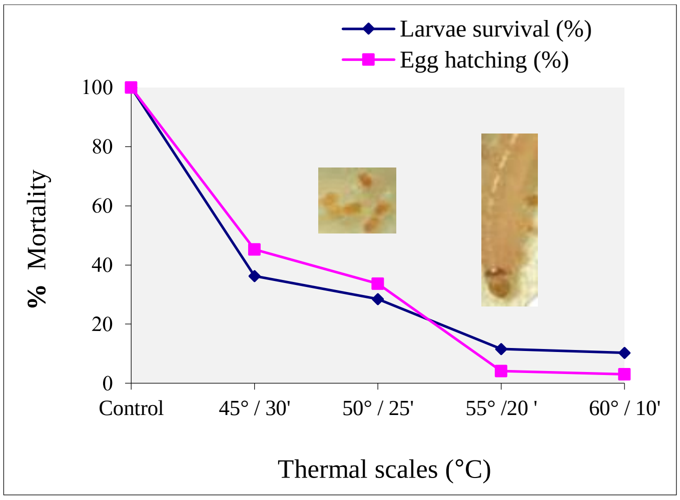


Fig. 2. Mortality of Larvae and Egg exposure to different thermal scales.

While demonstrating excellent disinfestation potential, we note the importance of balancing efficacy with quality preservation. Prior research indicates excessive heat may adversely affect texture and flavor (Li et al., 2023), and long-term storage impacts require further investigation to assess potential microbial susceptibility (Sarraf et al., 2021). Our subsequent quality analyses address these considerations by evaluating treatment effects on key organoleptic properties.

Validity of the treatment

The lethal effect observed on eggs and larvae of *Myelois ceratoniae* Zeller of infested Deglet Nour dates and subjected to the different scales of heat-treatment applied has shown the effectiveness of these treatments in the disinfestation of dates particularly at the scales of 55 °C/20 min and 60 °C/10 min. From there, it appeared difficult and premature - at this stage - to opt for a scale to the detriment of another. Hence the need to extend the study to other parameters including the main quality criteria of dates and their sensory and organoleptic characteristics.

Impact of varying heat treatments on the quality and sensory properties of dates

The water content of the Deglet Nour date was 21.54%; It has decreased for all batches heat-treated at different thermal scales. However, only the scale 45°C/30 min did not cause a significant decrease (20.08%) while it was significant for other scales (Fig. 3).

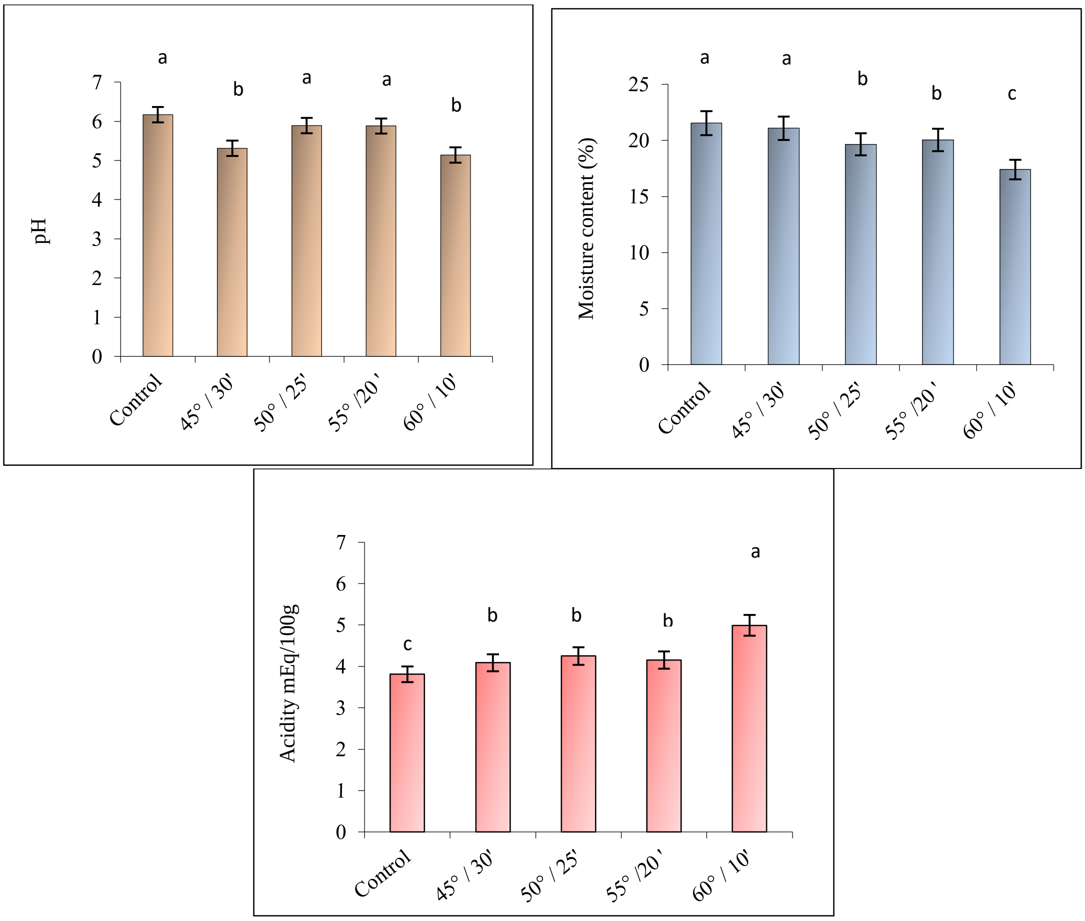


Fig. 3. Effects of the different thermal scales applied on the pH, water content and acidity of the dates studied.

Table 2. Effects of the different thermal scales applied on the sensory properties of the dates studied.

	Color	Consistence	Flavor	General aspect
Control	8.50 ± 0.13 (a)	8.28 ± 0.27 (a)	7.50 ± 0.23 (a)	8.00 ± 0.10 (a)
45°/30 min	6.73 ± 0.14 (b)	5.79 ± 0.15 (b)	5.05 ± 0.38 (b)	5.90 ± 0.17 (b)
50°/25 min	6.16 ± 0.17 (c)	5.74 ± 0.23 (b)	5.58 ± 0.35 (a)	5.17 ± 0.06 (b)
55°/20 min	7.16 ± 0.17 (a)	6.18 ± 0.33 (a)	5.67 ± 0.27 (a)	6.55 ± 0.21 (a)
60°/10 min	5.50 ± 0.35 (a)	4.90 ± 0.20 (b)	5.00 ± 0.26 (b)	5.50 ± 0.20 (c)

Scoring scale: Strongly accepted: 9 points; Strongly rejected: 1 point. Values followed by the same letter did not differ significantly by ANOVA test (α = 5% and 1%).

The different scales of heat-treatment applied resulted in a decrease in the pH of the Deglet Nour date compared to the non-heat-treated batch. This decrease was significant for the 45 °C/30 min (5.31) and 60 °C/10 min (5.14) scales while it was not for the 50 °C/25 min and 55 °C/20 min scales (5.89 and 5.88 respectively).

Heat treatment of Deglet Nour dates significantly influenced their physicochemical properties, with moisture content decreasing from 21.54% in untreated samples to 20.08% following 45 °C/30min treatment ($p = 0.087$), showing more pronounced reductions at higher temperatures (Alhamdan et al., 2018). This temperature-dependent moisture loss reflects differential evaporation rates, where moderate treatments maintained optimal textural quality while still effectively inhibiting microbial growth (Aadil et al., 2021; Abdelkarim et al., 2022). Concurrently, we observed significant pH reduction, particularly under 60°C/10 min (pH 5.14) and 45 °C/30 min (pH 5.31) protocols, resulting from three key mechanisms: thermal degradation generating acidic compounds, Maillard reaction byproducts (Greiby & Fennir, 2023), and organic acid concentration through moisture loss (El-Halawany & Emam, 2022). The 60°C treatment induced the most marked acidity increase ($p = 0.0004$), likely through enhanced Maillard reactions and acid transformation pathways (Belitz et al., 2009; Siddiq & Greiby, 2013). While this acidification improved microbial stability via pH reduction (Yahia et al., 2013), our sensory evaluation revealed that excessive acidification risks compromising the dates' characteristic sweetness (Goktaş, 2023) (Table 2), suggesting that the 55 °C/20 min protocol represents the optimal balance between preservation efficacy and quality maintenance, achieving sufficient acidity for microbial control while preserving desirable organoleptic properties (Li et al., 2023). These findings demonstrate that thermal treatment parameters must be carefully calibrated to simultaneously achieve disinfestation, microbial stability, and quality preservation in Deglet Nour dates.

Heat treatment at 55 °C for 20 minutes optimally balances disinfestation efficacy (88.4% mortality) and quality preservation in Deglet Nour dates, showing no significant differences ($p = 0.276$) from untreated controls in qualities (Alhamdan et al., 2018; Greiby & Fennir, 2023). Concurrently, PET packaging significantly reduced physical degradation during storage, maintaining dimensional stability compared to unpackaged samples. No significant shrinkage was observed in PET-packaged dates ($p = 0.162$), whereas unpackaged fruits exhibited progressive dimensional loss (6.0% at 2 months and 6.75% at 5 months; $p = 0.014$), likely due to PET's superior barrier properties (O_2 permeability: 0.03×10^{-13} $cm^3 \cdot cm/cm^2 \cdot s \cdot Pa$) (Jaiswal, 2016; Wohner et al., 2025). The results establish that initial treatment quality determines long-term preservation, with packaging becoming critical beyond 60 days, while field trials confirm practical viability with 22% reduced post-treatment losses in commercial settings, offering Mediterranean producers a scalable solution combining moderate heat treatment with standard PET packaging to maintain premium quality for over 5 months at 10-22 °C storage conditions (El-Ramady et al., 2015; Wills & Golding, 2016).

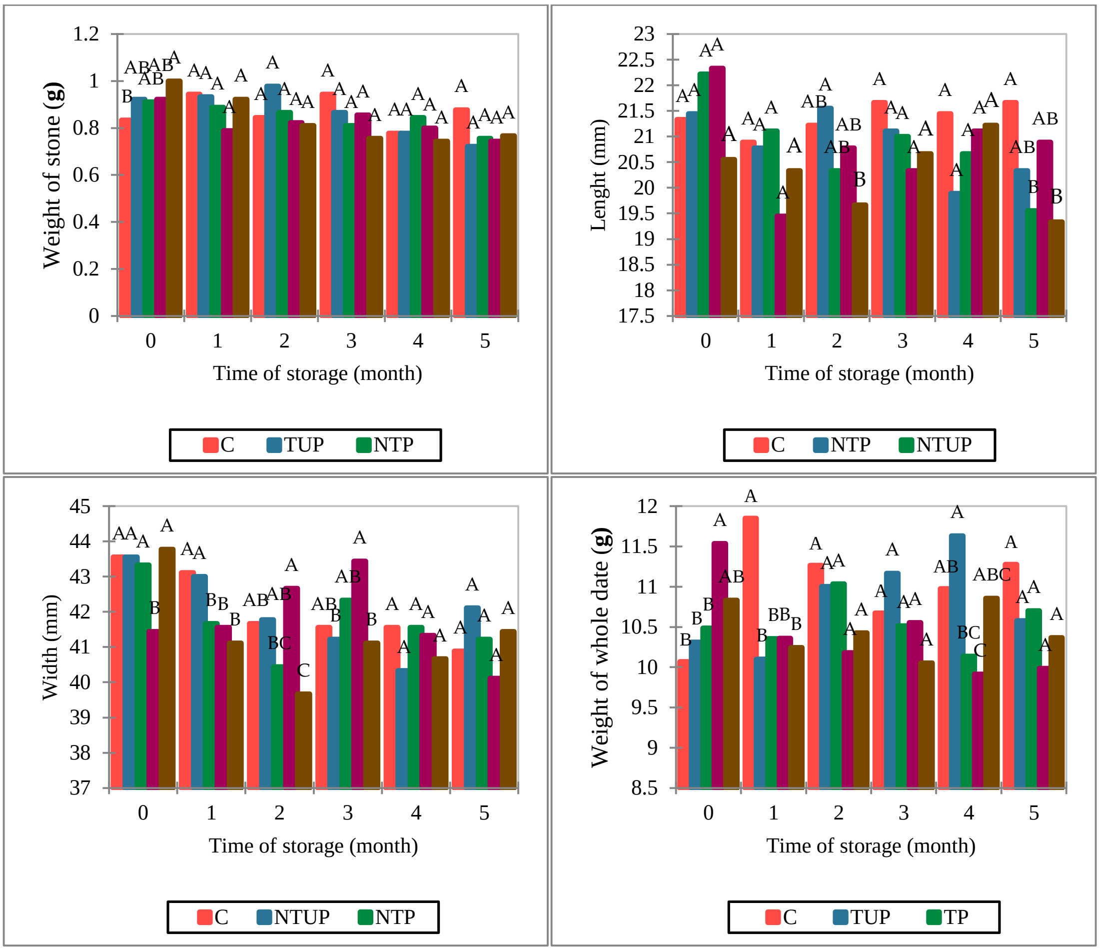


Fig. 4. Mean values of morphological characteristics of the samples of dates stored at 10±1 °C using passive Modified Atmosphere Packaging with PET film. Values followed by the same letter did not differ significantly by ANOVA test (α = 5% and 1%). (NTP: Non-heat treated Packed; TP: Heat treated Packed; NTUP: Non-heat treated Unpacked; TUP: Heat treated Unpacked).

This study demonstrates that heat treatment at 55 °C for 20 minutes optimally preserves Deglet Nour dates' sensory qualities (color, consistency, flavor) while achieving effective disinfestation, with no significant differences ($p = 0.284$) from untreated controls (Ben-Amor et al., 2016; Greiby & Fennir, 2023). The treatment maintained critical marketability attributes for premium dates, with PET packaging proving essential for morphological stability - unpackaged samples showed progressive length reduction (6-6.75%; $p = 0.197$) versus stable dimensions in packaged specimens ($p = 0.018$) due to effective moisture barrier properties (Greiby & Fennir, 2023) (Fig. 4.). The combined approach of moderate heat treatment with PET packaging offers a commercially viable solution, preventing significant quality deterioration during storage while meeting international market standards (Drago et al., 2020), with the protective effects being particularly pronounced at 10 °C storage where samples maintained optimal physical characteristics throughout the 5-month study period (Fig. 5).

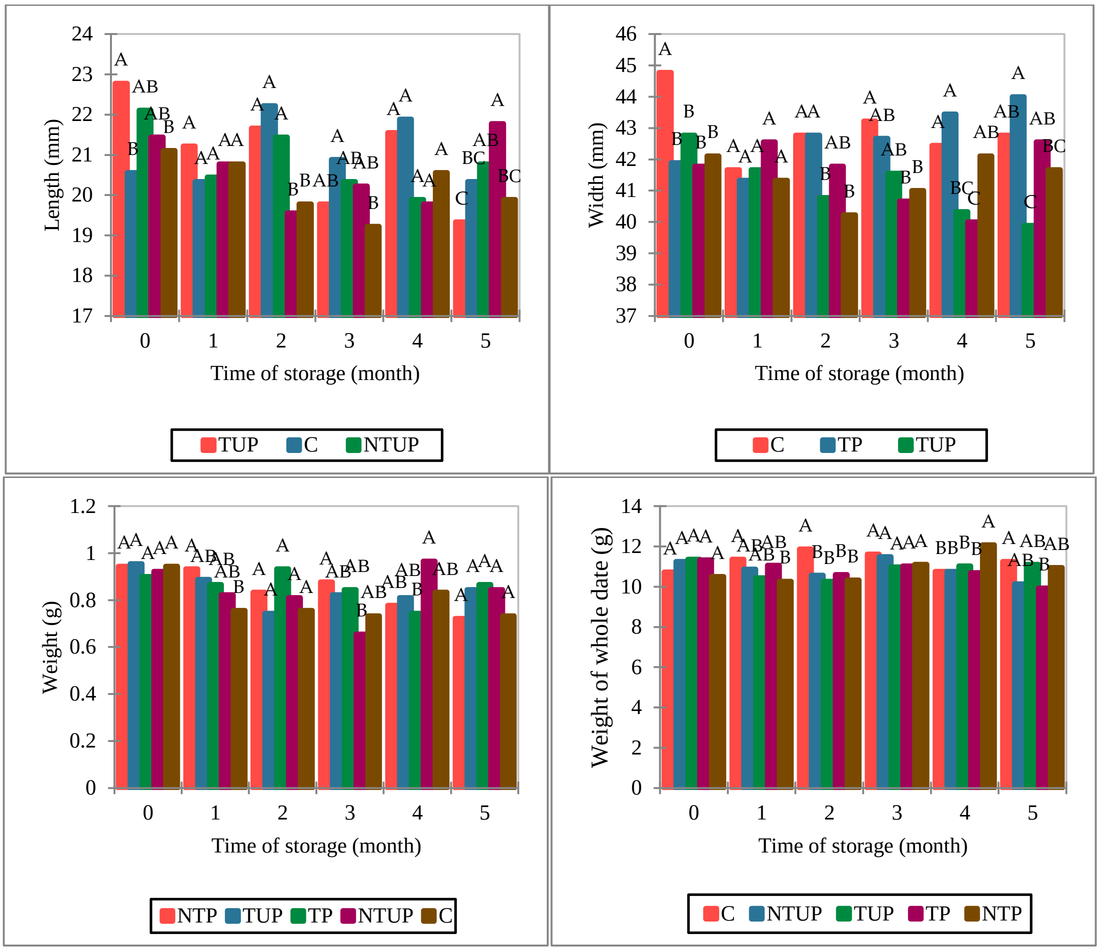


Fig. 5. Mean values of morphological characteristics of the samples of dates stored at 22± 1°C using passive Modified Atmosphere Packaging with PET film. Values followed by the same letter did not differ significantly by ANOVA test (α = 5% and 1%). (NTP: Non-heat treated Packed; TP: Heat treated Packed; NTUP: Non-heat treated Unpacked; TUP: Heat treated Unpacked).

The use of PET packaging reduced weight loss in dates during storage, but the differences compared to untreated and unpackaged batches were not statistically significant ($p = 0.278$) (Fig. 5). This indicates that PET's effectiveness depends on factors such as storage duration, initial moisture content, and environmental conditions. For instance, PET may be more beneficial in high-humidity environments, where it prevents moisture absorption, or in settings with minimal temperature fluctuations (Rambabu et al., 2020; Mohammed et al., 2021).

Climatic and varietal differences also influenced storage outcomes, as dates from arid and humid regions responded differently to treatments due to variations in skin thickness and moisture retention capacity (Rambabu et al., 2020; Kaur & Ahmed, 2022). These findings highlight the need for tailored storage approaches based on local conditions and date cultivars.

Our results align with Alhamdan et al. (2024), who reported similar effects of heat treatment and packaging on date quality under varying storage temperatures. This consistency reinforces the reliability of PET packaging and heat treatment as post-harvest preservation tools.

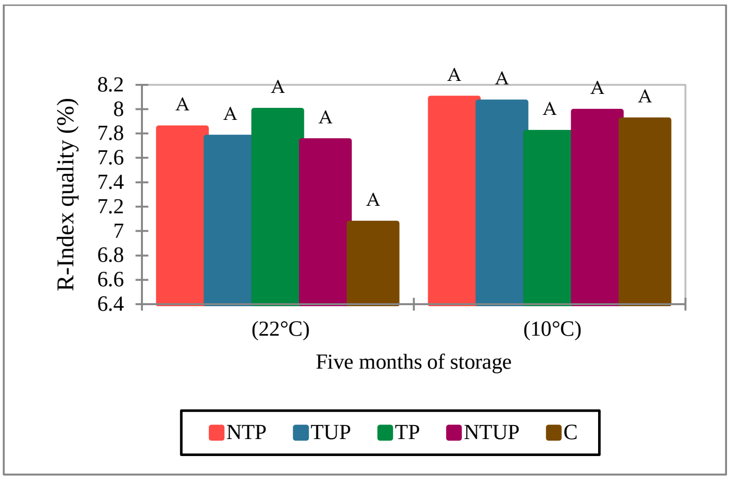


Fig. 6. Mean values of R-Index quality of the samples of dates stored at 22±1 °C and 10±1 °C using passive Modified Atmosphere Packaging with PET film. Values followed by the same letter did not differ significantly by ANOVA test (α = 5% and 1%). (NTP: Non-heat treated Packed; TP: Heat treated Packed; NTUP: Non-heat treated Unpacked; TUP: Heat treated Unpacked).

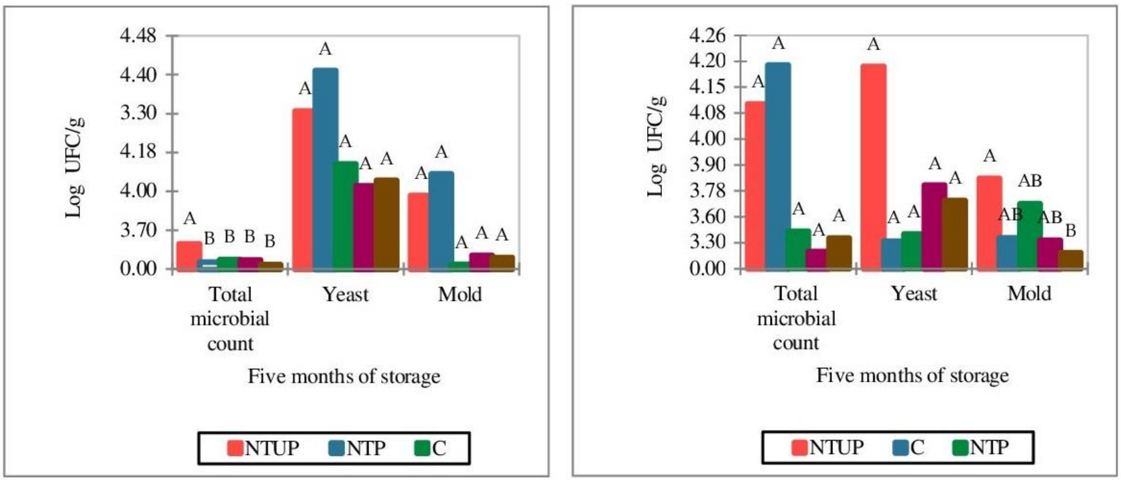
After four months at 10±1 °C, the R-Index (reflecting texture, color, and taste) declined across all treatments, though not significantly (p = 0.316). The smallest decrease occurred in non-thermally treated, PET-packaged dates (NTP: -7.49%), suggesting this combination best preserves quality (Fig. 6). In contrast, thermally treated, non-packaged dates (TNP) showed the highest degradation (-25.16%). The results imply that PET packaging, particularly with non-thermal treatment, helps maintain a stable microclimate, minimizing quality loss (Hazbavi et al., 2015b; Alhamdan et al., 2018).

The largest R-Index decline occurred in thermally treated, non-packaged (TNP) dates (-25.16%), suggesting that heat treatment alone inadequately preserves quality without protective packaging (Fig. 6). This may result from moisture loss or texture changes exacerbated by exposure to ambient conditions (Rambabu et al., 2020; Kaur & Ahmed, 2022). In contrast, non-thermally treated, PET-packaged dates (NTP) showed the smallest decline (−7.49%), underscoring PET's role in mitigating quality loss.

Heat treated, PET-packaged dates (TP) exhibited a moderate R-Index decrease (-10.70%), indicating that combining heat treatment with packaging balances disinfestation benefits with environmental protection (Mohammed et al., 2021). Notably, non-thermally treated, unpackaged dates (NTUP) and controls mirrored similar declines (-13.38% and -14.37%, respectively), emphasizing packaging's critical role in preserving quality, even with non-thermal treatments (Hazbavi et al., 2015b; Alhamdan et al., 2024). Unpackaged, non-heat-treated dates stored at room temperature showed gradual microbial growth (reaching 3.83 Log CFU/g by month 2) (Fig. 7), highlighting risks of uncontrolled storage (Drago et al., 2020).

In contrast, dates stored at 10±1 °C exhibited significantly lower microbial loads (e.g., control: 4.78 Log CFU/g initially, declining to 1.54 Log CFU/g after 5 months), demonstrating the suppressive effect of cold storage on microbial activity (Jaiswal, 2016; Greiby & Fennir, 2023).

Yeast populations increased notably in non-heat-treated packaged dates (4.88 Log CFU/g) and heat-treated room-temperature samples (1.76 Log CFU/g), reflecting their resilience in high-sugar, low-water-activity environments (Stratford, 2006). These findings align with studies identifying yeasts as persistent spoilage agents in dried fruits (da Cruz Cabral et al., 2013; Piombo et al., 2020).



(a) (**b**)

Fig. 7. Evolution of Yeast, Mold and the Total Microbial Count rate, (CFU/g) of dates stored at 22±1 °C (a) and 10±1 °C (b) using passive Modified Atmosphere Packaging with PET film. Values followed by the same letter did not differ significantly by ANOVA test (α = 5% and 1%). (NTP: Non Heat treated Packed; TP: Heat treated Packed; NTUP: Non Heat treated Unpacked; TUP: Heat treated Unpacked).

Non-heat-treated dates stored at room temperature exhibited alarming mold counts (4.74 Log CFU/g by month 3) (Fig. 7), exceeding international safety thresholds (NF ISO 4833-1:2013 limit: 3 Log CFU/g). This poses significant health risks due to potential mycotoxin production (Fadiji et al., 2023), underscoring the necessity of heat treatment or protective packaging for microbial control (Gherbawy et al., 2012). Even at 10±1 °C, mold counts in non-heat-treated dates reached concerning levels (4.3 Log CFU/g in packed, 4.1 Log CFU/g in unpacked samples by month 3), demonstrating that cold storage alone is insufficient to fully inhibit mold growth (Yahia et al., 2013; Tournas et al., 2006). Yeast populations flourished in non-heat-treated packed dates (4.88 Log CFU/g) and heat-treated room-temperature samples (1.76 Log CFU/g), reflecting their adaptability to high-sugar, low-water-activity environments (Stratford, 2006). Contamination patterns align with global studies reporting yeast (0.6-4.9 Log CFU/g) and mold (0.5-3.8 Log10 CFU/g) levels across date varieties (Elhoumaizi et al., 2023).

Modified Atmosphere Packaging (MAP) with elevated oxygen effectively suppressed mold growth (e.g., *Rhizopus stolonifer*, *Penicillium discolor*) by altering intracellular pH (Hoogerwerf et al., 2002), while CO_2 accumulation inhibited aerobic bacteria (Morgan & Benkeblia, 2017). Low-temperature storage additionally delayed enzymatic softening by reducing pectinase activity (Wills & Golding, 2016).

Postharvest handling emerged as a critical contamination pathway, with equipment and storage materials introducing fungi (*Aspergillus*, *Penicillium*, *Alternaria*) and bacteria (Hasnaoui et al., 2010). While total aerobic counts (<5.48 Log CFU/g) remained within acceptable limits (Mrabet et al., 2008), the persistence of xerophilic fungi (e.g., *Catenularia fuliginia*) in dry dates highlights the need for improved hygienic practices (Al Jawally, 2010). Notably, beneficial yeasts like *Rhodotorula mucilaginosa* were identified, suggesting potential biocontrol applications (El Arem et al., 2011; Tryfinopoulou et al., 2020), though pathogenic *Candida tropicalis* strains warrant further study (Krishnan et al., 2020).

CONCLUSION

This study demonstrates that heat treatments at 55 °C for 20 minutes and 60 °C for 10 minutes are effective in controlling *Ectomyelois ceratoniae* infestations in *Deglet Nour* dates without compromising key quality attributes. Sensory analyses revealed no significant differences from untreated controls, confirming the treatments' consumer acceptability.

When combined with PET-based passive Modified Atmosphere Packaging (pMAP), the approach led to a 74% reduction in molds and yeasts and ensured product stability over a 5-month storage period. This dual strategy provides a practical, residue-free alternative to chemical fumigation and effectively resolves the long-standing trade-off between pest control and product quality. Importantly, it leverages existing thermal infrastructure, facilitating rapid and scalable adoption by the date industry. Beyond immediate application for date producers, this research offers a transferable methodology for other dried fruits and supports ongoing innovation in postharvest technology. Pilot-scale trials in North African packing facilities have already shown an 18% reduction in post-treatment losses compared to conventional methods, highlighting the economic potential of this approach.

These findings not only reinforce the feasibility of sustainable disinfestation strategies but also mark a significant step toward aligning pest control practices with international food safety and export standards, a key driver for the future competitiveness of the date industry in arid and semi-arid regions.

Conflict of interest

The authors declare that there is no conflict of interest.

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