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Research article

Combined influences of edible coating and storage conditions on the quality of fresh dates: An investigation and predictive analysis using artificial neural networks

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ABSTRACT

The postharvest preservation of fresh produce is crucial for enhancing food sustainability and security. The study investigates the combined effects of coating with gum Arabic (GA), storage temperature, and packaging methods on the quality of Barhi date during storage. In addition, the artificial neural network (ANN) model was used to predict fruit quality parameters, including fruit weight, volume, density, weight loss, hardness, decay percentage, moisture content, pH, Total soluble solid, water activity, color parameters, color difference, and browning index based on the coating and storage conditions and the initial fruit weight, size, moisture content, total soluble solids, and color parameters at the beginning of storage. The findings indicated that vacuum packaging, coating with 10 % GA concentration, and cold storage were the most effective combinations for prolonging shelf life and preserving the quality parameters of stored Barhi dates. The implemented ANN model effectively predicted most fruit quality parameters, closely corresponding with observed data across various storage environments, as indicated by the low values of the evaluation metrics, i.e., mean absolute error, mean absolute percentage error, relative error, and root mean squared error. The R^2 values observed for the quality parameters of fruit weight (0.951), volume (0.746), density (0.735), weight loss (0.989), hardness (0.967), decay percentage (0.962), moisture content (0.901), pH (0.965), total soluble solids (0.973) water activity (0.859), and color parameters of L* (0.978), a* (0.784), b*, ΔE* (0.955), and browning index (0.951), validate the precision and dependability of the ANN models in their ability to predict the quality attributes of Barhi date fruits. The study outcomes contribute to food quality and supply chain management by finding the best combination of edible GA coating and storage conditions. Inaddition, predicting fruit quality during storage helps maintain their quality and reduce postharvest losses.

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Acronym list

ANN	Artificial Neural Network
FW	Fruit Weight
FV	Fruit Volume
FD	Fruit Density
WL	Water Loss
FH	Fruit Hardness
DP	Decay Percentage
MAE	Mean Absolute Error
MAPE	Mean Absolute Percentage Error
MC	Moisture Content
$\mathbf{R^2}$	R-squared
RE	Relative Error
RMSE	Root Mean Squared Error
TSS	Total Soluble Solids
pH	Hydrogen Ion Concentration
aw	Water Activity
L*	Lightness
a*	Red-Green Chromaticity
b*	Yellow-Blue Chromaticity
ΔE*	Total Color Difference
BI	Browning Index
GA	Gum Arabic
GAC	Gum Arabic Concentration
ST	Storage Temperature
PM	Packaging Material
VP	Vacuum Packaging
CBP	Carton Box Packaging
PBP	Plastic Box Packaging

1. Introduction

Fruits of date palm (Phoenix dactylifera L.), including Barhi, are rich in carbohydrates, fiber, and protein with minimal fat content. They also contain numerous micronutrients, vitamins (C, E, riboflavin, thiamine, and niacin), minerals (potassium, calcium, and magnesium), and phytochemicals (carotenoids and phenolic compounds) [1]. Barhi fruit serves its peak freshness and unique crispy texture, making it the best choice for those who enjoy dates in their fresh and unprocessed form. The broadly ovate to nearly round Khalal stage fruit has a short life span after harvest and quickly turns to the Rutab and Tamr stages [2].

Postharvest losses have significant environmental, economic, and resource implications, representing wasted food and the loss of water, energy, and fertilizers used in production. Sustainable postharvest practices, such as edible coatings and optimized packaging methods, have emerged as eco-friendly alternatives to conventional chemical treatments, posing risks to health and the environment. Integrating edible coatings with advanced technologies, such as vacuum packaging, can further reduce food waste and extend shelf life, contributing to food security and resource sustainability. These approaches align with the global need to minimize greenhouse gas emissions and promote sustainable agricultural practices [3]. In addition, consumers demand high-quality fruits without synthetic preservatives, prompting researchers to develop natural preservatives. Natural polymers are used as natural preservatives and offer biocompatibility, biodegradability, and chemical adaptability benefits. Natural polymers, such as gum Arabic (GA), used alone or combined with specific additives, form edible films that preserve fruit quality and extend their shelf life [4].

Edible coating, often referred to as fruit edible coating or fruit wax, is comprised of plant-based polymers, polysaccharides, proteins, or lipids and plays a vital role in preserving and managing fruits after harvest. It is made from starch, chitosan, Aloe vera, GA, pectin, hydroxypropyl methylcellulose, or carboxymethyl cellulose. It can reduce moisture loss and maintain plum texture and quality [5]. Natural coatings and essential oils have shown promising potential in postharvest management by preserving quality and reducing disease incidence in perishable crops [6]. Edible coating is a thin film applied on fruits to prolong their shelf life, protect them from physical damage, improve their appearance, preserve their nutritional value, and increase customer satisfaction. It functions as a barrier, impeding the loss of moisture, decreasing gas exchange, and preventing the growth of microbes [7]. Fruit coating is a marketing tool promoting specific features to categorize and promote fruits. Effective regulation guarantees that fruit coatings adhere to food safety regulations, ensuring their safe consumption [8]. The GA coating enhances the appearance and texture of fruits, preventing weight loss (WL) and promoting firmness, crispness, and juiciness. During storage, the GA coating pre-served the qualitative characteristics of the strawberries and delayed the ripening and senescence processes [9].

During storage, the freshness and shelf life of fruits are greatly influenced by temperature. Different fruits require different storage temperatures (STs) to avoid spoilage, water loss, and physiological disorders, which is crucial for maintaining the quality and longevity of the produce [10]. Fruit stored at higher than optimal temperatures triggers microorganism growth, leading to spoilage and decay, while lower temperatures inhibit microbial growth, extending shelf life and thus preserving fruit quality [11]. Storing fruits at optimal low temperatures can improve fruit quality and freshness by slowing down metabolic processes such as respiration and enzymatic activity, which break down sugars and release carbon dioxide, water, and energy, extending their shelf life [12,13]. High temperatures stimulate ethylene production, accelerating fruit ripening and senescence, while storing fruits at lower temperatures reduces ethylene production, slows ripening, and preserves freshness [14,15]. The high water content of fruits leads to moisture loss during storage, resulting in shriveling and a decline in juiciness and texture [16]. Lower temperatures preserve freshness and crispness [17]. Temperature also affects fruit pigment and flavor degradation, causing color changes and flavor loss at higher temperatures, while lower temperatures preserve their color and flavor profiles [18].

Fruit packaging is essential in preserving and enhancing the quality of fruits throughout the entire supply chain. Adequate fruit packaging is crucial for preventing physical damage, maintaining moisture, controlling respiration, preventing premature ripening, and upholding against spoilage. With the help of ethylene control packaging, the risk of senescence, decay, and microbial contamination can be minimized [19]. Furthermore, the packaging controls the natural color of the fruit, nutritional value, and overall quality [20]. By employing suitable packaging materials and techniques, fruits can be delivered to consumers optimally, extending their shelf life and ensuring a delightful and satisfying experience [21].

Natural polymers, such as GA, used alone or combined with specific additives, form edible films that preserve fruit quality and extend their shelf life. Similarly, the optimal ST for fruits varies. However, it is crucial to maintain it to ensure quality preservation, extended shelf life, and retention of nutritional value [22]. Adequate fruit packaging protects against physical damage, moisture loss, and microbial contamination while facilitating gas exchange regulation to maintain the ideal storage condition [23]. Combining edible coating, ST, and packaging types synergistically improves fruit preservation. Edible coatings act as a protective barrier, safeguarding against moisture loss and microbial contamination [24]. Optimal ST decreases enzymatic activity and microbial growth [25]. Different packaging types offer physical protection, regulate gas exchange, and minimize external contaminants [26].

Predictive analysis employing artificial neural networks (ANN) is a methodology that leverages machine learning algorithms for analyzing experimental data and formulating predictions regarding future events. The ANN is composed of interconnected nodes that bear a resemblance to biological neurons. The connections between these nodes, like synapses in the brain, can transmit signals to other neurons. ANN provides a form of adaptive learning in which the learning rate plays a crucial role in determining the magnitude of adjustments made by the model to rectify errors. The efficacy of ANN in addressing intricate problems relies heavily on the arrangement of their network architecture to yield optimal solutions [27,28]. The ANNs help manage extensive datasets and exhibit a faster processing ability for continuous data streams than linear models. Hence, the utilization of ANNs in this study was motivated by their ability to model complex problems and effectively derive the most suitable solutions.

The current study investigates the combined effects of edible GA coating, storage temperature (ST), and packaging methods (PMs) on the physical and chemical characteristics of fresh Barhi dates during storage. In addition, the implementation of the ANN prediction model to predict the quality parameters of Barhi date fruits based on the initial fruit weight, size, moisture content, total soluble solids, and color parameters at the beginning of storage, coating, and storage conditions to enhance quality control and management.

2. Materials and methods

2.1. Material and samples preparation

2.1.1. Date samples

Fresh Barhi dates used in the current study were obtained from a local farm in Alahsa, Saudi Arabia. To guarantee consistency in the investigation, Uniform Barhi dates at the Khalal (yellow) stage were meticulously chosen based on criteria such as size, color, and maturity. The selected dates were then gently cleansed using running purified water at room temperature (22 °C) to eliminate superficial particles, debris, and potential impurities that could impact the coating application and the comprehensive quality evaluation. After the cleansing process, the dates were permitted to dry at ambient temperature naturally, ensuring they were devoid of surplus moisture before advancing to the coating application phase.

2.1.2. Edible gum Arabic

The pure edible GA powder extracted from Sudanese Hashab, devoid of any additional color or flavor, was used for the coating treatments. The GA solutions were prepared at four different concentrations: 2.5 %, 5 %, 7.5 %, and 10 % (w/v) using distilled water. The GA powder was meticulously quantified for each concentration: 2.5, 5, 7.5, and 10 g per 100 mL of distilled water, respectively, to prepare coating solutions of GA with varying concentrations. Each quantified quantity of GA powder was added to a particular volume of distilled water in uncontaminated receptacle glasses, with continuous agitation to ensure uniform dispersion and dissolution. Utilizing magnetic and mechanical stirrers facilitated the thorough amalgamation of each solution until a uniform blend was achieved, which typically lasted several minutes, contingent upon the concentration. Then, the solutions were inspected for any remaining undissolved particles and underwent filtration to guarantee solution clarity. The prepared solutions were hermetically sealed in glass containers, identified with the concentration and preparation date, and poised for application on Barhi dates to assess the impact of different GA concentrations (GAC) on Barhi date fruits postharvest characteristics.

2.1.3. Coating system

An ultrasonic coating system was utilized to apply the GA coating on Barhi dates to ensure a consistent and practical application. Fig. 1A–B shows the schematic diagram (A) and a photograph (B) of the used ultrasonic-based coating system. This advanced coating system includes a stainless-steel basket for holding the date samples, tubes, an air blower with a DC motor, air purifiers, floats, a stainless-steel reservoir for the GA solution, ultrasonic transducers, a 24 VDC power supply for the power of the transducer, and the control unit. The 20 × 20 × 35 cm reservoir holds up to 1.5 L of the aqueous GA solution. The ultrasonic transducer transforms the solution into fine droplets and then evenly applies them to the dates. The system is controlled by an ATmega328P Arduino Mega board, ensuring precise liquid level regulation and optimal droplet generation. Float sensors and an electronic water-level circuit maintain the liquid level in the stainless-steel reservoir. The airflow rate was adjusted at 2 m/s, the height of the GA solution above the ultrasonic transducer was 0.65 cm, the solution temperature was approximately 40 °C, and the coated date fruit sample was dried for 8 min at a drying temperature of 30 °C, according to Mohammed et al. [29] recommendations. The use of an ultrasonic coating system in this study was chosen over traditional methods due to its superior efficiency and ability to ensure a more uniform application of the gum Arabic (GA) coating. Ultrasonic systems generate high-frequency vibrations that create fine and consistent droplets, allowing for an even distribution of the coating material across the fruit surface. This uniformity minimizes inconsistencies with traditional dipping or spraying methods, often resulting in uneven coverage or excessive coating material. Additionally, the ultrasonic system reduces coating wastage, shortens application time, and enhances coating adhesion to the fruit surface, improving the protective barrier's effectiveness. These advantages make ultrasonic coating a more efficient and sustainable alternative, particularly for large-scale postharvest applications, where consistency and cost-effectiveness are crucial.

The Barhi dates coated were divided into three categories based on the PM employed: vacuum packaging (VP), plastic basket packaging (PBP), and carton box packaging (CBP). The total weight of the dates used in the experiment was 18 kg. Each sample consisted of 250 g of Barhi dates, including an estimated 20 fruits per sample, depending on the weight. The experiment utilized 24 carton boxes, 24 vacuum-sealed bags, and 24 plastic baskets, divided equally among the packaging methods. Each method involved packaging approximately 250 g of the coated dates. In the case of VP, the samples were placed after the precooled samples were packaged in vacuum-sealed bags utilizing a VS6611X vacuum sealer.

Regarding PBP, the samples were placed in mini plastic baskets sized 30 × 25 × 10 cm. For CBP, the dates were positioned inside carton boxes, each accommodating 250 g of fruit. After the packaging process, the dates were divided and stored under treatment temperature conditions. Half the packaged dates were preserved at 5 °C in a cold storage room, while the remaining half were stored at 24 °C.

Two cold storage rooms (CSRs) were employed at the Date Palm Research Center of Excellence, King Faisal University, Saudi Arabia, at 4 °C and 24 °C. Each CSR comprises a thermally insulated cold room, an evaporator unit, a condensing unit, a control unit, a humidification unit, and a defrosting unit. The cold rooms' internal dimensions measured 5.8 m in length, 2.9 m in width, and 2.9 m in height. The walls and ceiling were constructed using polyurethane sandwich panels with a thickness of 12 cm. Each CSR was equipped with high-precision ultrasonic humidifiers designed by Mohammed et al. [30] and an IoT-based control and monitoring system developed by Mohammed et al. [31]. The precise control of RH was achieved through a high-precision humidity control unit, ensuring the optimum storage conditions for Barhi date fruits. The relative humidity was upheld at 85 % in both rooms.

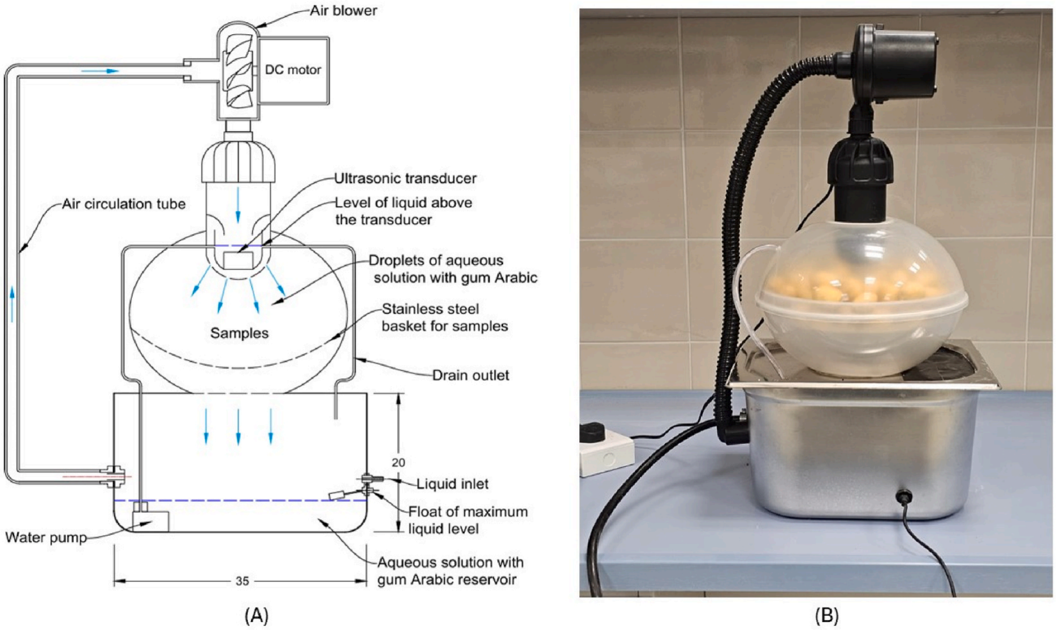

Fig. 1. Schematic diagram (A) and a photograph (B) of the used ultrasonic-based coating system.

2.2. Fruit characteristics

2.2.1. Physical characteristics

A precise electronic balance determined the individual date fruit weight (FW). The water displacement technique determined the fruit volume (FV). Submerging the dates in a graduated cylinder filled with water enabled the recording of the displaced volume. The fruit density (FD) calculation was executed by dividing the mass of the fruit by its volume. The weight loss (WL) was quantified by expressing it as a percentage of the initial FW, employing formula (1).

$$\text{Weight Loss}\ (\%) = \frac{\text{Initial Weight} - \text{Final Weight}}{\text{Initial Weight}} \times 100 \tag{1}$$

A portable hardness tester (Models: CS-402-1122, China) was used to determine fruit hardness (FH). The measurement involved a 7 mm diameter cylindrical puncture probe penetrating the fruit at an ambient temperature of 24 °C. The peak force recorded during the puncturing operation indicated the hardness of the date fruit samples treated. The decay percentage (DP) of decayed fruits was determined by visually examining the samples and computing the ratio of fruits displaying indicators of decay. The DP was calculated utilizing formula (2).

$$\text{Decay Percentage}\ (\%) = \frac{\text{Number of Decayed Fruits}}{\text{Total Number of Fruits}} \times 100 \tag{2}$$

2.2.2. Chemical characteristics

The moisture content (MC) of Barhi date samples was determined using a vacuum-drying oven (LVO-2041P, Korea) following the established protocols by the Association of Official Analytical Chemists [32]. One hundred grams of dates were dried at 70 °C under a vacuum for 48 h, and the fruit MC was calculated based on the sample's weight reduction post-drying. The pH was measured using a laboratory pH meter (HI-99121, Hanna Instruments, UK). A homogenized date pulp sample was readied, and the pH electrode was inserted into the sample to derive the pH measurement in compliance with the standard AOAC methodologies. A laboratory refractometer (RFM 860, UK) determined the fruit TSS content. Several drops of date juice were positioned on the refractometer prism, and the TSS level was recorded in percentage, following the AOAC standard techniques. The water activity (aw) was determined using a portable aw apparatus (Aqualab Series 3, USA). A date pulp sample was introduced into the device, and the aw measurement was noted, aligning with the recognized AOAC methodologies [32].

2.2.3. Color parameters

The color parameters (L*, a*, and b*) of Barhi dates were measured according to the method described by Hunter and Harold [33] utilizing the digital Hunter lab Color Quest-4500 LAV meter (HAL, Inc., Reston, VA, USA) as CIE L*, a*, and b* values [34].

The color difference (ΔE*) was determined based on the International Commission on Illumination (CIE) lab utilizing formula (3).

$$\Delta E^* = \sqrt{\left(L_i^* - L_s^*\right)^2 + \left(a_i^* - a_s^*\right)^2 + \left(b_i^* - b_s^*\right)^2} \tag{3}$$

where ΔE* is the color difference, L_i*, a_i*, and b_i* are the initial color values, and L_s*, a_s*, and b_s* are the color values at the target time.

The browning index (BI) was calculated based on the a* and b* values utilizing formula (4).

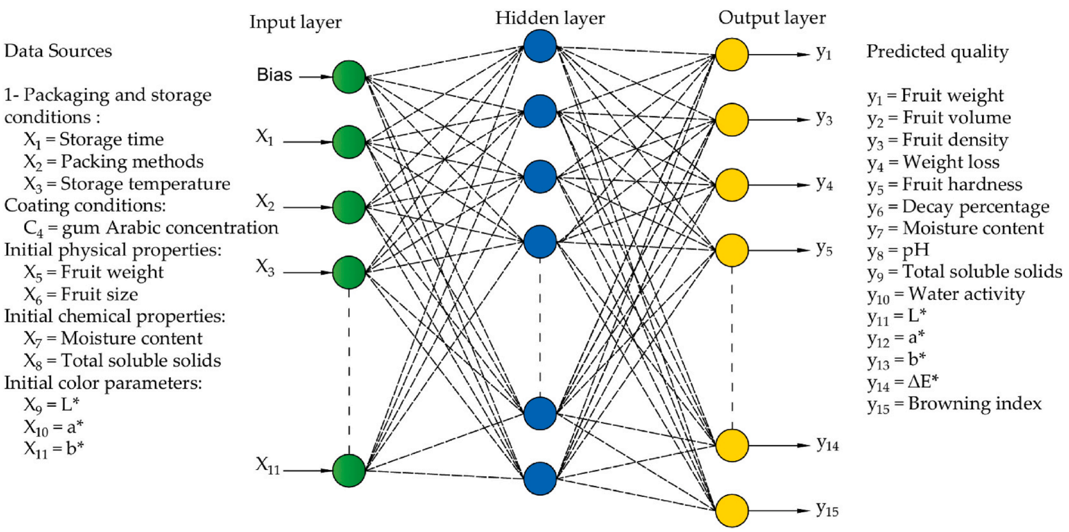

Fig. 2. ANN model architecture for predictive analysis of Barhi date fruit quality parameters.

$$\text{Browning Index (BI)} = \frac{100 \times (a^* + 1.75L^*)}{5.645L^* + a^* - 0.3012b^*} \tag{4}$$

2.3. ANN-based predictive analysis

An artificial neural network (ANN) model was created to predict quality changes in Barhi date fruits' physical, chemical, and color parameters under various storage conditions and PMs using SPSS software version 26.

The dataset was divided into training, validation, and testing subsets following a distribution ratio of 60:20:20. The training subset was used to train the ANN model, the validation subset to fine-tune the model's parameters, and the testing subset to assess the predictive model's performance.

A multi-layer feedforward ANN architecture composed of input, hidden, and output layers contains neurons interconnected through weights, as shown in Fig. 2. In the current study, the input layer was composed of 11 neurons that correlated with the number of input characteristics, encompassing variables of ST, PMs, GAC, and initial measurements of some attributes. The hidden layer with different numbers of neurons was tested to ascertain the most effective network structure. The hyperbolic tangent was the chosen activation function for the hidden layer. The output layer comprised 15 neurons corresponding to the predicted physical, chemical, and color parameter values. The mean squared error function was employed as the loss function.

The optimization of hyperparameters involved adjusting factors of the number of hidden layers, the number of neurons in each layer, the learning rate, and the batch size. This procedure used grid search and cross-validation procedures to acquire optimal model performance. The ANN model was trained by utilizing the training dataset for several epochs. Early stopping mechanisms were implemented to mitigate overfitting, which was achieved by continually monitoring the validation loss.

The testing dataset was utilized to evaluate the model's performance. Various evaluation metrics, i.e., mean absolute error (MAE), mean absolute percentage error (MAPE), relative error (RE), root mean squared error (RMSE), and R-squared (R^2) score, were employed to gauge the model's precision and ability to make accurate predictions using the following formulas:

$$\text{MAE} = \frac{1}{n} \times \sum_{i=1}^{n} |O_i - P_i| \tag{5}$$

$$\text{MAPE} = 100 \times \frac{1}{n} \times \sum_{i=1}^{n} \left| \frac{O_i - P_i}{O_i} \right| \tag{6}$$

$$\text{RE} = \frac{|O_i - P_i|}{O_i} \tag{7}$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (O_i - P_i)^2}{n}} \tag{8}$$

$$R^2 = 1 - \frac{\sum (O_i - P_i)^2}{\sum O_i^2 - \frac{\left(\sum O_i\right)^2}{n}} \tag{9}$$

where, O_i is the observed value, P_i is the predicted value of a parameter data i, and n is the number of measurements.

The trained ANN model was deployed for predictive analysis of new data. The SPSS data interface enabled the input of fresh data and the display of the predicted values about the physical, chemical, and color parameters of Barhi date fruits based on the input data. Utilizing the ANN model, predictions were made regarding the changes in the quality attributes of fruits across different storage environments and PMs.

2.4. Statistical analysis

The experimental design was formulated to examine the impacts of four variables on the postharvest quality of Barhi dates: GA concentration (2.5 %, 5 %, 7.5 %, and 10 % w/v), storage temperature (4 and 24 °C), packaging method (VP, PBP, and CBP), and storage time (every seven days from 0 to 56 days. The study employed a factorial design, with three replicates assigned to each treatment combination. The samples were regularly monitored to evaluate the treatment effects. The fruit quality parameters were measured at consistent weekly intervals during the storage period. The statistical analysis of the data collected in this study was conducted using SPSS (Statistical Package for the Social Sciences) software, version 24 (SPSS Inc., Chicago, IL, USA). The factorial analysis of variance (ANOVA) was executed to assess the primary effects and interactions of the independent variables on each quality parameter. The Tukey test was used to determine the least significant difference (LSD) between the mean values of the experiments at a significance level of 0.05.

3. Results

3.1. Quality of Barhi date fruits

3.1.1. Physical properties of Barhi dates

Table 1 shows the average values of the physical properties of the evaluated Barhi date fruit under various packaging methods, storage temperatures, and GACs on the physical properties of the fruits. The same letters within each column for each attribute in the table indicated no significant differences at $p \leq 0.05$. The data in the table reveals significant differences at $p \leq 0.05$ in the average values of each attribute across diverse GAC and storage conditions, indicating that these variables influence the physical properties of the date varieties. The findings indicate that the high levels of GAC (7.5 % and 10 %) at a temperature of 4 °C are most efficient in preserving the physical properties of evaluated Barhi dates. The VP method at a temperature of 4 °C, especially with GAC of 5 % and 10 %, effectively maintains qualities such as FW, FV, FD, and FH while reducing fruit WL and Dp rate. Conversely, when the fruit was stored at 24 °C, CBP and PBP methods demonstrated a decline in physical properties. These results indicated the significance of lower storage temperatures and the incorporation of GA in maintaining the physical properties of Barhi dates.

In contrast, higher temperatures and insufficient packaging methods accelerated fruit decay and decreased FH. The 10 % GA coating showed a minor decline in fruit quality and displayed the most significant preservation rate at 24 °C, demonstrating its efficacy even under high temperatures. In contrast, dates stored at 24 °C, exceptionally when packaged in carton and plastic basket packaging containers with reduced or no concentrations of GA, displayed heightened WL and decay rates, indicating notable degradation in such conditions.

Fig. 3 shows the average changes and standard deviations in FW (Fig. 3A), FV (Fig. 3B), FV (Fig. 3C), WL (Fig. 3D), FH (Fig. 3E), DP (Fig. 3F) of Barhi date fruits throughout the storage period under different GAC. The findings indicate that the higher GAC significantly ($p < 0.05$) maintained the FW, FV, FD, and FH, reduced WL, and decreased DPs of Barhi date fruits during storage. The trend indicates that coating with GA allows the fruits to maintain their structural integrity and improve FV, reducing dehydration, water loss, and DP. The average values of the physical properties of the evaluated Barhi date fruit under various PMs, STs, and GACs on the physical properties of fruits. The data reveals significant differences at $p \leq 0.05$ in the average values of each attribute across diverse GAC and storage conditions, indicating that these variables influence the physical properties of the date varieties. The findings indicate that the high levels of GAC (7.5 % and 10 %) at a temperature of 4 °C are most efficient in preserving the physical properties of evaluated Barhi dates. The VP method at a temperature of 4 °C, especially with GAC of 5 % and 10 %, effectively maintains qualities such as FW, FV, FD,

Table 1
Impact of packaging methods (PM), storage temperature (St), and gum Arabic concentrations (GAC) on physical properties (fruit weight (FW), fruit volume (FV), fruit density (FD), weight loss (WL), fruit hardness (FH), fruit decay (FD) of fresh Barhi fruits.

PM	St	GAC, %	Physical properties					
			FW, g	FV, cm^3	FD, g/cm^3	WL, %	FH, N	FD, %
VP	4 °C	0	12.73 $^{a-c}$	13.3 ^{ab}	0.957 $^{a-c}$	1.3 ^{ij}	119.48 $^{a-c}$	1.19 $^{h-i}$
		2.5	12.75 $^{a-c}$	13.33 ^{ab}	0.957 $^{a-c}$	0.74^{j}	120.99 ^{ab}	0.52 $^{h-i}$
		5	12.8 ^{ab}	13.37^{a}	0.957 $^{a-c}$	0.57^{j}	121.06 ^{ab}	0.29 $^{h-i}$
		7.5	12.8 ^{ab}	13.28 $^{a-c}$	0.964 ^{ab}	0.51^{j}	121.58^{a}	0.14^{i}
		10	12.87^{a}	13.29 ^{ab}	0.966^{a}	0.44^{j}	121.53^{a}	0.04^{i}
	24 °C	0	12.63 $^{a-c}$	13.2 $^{a-c}$	0.957 $^{a-c}$	3.44 ^{ij}	114.69 $^{a-e}$	3.15 $^{f-g}$
		2.5	12.67 $^{a-c}$	13.09 $^{a-d}$	0.965^{a}	3.06 ^{ij}	115.61 $^{a-d}$	2.16 $^{g-i}$
		5	12.68 $^{a-c}$	13.15 $^{a-c}$	0.964 ^{ab}	2.26 ^{ij}	117.65 $^{a-d}$	1.13 $^{h-i}$
		7.5	12.71 $^{a-c}$	13.2 $^{a-c}$	0.963 ^{ab}	1.75 ^{ij}	118.9 $^{a-c}$	0.52 $^{h-i}$
		10	12.79 $^{a-c}$	13.32 ^{ab}	0.96 $^{a-c}$	1.47 ^{ij}	119.77 $^{a-c}$	0.12^{i}
CBP	4 °C	0	12.37 $^{a-g}$	12.89 $^{b-d}$	0.96 $^{a-c}$	6.37 $^{e-j}$	111.98 $^{a-g}$	5.84 $^{e-h}$
		2.5	12.45 $^{a-f}$	13.00 $^{a-d}$	0.957 $^{a-c}$	5.49 $^{f-j}$	113.49 $^{a-f}$	3.9 $^{e-h}$
		5	12.49 $^{a-e}$	13.05 $^{a-d}$	0.957 $^{a-c}$	1.01 $^{g-j}$	114.99 $^{a-e}$	2.49 $^{g-i}$
		7.5	12.6 $^{a-d}$	13.23 $^{a-c}$	0.951 $^{a-d}$	4.49 $^{h-j}$	116.31 $^{a-d}$	1.31 $^{h-i}$
		10	12.53 $^{a-d}$	13.32 ^{ab}	0.942 $^{a-e}$	3.96 $^{h-j}$	117.24 $^{a-d}$	0.33 $^{h-i}$
	24 °C	0	11.68 $^{h-j}$	12.37 ^{ef}	0.939 $^{a-g}$	17.65 $^{a-c}$	91.62 $^{h-i}$	16.18 ^{ab}
		2.5	11.73 $^{g-j}$	12.65 $^{d-f}$	0.925 $^{d-g}$	16.6 $^{a-d}$	94.07 $^{f-i}$	11.76 $^{b-d}$
		5	11.79 $^{g-j}$	12.65 $^{d-f}$	0.931 $^{c-g}$	15.51 $^{a-d}$	95.97 $^{e-i}$	7.77 $^{c-g}$
		7.5	11.87 $^{e-j}$	13.02 $^{a-d}$	0.911^{g}	14.17 $^{a-g}$	99.17 $^{d-i}$	4.13 $^{e-h}$
		10	11.99 $^{d-j}$	13.13 $^{a-c}$	0.913 $^{f-g}$	13.11 $^{a-h}$	101.65 $^{b-h}$	1.08 $^{h-i}$
PBP	4 °C	0	12.16 $^{c-i}$	12.81 $^{c-e}$	0.949 $^{a-d}$	10.15 $^{b-i}$	107.82 $^{a-h}$	9.3 $^{c-e}$
		2.5	12.31 $^{a-h}$	12.89 $^{b-d}$	0.955 $^{a-c}$	8.59 $^{c-j}$	111.38 $^{a-g}$	6.09 $^{d-h}$
		5	12.22 $^{b-i}$	12.90 $^{a-d}$	0.947 $^{a-d}$	8.19 $^{d-j}$	111.88 $^{a-g}$	4.09 $^{e-h}$
		7.5	12.38 $^{a-g}$	13.04 $^{a-d}$	0.949 $^{a-d}$	7.34 $^{e-j}$	114.43 $^{a-e}$	2.14 $^{g-i}$
		10	12.39 $^{a-g}$	13.22 $^{a-c}$	0.936 $^{b-g}$	6.84 $^{e-j}$	115.09 $^{a-e}$	0.57 $^{h-i}$
	24 °C	0	11.49^{j}	12.20^{e}	0.94 $^{a-f}$	20.09^{a}	87.08^{i}	18.41^{a}
		2.5	11.67 $^{i-j}$	12.63 $^{d-f}$	0.922 $^{d-g}$	18.57 ^{ab}	90.63 $^{h-i}$	13.15 $^{a-c}$
		5	11.69 $^{g-j}$	12.64 $^{d-f}$	0.923 $^{d-g}$	17.39 $^{a-c}$	93.26 $^{g-i}$	8.7 $^{c-f}$
		7.5	11.85 $^{f-j}$	12.95 $^{a-d}$	0.914 $^{e-g}$	14.56 $^{a-f}$	99.26 $^{d-i}$	4.25 $^{e-h}$
		10	11.88 $^{d-j}$	12.99 $^{a-d}$	0.913 $^{e-g}$	13.94 $^{a-g}$	100.52 $^{c-i}$	1.16 $^{h-i}$

The same letters within each column for each physical attribute indicate the average values that are not significantly different at $p \leq 0.05$.

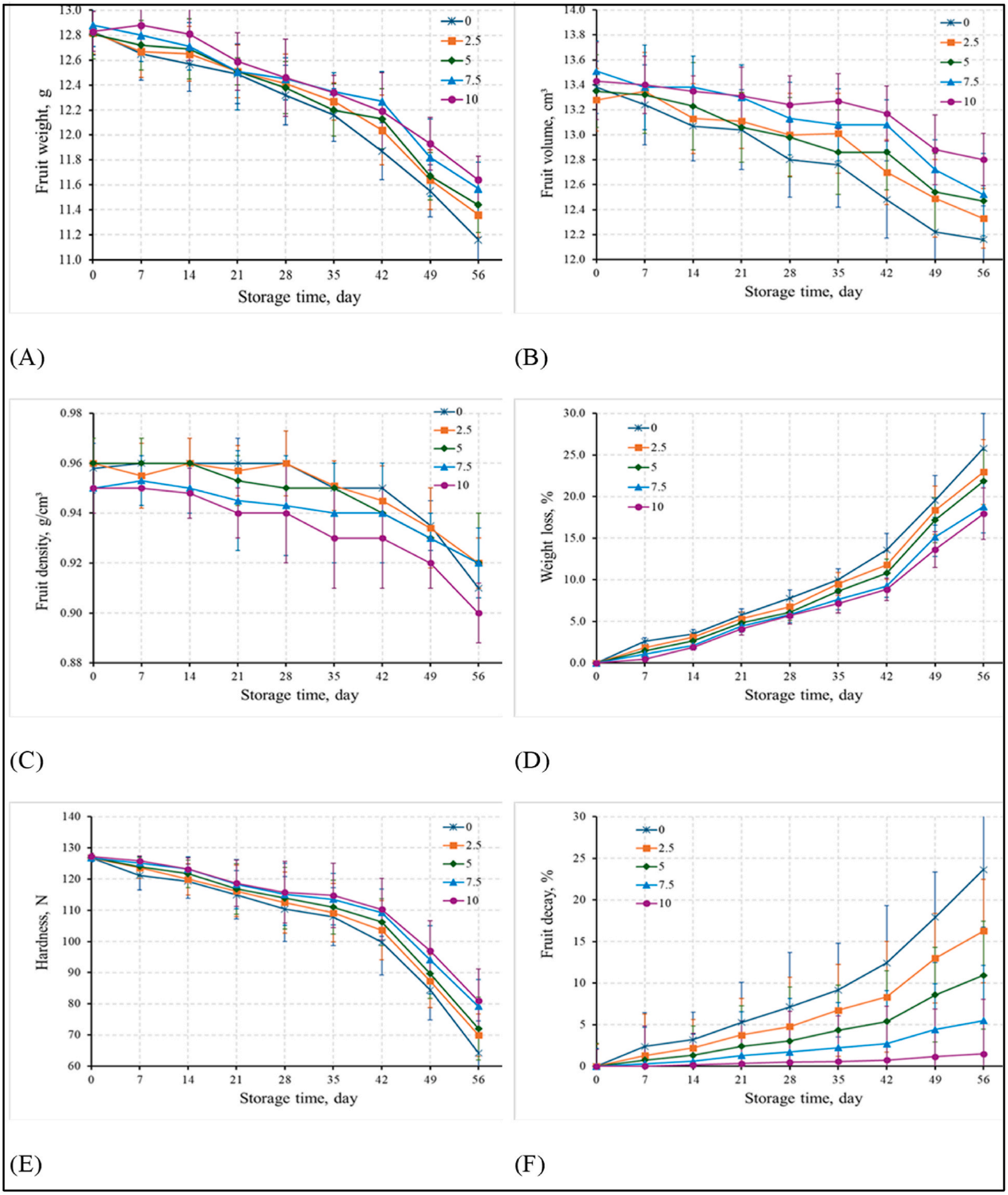

Fig. 3. Effects of GAC on physical properties: fruit weight (A), fruit volume (B), fruit density (C), weight loss (D), fruit hardness (E), decay percentage (F) of Barhi date fruits during storage.

and FH while reducing fruit WL and Dp rate. Conversely, when the fruit was stored at 24 °C, CBP and PBP methods demonstrated a decline in physical properties. These results indicated the significance of lower STs and the incorporation of GA in maintaining the physical properties of Barhi dates.

3.1.2. Chemical properties of Barhi dates

Table 2 shows the impact of packaging methods, storage temperatures, and GACs on the chemical properties of the evaluated Barhi dates. The results indicate that VP at 4 °C with higher GAC effectively maintains fruit MC and stable pH, TSS, and aw. In contrast, at 24 °C storage temperature, all packaging methods reduced MC and aw, with the most significant reductions observed in CBP and PBP. The results indicate that cold storage and edible GA led to preserving the chemical properties of Barhi dates. In contrast, higher temperatures and less effective packaging of CBP and PBP led to increased dehydration and changes in the chemical properties of fresh date fruit.

Fig. 4 shows the average changes and standard deviations in fruit MC (Fig. 6A), fruit pH (Fig. 4B), TSS (Fig. 4C), and aw (Fig. 4D) of Barhi date fruits throughout the storage period under different GAC. The impact of PMs, STs, and GACs on the chemical properties of the evaluated Barhi dates. The results indicate that VP at 4 °C with higher GAC effectively maintains fruit MC and stable pH, TSS, and aw. In contrast, at 24 °C ST, all PMs reduced MC and aw, with the most significant reductions observed in CBP and PBP. The results indicate that cold storage and edible GA led to preserving the chemical properties of Barhi dates. In contrast, higher temperatures and less effective packaging of CBP and PBP led to increased dehydration and changes in the chemical properties of fresh date fruit.

3.1.3. Color parameters of Barhi dates

Table 3 shows the influence of packaging methods, storage temperatures, and GAC on the color parameters of fresh Barhi dates. At a storage temperature of 4 °C, the VP method displays L* values ranging from 71.01 to 73.49 compared to CBP and PBP, indicating lighter fruit color. However, at 24 °C storage temperature, all packaging methods show reduced L* values. The most significant reductions in color parameters were observed in CBP and PBP. The fruits' a* and b* values under the VP method maintain lower values at the different GACs and storage temperatures, indicating less intense red and yellow hues of the evaluated fruit than the packaged fruit in CBP and PBP. The ΔE* and BI values are significantly higher at 24 °C compared to 4 °C, indicating increased fruit ripening and color browning at high storage temperatures. The elevated GACs lead to a partially lighter fruit hue, as evidenced by increased L* values, particularly in the VP method at both 4 and 24 °C. This result can be linked to the protective layer offered by Gum Arabic, which maintains the fruit's original color by diminishing moisture loss and impeding oxidation reactions. The slight variations in a* and b* values are consistently shown across various GAC levels, indicating that the GAC might have a limited effect on the saturation of red and yellow color in Barhi dates. However, the general pattern indicates that higher GAC enhanced color preservation, mainly fruit lightness.

Fig. 5 shows the average changes and standard deviations in L* (Fig. 5A), a* (Fig. 5B), b* (Fig. 5C), ΔE* (Fig. 5D), and BI (Fig. 5E) of

Table 2
Impact of packaging methods, storage temperature, and gum Arabic concentrations on chemical properties (moisture content (MC), pH, total soluble solids (TSS), and water activity (aw) fresh Barhi fruits.

PM	ST	GAC, %	Chemical properties			
			MC, %	pH	TSS	aw
VP	4 °C	0	59.42 ^{ab}	6.34 $^{d-f}$	35.37 ^{hi}	0.876 ^{ab}
		2.5	59.45 ^{ab}	6.34 $^{d-f}$	34.99 ^{hi}	0.875 ^{ab}
		5	60.12^{a}	6.32^{g}	34.67^{i}	0.883^{a}
		7.5	57.26 $^{a-e}$	6.33 $^{e-f}$	34.85^{i}	0.853 $^{a-e}$
		10	57.96 $^{a-d}$	6.33 $^{e-f}$	33 ^{hi}	0.86 $^{a-d}$
	24 °C	0	57.45 $^{a-d}$	6.4 $^{a-f}$	36.61 $^{e-i}$	0.855 $^{a-d}$
		2.5	57.83 $^{a-d}$	6.39 $^{a-f}$	36.47 $^{f-i}$	0.861 $^{a-d}$
		5	58.82 $^{a-c}$	6.38 $^{c-f}$	36.04 $^{f-i}$	0.869 $^{a-c}$
		7.5	58.5 $^{a-d}$	6.38 $^{b-f}$	35.6 $^{g-i}$	0.865 $^{a-d}$
		10	59.72 ^{ab}	6.38 $^{c-f}$	35.41 ^{hi}	0.877 ^{ab}
CBP	4 °C	0	57.47 $^{a-d}$	6.39 $^{a-f}$	36.79 $^{e-i}$	0.86 $^{a-d}$
		2.5	57.21 $^{a-e}$	6.39 $^{b-f}$	36.27 $^{f-i}$	0.857 $^{a-d}$
		5	56.95 $^{a-e}$	6.38 $^{c-f}$	36.06 $^{f-i}$	0.856 $^{a-d}$
		7.5	47 $^{a-e}$	6.36 $^{c-f}$	35.45 ^{hi}	0.853 $^{a-d}$
		10	58.77 $^{a-d}$	6.37 $^{c-f}$	35.48 ^{hi}	0.874 $^{a-c}$
	24 °C	0	50.17 ^{ij}	6.53 $^{a-c}$	43.57 $^{a-c}$	0.787 ^{gh}
		2.5	52.19 $^{e-j}$	6.53 $^{a-c}$	42.97 $^{a-d}$	0.805 $^{e-h}$
		5	50.59 $^{h-j}$	6.51 $^{a-d}$	42.44 $^{a-e}$	0.789 ^{gh}
		7.5	53.56 $^{d-j}$	6.5 $^{a-e}$	41.49 $^{a-f}$	0.82 $^{d-h}$
		10	53.96 $^{c-j}$	6.48 $^{a-f}$	40.79 $^{a-h}$	0.826 $^{c-g}$
PBP	4 °C	0	54.55 $^{b-i}$	6.44 $^{a-f}$	39.12 $^{b-i}$	0.831 $^{b-g}$
		2.5	54.98 $^{a-i}$	6.41 $^{a-f}$	38.06 $^{c-i}$	0.834 $^{b-g}$
		5	56.19 $^{a-g}$	6.41 $^{a-f}$	37.85 $^{c-i}$	0.847 $^{a-e}$
		7.5	55.69 $^{a-h}$	6.39 $^{a-f}$	37.26 $^{d-i}$	0.842 $^{a-f}$
		10	56.7 $^{a-f}$	6.4 $^{a-f}$	37.03 $^{e-i}$	0.85 $^{a-e}$
	24 °C	0	49.3^{j}	6.56^{a}	45.12^{a}	0.777^{h}
		2.5	51.11 $^{g-j}$	6.55 ^{ab}	44.22 ^{ab}	0.794 $^{f-h}$
		5	51.61 $^{f-j}$	6.53 $^{a-c}$	43.38 $^{a-c}$	0.799 $^{f-h}$
		7.5	53.55 $^{d-j}$	6.51 $^{a-d}$	41.69 $^{a-f}$	0.82 $^{d-h}$
		10	54.59 $^{b-i}$	6.49 $^{a-f}$	41.35 $^{a-g}$	0.832 $^{b-g}$

The same letters within each column for each chemical attribute indicate the average values that are not significantly different at $p \leq 0.05$.

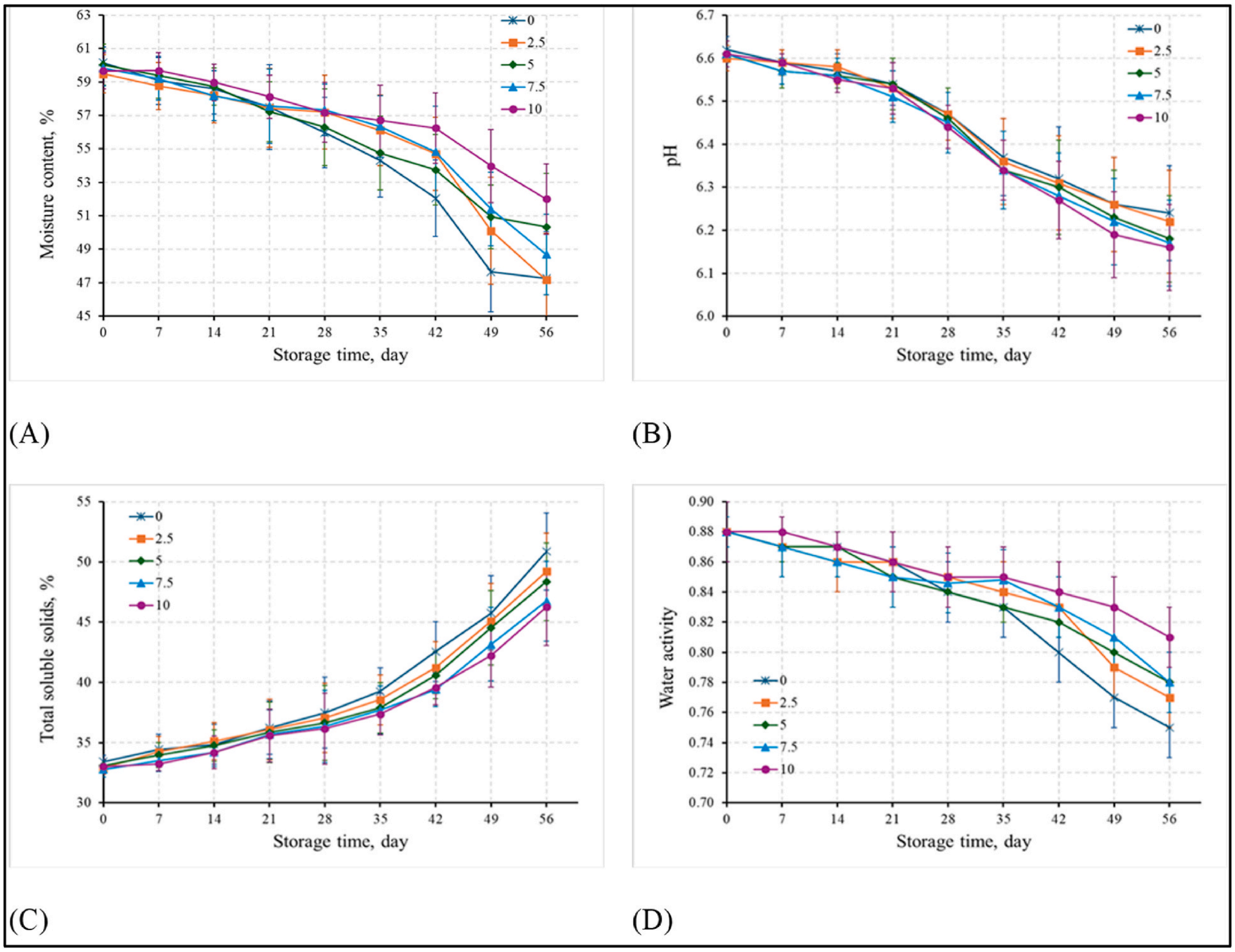

Fig. 4. Effects of GAC on chemical properties: fruit moisture content (A), pH (B), total soluble solids (C), and water activity (D) of Barhi date fruits during storage.

Barhi date fruits throughout the storage period under different GAC. Applying a GA coating affected the color parameters of Barhi date fruits over the storage period. The influence of PMs, STs, and GAC on the color parameters of fresh Barhi dates. At ST of 4 °C, the VP method displays L* values ranging from 71.01 to 73.49 compared to CBP and PBP, indicating lighter fruit color. However, at 24 °C ST, all PMs show reduced L* values. The most significant reductions in color parameters were observed in CBP and PBP. The fruits' a* and b* values under the VP method maintain lower values at the different GACs and STs, indicating less intense red and yellow hues of the evaluated fruit than the packaged fruit in CBP and PBP. The ΔE* and BI values are significantly higher at 24 °C compared to 4 °C, indicating increased fruit ripening and color browning at high STs. The elevated GACs lead to a partially lighter fruit hue, as evidenced by increased L* values, particularly in the VP method at both 4 and 24 °C. This result can be linked to the protective layer offered by GA, which maintains the fruit's original color by diminishing moisture loss and impeding oxidation reactions. The slight variations in a* and b* values are consistently shown across various GAC levels, indicating that the GAC might have a limited effect on the saturation of red and yellow color in Barhi dates. However, the general pattern indicates that higher GAC enhanced color preservation, mainly fruit lightness.

3.2. ANN-based predictive analysis

3.2.1. Architecture of the implemented ANN model

Fig. 6 shows the actual architecture of the implemented ANN model for predicting quality parameters of Barhi date fruits across varying storage conditions. The constructed ANN prediction model is characterized by a single hidden layer with 18 units (excluding the bias unit). The input layer was comprised of 11 nodes representing independent variables. The output layer consists of 15 nodes corresponding to dependent variables of quality parameters. Normalization was employed as the rescaling method for covariates, with the activation function of the hyperbolic tangent applied to the hidden layers and the Identity function utilized for the output layers in all ANN prediction models. The dataset was divided into 60 % for training, 20 % for model testing, and another 20 % for evaluation,

Table 3
Impact of packaging methods, storage temperature, and gum Arabic concentrations on color parameters of fresh Barhi fruits.

PM	ST	GAC, %	Color parameters				
			L*	a*	b*	ΔE*	BI
VP	4 °C	0	71.01 $^{a-c}$	10.35 ^{jk}	53.54 ^{ab}	2.87 ^{hi}	135.83 $^{a-g}$
		2.5	71.73 $^{a-c}$	10.51 $^{i-k}$	54.09 ^{ab}	2.58 ^{i}	135.84 $^{a-g}$
		5	72.11 $^{a-c}$	10.42 ^{jk}	54.38 ^{ab}	3.24 $^{g-i}$	135.83 $^{a-g}$
		7.5	72.67 ^{ab}	10.31 ^{jk}	55.18 ^{a}	4.6 $^{f-i}$	136.47 $^{a-f}$
		10	73.49 ^{a}	10.24 ^{k}	55.48 ^{a}	5.81 $^{e-i}$	135.22 $^{a-g}$
	24 °C	0	70.29 $^{a-c}$	10.65 $^{g-k}$	50.93 $^{b-g}$	4.49 $^{f-i}$	127.67 $^{c-i}$
		2.5	70.98 $^{a-c}$	10.94 $^{d-k}$	51.63 $^{a-f}$	3.18 $^{g-i}$	128.52 $^{b-i}$
		5	71.62 $^{a-c}$	10.55 $^{h-k}$	51.78 $^{a-f}$	2.98 ^{hi}	126.93 $^{d-i}$
		7.5	72.38 ^{ab}	10.58 $^{h-k}$	52.22 $^{a-e}$	3.73 $^{g-i}$	126.42 $^{d-i}$
		10	72.88 ^{ab}	10.52 $^{i-k}$	52.58 $^{a-d}$	5.66 $^{e-i}$	126.12 $^{e-i}$
CBP	4 °C	0	68.93 ^{bc}	11.05 $^{b-k}$	53.13 $^{a-c}$	6.76 $^{d-i}$	142.67 ^{ab}
		2.5	70.06 $^{a-c}$	11.01 $^{b-k}$	53.29 $^{a-c}$	4.95 $^{f-i}$	139.59 $^{a-e}$
		5	71.05 $^{a-c}$	10.97 $^{c-k}$	53.86 ^{ab}	3.75 $^{g-i}$	138.29 $^{a-e}$
		7.5	71.79 $^{a-c}$	10.78 $^{f-k}$	54.65 ^{ab}	3.83 $^{g-i}$	138.38 $^{a-e}$
		10	72.26 $^{a-c}$	10.87 $^{e-k}$	54.85 ^{ab}	4.5 $^{f-i}$	137.91 $^{a-e}$
	24 °C	0	65.49 ^{bc}	12.08 ^{ab}	47.41 $^{g-j}$	14.53 ^{ab}	132.78 $^{a-h}$
		2.5	66.71 ^{bc}	11.99 $^{a-d}$	47.82 $^{f-h}$	12.58 $^{a-d}$	129.69 $^{a-i}$
		5	67.28 ^{bc}	11.8 $^{a-f}$	48.29 $^{e-i}$	10.76 $^{a-f}$	129.12 $^{a-i}$
		7.5	68.22 ^{bc}	11.74 $^{a-g}$	48.7 $^{d-i}$	8.98 $^{b-h}$	127.1 $^{c-i}$
		10	68.92 ^{bc}	11.61 $^{a-i}$	49.31 $^{c-i}$	8.02 $^{c-i}$	127.15 $^{c-i}$
PBP	4 °C	0	68.01 ^{bc}	11.41 $^{a-j}$	52.45 $^{a-d}$	9.12 $^{b-h}$	143.83 ^{a}
		2.5	69.42 $^{a-c}$	11.34 $^{a-k}$	52.99 $^{a-c}$	6.78 $^{d-i}$	133 $^{a-d}$
		5	69.84 $^{a-c}$	11.02 $^{b-k}$	53.4 ^{ab}	5.11 $^{f-i}$	140.46 $^{a-e}$
		7.5	70.51 $^{a-c}$	11.08 $^{b-k}$	53.74 ^{ab}	4.17 $^{g-i}$	139.63 $^{a-e}$
		10	70.86 $^{a-c}$	10.95 $^{d-k}$	54.67 ^{ab}	4.05 $^{g-i}$	141.76 $^{a-c}$
	24 °C	0	64.60 ^{c}	12.29 ^{a}	44.13 ^{j}	16.43 ^{a}	122.48 $^{f-i}$
		2.5	65.53 ^{bc}	12.07 $^{a-c}$	44.75 ^{ij}	13.91 $^{a-c}$	121.23 $^{g-i}$
		5	66.28 ^{bc}	12.08 $^{a-c}$	45.01 ^{ij}	11.83 $^{a-e}$	119.67 $^{h-i}$
		7.5	67.34 ^{bc}	11.98 $^{a-e}$	45.53 $^{h-j}$	9.41 $^{b-g}$	118.06 ^{i}
		10	67.89 ^{bc}	11.64 $^{a-h}$	45.65 $^{h-j}$	8.76 $^{b-i}$	116.63 ^{i}

The same letters within each column for each color parameter indicate the average values that are not significantly different at $p \leq 0.05$.

with the error function being the sum of squares attributed to the Identity function. The architecture of the ANN model was carefully designed to balance predictive accuracy and computational efficiency. A single hidden layer with 18 neurons was selected after iterative testing, where different configurations of hidden layers and nodes were evaluated based on performance metrics such as mean absolute error (MAE). The choice of a single hidden layer aligns with studies demonstrating its effectiveness in capturing complex, non-linear relationships in moderately sized datasets without overfitting. The number of neurons in the hidden layer was determined by optimizing model performance through grid search techniques, ensuring sufficient capacity to process the input variables—gum Arabic concentration, storage temperature, packaging methods, and initial quality parameters—while maintaining computational efficiency. This architecture provided a robust predictive framework for modeling the quality parameters of Barhi dates during storage.

3.2.2. *Evaluation of the implemented ANN model*

Table 4 compares the relative errors in the training, testing, and evaluation phases of the implemented ANN model for predicting each parameter of Barhi fruit quality. The table shows the sum of squares error, average overall relative error, and relative error concerning the dependent variables, including all Barhi date quality parameters. The error metrics reveal that the datasets yielded satisfactory outcomes regarding model errors across the training, testing, and evaluation phases. The results highlight the ability of the implemented ANN models to effectively predict Barhi date fruits' quality throughout storage, utilizing independent variables such as ST, PMs, GAC, storage time, and limited initial quality parameters.

3.2.3. *Validation of the implemented ANN model*

Fig. 7A–O shows the plots of measured/calculated quality parameters FW (Fig. 7A), FV (Fig. 7B), FD (Fig. 7C), WL (Fig. 7D), FH (Fig. 7E), DP (Fig. 7F), MC (Fig. 7G), pH (Fig. 7H), TSS (Fig. 7I), aw (Fig. 7J), L* (Fig. 7K), a* (Fig. 7L), b* (Fig. 7M), ΔE* (Fig. 7N), and BI (Fig. 7O)) the Barhi fruits versus the predicted values by the ANN prediction models in the validation phase using new data based on storage time, PMs, GAC, ST, and initial fruit quality. The figure indicated that the implemented ANN prediction models efficiently predicted the most quality parameters with linear regression nearly overlapping the 1:1 line ($y = x + 0$), indicating strong model performance.

Table 5 shows the evaluation of the ANN prediction models using the evaluation metrics of MAPE and RMSE. The table indicates that the prediction ANN model has achieved satisfactory prediction of the quality parameters of Barhi dates. The low MAPE and RMSE values indicate a high level of accuracy in the projections, providing the reliability of this implemented ANN model for predicting the quality parameters of Barhi date fruits. These findings indicated that the implemented ANN model predicted the evaluated quality parameters of the Barhi dates.

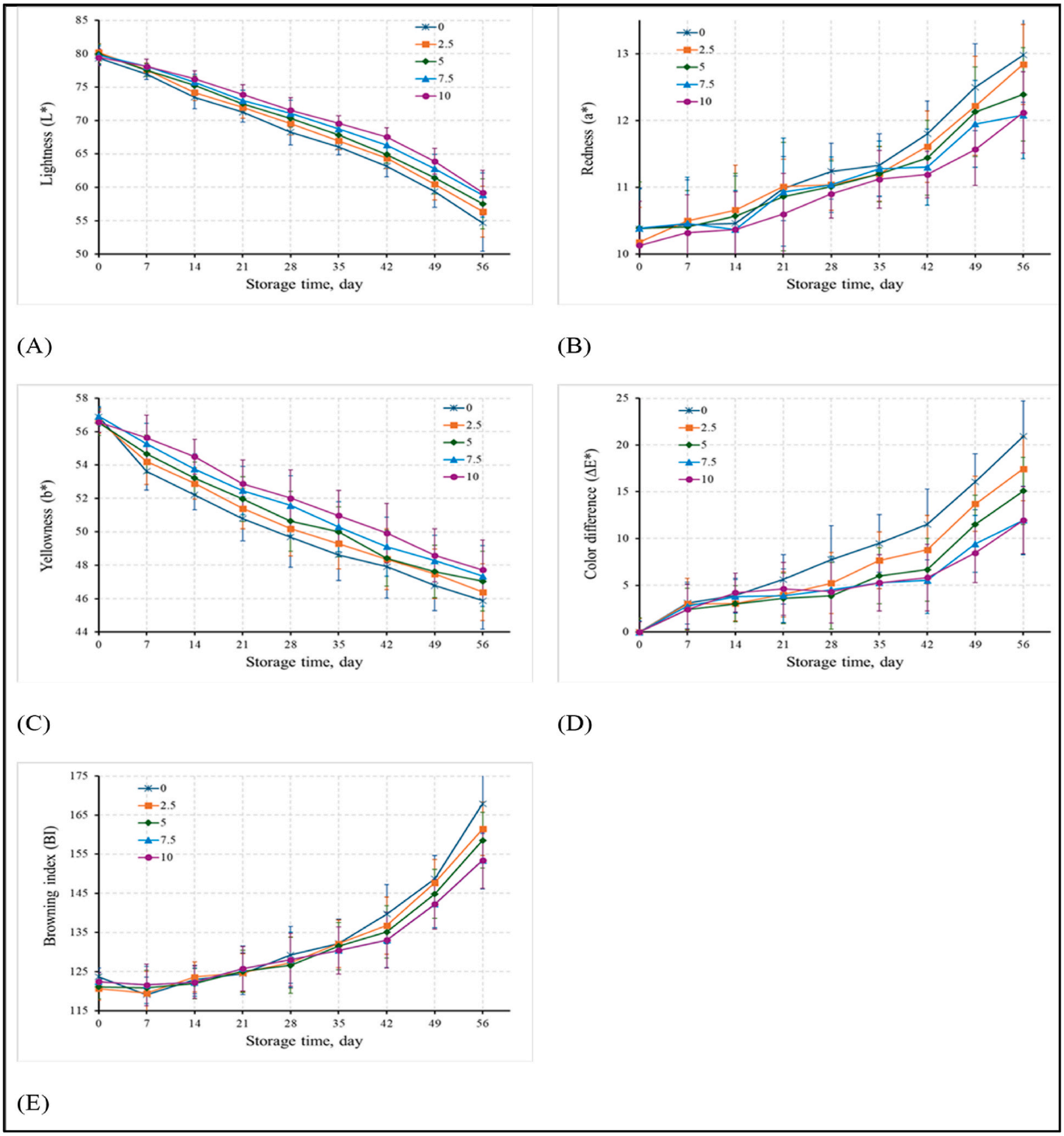

Fig. 5. Effects of GAC on the color parameters: L* (A), a* (B), b* (C), ΔE* (D), and BI (E) of Barhi date fruits during storage.

4. Discussion

4.1. Effects of Gum Arabic edible coating on Fruit quality

Recent studies have explored the impact of GA edible coating on postharvest quality preservation of fruit and vegetables [35]. However, there is no extensive study on the combined effects of GA coating, storage temperatures, and packaging materials at different storage durations on the fruit quality characteristics of date palm cv. Barhi. The effects of GA edible coating, storage temperature, and type of packaging on fruit physicochemical properties can vary depending on the specific fruit variety and the storage duration [22]. The current study shows that the fruit weight, volume, density, hardness, moisture content, pH, water activity, lightness, and yellowness of Barhi dates with different levels of GA decreased with an increased storage duration of up to 56 days. These attributes were

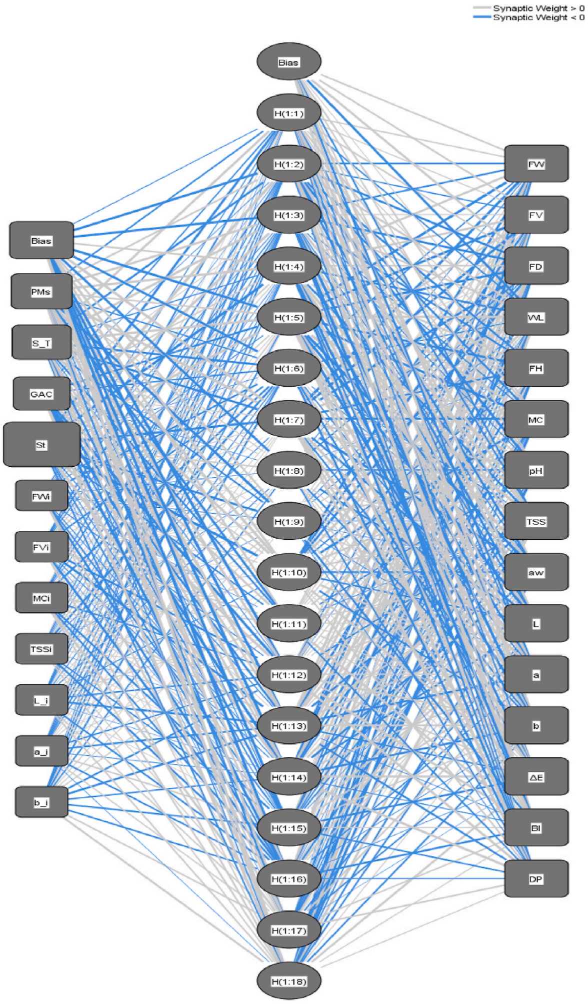

Fig. 6. Actual architecture of the implemented ANN model for predicting quality parameters of Barhi date fruits.

Table 4
A comparison between the relative errors in the training, testing, and evaluation phases of the implemented ANN Model for predicting Barhi fruit quality.

Evaluation metrics		Training	Testing	Evaluating
The sum of squares error		402.66	152.82	
Average overall relative error		0.115	0.191	0.119
Relative error	FW	0.067	0.134	0.073
	FV	0.263	0.45	0.304
	FD	0.345	0.483	0.351
	WL	0.017	0.034	0.022
	FH	0.054	0.101	0.057
	MC	0.143	0.241	0.113
	pH	0.053	0.057	0.066
	TSS	0.032	0.063	0.036
	aw	0.175	0.293	0.138
	L*	0.036	0.057	0.037
	a*	0.237	0.35	0.203
	b*	0.052	0.089	0.062
	ΔE*	0.067	0.182	0.08
	BI	0.128	0.142	0.145
	DP	0.051	0.243	0.084

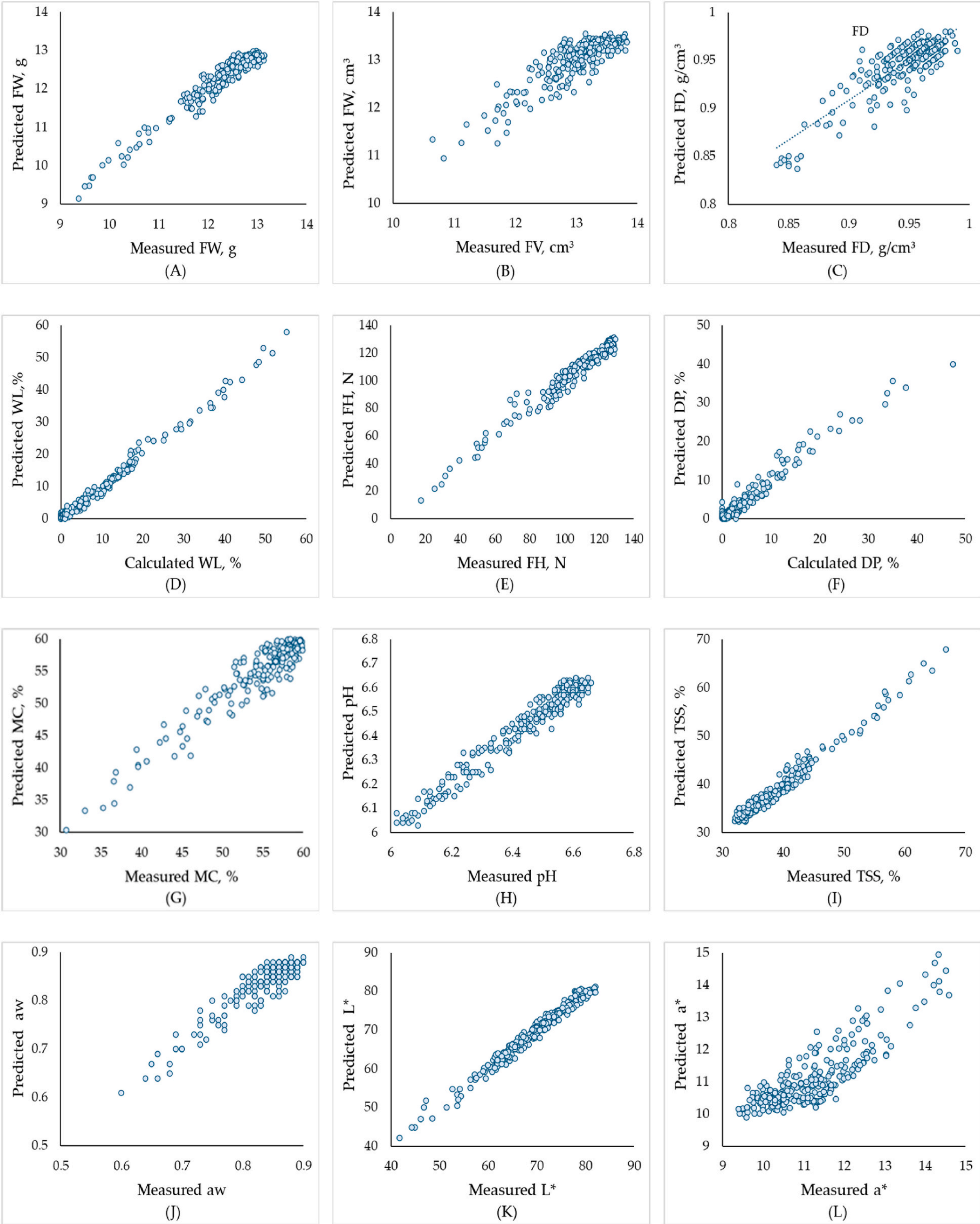

Fig. 7. The plots of measured/calculated quality parameters (FW (A), FV (B), FD (C), WL (G), FH (E), DP (F), MC (G), pH (H), TSS (I), aw (J), L* (K), a* (L), b* (M), ΔE* (N), BI (O) the Barhi fruits versus the predicted values.

Table 5
The ANN prediction model validation uses root mean squared error (RMSE), mean absolute percentage error (MAPE), and mean absolute error (MAE) metrics.

Quality Parameters	RMSE	MAPE, %	MAE
FW	0.185	1.2	0.152
FV	0.273	1.7	0.221
FD	0.015	1.2	0.011
WL	1.106	–	0.82
FH	3.912	3.1	2.903
DP	1.455	–	0.963
MC	1.749	2.5	1.342
pH	0.034	0.4	0.028
TSS	1.059	2.2	0.84
aw	0.019	1.8	0.015
L*	1.147	1.3	0.913
a*	0.567	4.2	0.475
b*	0.787	1.2	0.605
ΔE*	1.522	3.3	1.233
BI	4.423	2.7	3.543

significantly better when fruits were coated with a 10 % GA solution compared to the control at each storage duration. Edible coatings have shown significant potential in the postharvest management of fruits by reducing moisture loss, delaying ripening, and preserving nutritional quality. As a natural polysaccharide, GA has demonstrated its effectiveness in reducing weight loss, maintaining firmness, and delaying biochemical changes in various fruits. GA coatings enriched with calcium chloride have been reported to enhance the storage quality of mangoes by reducing oxidative stress and maintaining cell wall integrity. Such coatings act as semi-permeable barriers, minimizing gas exchange and water loss and slowing metabolic processes like respiration and ethylene production. In the case of Barhi dates, GA's role in mitigating dehydration and extending shelf life aligns with the growing need for sustainable and biodegradable postharvest technologies [36].

Fruit redness, browning index, and decay parameters were minimal after 56 days of storage when coated with 10 % GA compared to other treatments. There was an antagonistic relationship between the weight of the fruits and their weight loss during the storage period. The fruit weight was higher when the date palm cv. Barhi fruits were coated with 10 % GA and stored at a low temperature (4 °C) in a vacuum-sealed package, indicating minimal fruit weight loss after 56 days of storage. These results also coincide with the moisture content data of fruits, indicating that where the fruit weight was higher, the moisture content was also higher, and the weight loss was lower. Due to their hydrophilic properties, GA coatings can prevent fruit weight loss by acting as a moisture barrier, absorbing and retaining water, and creating a protective layer on the fruit surface, reducing respiration, water evaporation, and metabolic activities [37]. The gas barrier attribute of edible coating prevents respiration by restricting oxygen intake by the fruit; maintaining an oxygen content above 3 % is crucial to prevent anaerobic respiration and unpleasant flavor development [38]. Many studies reported that the GA delays the respiration rate and postharvest ripening in fresh produce such as guava [39], sweet cherry [40], and chili pepper [41]. Tomatoes coated with 10 % GA have a reduced respiration rate [42]. Using a 10 % GA edible coating significantly reduced water loss and enhanced the quality of fruit stored at ambient temperature for 8 days [43]. GA coatings can reduce fruit shrinkage and dehydration by forming a protective layer on the surface, reducing water loss through transpiration, and potentially preserving fruit weight [44]. In mangoes, the gum coating functions as a semi-permeable barrier, inhibiting the movement of oxygen, carbon dioxide, moisture, and solutes. This decreases respiration rates, water loss, and oxidation reactions, preventing weight loss [45]. By preserving the fruit's moisture, GA helps maintain its size and volume and prevents it from shrinking.

The present study also showed that the fruit hardness of the cv. Barhi significantly corresponds to fruit weight loss—uncoated Barhi fruits showed lower hardness and higher weight loss than gum-abroad coated ones. Similar results were observed in tomatoes at 15–20 % GA coating after 16 days of storage [46]. Applying 15 % GA in strawberries improved fruit hardness after 24 days of storage [47]. Fruit softening is a biochemical phenomenon characterized by the enzymatic hydrolysis of pectin and starch during ripening [48]. This enzymatic action, primarily driven by pectinesterase and polygalacturonase, leads to the breakdown of pectin molecules, reducing pectin's chain length [49]. However, when fruits are stored in an environment with low oxygen levels and high carbon dioxide concentrations, it can inhibit the activity of these enzymes, thereby helping to maintain fruit hardness during storage [50]. Coating tomatoes exhibit reduced respiration rates and can further delay the ripening process, ensuring enhanced stability during storage.

The findings of the present study also depicted that the fruits of cv. Barhi coated with 10 % GA retained moisture content, pH, water activity, and color and had minimum TSS and fruit decay. GA, a hydrocolloid, forms a protective barrier on fruit surfaces, reducing water evaporation and preventing moisture loss, thus preserving the fruit's moisture content and water activity [44]. It also acts as a pH buffer on the fruit's surface, preventing the microbial growth that causes fruit decay. It stabilizes the pH and produces an environment less conducive to decay [51]. The higher b values of 10 % gum-coated fruits after 56 days of storage indicate an increase in yellow color, possibly due to changes in chlorophyll and carotenoid pigments and the formation of brown pigments [52]. A similar trend was observed in the L values of 10 % coated fruits after 56 days of storage. The concentration of GA increased, and the lightness also increased. The findings revealed that gum effectively maintained the fruit's brightness and shiny appearance. The redness, color difference, and browning index values were higher in uncoated Barhi fruits. The gum coating effectively inhibited gas exchange between the outer and inner coats of stored fruit, reducing the browning index increase and delaying the Maillard reaction. Similar results were reported in tomatoes, where the variation in fruit lightness was considered an indicator of color browning [47]. The reduction in TSS of coated fruit is directly linked to the concentration of gum solution used and lower respiration rates in cherries, resulting in reduced metabolite utilization [49]. As reported in mango, the reduction in fruit decay could be due to oxygen, carbon dioxide, and ethylene reduction [53].

4.2. Effects of storage temperatures on Fruit quality

Storage temperature significantly influences various quality attributes of fruits. The outcome of current research indicated that the GA-coated fruits of date palm cv. Barhi stored at a low temperature (4 °C) increased fruit weight, fruit volume, fruit density, hardness, moisture content, water activity, lightness, yellowness, and browning index, whereas fruit weight loss, pH, TSS, redness, delta E, and fruit decay were significantly lower during the 56 days of storage. When fruits were stored at a higher temperature (24 °C), these fruit quality characteristics were opposite. Higher storage temperature accelerates metabolic processes, increasing respiration rates and transpiration [54]. This results in elevated weight loss and potential size reduction due to moisture depletion [55].

Moreover, higher storage temperatures promote fruit softening by hastening cell wall degradation, thereby decreasing hardness [56]. The storage temperature significantly affects the pH of the fruit, with higher temperatures potentially enhancing enzymatic activity and causing changes in the fruit's acidity [57]. The higher temperature during storage also increases the TSS due to the breakdown of starches [58]. Color retention is also temperature-dependent, with higher temperatures accelerating pigment degradation and undesired color changes [56]. The browning index, an indicator of enzymatic browning, increases at elevated temperatures due to enhanced enzymatic activity [59]. Higher temperatures accelerated oxidative damage and promoted microbial activities that led to fruit decay [60]. Therefore, maintaining optimal storage temperatures is crucial to minimizing fruit quality loss during post-harvest storage.

Previous studies showed that the GA-coated mango fruits retained moisture loss and quality traits when stored at low temperatures [53]. Date fruits coated with GA stored at low temperatures significantly maintained firmness and increased TSS [61]. A composite of GA (10 %) plus chitosan (1 %) coating retained firmness, reduced weight loss and TSS, and delayed fruit color in bananas stored at 13 °C [62]. Wax-coated fruits of tangerine citrus stored at 5 °C maintained their quality, with the lowest percentage of weight loss and fruit decay after 35 days of storage. Chitosan-coated plum fruits stored at low temperatures maintained firmness, retard water loss, and delayed color changes after 35 days of storage [63]. The shelf life of coated litchi fruits can be extended up 20 days at 2–5 °C [64]. The storage of chitosan-coated Ziziphus Mauritiana fruits at high temperatures adversely affected weight loss, shelf life, and fruit quality [65]. Protein isolate and Cajanus cajan seed gum coating on strawberries effectively prevents water vapor transfer, reduces dehydration and TSS, delays ripening, and maintains fruit color after 10 days of storage at 5 °C [66]. Blueberries stored at 15–20 °C for 14 days had higher weight loss and fruit decay and the lowest firmness and color lightness [67]; however, Eum et al. [68] observed no change in blueberries' color lightness except weight loss after 16 days of storage at 10 °C. Dehydration is the primary factor leading to changes in firmness during the storage of blueberries after they have been harvested [69]. Blueberries stored at 5 °C maintained higher fruit firmness than those stored at 10 °C. Firmness declined with increased water-soluble pectin and decreased sodium carbonate-soluble pectin, cellulose, and hemicellulose [70]. A 20–25 % weight loss was observed when pomegranate fruits were stored at 22 °C for 4 weeks. However, when the fruit was stored at 5 °C, the fruits maintained better color, TSS, and acidity and delayed fruit decay [71]. Strawberry fruits coated with chitosan and stored at 2 °C reduced water loss and delayed the qualitative changes in color, TSS, and acidity [72]. Sheng et al. (2017) concluded that cold storage alone cannot reduce the fruit decay of unwaxed apples, and additional intervention should be taken during fruit packing.

4.3. Effects of packaging types on Fruit quality

The choice of storage packaging materials, including vacuum-sealed, carton, and plastic boxes, significantly affects the attributes of fruits [73]. The present study showed that the GA coated fruits of date palm Barhi packed in vacuum-sealed packaging had higher fruit weight, volume, density, hardness, moisture content, water activity, lightness, and yellowness. Weight loss, pH, TSS, redness color difference, browning index, and fruit decay attributes were the lowest in the same packaging. The highest weight loss, TSS, redness, and decay were observed in plastic box packaging. Fruit packed in carton boxes had higher fruit firmness and browning index and shared the lowest moisture content and water activity traits with plastic box packaging. Vacuum-sealed packaging reduces weight loss by minimizing moisture evaporation, maintains fruit size and moisture content, and contributes to fruit firmness by limiting gas and moisture exchange with the external environment. This airtight seal also helps maintain fruit firmness [74]. Vacuum-sealed packaging improved water activity and reduced water loss, preventing evaporation in Hilali date fruit [75] and almonds [76]. Thyme-coated date palm fruits exhibited higher moisture retention and reduced browning rates after six months of vacuum-sealed storage [77]. Barhi fruits stored in modified atmosphere packaging showed minimal weight loss, Rutab fruit percentage, and high water activity. The weight loss was also minimal in vacuum packaging. However, the Rutab fruit percentage was higher [78]—the reduction in the TSS of date fruits in vacuum-sealed packaging could be due to sugar–acid metabolism. The increase in carbon dioxide in modified atmosphere packaging has been found to hinder the decrease in date TSS over time [13,75]. In Jujube, the vacuum packaging and passive-modified atmosphere packaging significantly reduced fruit weight loss, TSS, and browning index, maintained fruit firmness, and enhanced shelf life [74]. Olive fruits, stored at 4 °C in vacuum sealing and modified atmosphere packaging, effectively prevented microbial growth [79]. Another study found that low-density polyethylene vacuum-sealed pouches are the most preferred for refrigerated storage of fresh-cut papaya and maintain good color, firmness, and microbiological stability, resulting in minimal changes in physical and biochemical properties [80]. In another study, modified atmosphere packaging and vacuum skin packaging techniques were used to extend fresh-cut asparagus's shelf life (21 days) at 4 °C. Both packaging techniques help maintain the product's freshness [81].

4.4. Effects of packaging types on Fruit quality

The performance validation of ANN prediction models for Barhi date fruits has shown high efficacy and reliability in predicting quality parameters across various storage conditions. The validation of the implemented model aligns with findings from multiple studies emphasizing quality prediction accuracy in date palm fruit during storage and processing, employing the ANN for predictive analysis of the impact of modified atmosphere packaging conditions on the quality of various date fruit cultivars [11], predicting date fruit quality parameters based on their electrical properties during cold storage [82], enhancing the precision and effectiveness of sorting date palm fruits based on size, moisture, and color [29]. Utilizing ANN models to predict the quality of date fruits stored is a promising utilization of AI technology for date palm fruits. The ANN models expeditiously assessed the fruits' physicochemical characteristics using affordable spectral sensors [13,75]. While the ANN model showed high accuracy in predicting quality parameters of Barhi dates during storage, several limitations should be acknowledged. For example, the model's performance depends on the dataset's size and diversity; a more extensive dataset, including different fruit cultivars, storage conditions, and coating compositions, could enhance its generalizability. Additionally, the ANN model limits its interpretability, making it challenging to understand the exact contributions of individual variables to the predictions. Therefore, future studies could explore hybrid models that combine ANN with explainable AI techniques, such as decision trees, to provide more transparent insights. Moreover, integrating real-time data collection, such as spectral or imaging technologies, could improve the model's predictive power and enable dynamic adjustments during storage.

5. Conclusions

This study investigated the impact of edible GA coating and storage conditions on postharvest Barhi date quality. The results demonstrated that vacuum packaging (VP) with a high concentration of GA coating (7.5%–10 %) and cold storage (4 °C) produced superior outcomes for preserving quality parameters compared to carton box (CBP) and perforated plastic bag (PBP) methods. The artificial neural network (ANN) models showed high effectiveness and reliability in predicting quality parameters during storage, as evidenced by low mean absolute error (MAE) and root mean square error (RMSE) values and high R^2 values. These findings indicate the ANN model's capability to capture complex relationships among independent variables and accurately predict fruit quality attributes. The study highlights the potential of combining VP, GA coatings, and cold storage to maintain fruit quality, extend shelf life, and reduce postharvest losses. The ANN model can be utilized to predict fruit quality during storage. Therefore, the study represents a step forward in integrating sustainable postharvest technologies with predictive modeling to reduce food losses and improve supply chain efficiency. However, more supplementary datasets would be advantageous in validating the reliability and applicability of the ANN models for the other fresh fruit cultivars to rectify the model constraints and broaden its applicability.

CRediT authorship contribution statement

Nashi K. Alqahtani: Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Bayan Alkhamis:** Writing – review & editing, Writing – original draft, Validation, Methodology, Conceptualization. **Tareq M. Alnemr:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Conceptualization. **Maged Mohammed:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation.

Data availability statement

The data is contained within the article.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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