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Research Article

Effects of Wax Coating on the Moisture Loss of Cucumbers at Different Storage Temperatures

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The effects of wax coating on moisture loss of cucumbers (*Cucumis sativus* L., cv. Jinglv) were investigated at different temperatures. Cucumbers were treated with 10% (volume : volume) wax and then stored at 15, 20, 25, or 30°C and 55% relative humidity. The changes in the mass of samples were recorded every 6 h. Results showed that wax coating along with low temperature was very effective in preventing moisture loss of cucumbers during simulated distribution. After 48 h storage, moisture loss in wax treated cucumbers at 15°C was 45% lower than the control at 30°C. Furthermore, a kinetic model was developed to study the influence of temperature on moisture loss based on the Arrhenius law. The model successfully described changes in cucumber moisture loss at different temperatures during storage. The shelf life of cucumber was also predicted using the kinetic model. A synergistic effect was found between wax coating and storage temperature on cucumber shelf life. Wax coating combined with low storage temperature was an effective method to extend the shelf life of cucumber fruit.

1. Introduction

Cucumber is a nonclimacteric fruit vegetable that contains more than 90% water. The principal factor affecting fruit quality during transportation, storage, and marketing is often excessive moisture loss [1]. Besides weight loss resulting in a lower price when sold on a weight basis, postharvest moisture loss also reduces fruit quality through loss of glossiness, shriveling, and increased susceptibility to postharvest pathogens [2, 3].

Fruits and vegetables have diverse adaptive mechanisms to control moisture loss [4]. Cuticular wax is a major barrier restricting moisture transfer. It has been reported that a high content of the cuticles was correlated with moisture retention capacity of plant tissue [5]. Immature fruits typically have a relatively thin cuticle and the cuticle is often at least partially removed during washing. Postharvest moisture loss of such commodities can be reduced by coating with a wax after harvest [6]. In addition, wax coatings may result in the development of a modified atmosphere within coated products, slowing respiration and other physiological processes and possibly improving the quality and extending shelf life [7, 8]. Such practices have been used successfully in fruits and vegetables such as tomato [9], orange [10], and avocado [11].

Previous studies have evaluated the effects of wax coatings on postharvest moisture loss at a specified controlled temperature [7, 12]. However, temperature is the most critical factor influencing the rate of moisture loss. Thus, the objective of this work was to evaluate the influence of different temperatures on moisture loss of waxed cucumbers. A kinetic model was also developed to investigate the relationship between temperature, wax coating, and moisture loss. The shelf life of cucumber under different temperatures was also predicted based on the kinetic model.

2. Materials and Methods

2.1. Materials and Wax Treatments. Commercially ripe cucumbers (*Cucumis sativus* L., cv. Jinglv) were harvested in the local orchard. All cucumbers were grown under the same environment and harvested at the same time for subsequent experiments. Cucumbers were selected for uniformity in appearance and size (180 ± 5 g), and any with damage or defects were discarded.

The cucumbers were briefly dipped in a fruit wax (containing 50% shellac and 50% carnauba) at a concentration of 10% (v : v) for 1 min. Thereafter, samples were air-dried for 1 h at 16°C. Unwaxed fruit served as controls. One layer of treated and control samples was placed in 60 cm × 37 cm × 20 cm plastic containers and then stored in the test chamber (TH80, ASLI) with temperature and RH control system at 15, 20, 25, or 30°C with 55% RH. Forty samples were used for each treatment and the experiment was repeated three times.

2.2. Moisture Loss Measurement. Moisture loss was measured by weighing 10 fruit per treatment for every 6 h during storage and was calculated using the following equation:

$$M = \frac{m_0 - m_i}{m_0} \times 100\%, \tag{1}$$

where M is the moisture loss (%); m_0 is original mass (g); m_i is determined mass at a particular hour after harvest.

2.3. Kinetics Modeling. Food quality deterioration, such as browning and moisture loss [13–16], in storage followed a zero-order kinetic model, which can be represented by the following mathematical equation:

$$\frac{dQ}{dt} = k, \tag{2}$$

where Q is the quality factor measured; t is time; k is a rate constant which depends on temperature and relative humidity; dQ/dt is the rate of change of Q with time.

And by integration it results in

$$Q(t) = Q_0 + kt, \tag{3}$$

where Q_0 is the quality factor at time zero.

Moisture loss at time zero (m_0) is equal to zero, (3) for moisture loss then becomes:

$$M = kt, \tag{4}$$

where M is the moisture loss (%); t is time; k is the rate constant of moisture loss.

The influence of temperature on the rate constant k can be described by the Arrhenius equation [14, 17, 18] as follows:

$$k = K_0 \exp\left(\frac{-Ea}{RT}\right), \tag{5}$$

where K_0 is the index of Arrhenius equation ($m^2\,s^{-1}$); Ea is the energy of activation ($kJ{\cdot}mol^{-1}$); R is gas constant ($8.31\,kJ{\cdot}mol^{-1}K^{-1}$); T is absolute temperature (K).

So the equation expressing the relation between moisture loss, time, and temperature follows the form

$$M = K_0 \exp\left(\frac{-Ea}{RT}\right) t. \tag{6}$$

2.4. Shelf Life Prediction. Cucumbers contain approximately 95% water. Moisture loss is a main factor limiting cucumber postharvest life and economic value. Moalemiyan and Ramaswamy [19] reported that the maximum acceptable moisture loss was considered 8-9%. In this study, 9% moisture loss was used as the end point of shelf life. Combining with (6), the following equation for shelf life prediction is obtained:

$$t_S = \frac{9}{K_0} \exp\left(\frac{Ea}{RT}\right), \tag{7}$$

where t_S is the shelf life of cucumber.

2.5. Data Analysis. Analysis of the experimental data was performed using linear regression (Excel 2000) to obtain the rate constant of moisture loss (k) at a constant temperature. The rate constant for each temperature was then analyzed by nonlinear regression (OriginPro 7.5) analysis using the model formulation of (5) and the index of Arrhenius equation (K_0) and the energy of activation (Ea) were thus estimated. The quality of fit of the mathematical models to the experimental data was evaluated with the correlation coefficient (R^2). To verify the validity of the models, the mean relative percentage deviation modulus (P%) between experimental and calculated values was determined using the following expression as suggested by Kaymak-Ertekin and Gedik [17]:

$$P(\%) = \frac{100}{N} \sum_{i=1}^{N} \frac{\left|m_i - m_{pi}\right|}{m_i}, \tag{8}$$

where m_i is the experimental value, m_{pi} is the predicted value from the model, and N is the number of experimental data. A model is considered acceptable if P values are below 10%.

3. Results and Discussion

3.1. Effect of Temperature on Moisture Loss of Cucumber Fruit. During storage and transportation, cucumbers will lose moisture gradually [20]. In this study, all samples showed a gradual decrease in weight during storage (Figure 1). At the end of storage, moisture loss of cucumbers increased to 17.2%, 17.7%, 20.7%, or 21.6% at 15°C, 20°C, 25°C, or 30°C, respectively.

Moisture loss from fruits and vegetables is driven by the water potential gradient between the internal fruit space and the surrounding air [21]. This gradient is related to the water vapor pressure deficit (WVPD), which is the difference between the actual water vapor pressure and the saturation vapor pressure. Even at the same RH, WVPD changes with temperature so that higher temperatures result in higher

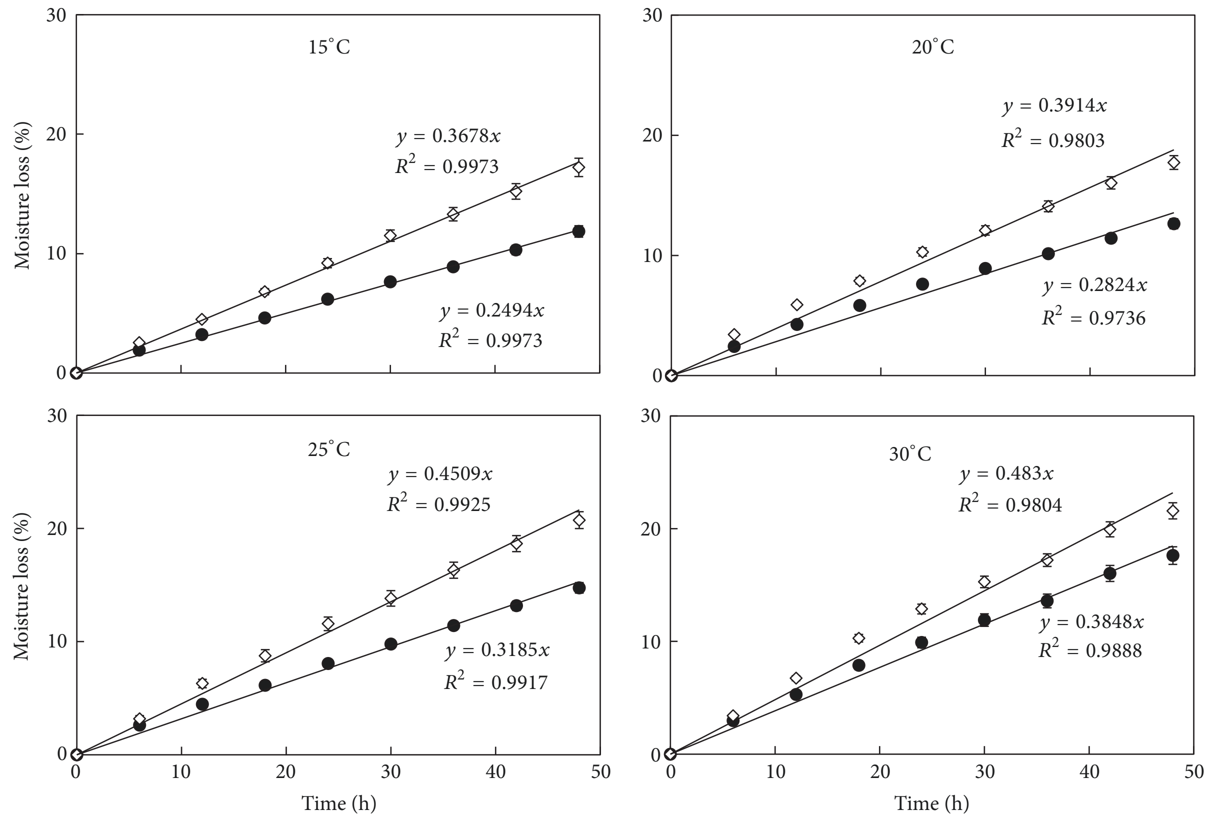

Figure 1: Moisture loss of control (◇) and wax treated (●) cucumbers stored at different temperatures, but all with 55% relative humidity. The lines (—) represent model estimates from (4).

WVPD than at lower temperatures [22]. Consequently, moisture loss increases with increased storage temperatures. As shown in Figure 1 and in the same RH environment, cucumbers stored at high temperature lost more moisture than those at low temperature. The final moisture loss of cucumbers at 30°C was 21.6%, while it was 17.2% at 15°C. These results demonstrate that temperature was an important factor in moisture loss. Lower temperatures slow moisture loss from cucumber. However, cucumber is very sensitive to chilling injury when stored at temperature lower than 10°C and so there is a limit to how low one can lower temperature to successfully store cucumber.

3.2. Effect of Wax Coating on Moisture Loss of Cucumber Fruit. Moisture loss is also closely related to diffusion resistance, which is related to wax content [23]. Lownds et al. [24] found that the rate of moisture loss and epicuticular wax content of three New Mexican-type pepper fruit were negatively correlated, suggesting that this natural wax was a good barrier to moisture loss. Coating fresh produce with a wax may be used to slow moisture loss from the fruits and vegetables. In this study, after storage for 48 h, moisture loss in wax treated fruit was 33.9%, 27.6%, 29.9%, or 20.3% lower than that in control fruit at 15°C, 20°C, 25°C, or 30°C, respectively. The moisture loss in waxed fruit at 30°C was 45% lower than that in the control at 15°C, which suggested that wax coating along with the low temperature contributed to a reasonable shelf life.

3.3. Relationships between Moisture Loss and Storage Time. In order to obtain the functional relationships between moisture loss and storage time, the kinetic model was developed by linear regression analysis. The predicted and experimental moisture losses for cucumbers at different temperatures and storage time are shown in Figure 1. In all cases, the correlation coefficient (R^2) values were higher than 0.97, which shows good agreement with experimental results. The moisture loss rate constant (k) and the mean relative percentage deviation modulus (P%) are listed in Table 1. The mean relative percentage deviation modulus (P%) between model and experiment ranged between 3.35% and 9.96%. The results suggest that a linear model is suitable for describing the relationship between time and moisture loss.

3.4. Relationships between Moisture Loss and Storage Temperature. To get a better idea of the effects of temperature and wax coating on cucumber moisture loss, the natural logarithm of the rate of moisture loss was fitted against the inverse of air temperature (Figure 2). The relationship between moisture loss rate constants and temperature followed the Arrhenius relationship ($R^2 > 0.97$). Then, the activation energies (Ea) and the index of Arrhenius equation (K_0) values, given by

Table 1: The moisture loss rate constant (k), correlation coefficient (R^2), and the mean relative percentage deviation modulus (P%) in control and wax treated cucumbers at various temperatures.

Temperature (°C)	Treatments	k (h^{-1})	R^2	P (%)
15	Control	0.3678	0.9973	5.82
	Wax coating	0.2494	0.9973	3.35
20	Control	0.3914	0.9803	9.96
	Wax coating	0.2824	0.9736	9.08
25	Control	0.4509	0.9925	6.78
	Wax coating	0.3185	0.9917	5.24
30	Control	0.438	0.9804	7.16
	Wax coating	0.3848	0.9888	7.73

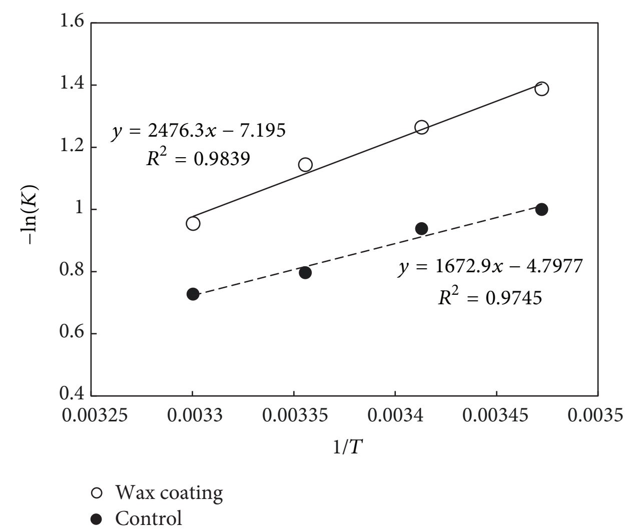

Figure 2: $-\ln(k)$ versus $1/T$ for control (A) and wax treated (B) cucumbers.

Table 2: Estimated parameter values for the kinetic model in (5).

	K_0 (m^2/s)	Ea (kJ/mol)	R^2
Control	121.2	13908	0.9745
Wax coating	1332.7	20587	0.9839

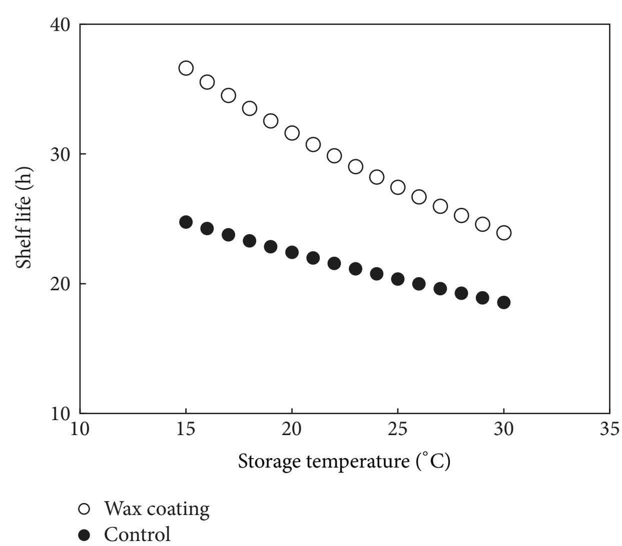

Figure 3: Shelf life of cucumbers at different storage temperatures, but all with 55% relative humidity.

the Arrhenius relationship in (5), were calculated from the linear relationship in Figure 2. The Arrhenius equation then becomes

$$\text{Control: } M_c = 121.2 \exp\left(-\frac{1672.9}{T}\right) t$$
$$\text{Wax coating: } M_w = 1332.7 \exp\left(-\frac{2476.3}{T}\right) t. \qquad (9)$$

The index of Arrhenius equation (K_0) and the activation energies (Ea) are shown in Table 2. The index of Arrhenius equation for control (K_{0C}) was lower than that for wax treated cucumbers (K_{0w}), which revealed that the wax coating slowed down the moisture diffusion of cucumbers. Furthermore, the wax treatment had a higher activation energy (Ea), therefore, increasing the influence of temperature on moisture loss. The result again was that a wax coating combined with low temperature delayed moisture loss during storage.

3.5. Shelf Life Prediction. Based on (7), the shelf life of cucumber when moisture loss exceeded its limit of acceptability was predicted at any constant temperature. As shown in Figure 3, the shelf life of both control and wax-coated fruit was decreased with increased storage temperature. The maximum acceptable storage period for control fruit was only 18.6 h at 30°C, but 24.7 h at 15°C. Wax coating also extended the shelf life of cucumber. For fruit held at 15°C, the shelf life of control samples was 24.7 h while the coated samples were acceptable for 36.6 h. Similar results were reported by Bahnasawy and Khater [25]. We also found that the shelf life of wax coated fruit was 32.4% higher than that of control at 15°C, and 22.4% higher at 30°C, which showed the synergistic effect between wax coating and storage temperature. Our findings indicated that the shelf life of cucumber, which had such a short life, could be extended by application of a wax coating combined with low temperature storage.

4. Conclusions

A predictive model was developed to describe the changes in cucumber moisture loss, which could be used to predict moisture loss at different times and temperatures during the storage period. A decrease in temperature resulted in a decrease in moisture loss. Meanwhile, a wax treatment changed the activation energy for moisture loss. So, wax coating combined with low temperature is recommended to reduce moisture loss and prolong the shelf life of the cucumber.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

Acknowledgments

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