Application and Evaluation of a Pectin-Based Edible Coating Process for Quality Change Kinetics and Shelf-Life Extension of Lime Fruit (*Citrus aurantifolium*)

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Abstract: Uncertain storage conditions lead to considerable quality loss in lime fruits, which affect their consumer acceptability. Studies aimed at quantifying the kinetics of quality changes under different storage conditions are valuable for minimizing the product quality loss and improving their marketability. The objective of this study was to quantify the effect of pectin-based coating on the kinetics of quality change in stored limes fruits using a pre-established coating process. Lime fruits were immersed in the coating emulsion and then surface dried, cooled, and evaluated after storage for different times at selected temperatures (10–25 °C). Quality characteristics evaluated include physical (texture and color), chemical (ascorbic acid, pH, titrable acidity, total soluble solids), and physiological (respiration rate) properties. Results revealed that with the passage of time, the fruits showed progressive increase in shriveling or wilting and loss in green color, and higher temperatures accelerated these changes. The respiration rate in control samples reached 79, 35, and 7 mL CO_2/(kg·h) after 7 days at 25 °C and 22 days at 15 and 10 °C, respectively, while those of coated samples were limited to 40, 32, and 1.06 mL CO_2/(kg·h) after 11, 25, and 32 days at the same storage temperatures. Control fruits suffered 6%, 10%, and 24% weight loss following 8 days of storage at 10, 15, and 20 °C, respectively, while the losses in coated fruits were lower (2%, 4%, and 17%, respectively). A zero-order model was found appropriate for weight loss, along with a color *a* value and ΔE, while a first-order model was found to be better for firmness, brix to acidity ratio, ascorbic acid, and *b* and *L* values ($R^2 > 0.9$). The Arrhenius model was suitable for temperature sensitivity of the rate constants.

Keywords: edible coating; pectin; lime fruit; respiration; shelf-life

1. Introduction

Lime fruit (*Citrus aurantifolium*) is an important horticultural crop worldwide, including Iran, with an annual production of 650,000 tons [1]. Because of its high acidity and vitamin C content, lime is highly valuable in nutrition and lemon juice is used as a common food acidulant. This fruit is quite perishable and its shelf life depends on storage conditions and other factors. Postharvest handling and injuries can further influence their respiration rates and storage quality. Proper packaging, on the other hand, can help to reduce these losses because it can reduce not only the respiration rate but also produce transpiration, helping to restrict weight loss. Refrigerated storage retards ripening and enhances shelf life, but chilling injuries may pose problems during extended storage [2].

The quality of a fruit is determined by the combination of different physical, chemical, and physiological characteristics, as well as nutrient concentration. High-quality lime fruits are firm, green, and without any defects. In addition, the harvest maturity and time, fruit variety, and environmental conditions also influence the quality. Respiration rate is a major factor contributing to postharvest losses and accelerates the product senescence, while it provides energy for the various biochemical and physiological activities. A high respiration rate is generally detrimental to the maintenance of high fruit quality. Decreasing the respiration rate leads to extending the shelf life and retaining the produce quality [3].

There are several techniques to retard the rate of ripening after harvest, and thus extend shelf life. These include controlled/modified atmosphere (CA/MA) storage, modified atmosphere packaging (MAP), and use of biodegradable coatings. In these novel concepts, O_2 level is lowered and CO_2 level is enhanced, which generally contribute to extended shelf-life [4]. This atmosphere modification reduces respiration rate, and hence minimizes the quality loss. Refrigeration is an important step in this regard because both produce respiration and skin or package permeation are influenced by temperature.

A number of studies have been performed on the benefits of coating applications on fruits and vegetables. These materials can help to prolong shelf life and color retention, reduce moisture loss [5], inhibit ethylene production [6], improve visual appearance, reduce shriveling and wilt while retaining biochemical properties [7], improve texture and color retention, cell membrane stability, and storage life [8] inhibit browning [9], and reduce weight loss and decay incidence [10]. Coating emulsions can be prepared from a combination of different levels of hydrocolloid components (lipids, resins, polysaccharides, proteins, etc.). Pectin is a soluble component of plant fiber derived from cell walls of plants. Martiñon et al. [11] used pectin and other materials for development of multilayered coating systems to extend shelf-life of fresh-cut cantaloupe. Pectin-based (2%, *w/v*) edible coatings containing N-acetylcysteine at 0.75% (*w/v*) and glutathione at 0.75% (*w/v*) were investigated to determine their effect on quality and microbial stability of fresh-cut pears by Oms-Oliu et al. [12]. The results indicated that the pectin based coating best maintained sensory attributes of pear wedges for 14 days. Pectin-based emulsion has been effectively used in several of our previous studies for different fruits and vegetables, such as avocado, peach, mango, and cucumbers [13–17]. Understanding the quality loss kinetics is important determining the shelf life of fruits [18].

The present study was, therefore, carried out with a focus on the quality change kinetics associated with pectin-based edible film-coated limes in comparison with uncoated control fruits as influenced by storage temperature.

2. Materials and Methods

2.1. Preparation of Coating Emulsion,

The coating emulsion was prepared based on the optimized formulations described in Maftoonazad and Ramaswamy [3]. Briefly, a pectin (HM Rapid Set powder, TIC Gums, Belcamp, MD, USA) solution (3% *w/w*) was prepared in distilled water (12 h soaking at 20 °C), to which sorbitol (Sigma, Oakville, Ontario, Canada) (at 45% of pectin dry weight basis) was added with continuous mixing with a magnetic stirrer. Then, melted beeswax (Sigma, Oakville, Ontario, Canada) (40% pectin dry weight basis) and monoglyceride (30% dry weight basis) were added and emulsified using a homogenizer (PowerGen 700, Fisher Scientific, Pittsburg, PA, USA) at 14,000 rpm for 4 min.

2.2. Coating of Fruits

Fresh lime fruit was purchased from a local source (custom made). Fruit with similar sizes, color, and firmness were separated and surface disinfected by immersion in 0.5% commercial bleach for 3 min, washed and air-dried. The fruits were then divided into six replicate lots. The first three lots were stored without coating and the others were coated with a pectin-based emulsion using the coating apparatus. Both coated and uncoated limes were held in a cold storage maintained at a relative

humidity of about 90% for different times at selected temperatures (10–25 °C). At each testing day, 6 fruits were taken randomly from each replicate for firmness and chemical analysis (total 360 fruits). For respiration rate, weight loss, and color changes, the same marked limes consisting of 6 fruits per replicate were used at each day of measurement (108 fruits).

2.3. Experimental Set-Up for Coating of Fruits

The coating equipment, which was pre-designed, custom fabricated, and evaluated by Maftoonazad [19], was used for coating of lime fruits (Figure 1). The equipment consisted of a hopper filled with the coating emulsion and had prongs to direct the fruits from the hopper to the dryer. Two dividers partitioned the hopper into three parts to stop the fruit from piling up. A conveyor carried the fruits through the dryer and cooler. The dryer was a tunnel that the conveyor chain passed through, and hot air at 40 °C was blown from a fan mounted on the bottom of it onto the fruits. Underneath the conveyor chain there was a single lattice plate, which by creating a pressure drop, caused a uniform airflow of hot air exhausted from the heater. Two windows were designed on top of the drying tunnel to monitor the samples inside the machine. After drying, the conveyor entered another tunnel where cold air was blown to reduce the product temperature. An electric motor with a power of 0.18 kw was used to drive the device. Table 1 gives some details of the set and calculated parametric values of the coating equipment.

Lime fruits were immersed in the coating emulsion and transferred through the drier and cooler as detailed above. Once coated, the fruits were segregated into six lots and cold stored at different temperatures.
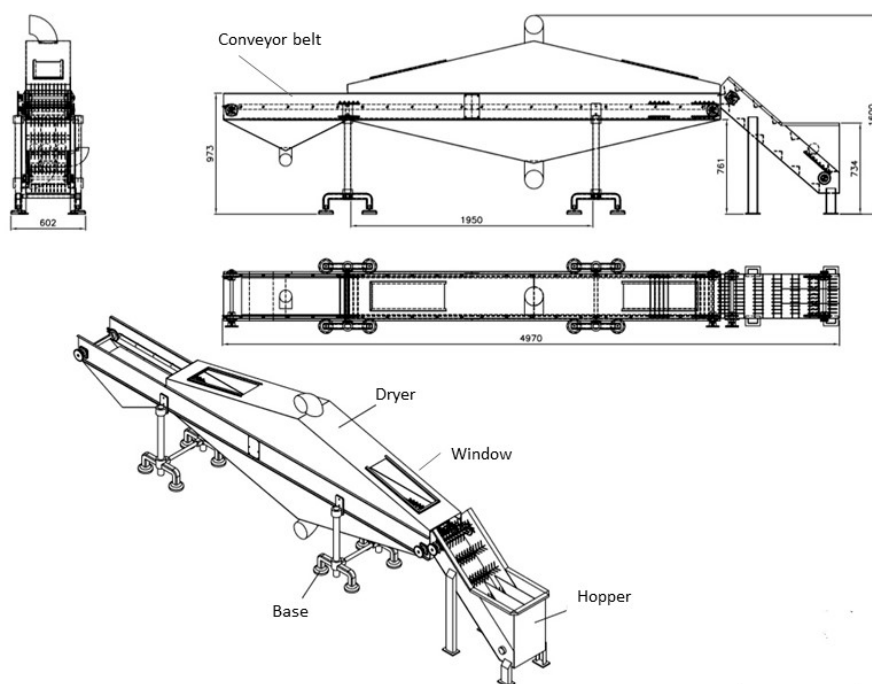

Figure 1. Overview of coating equipment.

Table 1. System configuration.

System Parameter	Parameter Value
Capacity	40 kg/h
Average fruit diameter	4 cm
Conveyor belt in drying section	40 cm × 3.4 m
Conveyor belt in cooling section	40 cm × 0.6 m
Total	40 cm × 4 m
Drying time	960 s
Cooling time	180 s
Conveyor speed	0.2 m/min
Inlet drying air	20 °C and 30% RH
Fresh air flow rate	1083 kg/h (920 m^3/h)
In-flow air	6123 kg/h (5200 m^3/h)
Electric power	9 kw

2.4. Physical and Physiological Characteristics of Lime Fruits

Moisture loss, respiration rate, firmness, and color were measured during storage, as described in our previous work [3].

2.5. Brix, Triable Acidity, and Ascorbic Acid

Titrable acidity and total soluble solids were determined using the method described in a previous study [3]. The ascorbic acid content of lime juice was determined by the 2, 6-dichlorophenol indophenol method [20].

2.6. Kinetic Data Analysis

Kinetic changes in quality characteristics of lime fruits at different temperatures during storage were evaluated either by a zero or first order model and the rate constant (*k*) were determined. The temperature dependence of rate constants were evaluated based on the Arrhenius model as activation energy (E_a). Using the thermal death time models, the associated decimal reduction time (*D*) and *z* were evaluated [3,18].

2.7. Statistical Analysis

For shelf life evaluation, the experiments were designed according to a factorial test in the form of a completely randomized design, with two main factors of storage temperature and time. Each experimental unit consisted of a plastic tray. The data output consisted of respiration rate, weight loss, color, brix, acidity, ascorbic acid, and firmness. A statistical package (SAS Institute Inc., Cary, NC, USA, version 8.0, 2000) was used for ANOVA analysis using PROC GLM. Duncan's multiple range test was used to compare the mean values for different storage days. Each experiment was conducted three times.

3. Results and Discussion

3.1. Overall Acceptability

Consumer acceptability of lime fruits was evaluated subjectively from visual quantification of loss in green color and progression toward yellow and final appearance of brown spots on the lime peel (Figure 2). The acceptable shelf-life of lime fruits were estimated to be 8, 25, and 32 days at 25, 15, and 10 °C, respectively, for control samples and 13, 32, and 40 days for the coated limes.
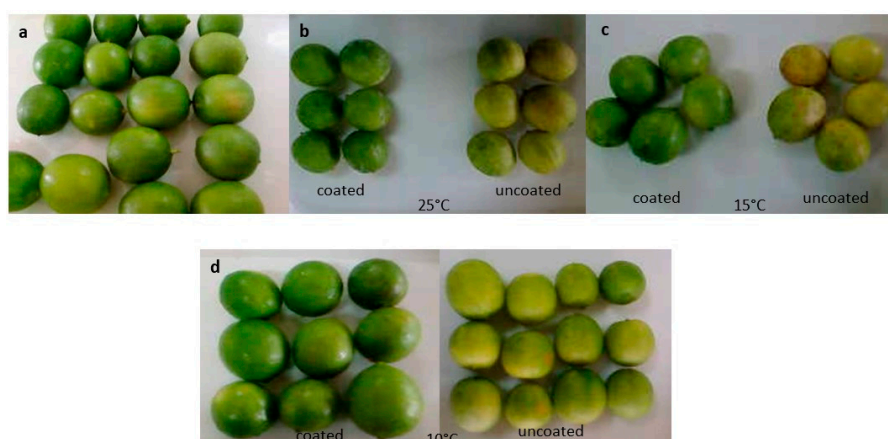
Figure 2. Photographs of lime samples: (**a**) day 1; (**b**) day 8; (**c**) day 25; and (**d**) day 32.

3.2. Respiration Rate

The changes in respiration rate of stored limes with storage times at different temperatures are shown in Figure 3. With the progression of storage time, all test samples showed a declining trend in respiration rate. Also respiration rates associated with higher temperature were higher. Statistics showed significant differences between test samples that were coated versus uncoated, and with respect to different storage temperatures. Peak CO_2 evolution rates of 150.7, 91.5, and 49.0 mL/(kg·h) were observed in control, while for coated limes, the peak values were 131.5, 52.6, and 18.8 mL/(kg·h). Thus, the respiration rate was effectively controlled by use of the pectin-based coating. Surface coating can modify the internal atmosphere of the fruit, thereby delaying senescence. Elevation of CO_2 level in the environment up to about 5% leads to a reduction in respiration rate [4]. Low O_2 together with high CO_2 can synergistically suppress the C_2H_4 biosynthesis. Generally, the kinetic behavior of respiration rate has been associated with a first order or semi-logarithmic kinetic model [18]. Similar results for respiration rate for coating with pectin-based edible films has been reported for mango and cucumber [16,17], strawberry [21,22], and raspberry [23].
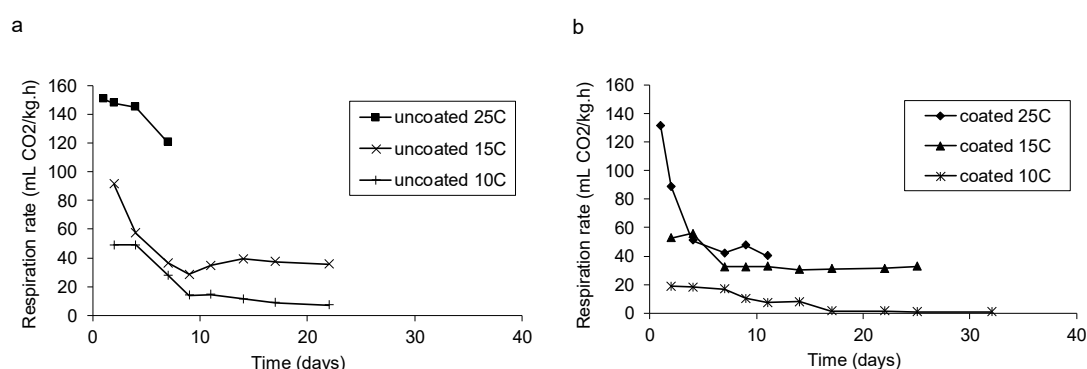

Figure 3. Respiration rate of (**a**) uncoated and (**b**) coated limes at different temperatures.

3.3. Weight Loss

Weight loss values as influenced by the length of storage at different temperatures are shown Figure 4 for both coated and control limes. Weight loss during storage under various conditions accounted for 16%–39%. Coating contributed significantly ($p < 0.05$) to reducing the associated weight loss under each storage condition. While uncoated fruits had 20%–34% weight loss during 8–32 day storage at 10–20 °C, the coated limes lost only 12%–17%. At 25 °C, large weight loss, produce shriveling, and spoilage reduced the shelf life to less than 8 days. Weight loss is a vapor diffusion process driven by the water vapor pressure gradient and the skin resistance. Coating adds an additional barrier to

the vapor diffusion and helps to reduce the weight loss. These concepts have also been considered in several previous studies as being responsible for the weight loss in produce during storage. Produce respiration can also lead to some small loss in weight [24]. The weight loss in limes during storage was well fitted to a linear zero order model and the calculated rate constants are summarized in Table 2. The rate constant (k) increased with storage temperature, and was 1.7 to 2.1 times higher in control as compared to coated limes. The associated activation energies (Arrhenius model) are also summarized in Table 2, indicating high R^2 values. These results were in agreement with those of weight loss in avocado fruit [3].
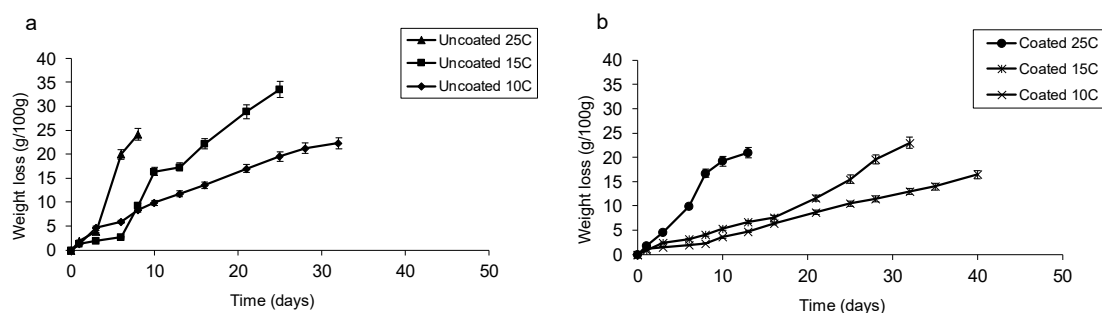

Figure 4. Weight loss in (**a**) uncoated control and (**b**) coated limes during storage at different temperatures.

Table 2. Kinetic parameters for weight loss of coated and uncoated limes stored at different temperatures.

Storage Temperature (°C)		k Value (day^{-1})	R^2
10	coated	0.411	0.995
	uncoated	0.692	0.981
15	coated	0.680	0.969
	uncoated	1.42	0.971
25	coated	1.77	0.969
	uncoated	3.25	0.949
Other Kinetic Parameters			
E_a = 70.6 kJ/mole (uncoated)		E_a = 68.3 kJ/mole (coated)	

3.4. Color Changes

Figure 5 shows the effect of storage on color parameters of control and coated limes under different conditions. All associated color parameters increased with storage time at each temperature. Figure 5a,b compares the *L* value of coated versus control, showing a more rapid increase in the *L* value with the control as compared the coated samples. Since *L* is an indicator of the lightness–darkness axis, this enhancement of value is demonstrated by the loss in darker green color and a simultaneous appearance of the lighter yellow color. Statistical analysis showed the storage effects of coating on *L* values to be significant ($p < 0.01$) at each temperature. However, the coated samples at 15 °C behaved somewhat similarly to the control samples at 10 °C ($p > 0.05$). Again, the rate of increase was higher at elevated temperatures.

Test results showed that *a** values were more negative and the coated limes were greener (Figure 5c–e, $p < 0.01$) than the control samples. The *a** value shifting from negative to positive generally indicates the loss in greenness of samples, which is obviously the result of ripening. Fruits stored at higher temperature showed more rapid changes in *a** value. The color *b** value showed a similar pattern demonstrating significant ($p < 0.01$) increases with temperature and differences between control and coated samples (Figure 5e,f). Finally, Figure 5g,h shows changes associated with ΔE, the total color difference, which comes from the combined effect of all three previously described color parameters. The results were similar. The total color difference ΔE has been extensively used in food research involved with fruit ripening. Overall, it is recognized that both coating and storage at lower

temperature had a significant beneficial effect on delaying the ripening and extending the shelf life. Similar results have been reported with the application of aloe vera gel on papaya [25], pectin on cucumber [16], chitosan on sweet pepper [26], and pectin on fresh cut persimmon [9]. The lower rate of color change in coated fruits may be related to the effect of coating in creating modified atmospheres within the fruit. The lowering of O_2 and elevation of CO_2 in the storage atmosphere has already been demonstrated to be beneficial in preventing chlorophyll degradation [13,16].
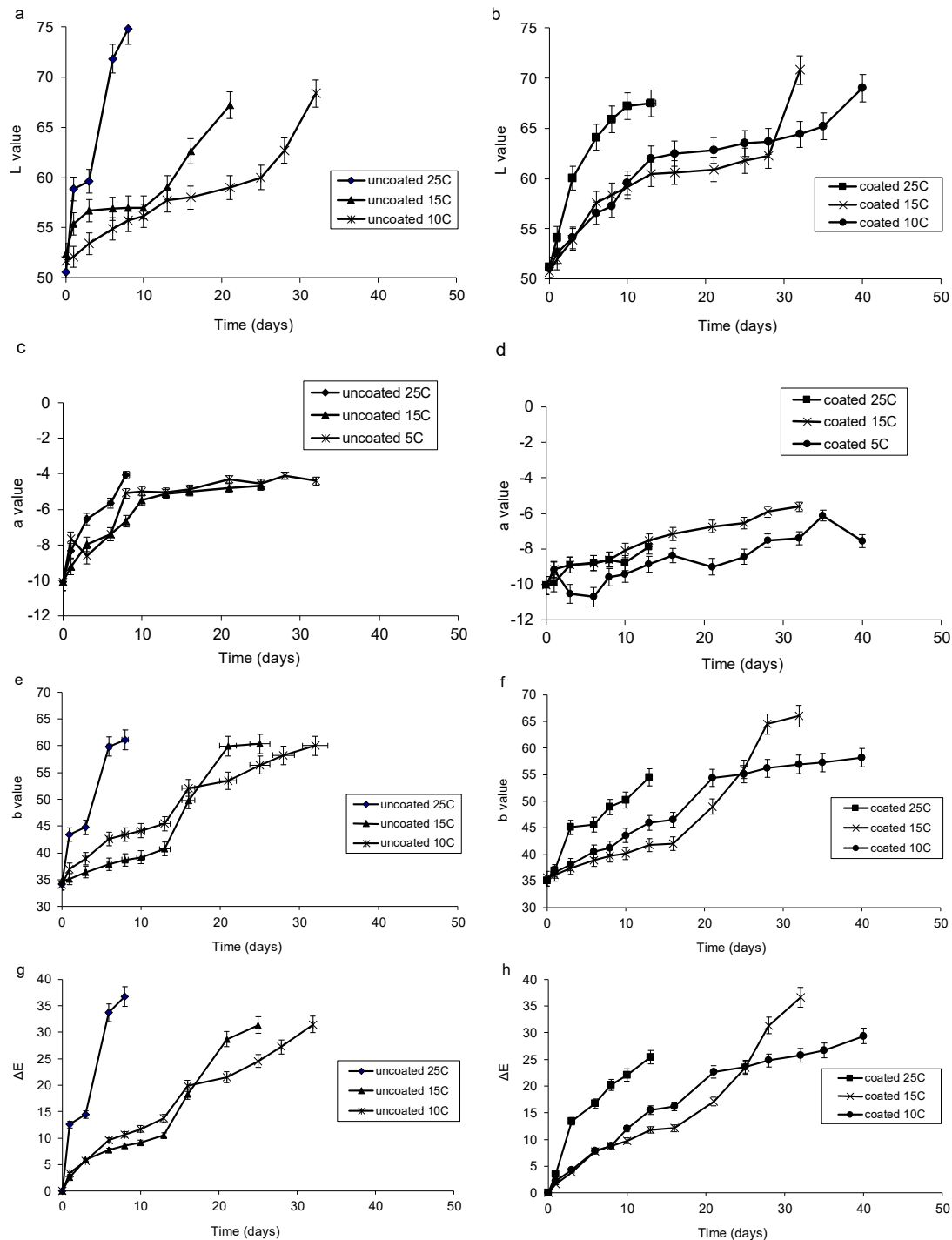

Figure 5. *L* value (**a**, **b**), a value (**c**, **d**), b value (**e**, **f**), and Δ*E* value (**g**, **h**) of uncoated (control) and coated limes during storage at 10–25 °C.

In terms of modeling color changes in lime fruit as influenced by coating and storage temperature, a zero-order model was used for *a** and Δ*E*, and a first-order model was used for *L** and *b** values. Table 3 summarizes the derived kinetic parameters. These results indicate that *D* values related to changes in the *L* parameter increased at 45, 58, and 59 days at 10, 15, and 25 °C as a consequence of the coating process in lime fruits. The rate of increasing yellowness in uncoated samples decreased from 0.017, 0.024, and 0.0691 (day^{-1}) to 0.013, 0.0195, and 0.0317 (day^{-1}) by coating of the fruits at 10, 15, and 25 °C, indicating the higher effectiveness of the coating process at higher temperatures. Such models have been demonstrated in several different studies with fruit products—concentrated tomato paste [27], peach puree [28], and kiwi fruit [29].

Table 3. Kinetic parameters for color changes of coated and uncoated limes stored at different temperatures.

Storage Temperature (°C)	Parameter	Zero-Order Model		First-Order Model		
		K_0 (day^{-1})	R^2	K_1 (day^{-1})	D (day)	R^2
10	Coated					
	L	–	–	0.00625	369	0.872
	a	0.0921	0.883	–	–	–
	b	–	–	0.0133	173	0.931
	Δ*E*	0.731	0.950	-	–	–
	Uncoated					
	L	–	–	0.00712	324	0.838
	a	0.167	0.853	–	–	–
	b	–	–	0.0167	137	0.951
	Δ*E*	0.908	0.982	–	–	–
15	Coated					
	L	–	–	0.00757	304	0.935
	a	0.126	0.965	–	–	–
	b	–	–	0.0195	117	0.941
	Δ*E*	0.994	0.879	–	–	–
	Uncoated					
	L	–	–	0.00936	246	0.903
	a	0.221	0.874	–	–	–
	b	–	–	0.0240	96.0	0.903
	Δ*E*	1.22	0.943	–	–	–
25	Coated					
	L	–	–	0.0212	109	0.854
	a	0.149	0.899	–	–	–
	b	–	–	0.0317	72.5	0.897
	Δ*E*	1.90	0.915	–	–	–
	Uncoated					
	L	–	–	0.0458	50.3	0.927
	a	0.673	0.935	–	–	–
	b	–	–	0.0691	33.3	0.907
	Δ*E*	4.42	0.940	–	–	–
Other Kinetic Parameters						
	L	E_a = 128.9 kJ/mole (uncoated); R^2 = 0.864		E_a = 84.7 kJ/mole (coated); R^2 = 0.871		
	a	E_a = 96.3 kJ/mole (uncoated); R^2 = 0.900		E_a = 32.9 kJ/mole (uncoated); R^2 = 0.963		
	b	E_a = 97.9 kJ/mole (uncoated); R^2 = 0.930		E_a = 59.9 kJ/mole (uncoated); R^2 = 0.997		
	Δ*E*	E_a = 110 kJ/mole (uncoated); R^2 = 0.889		E_a = 65.9 kJ/mole (uncoated); R^2 = 0.963		

3.5. Chemical Changes

3.5.1. Ascorbic Acid

Ascorbic acid content decreased during storage and this reduction was more rapid at higher temperature, as expected (Figure 6). The coating was effective for better retention of ascorbic acid. The higher ascorbic acid retention following coating treatment can be attributed to the ability of coating as a gas barrier to reduce the O_2 tension in the fruit tissue [30]. Mahajan, Dhillon, and Kumar [31] found that chitosan coating significantly minimized the loss of ascorbic acid following 3 months of storage at 4 °C and 80% RH. The atmosphere composition around the fruit has a significant role in ascorbic acid retention. Ascorbic acid loss was increased by higher concentration of O_2. More recently,

Mditshwa et al. [30] reported that lower respiration rate and ethylene production in fruits improved vitamin C retention.
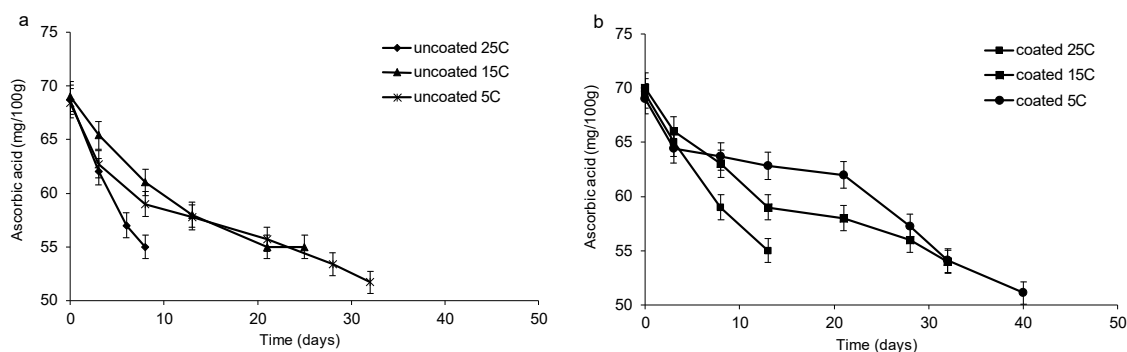

Figure 6. Changes in ascorbic acid content of (**a**) uncoated and (**b**) coated limes during storage at different temperatures.

Ascorbic acid loss was more pronounced under higher temperatures than under refrigerated storage conditions. In agreement with results of this study, Qiu and Wang [32] reported that vitamin C in "Satsuma" mandarins stored at 4 °C was much higher compared to those stored at 20 °C. Moreover, vitamin C of coated and uncoated limes decreased as the storage duration increased. Another study [33] demonstrated a better vitamin C retention in "Blood Red" sweet oranges stored at 10 °C than those stored at 5 or 20 °C, which is almost similar to those found in this experiment. Fruit stored at 10 °C lost vitamin C at a rate of 0.00667 and 0.00741 per day for coated and uncoated limes, respectively, whilst those stored at 15 and 25 °C had a rate of 0.00907 and 0.0281 per day for uncoated limes and 0.00727 and 0.0180 per day for coated samples (Table 4). The storage of limes at 10 °C also led to decreased incidence and prevalence of contamination.

Table 4. Kinetic parameters for ascorbic acid changes of coated and uncoated limes stored at different temperatures.

Storage Temperature (°C)		K_1 Value (day^{-1})	D (day)	R^2
10	coated	−0.00667	343	0.933
	uncoated	−0.00741	317	0.912
15	coated	−0.00727	313	0.939
	uncoated	−0.00907	254	0.933
25	coated	−0.0180	128	0.991
	uncoated	−0.0281	82.0	0.987
Other Kinetic Parameters				
E_a = 92.2 kJ/mole (uncoated) R^2 = 0.868			E_a = 68.7 kJ/mole (coated) R^2 = 0.822	

3.5.2. Brix to Acidity Ratio

The initial total soluble solids (TSS value) in the lime fruit on average was 10.5 ± 0.1 °Brix, and during the storage days it increased progressively. In general, the TSS demonstrated an increasing trend, which was slower with coated fruits as compared to the control. After 28 days of storage, TSS maximum in the control at 10, 15, and 25 °C was 12.3, 11.5, and 12.3 °Brix after 8, 25, and 32 days, respectively, while the maximum TSS in coated samples were 12.7, 12.1 and 11.5 °Brix, respectively, under the same storage conditions. Most of these differences were statistically significant ($p < 0.05$). Increased TSS in control may be due to accumulation of different solutes in vacuoles of cells as a result of the normal respiratory and physiological process of fruit ripening, which hydrolyses starch into sugars. The reason for the slower rate of TSS increase in coated samples is obviously due to the slowing

down of the respiratory and physiological ripening activity. These results are in line with the findings of Yimenu, Abera, and Solomon [34].

The initial value of acidity (TA) ranged from 10% to 11.5% and it showed a decreasing trend throughout the storage period for all treatments. The reduction of TA in all treatments during the storage period is in line with the normal course of the ripening of fruit. Coating treatment preserved significantly ($p < 0.05$) higher TA for storage periods. This may be due to the reason that the coating treatment results in less O_2 being available for the respiratory process, and may therefore delay the utilization of organic acids [35,36].

In general, the titrable acidity decreased and °Brix increased during storage for both control and coated limes, and the associated change rates were higher at higher temperatures (Figure 7). These values of concentrations of acid and sugars will be influenced to some extent by weight loss factor, which affects the residual weight of lime fruits (however, the ration would be influenced less because it is a factor that would appear in both the numerator and denominator of the °Brix/acid ratio). The °Brix/acid ratio was significantly influenced in respect to both coating and storage at different temperatures. The associated rate constants for these parameters are summarized in Table 5. It should be noted that the *k* values for titrable acidity was for reduction, while that of soluble solids was for accumulation. The *D* value, which is reciprocally related to *k*, decreased by increasing the temperature of storage, while the *D* values of coated limes were higher than those of control fruits. The activation energy for changing Brix to acid ratio in control fruits was much higher than that of coated ones.
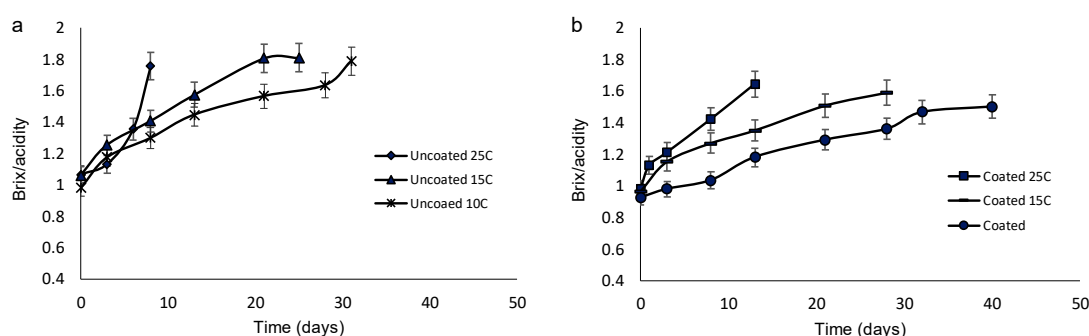

Figure 7. Changes in brix/acidity ratio of (**a**) uncoated and (**b**) coated limes during storage at different temperatures.

Table 5. Kinetic parameters for brix/acidity changes of coated and uncoated limes stored at different temperatures.

Storage Temperature (°C)		k_1 Value (day^{-1})	D (day)	R^2
10	coated	0.0143	160	0.957
	uncoated	0.0152	152	0.977
15	coated	0.0164	141	0.915
	uncoated	0.0206	111	0.957
25	coated	0.0360	64.0	0.953
	uncoated	0.0604	38.0	0.887
Other Kinetic Parameters				
E_a = 99.3 kJ/mole (uncoated)			E_a = 59.8 kJ/mole (coated)	
R^2 = 0.930			R^2 = 0.825	

3.6. Firmness

Fruits ripen during storage, and hence tend to become softer. Therefore, the firmness of lime fruits decreased with time and temperatures of storage for both control and coated limes (Figure 8). The changes were slower at lower storage temperatures, as well as in coated fruits ($p < 0.05$). The firmness value of the control lime at the end of storage (day 8) at 25 °C was 7.21 N, while the

firmness in coated fruits was 12.2 N. After the same duration, the firmness in control and coated samples at 15 and 10 °C were 13 and 19 N, respectively. No difference was observed between the firmness of coated samples stored at 15 and 10 °C. In coated fruits, during fruit ripening, a decrease in pectin-estrase and polygalactronase activities is generally observed due to low oxygen and high carbon dioxide concentration regime; therefore, degradation of insoluble protopectins to the more soluble pectic acid and pectin may be retarded, allowing firmness retention. In previous studies on pectin coated avocados [3,13], a similar effect was observed. The textural softening of avocados during storage was found to follow a first-order kinetic model ($R^2 > 0.94$) (Figure 8). The evaluated kinetic parameters are summarized in Table 6. *D* values decreased and *k* values increased at higher temperatures. The associated activation energies (E_a) calculated from the regression of *k* values versus reciprocal absolute temperature are also summarized in Table 6.
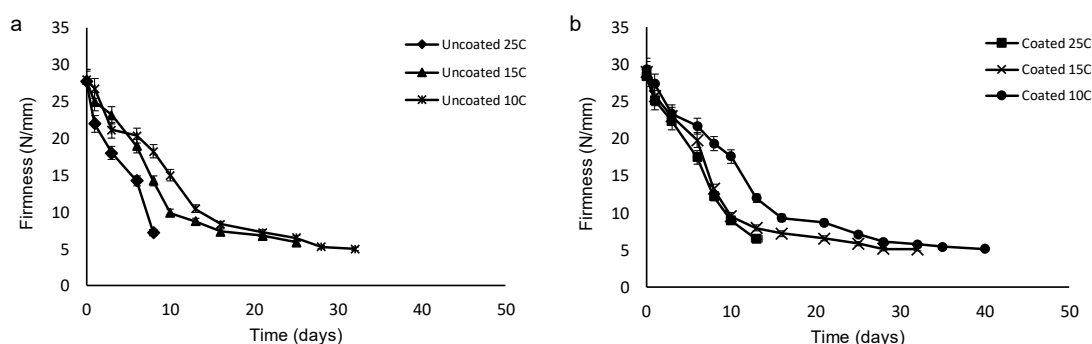

Figure 8. Changes in firmness of coated and uncoated limes during storage at different temperatures.

Table 6. Kinetic parameters for firmness changes of coated and uncoated limes stored at different temperatures.

Storage Temperature (°C)		k_1 Value (day^{-1})	D (day)	R^2
10	coated	−0.0475	49.0	0.951
	uncoated	−0.0574	40.1	0.964
15	coated	−0.0568	41.0	0.903
	uncoated	−0.0670	34.0	0.925
25	coated	−0.115	20.0	0.980
	uncoated	−0.147	16.0	0.923
Other Kinetic Parameters				
E_a = 65.3 kJ/mole (uncoated)			E_a = 60.9 kJ/mole (coated)	
R^2 = 0.835			R^2 = 0.859	

The edible coating maintained the firmness by limiting the rapid respiration and transpiration rates, which are the primary physiological activities involved in depleting storage reserves. Edible coating directly affects fruit firmness by delaying the ripening process and decreasing the activity of cell wall degrading enzymes [36–38].

4. Conclusions

To evaluate the effectiveness of an edible coating applied on fruits and vegetables, quality parameters of coated products are usually measured as indicators. This study confirmed that coating of fruits in combination with lower storage temperature helps to slow down the ripening and related physico-chemical, color, and texture quality parameters.

The fruit became softer and lost its green color during storage. All physico-chemical changes were accelerated at higher temperatures and retarded by coating. Hence, the combination is effective and often creates synergistic effects. The storage-associated changes were successfully modeled by zero or first-order kinetic models. The temperature sensitivity of rate constants were adequately described

by the Arrhenius relationship. Validation of these models under scale-up conditions for coating and storage can facilitate the prediction of fruit behavior during storage at the commercial scale.

Results of this study confirmed that by using pectin-based coating on lime fruit, food producers will profit from higher manufacturing quality with longer shelf life, retailers will benefit from lower refrigeration costs, ease of handling, and improved product safety, and the consumer will benefit from a safe product in an edible package with no plastic waste for disposal. The concepts can easily be adopted to other fruits and vegetables. The ability to store and display food at ambient temperatures combined with longer storage times will generate economic savings for food retailers by reducing the need for regular stocking, reducing the capital plant and energy costs of refrigeration, and also, the associated "food miles", hence reducing the carbon footprints associated with transportation costs.

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