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Delayed Cooling or Suboptimal Storage Temperatures Reduce Butterhead Lettuce Shelf-Life

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Crated or uncrated butterhead lettuce (*Lactuca sativa* L.) var. Lores responds to environmental conditions during early postharvest, the first 24 h after harvest. The present work examines the effects of environmental conditions during early postharvest on quality indices in refrigerated storage. Additionally, effects on shelf-life were estimated using the modified Global Stability Index methodology. Quality indices at the start of storage were higher for heads exposed to optimal conditions immediately after harvest than for heads exposed to suboptimal ones. Despite these initial differences, changes in almost all quality indices were independent of storage condition. Similar responses were found for water content, bound and free water, ascorbic acid, total chlorophyll, and overall visual quality. Changes in relative water content and mesophilic bacteria counts during refrigerated storage were a function of environmental condition during the first 24 h after harvest. Maintenance of optimal environmental conditions during the first hours after harvest prolonged shelf-life to 12 days compared to heads exposed to suboptimal conditions during the early postharvest period. These results impact marketing of the produce and support the idea that proper handling during early postharvest diminishes quality loss and prolongs shelf-life, allowing butterhead lettuce to reach more distant markets.

Keywords Cold chain, Early postharvest, Leafy vegetables, Quality.

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Fresh vegetables constitute a source of minerals, vitamins, antioxidants, and dietary fiber (Kader, 2002b). Consumers are aware of the importance of maintaining a diet rich in vegetables, and their consumption has increased. The stability of fresh products depends on type of vegetable, production process, maturity at harvest, environmental conditions after harvest, and others, but temperature is the critical postharvest factor affecting shelf-life (Kader, 2002a; Paull, 1999; Zanoni et al., 2007). Poor handling conditions without temperature control, often encountered during distribution from farm to consumer, are causes of deterioration in vegetable appearance, quality, and nutritional value (Moreira et al., 2006). When vegetables are obtained by consumers at the point of purchase, a large part of their initial nutritional value may have been lost, even though the appearance is still acceptable.

Butterhead lettuce (*Lactuca sativa* L.), var. Lores, is a popular vegetable worldwide. Studies have been conducted on how lettuce shelf-life is affected by postharvest procedures such as refrigeration under different environmental conditions (Ares et al., 2008; Del Nobile et al., 2006; Jamie and Saltveit, 2002; Mattos et al., 2007; Mónaco et al., 2005), washing with different solutions (Delaquis et al., 1999; Esparza-Rivera et al., 2006; Ihl et al., 2003; Martín-Diana et al., 2005; McKellar et al., 2004), heating (Martín-Diana et al., 2005, 2007; Saltveit, 2005; Saltveit and Qin, 2008), application of antimicrobials (Randazzo et al., 2009), application of irradiation (Niemira, 2008; Zhang et al., 2006), and ultrasonication (Ajlouni et al., 2006). Most of those studies used fresh lettuce heads, and different treatments were applied immediately after harvest. However, few studies consider real management conditions in the supply chain (use of wooden crates, fluctuation of environmental conditions, and delay in reaching optimal temperature) before application of those procedures.

Under commercial practices in the period between harvest, storage, and distribution (early postharvest), heads are transported from producer to distribution center, often 20–24 h away. Once in the distribution center, heads are stored at optimal conditions until made available for retail sale. If environmental conditions during early postharvest are suboptimal, quality degradation occurs regardless of refrigeration in the distribution center.

A description of changes occurring in quality of lettuce heads packed in wooden crates exposed during 24 h at optimal or suboptimal handling conditions was done (Agüero et al., 2012). The effect of placement of lettuce within the crate was also analyzed. Lettuce heads were packed with 21 plants distributed in three layers (lower, middle, and upper). When environmental conditions are the best recommended for butterhead lettuce (0–2°C, 97%–99% relative humidity [RH]), a temperature profile develops inside the crate that slows down heat transfer. Cold temperature is achieved between 5 to 16 h depending on placement of product within the crate, and this cooling delay negatively impacts quality indices compared to uncrated heads (Agüero et al., 2012). In addition to the temperature effect, the wooden crate system causes mechanical damage to tissue due to pressure exerted on lettuce heads during placement in the wooden crate. When environmental conditions are suboptimal, respiration and transpiration of lettuce in crates permits development of a saturated atmosphere. Proximity of heads constitutes a physical barrier against low relative humidity. However, crated lettuce heads exposed to suboptimal conditions had bigger quality losses than crated heads exposed to optimal conditions. Weight losses of 10% to 35% occurred in the first 24 h after packing for crates stored under optimal and suboptimal conditions, respectively (Agüero et al., 2012). These losses have economic impact for producers and distributors. However, the effects of handling during the first hours after harvest on lettuce shelf-life were not determined. To assess this, the impact of 24 h of exposure of lettuce crates to optimal or suboptimal conditions on lettuce quality during storage was examined. In addition, the effects of lettuce quality during refrigerated storage was examined.

MATERIAL AND METHODS

Plant Material and Sample Preparation

Heads of butterhead lettuce were grown in Sierra de los Padres, Mar del Plata, Argentina. Lettuce heads were harvested after reaching a marketable size (approximately 24–30 leaves and 260 g per head) and immediately transported to the laboratory. Eight plants were analyzed in the first hour after harvest to evaluate the initial lettuce quality status. Other plants were not subjected to any preconditioning; they were individually weighed and placed in a wooden crate following the protocol used in commercial practice (Figure 1). A layer of six lettuce heads (lower layer) was placed at the bottom of the crate with the cut end upwards. The next six heads, forming the middle layer, were placed above the first one. The assembly of the crate was completed by placing nine heads with the same orientation, forming the upper layer. During the early postharvest period, the first 24 h after harvest, two crates were exposed to optimal conditions (0–2°C, 97%–99% RH), and two were exposed to suboptimal conditions (20–22°C, 60%–62% RH, typical for lettuce management).

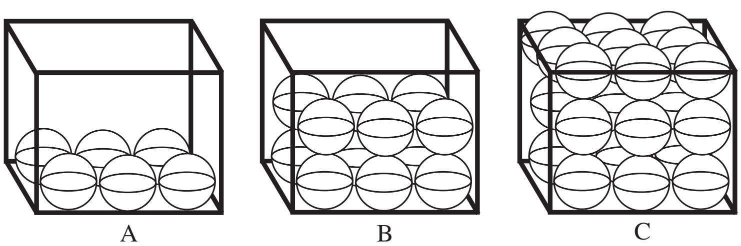

Figure 1: Schematic representation of crate assembly with (A) six lettuce heads in the lower layer, (B) six lettuce heads in the middle layer, and (C) nine heads in the upper layer.

Two environmental chambers (SCT, Pharma, Buenos Aires, Argentina) were used. Temperature and relative humidity were recorded from different locations inside crates to evaluate changes in the space around plants. For this purpose, two data acquisition systems were used: Testostor 175-H1 (TESTO, Buenos Aires, Argentina) and EASYLOG (Lascar Electronics, Buenos Aires, Argentina).

After 24 h, crates were disassembled and lettuce heads were individually weighed. Two heads from each layer were used to evaluate effects of environmental conditions during early postharvest. Other heads were stored at optimal conditions recommended for lettuce (0–2°C and 97%–99% RH), simulating a distribution center storage following Agüero et al. (2008). Two lettuce heads were put in polyethylene bags (28 × 55 cm, useful volume 4 L) with an O_2 permeability of 600 $cm^3/m^2{\cdot}d^{-1}$, CO_2 permeability of 4000 $cm^3/m^2{\cdot}d^{-1}$, and water vapor permeability 4 $g/m^2{\cdot}d^{-1}$. Bags were sealed and stored in a refrigerated chamber at 0–2°C (GAZA, Buenos Aires, Argentina). This storage allows development of optimal conditions recommended for lettuce. Below these conditions, respiration rate, ethylene production, and other physiological changes were minimized (Kader, 2002b; Rinaldi et al., 2010).

Postharvest shelf-life was evaluated at 7, 14, and 21 days of storage to determine changes in quality indices during storage. At each sampling, three plants were used to determine water status and three for other quality indices. To avoid the effects of layer in which the head had been located in the crate during the early postharvest period, a head from each layer was used in the groups of three. The experiment was replicated three times.

Weight Loss

Weight loss was determined in all lettuce heads after the early postharvest period. Each head was weighed after harvest when it arrived at the laboratory (W0) and again after 24 h (W24). Weight loss (WL) of each individual head was calculated (Agüero, Ponce, Moreira, and Roura, 2011). After W24 data were collected from stored heads. Broken and/or deteriorated leaves were removed from heads and an additional weight was taken (W24w, weight after waste disposal) and weight loss after discards made (WLd) was calculated to determine this new weight. The WL and WLd were expressed as percentages with respect to fresh initial weight. WL and WLd mean values were calculated for each layer.

Quality Indices

Quality was evaluated through physiological (water status: water content, WC; relative water content, RWC; free water, FW; bound water, BW; and the free water–to–total water ratio (FW/TW)); microbiological (mesophilic bacteria count, MBC); nutritional (ascorbic acid [AA] content); physicochemical (chlorophyll content, TC), and overall visual quality (OVQ) indices.

To determine water status, all leaves of each head were used following Viacava et al. (2011). Data from leaves were pooled and the mean was determined. To evaluate the other quality indices, three lettuce heads where subjected to a sensory panel to assess organoleptic quality and then heads were cut transversally in 2-cm portions and mixed, taking two samples from each head. The TC was determined using the methodology of Moreira et al. (2005); AA was determined following Roura et al. (2001), and MBC was evaluated with the method of Ponce et al. (2002). The OVQ was evaluated following Agüero, Moreira, Goñi, and Roura (2011). Mean values for each head were used to calculate the crate layer mean.

Global Stability Index Modified Methodology

Shelf-life modeling was with the method of Achour (2006) as modified by Ansorena et al. (2009). All quality indices (RWC, WC, FW, BW, FW/TW, AA, TC, and MBC) were considered in groups of four, producing formation of 70 tetrads. For each tetrad, the global stability index (GSI) was calculated as a function of time and correlated with OVQ.

Using the initial value of index i (C_{i0}), the value at time j (C_{ij}), the threshold value (L_i) for the index, and the weighting factor (α_i) for the index, the variation (V_{ij}) and the GSI_j were calculated with equations of Ansorena et al. (2010).

Values of L_i and α_i for each quality index were established with the method of Ansorena et al. (2009). All indices were correlated with OVQ using a linear model. The threshold value for each index was determined using the correlation with OVQ = 5 (acceptability limit). Weighting factors for each index within each tetrad were established as a function of the Pearson coefficient obtained from the correlation analysis performed between these indices and the OVQ.

Once GSI was calculated as a function of time for each tetrad, the correlation between GSI and OVQ was evaluated. The tetrad with the highest correlation coefficient was selected as best representing lettuce stability. The GSI obtained with this tetrad was modeled with the general kinetic equation, with parameters n (reaction order) and k (constant rate).

Statistical Analysis

Data were evaluated with LSMEAN values (mean values obtained with the least squares method; Kuehl, 2001). Data were analyzed using SAS statistical software (ver. 9.0, SAS Institute, 2002). The general linear model procedure (PROC GLM) was used to carry out the analysis of variance (ANOVA). For all indices, factors used as variation sources were as follows: COND (optimal or suboptimal, environmental condition in the early postharvest period before storage), TIME (days, storage time under optimal conditions), and TIME × COND interaction. Differences were evaluated with the Tukey-Kramer multiple comparisons test. PROC UNIVARIATE was used to validate ANOVA assumptions (Kuehl, 2001). Nonlinear regression fittings were calculated using SYSTAT 5.0 (SYSTAT, 1992). Q5

RESULTS AND DISCUSSION

Weight Loss

There was weight loss in heads during the early postharvest period. Loss was dependent on environmental conditions to which crates were exposed. Heads from crates exposed to optimal conditions had a 2.0 ± 0.4% weight loss; those from crates exposed to suboptimal conditions had a weight loss of 6.0 ± 1.0%. Losses could be related to higher water vapor pressure deficit under suboptimal conditions. This deficit could promote water loss in tissues, frequently the main cause of weight losses in leafy vegetables (Nguyen et al., 2007). When deteriorated or broken leaves were discarded, loss increased to 9.7% ± 3.9% and 34.7% ± 2.9% for plants treated with optimal and suboptimal conditions, respectively, in early postharvest. Tight packing of heads within crates generated greater leaf deterioration and a higher discard.

After being placed in storage there were no differences in weight loss between heads exposed to optimal and suboptimal conditions during the early postharvest period. With the atmosphere close to saturation, high relative humidity, and low temperature, there was low water vapor pressure deficit preventing tissue water loss.

Quality Indices

Analysis of variance (Table 1) indicated that TIME affected all but WC, and RWC; COND affected only WC, RWC and OVQ, and the interaction only affected RWC and MBC.

Table 1: Analysis of variance for WC, RWC, FW, BW, FW/TW, MBC, AA, TC, and OVQ occurring during optimal storage of lettuce heads after exposure to 0–2°C, 97%–99% RH or 20–22°C, 60%–62% RH for 24 h after harvest.

Source	WC	RWC	FW	BW	FW/TW	MBC	AA	TC	OVQ
Time (T)	ns	ns	**	**	**	*	**	*	**
Cond (C)	*	*	ns	ns	ns	ns	ns	ns	**
T × C	ns	*	ns	ns	ns	**	ns	ns	ns

ns, *, **Nonsignificant or significant at $P \leq 0.05$ or $P \leq 0.01$, ANOVA.

Water Status Indices

During early postharvest, heads exposed to optimal conditions did not exhibit changes in WC; heads exposed to suboptimal conditions had WC reductions of 0.9%, mainly due to exposure of upper layer heads to a high water vapor pressure deficit environment (Agüero et al., 2012). During storage under optimal conditions, WC and OVQ were higher for plants stored in early preharvest under optimal conditions than those stored under suboptimal conditions (Table 2). Differences among heads exposed to different conditions in early postharvest were maintained during storage. Under optimal storage conditions, maintenance of water content is a predictable result because lettuce heads were exposed to an essentially saturated atmosphere (Agüero et al., 2008).

Relative water content values (Figure 2), different at the end of early postharvest, were due to environmental conditions to which heads were exposed (Agüero et al., 2012). Decreases in this period were higher in heads from crates exposed to suboptimal conditions (3.9% ± 0.6%) than those exposed to optimal conditions (2.4% ± 0.7%). After placement in storage, RWC

Table 2: LSMean values for WC and OVQ as affected by COND effect.

Condition	WC	OVQ
Optimal	94.65a	7.48a
Suboptimal	93.92b	6.50b

Values in a column followed by the same letter are not significantly different, $P < 0.05$, least squares means analysis.

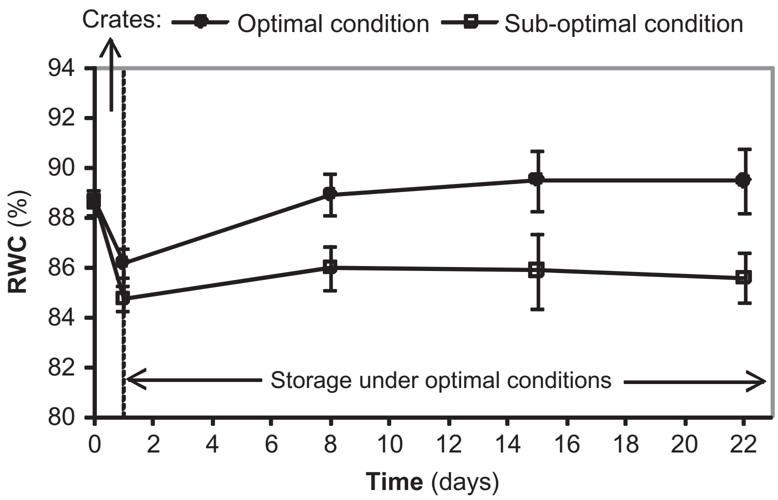

Figure 2: Changes in relative water content in lettuce heads during refrigerated storage after 24 h of exposure to 0–2°C, 97%–99% RH (optimal) or 20–22°C, 60%–62% RH (suboptimal). Vertical dashed lines indicate the end of the early postharvest period, after which crates were disassembled and heads were stored under optimal conditions.

changes between storage conditions were different at each sampling time. Heads exposed to optimal conditions in the early postharvest period exhibited increased RWC until day 14, which then remained constant until the end of storage. Agüero et al. (2008) reported similar results with butterhead lettuce stored under optimal conditions immediately after harvest. However, heads exposed to suboptimal conditions in early postharvest did not change in RWC during storage (there was a significant TIME × COND interaction; Table 1). Because storage conditions applied after the first 24 h were the same for heads exposed to optimal and suboptimal conditions during early postharvest, the different RWC behavior during storage could be attributed to events occurring in tissue during the early postharvest period under different storage conditions. Increases in RWC values could be interpreted as an adaptation response when heads were exposed to optimal environmental conditions, without differences (or with minimum differences) in water vapor pressure between air inside tissues and the environment. Below this threshold, cells are turgid with an RWC value close to 100%. It is probable that the early postharvest exposure to suboptimal conditions generated changes at the cell membrane level that may have limited lettuce tissue response when heads were transferred to a saturated environment. Though there were no detectable WC changes during storage, RWC values exhibited a change in this period. Though WC values indicate variation in water content in tissues, forced by high deficits in water vapor pressure difference, the RWC index can express structural changes in tissues in response to saturation of the environment.

There were no changes in FW in heads during storage due to early postharvest storage condition (Figure 3A). There was a gradual decrease in FW during storage (37% at the end of storage), with no difference between heads exposed to optimal or suboptimal conditions during early postharvest (COND factor was not significant; Table 1). Although there was no change in TWC during storage, FWC was reduced during storage.

Changes in BW content of heads placed in storage after the early postharvest period had a higher increase for heads exposed to suboptimal conditions (19.9% ± 2.3% with respect to the initial value) than heads exposed to optimal conditions (7.4% ± 1.9% with respect to the initial value; Figure 3B) in early postharvest. During storage the interaction did not affect BW from heads stored under optimal conditions, and as in FW, COND was not significant (Table 1), indicating that BW behavior was similar for heads exposed to optimal or suboptimal conditions during early postharvest. The BW in heads treated with optimal or suboptimal conditions in early postharvest increased up to 7 day of storage (72%) and remained constant at that level until the end of storage (Figure 3B). This demonstrated that during storage changes in water status took place.

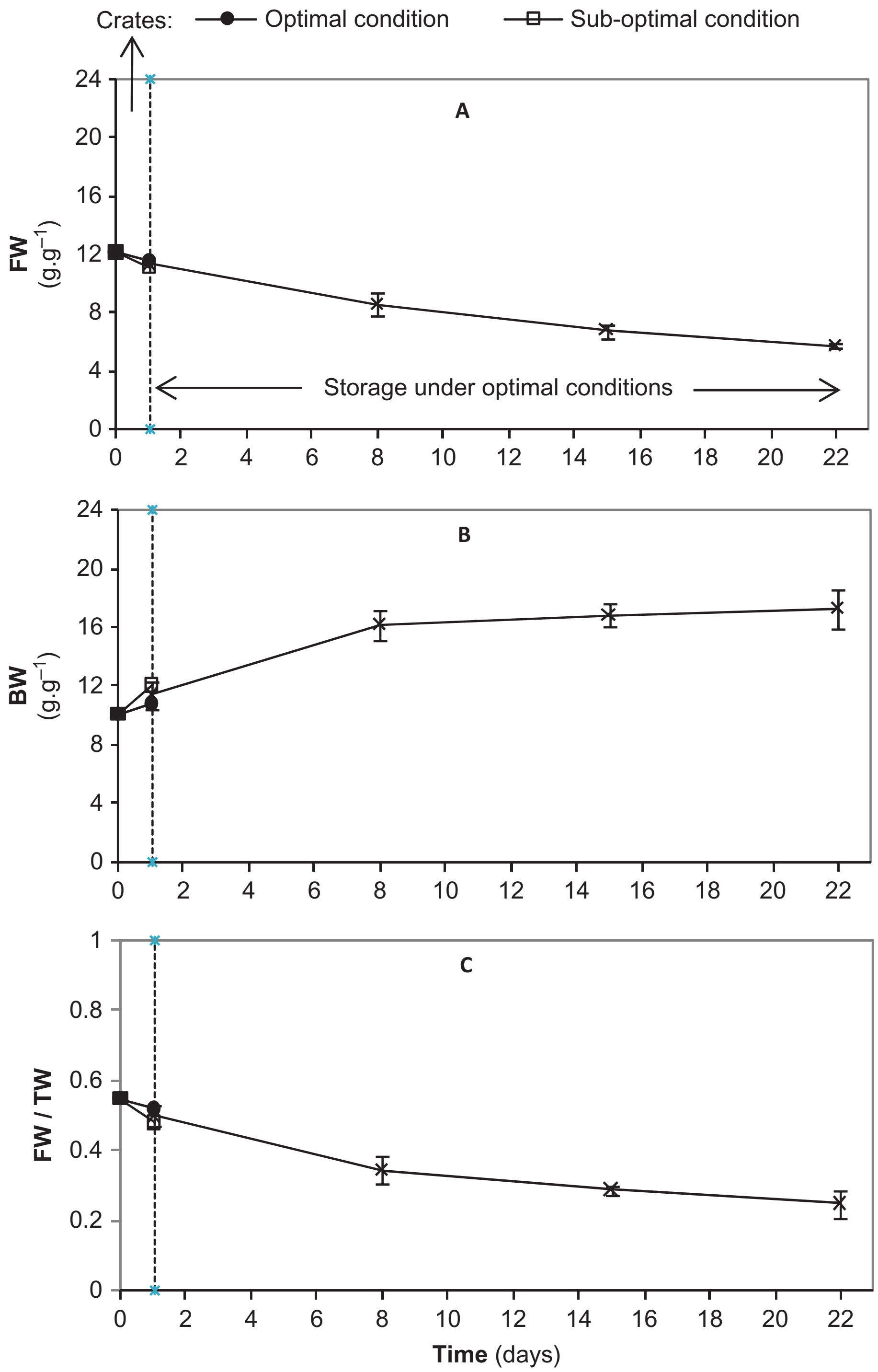

Figure 3: Changes in water status indices in lettuce heads during refrigerated storage after 24 h of exposure to 0–2°C, 97%–99% RH (optimal) or 20–22°C, 60%–62% RH (suboptimal). Vertical dashed lines indicate the end of the early postharvest period, after which crates were disassembled and heads stored under optimal conditions. (A) FW content; (B) BW content; and (C) FW/TW ratio (color figure available online).

Changes in FW/TW occurred in lettuce heads during storage after the early postharvest period (Figure 3C). A decrease was detected for both conditions, with higher values in heads from crates exposed to suboptimal conditions (12.4% ± 1.9% with respect to the value at harvest) than in those exposed to optimal ones (5.3% ± 2.1% with respect to the initial value). This index decreased for heads stored under optimal and suboptimal conditions during early postharvest. The TW was expressed as the sum of FW and BW. This index agrees with WC changes and did not vary due to storage after the early postharvest period (data not shown). Changes in FW and BW during storage indicated changes in water status within the tissue. There maybe an exchange between FW and BW; BW in living tissue is more likely to play a role in tolerance to abiotic stresses (Misik, 2000; Rascio et al., 1998). When heads were harvested and the water supply stopped, cells would link part of their free water as a tissue response to the cut, reducing FW and increasing bound water content.

Mesophilic Bacteria Counts

Mesophilic bacteria counts increased during early postharvest and were 1.5 log higher in heads exposed to suboptimal conditions than those for heads exposed to optimal conditions during early postharvest (Figure 4). This could be attributed to higher temperature under suboptimal conditions, ideal for microbial load development (Agüero et al., 2012). After this initial change, MBC behavior was different during refrigerated storage (significant TIME × COND interaction; Table 1). Heads exposed to suboptimal conditions during early postharvest had microbial counts that decreased during the first 7 days

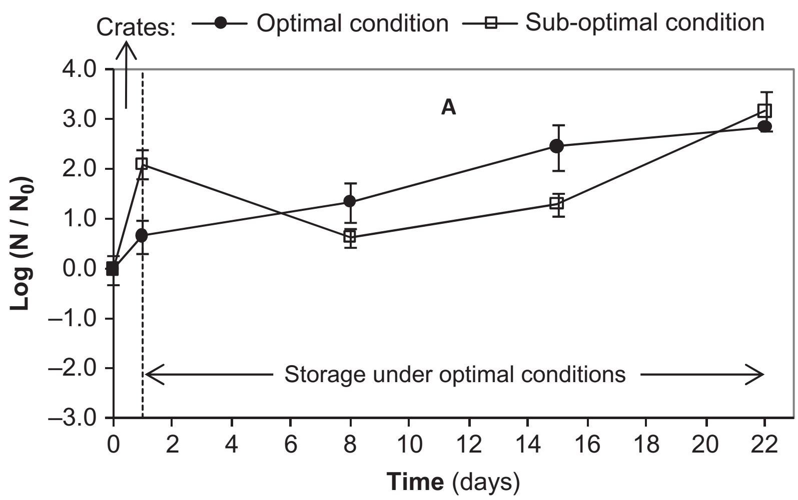

Figure 4: Changes in microbiological index of lettuce heads during refrigerated storage after 24 h of exposure to 0–2°C, 97%–99% RH (optimal) or 20–22°C, 60%–62% RH (suboptimal). Vertical dashed lines indicate the end of the early postharvest period, after which crates were disassembled and heads were stored under optimal conditions.

of storage. After this period, microbial counts gradually increased, reaching the same values (approximately 7.5 log) toward the end of storage as for lettuce heads exposed to optimal conditions in early postharvest. For the latter microbial count, changes were detected from the beginning of storage. This different behavior could be attributed to conditions affecting heads inside crates during the early postharvest period. Heads exposed to suboptimal conditions had a favorable environment for mesophilic bacteria development (high temperature and high relative humidity among heads). Although RH was low outside crates (heads exposed to suboptimal conditions during the early postharvest period), proximity of heads within crates and respiration and transpiration generated an increase in the relative humidity of the air between heads. The wooden crate and the upper layer of heads constituted a moisture barrier (Agüero et al., 2012). When crates were disassembled and heads exposed to optimal refrigerated storage, a thermal shock could have occurred, reducing microbial growth. Heads exposed to optimal conditions experienced a gradual temperature decrease during the first 24 h inside the crate (Agüero et al., 2012) and microorganisms could begin adaptation more quickly. For heads under storage, microflora were not exposed to a thermal shock and could continue development. At the end of storage, microbial counts were similar for heads exposed to optimal and suboptimal conditions during early postharvest with a final increment of 3 log.

The rate of microbial growth during the last days of storage was higher for heads exposed to suboptimal conditions during early postharvest. The conditions during that time likely increased tissue susceptibility for microbial colonization.

Ascorbic Acid Content

The early postharvest period produced changes in head AA content (Figure 5A). Heads exposed to optimal conditions had a 9.9% decrease in AA content just prior to being placed in storage; heads exposed to suboptimal conditions had a 19.0% decrease. Changes in ascorbic acid content during storage were similar for heads regardless of conditions in the early postharvest. Heads had decreases in AA over time in storage, with a 70% reduction in respect to the value at harvest. The AA reduction followed a first-order kinetic (Figure 6A), with a constant degradation rate of 0.053 mg AA/100 g fresh tissue per day. Agüero, Ponce, Bevilacqua, and Roura (2011) reported degradation rates for AA slightly lower for lettuce stored at optimal conditions without a delay in the early postharvest, with a constant rate of 0.043 mg AA/100 g fresh tissue per day. Physical damage to heads during the early postharvest period due to arrangement of heads in crates, together with environmental conditions, could promote tissue senescence, yielding a greater AA degradation.

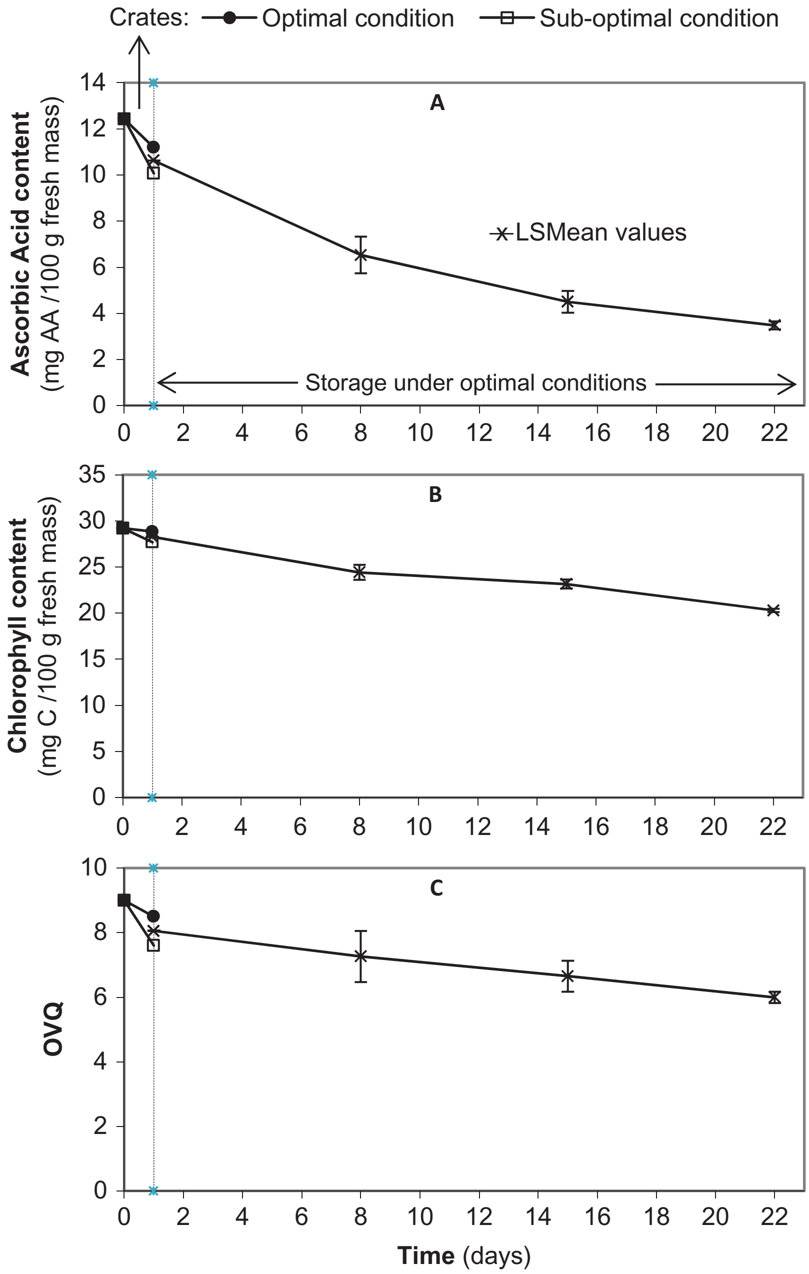

Figure 5: Changes in quality indices of lettuce heads during refrigerated storage after 24 h of exposure to 0–2°C, 97%–99% RH (optimal) or 20–22°C, 60%–62% RH (suboptimal). (A) AA content; (B) TC; and (C) = OVQ. Vertical dashed lines indicate the end of the early postharvest period, after which crates were disassembled and heads were stored under optimal conditions (color figure available online).

Total Chlorophyll Content

Heads under suboptimal conditions during the early postharvest period exhibited a decrease in TC content just prior to being placed in storage; plants exposed to optimal conditions did not produce any change in this index (Figure 5B). A slight decrease occurred in chlorophyll concentration

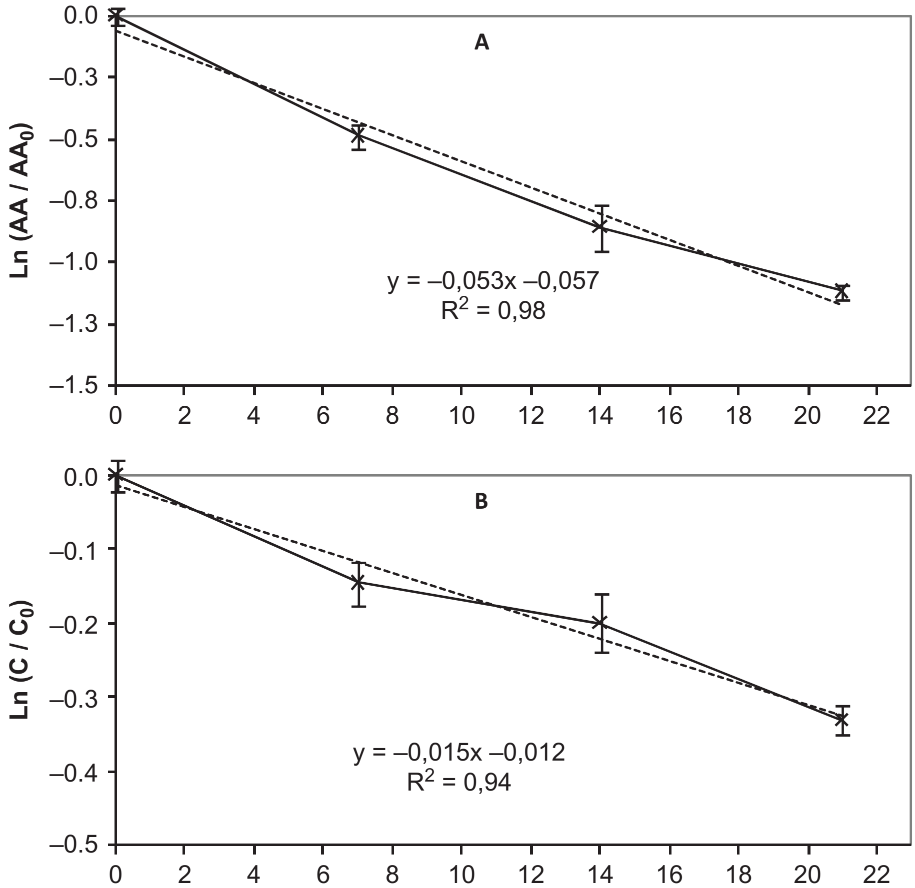

Figure 6: Kinetic response of (A) ascorbic acid and (B) total chlorophyll contents during storage after 24 h of exposure to 0–2°C, 97%–99% RH (optimal) or 20–22°C, 60%–62% RH (suboptimal). For AA and TC deterioration kinetics, only time of refrigerated storage was considered so that time 0 corresponds to the day on which the crate was disassembled and storage under optimal conditions began.

during storage without differences due to condition (only TIME was significant; Table 1), with a final reduction of 30% in chlorophyll content. A first-order kinetic (Figure 6B), with a constant degradation rate of 0.0149 mg TC/100 g fresh tissue per day occurred. Agüero et al. (2008) reported a higher value of total chlorophyll degradation rate in lettuce heads stored under optimal conditions without any delay after harvest. However, they analyzed kinetics of chlorophyll changes in different lettuce sections and found that the middle and inner leaves did not have decreased chlorophyll content, whereas significant decreases occurred in outer leaves with a kinetic constant of 0.049 mg TC/100 g per day. The lower value in the present research could be due to pigment evolution in the whole head, not only in the outer leaves.

Overall Visual Quality

After changes detected in OVQ during early postharvest (0.7 and 1.4 points for heads exposed to optimal and suboptimal conditions, respectively), values were similar during storage (Figure 5C). For OVQ there was no interaction between COND and TIME, but individual factors were significant (Table 1). Differences in OVQ during early postharvest were maintained during storage, with OVQ for heads exposed to optimal conditions always being 0.7 to 0.9 points higher than OVQ value for heads exposed to suboptimal conditions. For both cases, heads had significant decreases in OVQ values during storage, with a linear decrease of 0.096 points per day for heads exposed to optimal and suboptimal conditions, respectively (Figure 5C). Heads exposed to suboptimal conditions in the early postharvest reached the acceptability limit (5) before heads were moved to storage. At the end of storage, heads from crates exposed to optimal conditions retained an OVQ value higher than 5. Although lettuce section was not considered a factor (whole heads were analyzed as the experimental unit), panelists detected changes in sensory attributes principally in external leaves and the presence of browning in the cut area (stem butt). Changes observed by panelists toward the end of the storage were a decrease in brightness, with some discoloration and browning in leaf edges, with changes detected earlier in heads exposed to suboptimal temperature during the early postharvest period.

Shelf-Life Modeling

Quality indices with significant impact on shelf-life were FW, AA, TC, and MBC. The C_{ij} matrix together with threshold values associated with each index for optimal and suboptimal conditions were affected (Table 3). The variation matrix (V_{ij}) was obtained using as weighting factors (α_i) 0.25, 0.4, 0.25 and 0.1 for FW, AA, TC, and MBC, respectively. These values were adopted

Table 3: Matrix of values (C_{ij}) and threshold values (L_i) associated with each quality index of lettuce stored at optimal conditions after a 24-h delay under optimal or suboptimal conditions. Q6

Time (days)	FW (g·g^{-1})	AA (mg/100 g)	TC (mg/100 g)	MBC log(UFC·g^{-1})
Lettuce heads from crates with 24-h delay at optimal conditions				
0	11.6	11.2	28.8	5.4
7	8.7	6.9	24.1	6.0
14	7.3	4.6	23.1	7.2
21	6.0	3.6	20.4	7.6
L_i	7.1	3.9	7.5	9.1
Lettuce heads from crates with 24-h delay at suboptimal conditions				
0	11.1	10.1	27.7	6.7
7	8.5	6.2	24.7	5.2
14	6.3	4.4	23.3	5.9
21	5.5	3.3	20.2	7.8
L_i	7.1	3.9	7.5	9.1

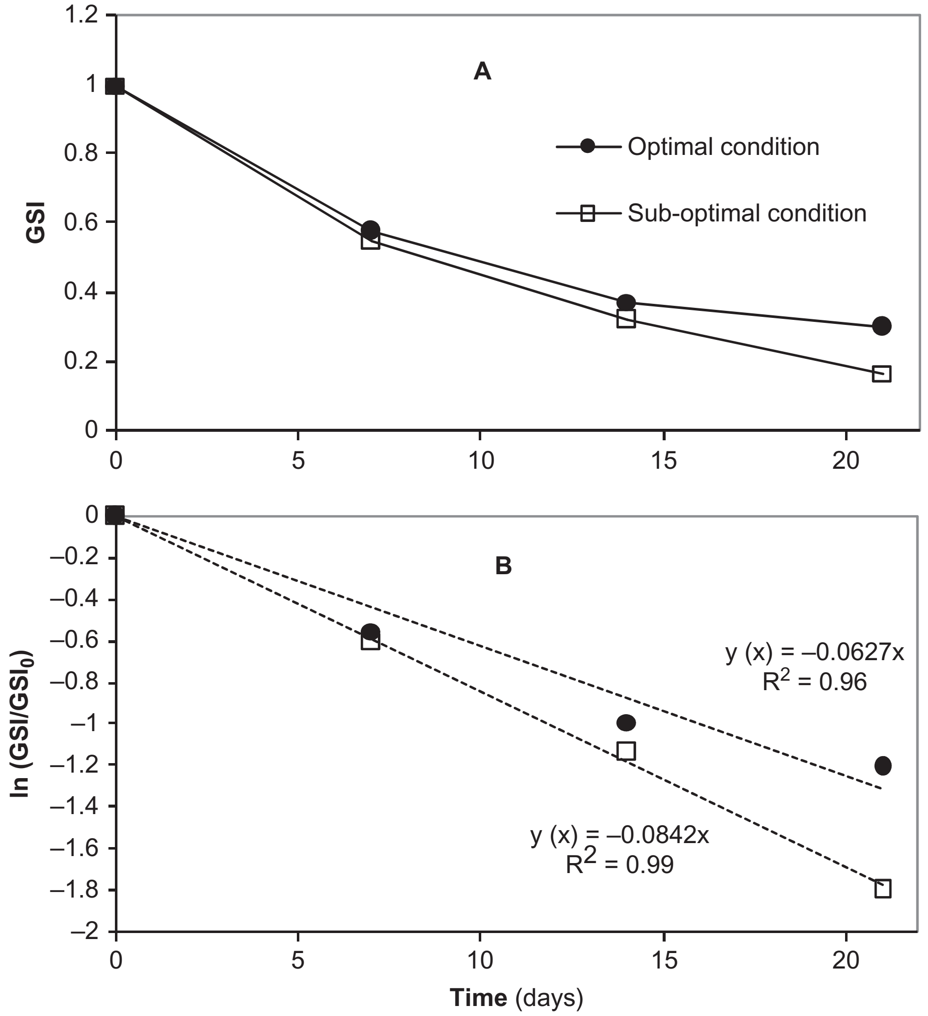

Figure 7: Evolution of the GSI in lettuce heads during refrigerated storage after 24 h of exposure to 0–2°C, 97%–99% RH (optimal) or 20–22°C, 60%–62% RH (suboptimal).

following the procedure of Ansorena et al. (2009) after correlations between each index and OVQ.

The GSI was reduced due to treatment (Figure 7A). Only at 21 days of storage was GSI higher for heads stored under optimal conditions than under suboptimal conditions. A first-order kinetic (Figure 7B) occurred for both situations. Although environmental conditions during early postharvest and storage were the same (0–2°C and 97%–99% RH), differences were detected in the GSI degradation rate. This could be attributed to events occurring in early postharvest. Heads from crates exposed to suboptimal conditions in early postharvest had lower stability during refrigerated storage, with a degradation rate ($0.0842 \cdot d^{-1}$) 31% higher than for heads from crates exposed to optimal conditions ($0.0627 \cdot d^{-1}$).

The GSI calculated for an OVQ value of 5 (the acceptability limit) resulted in values of 0.108 and 0.114 for heads from crates exposed to optimal and

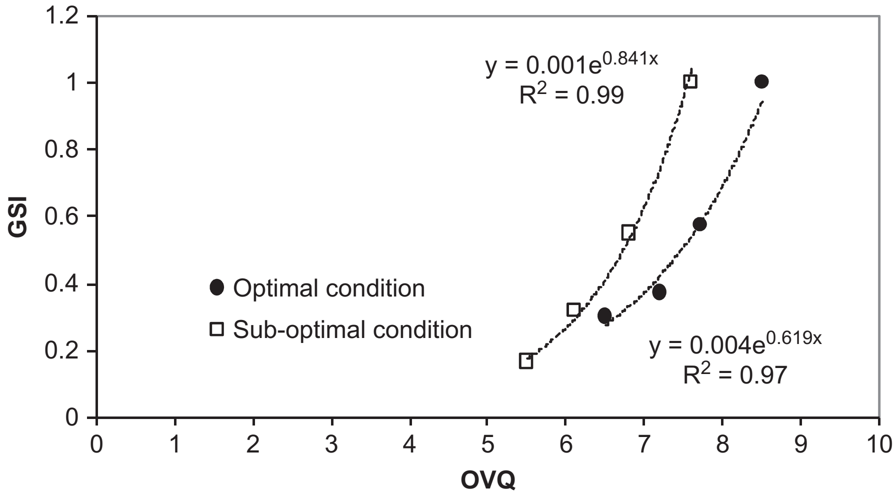

Figure 8: Evolution of the GSI as a function of the OVQ for lettuce heads during refrigerated storage after 24 h exposure to 0–2°C, 97%–99% RH (optimal) or 20–22°C, 60%–62% RH (suboptimal).

suboptimal conditions, respectively (Figure 8). The theoretical shelf-life was estimated as 37.1 and 25.7 days of storage, respectively. The model indicated higher stability of heads that had remained in crates under optimal conditions because shelf-life was 10 days longer than for heads exposed to suboptimal conditions in the early postharvest period.

Environmental conditions assayed during the early postharvest period introduced changes in all indices analyzed at the beginning of the subsequent storage. Application of the GSI method indicated that conditions during early postharvest impacted lettuce shelf-life. Maintenance of optimal environmental conditions from the first hours after harvest extended shelf-life of lettuce. These results have a direct impact on marketing of produce and support the idea that proper handling during the early postharvest period diminishes quality loss and prolongs shelf-life of this produce, allowing it to reach to more distant markets.

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