Cost, quality, and safety: A nonlinear programming approach to optimize the temperature during supply chain of leafy greens

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Abstract

Leafy green vegetables are highly susceptible to microbial contamination because they are minimally processed. Pathogenic bacteria of concern include *Escherichia coli* O157:H7, *Salmonella* spp., and *Listeria monocytogenes*. Leafy greens are a highly perishable commodity, and in some cases have a postharvest shelf-life limited to one week. This study provides an approach to optimize storage of leafy greens in the supply chain, considering the cost of refrigeration, sensory quality parameters (i.e., fresh appearance, wilting, browning, and off-odor), and microbial safety using nonlinear programming (NLP). The loss of sensory quality parameters was expressed as Arrhenius equations and pathogen growth were represented by three-phase linear (primary) and square-root (secondary) model. The objective function was refrigeration cost, which was to be minimized. The constraints were growth of pathogens and the loss of sensory characteristics. An interactive graphical user interface was developed in MATLAB. Pathogen growth is of more concern than loss of sensory quality in fresh-cut Iceberg lettuce when considering a shelf-life of up to two days, and the model indicates is difficult to maintain sensory qualities for longer shelf-life values. Browning is of maximum concern for fresh-cut Iceberg and Romaine lettuce, whereas off-odor is the biggest concern for fresh-cut chicory.

1. Introduction

Leafy greens are important sources of minerals, vitamins, antioxidants, and dietary fiber (Agüero, Viacava, Moreira, & Roura, 2014). Contamination of leafy greens with foodborne pathogens of particular concern because these foods are usually consumed raw without cooking or other interventions to kill any pathogens that might be present (Jacxsens et al., 2010). The Center for Science in the Public Interest ranked leafy greens at the very top of the “FDA Top Ten” riskiest foods in 2009 (Buchholz et al., 2012). In 12,714 documented foodborne outbreaks occurring in the U.S. during 1973–2012, 606 (about 5%) implicated a leafy vegetable, resulting in 20,003 illnesses, 1,030 hospitalizations, and 19 deaths (Herman, Hall, & Gould, 2015). Between 1973-2012 Shiga toxin-producing *E. coli* O157:H7 and *Salmonella* were the most common bacteria implicated in foodborne outbreaks associated with leafy greens (Herman et al., 2015). *E. coli* O157:H7 accounted for 49 leafy vegetable-related outbreaks, 1,634 hospitalizations, and 450 deaths. *Salmonella* was associated with 32 leafy vegetable-related outbreaks, 1447 hospitalizations and 83 deaths during this period (Herman et al., 2015). *Listeria monocytogenes* can also be transmitted through raw fruits and vegetables, and has been isolated from packaged lettuce (Allende et al., 2004; Szabo et al., 2000). The ability of *L. monocytogenes* to survive and grow under a wide range of environments and at low temperatures makes it also of concern in such foods (Ding, Jin, & Oh, 2010). The Centers for Disease Control and Prevention (CDC) reported that of all tracked foodborne pathogens, *L. monocytogenes* had the second highest case fatality rate (21%) during 2009-2011 (CDC, 2013). Listeriosis almost always occurs in people considered to be at higher risk, such as the elderly and those who have a preexisting illness that reduces the effectiveness of their immune system (Pradhan et al., 2009; U.S. FDA et al., 2003). The most recent multistate outbreaks in the USA, linked to consumption

of whole cantaloupes also indicates that this pathogen may pose a serious microbiological hazard in other plant foods like leafy greens (Zilelidou, Tsourou, Poimenidou, Loukou, & Skandamis, 2015).

The limited shelf-life of fresh processed leafy greens is one of the greatest problems faced by commercial marketers (Ana Allende, McEvoy, Luo, Artes, & Wang, 2006). The shelf-life of leafy greens depends on type, cultivation process, maturity at harvest, environmental conditions after harvest, among others, but temperature is the most critical postharvest factor affecting shelf-life (Agüero et al., 2014). The shelf-life of leafy greens ranges from less than a week to three weeks, depending upon variety and storage temperature (Cantwell, Rovelo, Nie, & Rubatzky, 1998). Poor temperature control during distribution results in deterioration of a fresh appearance and odor, including browning, wilting, and off-odor (Moreira, Ponce, Carlos, & Ansorena, 2006).

The specific objectives of this study were: (i) to estimate the upper limit of temperature to be maintained throughout the supply chain of leafy greens in order to minimize refrigeration cost, (ii) limit the microbial risk, and (iii) control the loss of sensory qualities. We also develop a modeling tool to integrate the results for different levels of microbial growth and sensory quality losses.

2. Materials and methods

2.1 Growth models

2.1.1 Primary models for growth

The exponential growth phase (log-phase) of the three-phase linear model (Buchanan, Whiting, & Damert, 1997) was used as the primary growth model because of its simplicity and

wider application. The three phase linear model fits lag phase, log phase, and stationary-phase as straight lines. Equation 1 represents the log phases of the three-phase linear model. As a conservative approach, lag-phase was not considered in this study.

$$\log N_t = \log N_o + \frac{\mu}{2.303} \times t \quad \dots(1)$$

Where, N_t = cell concentration (CFU g⁻¹) at time t ; N_o = initial cell concentration (CFU g⁻¹); t = time (h); μ = specific growth rate (ln CFU g⁻¹ h⁻¹).

2.1.2. Secondary model for growth

Square-root model was selected as the secondary growth model (Ratkowsky, Olley, Mcmeekin, & Ball, 1982).

$$\sqrt{\mu} = b(T - T_{min}) \quad \dots(2)$$

In Equation 2, μ is specific growth rate mentioned in Equation 1; b is the temperature coefficient, T is food temperature (°C) and T_{min} is the theoretical minimum temperature (°C) for growth of pathogens. The values of b and T_{min} are dependent on the types of pathogens and food products. These parameters for *E. coli* O157:H7, *Salmonella*, and *L. monocytogenes* were taken from different studies reporting the square-root models corresponding to the three-phase linear model. The values of b and T_{min} are 0.023 and 1.20 for *E. coli* O157:H7 (McKellar & Delaquis, 2011), 0.020 and -0.57 for *Salmonella* (Mishra & Pradhan, 2015b), and 0.023 and 0.60 for *L. monocytogenes* (Mishra & Pradhan, 2015a), respectively.

2.2 Death model.

A log-linear death model was used for gradual inactivation of *E. coli* O157:H7 and *Salmonella* that may occur at lower temperatures ($\leq 5^\circ\text{C}$). Since *L. monocytogenes* is known to

survive 3°C (Carlin, Nguyen-the, Abreu Da Silva, & Cochet, 1996; Ding et al., 2010; Kaminski, Davidson, & Ryser, 2014), it was modeled to grow at temperatures higher than 3°C, and survive (i.e. no change in concentration) in the temperature range of 0-3°C.

$$\log \left(\frac{N_t}{N_o} \right) = - \frac{k}{2.303} \times t \quad \dots(3)$$

Where, k is die-off coefficient in $\ln \text{CFU h}^{-1}$. The mean die-off coefficient for *E. coli* O157:H7 was reported as 0.0130 $\ln \text{CFU/h}$ below the storage temperature of 5°C (McKellar & Delaquis, 2011). Die-off coefficient of *Salmonella* was reported as 0.0128 $\ln \text{CFU/h}$ at temperature below 5°C (Mishra and Pradhan, 2015a).

2.3 Growth-death model

A dynamic growth-death model used by McKellar and Delaquis, (2011) and Zeng et al. (2014) was also applied to simulate the growth of *E. coli* O157:H7. The model was used to predict the growth and death of *E. coli* O157:H7, *Salmonella*, and *L. monocytogenes*.

$$\frac{dN_t}{dt} = \text{Rate} * N_t \quad \dots(4)$$

For *E. coli* O157:H7,

$$\text{Rate} = (\text{if } T \geq 5, \text{Growth } (\mu), \text{Death}(k)) \quad \dots(5)$$

For *Salmonella*,

$$\text{Rate} = (\text{if } T \geq 7, \text{Growth } (\mu), (\text{if } T > 5, 0, \text{Death } (k))) \quad \dots(6)$$

For *L. monocytogenes*,

$$\text{Rate} = (\text{if } T \geq 3, \text{Growth } (\mu), 0) \quad \dots(7)$$

2.4 Relative cooling cost

The cost of cooling during transportation and storage is directly related to the temperature. The coefficient of performance (COP) for refrigeration can be used to determine the cooling cost, as shown in Equation 8 (Rong, Akkerman, & Grunow, 2011):

$$COP = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_R}{W} = \frac{T_R}{T_A - T_R} \quad \dots(8)$$

Where, Q_R is the heat transferred to a high temperature environment (air) from a lower temperature environment (refrigerator) (kWh), W is the input energy (kWh), T_A and T_R are higher and lower environmental temperatures (Kelvin or K), respectively. The refrigeration cost for 0°C refrigeration temperature was assumed to be one unit, i.e., 1. The costs for other refrigeration temperatures were calculated with respect to this unit cost. For example, if the ambient temperature (T_A) is 293 K (20°C), refrigeration temperature (T_R) is 273 K (0°C), $COP=273/(293-273)=13.65$. For every unit of energy drawn from the electrical source, the coolant will absorb 13.65 units of heat from the refrigerator. We can calculate refrigeration costs for other temperatures on the basis of this unit cost. For example, the COP for 283 K (10°C) refrigeration temperature and 293 K (20°C) ambient temperature will be $283/(293-283)=28.3$, and the relative cost will be $13.65/28.3=0.48$.

2.5. Changes in sensory quality attributes

Major visual and quality changes that take place in leafy greens are loss of freshness in the general appearance and development of wilting, browning, and off-odor. One of the most commonly used models for sensory quality changes is the Arrhenius equation (Piagentini, Mendez, Guemes, & Pirovani, 2005).

$$\pm \frac{dQ}{dt} = k_q [Q]^n \quad \dots(9)$$

$$\text{Where, } k_{q(T)} = k_o \exp\left(\frac{-E_a}{RT}\right) \quad \dots(10)$$

Where Q is the score given for sensory quality attributes, t is time (in days), n is reaction order (n=1, i.e., the first order equation (Piagentini et al., 2005)), and k_q is quality change rate constant for the attribute. The pre-exponential factor (k_o) is the magnitude of the reaction rate independent of temperature and the activation energy (E_a) describes temperature sensitivity of the reaction. The + sign refers to attributes with increasing values with respect to time (e.g. browning, off-odor and wilting), whereas, the – sign refers to decreasing values (e.g. quality of appearance).

The information provided by Piagentini et al. (2005) was used to represent the changes in sensory quality attributes. In Piagentini et al. (2005), the evaluation of the scores (Q) for different sensory quality attributes was performed by a descriptive test. In that study, the panelists evaluated general appearance, wilting, browning, and off-odor of packaged leafy greens on a scale from 0 to 15. In our study, the sensory quality scores (Q) were rescaled by normalizing the scores reported in Piagentini et al. (2005) from 0 to 100. Normalization was done to better represent the percentage (i.e. 0 to 100) of sensory quality attributes retention at the end of the desired shelf life.

Changes in appearance, wilting, browning and off-odor were predicted using the Arrhenius Equation. Activation energy values for three fresh-cut leafy greens (fresh-cut Iceberg lettuce, Romaine lettuce and fresh-cut chicory) was as given by Piagentini et al. (2005) . Pre-exponential factors k_o were calculated in Microsoft Excel (Microsoft, 2010) for four sensory quality attributes for three kinds of leafy greens based upon the given activation energies and rate constants (Piagentini et al., 2005).

2.6. Nonlinear programming

Nonlinear programming (NLP) is the process of solving an optimization problem defined by a system of equalities and inequalities, collectively termed constraints, over a set of unknown real variables, along with an objective function to be maximized or minimized, where some of the constraints or the objective function are nonlinear (Perez, Jansen, & Martins, 2011). The objective function minimized in this study was cost. The constraints were growth of pathogens (*E. coli* O157:H7, *Salmonella*, and *L. monocytogenes*), and the loss of sensory characteristics of leafy greens.

2.7 Optimization of temperature for leafy greens

Two hypothetical standards (lenient and stringent), were set for sensory quality and microbial safety of leafy greens. The lenient standards were set to allow maximum 1 log CFU/g growth of any of three pathogens, and retention of at least 50% in all four sensory quality attributes. The limit of 1-log growth is consistent with recommendations from expert microbiologists (Busta et al., 2003; NACMCF, 2010; Schaffner, 2013). Less than a 1-log increase above the contamination level throughout the intended shelf life of the product and across replicate trials would be an appropriate acceptance criterion in determining whether a product supports growth of a pathogen throughout the supply chain. This level reflects the inherent variation that exists with enumeration of microorganisms (NACMCF, 2010). Retention of 50% sensory quality attributes as the end of useful shelf life was as suggested from Piagentini et al., (2005). While a 50% quality loss does not mean leafy greens will not be consumable at this point, it is useful as a relevant metric. A more stringent standard was also considered for the three leafy greens under study (pathogen growth $\leq 0.3 \log \text{CFU g}^{-1}$, and sensory quality $\geq 75\%$ of original). A lower limit

of 0°C was set for the optimized temperatures, as storage at temperatures lower than 0°C may result in freezing injuries to leafy greens.

2.8 Development of graphic-user interface (GUI) for calculations

A GUI named “SHELF” (Fig. 1) was developed in MATLAB (MathWorks, 2015b). There were three components of SHELF: an input panel, a result summary panel, and a panel for graphs for changes in sensory properties and microbial load with respect to time. The input panel records desired shelf-life (in days), the ambient temperature (°C), maximum allowed growth of *E. coli* O157:H7, *Salmonella*, and *L. monocytogenes* (log CGU g⁻¹), and minimum percent retention of sensory quality parameters (general appearance, browning, wilting, and off-odor) from the user. Ambient temperature does not impact optimized temperature, but was used in cost calculations (Equation 4). As noted above, retention of sensory quality was as estimated by sensory scores from the published literature (Piagentini et al., 2005). Initial sensory score was set at 100%, and decline in sensory score was modeled using first order Arrhenius equation (Equations 9 and 10). Growth of *E. coli* O157:H7, *Salmonella*, and *L. monocytogenes* were predicted using the growth and death models. The result summary panel shows the optimized temperature for the specified conditions, and the calculated refrigeration cost relative to the cost for refrigeration temperature of 0°C. This panel also gives the predicted change in pathogen concentration and decline in leafy greens’ sensory properties at the end of the desired shelf-life. The graph panel depicts the predicted change in pathogen concentration and sensory attributes over time.

3. Results

3.1 Parameters for Arrhenius equation for sensory quality changes

The values for pre-exponential factor k_o and activation energy E_a are shown in Table 1. For fresh-cut Iceberg and Romaine lettuce, the E_a values for browning were lower than those for other sensory quality parameters. Lower activation energy for sensory quality changes indicates the ease with which a food's sensory quality degrades (Arboatti et al., 2014). The overall rate of a food's sensory quality degradation is determined by the mixed effect of activation energy and pre-exponential factor.

3.2 Optimization of temperature for leafy greens

Optimized temperature and relative costs were calculated for fresh-cut Iceberg, Romaine lettuce, and fresh-cut chicory under (i) lenient, and (ii) standards. Ambient temperature was taken as 20°C (68°F) for calculation of relative costs at different refrigeration temperatures. As expected, the relative cost increased as the optimized temperature was close to zero (Table 2 and 3). Because leafy greens suffer from freezing injuries at temperatures lower than -0.5°C (Jobling, 2000), optimized temperatures below -0.5°C are not reported. Numbers in bold in Table 2 and Table 3 represent the corresponding parameters (sensory quality retention or microbial growth) that would just reach the maximum allowed values for lenient standards (Table 2) or stringent standards (Table 3) if leafy greens were maintained at the optimized temperature for the desired shelf-life.

Table 2 predicts that fresh-cut Iceberg lettuce will meet the lenient standards for up to four days. A 1-log increase in the concentration of *L. monocytogenes* was the constraining variable for 1 and 2 days shelf-life of fresh-cut Iceberg lettuce, whereas browning was the constraint for three and four day shelf-life of fresh-cut Iceberg lettuce. The models predict that fresh-cut Romaine lettuce can be stored for up to six days. Growth of *L. monocytogenes* would be the key constraint for the shelf-life of fresh-cut Romaine lettuce with 1 and 2 day shelf life. *Salmonella*

growth was predicted to be the key constraint for fresh-cut Romaine lettuce with a target shelf-life of three and four days. Browning becomes the key concern for fresh-cut Romaine lettuce with a target shelf-life of five days. The models predict that fresh-cut chicory can be kept under the lenient standards for up to 11 days. The limiting constraints fresh-cut chicory are the same as those for fresh-cut Romaine for a desired shelf-life of up to four days. Off-odor was predicted to be the primary shelf-life concern for fresh-cut chicory with a target shelf life from five to eleven days.

Predictions for shelf life under the more stringent standards are shown in Table 3. Fresh-cut Iceberg lettuce could not be stored for more than one day, and growth of *Salmonella* would be the primary concern for one-day storage (Table 3). Fresh-cut Romaine lettuce could be stored for up to two days and still meet the more stringent standards. As with fresh-cut Iceberg lettuce, growth of *Salmonella* is the limiting constraint for one day of storage for Romaine lettuce, whereas browning would be of primary concern for storage of two days for Romaine lettuce. Fresh-cut chicory was predicted to meet the stringent standards for up to four days of storage. *Salmonella* and *L. monocytogenes* were the limiting constraints for chicory under the stringent standards for one and two days, respectively, while off-odor was the limiting constraint for three or four days.

4. Discussion

Our models predict that Iceberg and Romaine lettuce can be stored for up to four and six days, respectively, under the more lenient standards and the results are in close agreement with the studies previously conducted on the shelf-life of minimally processed leafy greens (Allende et al., 2004; Gómez-López et al., 2008; Zhou et al., 2004). Browning was predicted as the sensory quality attribute of maximum concern for Iceberg and Romaine lettuce at the longer

shelf lives. Low temperatures are assumed to preserve sensory quality by slowing down all leaf metabolism. Color changes might be due to senescence (process of deterioration with age). The senescence usually leads to leaf browning as observed in leafy vegetables (Able, Wong, Prasad, & Hare, 2003; Ferrante, Incrocci, Maggini, Serra, & Tognoni, 2004).

Our predicted shelf-life of leafy greens was similar to that predicted by Piagentini et al. (2005) which is not surprising, since we used their data. For instance, we predicted maximum possible shelf-life of fresh-cut Iceberg, Romaine lettuce and fresh-cut chicory as 4, 6, and 11 days, respectively (assuming lenient standards), as compared with 6.4, 7.2 and 9.2 days, respectively predicted by Piagentini et al. (2005).

The general appearance scores reported in Piagentini et al. (2005) represent the overall visual impact of the sample, which was influenced by browning, wilting, and any other visual quality factors. In our study, the calculated sensory quality retention values for general appearance were within the range of browning and wilting values (Table 2 and Table 3) except for the shelf-life of fresh-cut chicory at 1 and 2 days as shown in Table 2.

Fresh-cut chicory was predicted to have a considerably longer shelf-life as compared with fresh-cut Iceberg and Romaine lettuce, which is not surprising as the behavior of different leafy greens varies in terms of their response to temperature abuse (Piagentini et al., 2005). For example, Allende et al., (2004) reported spinach samples with shelf-life of two days at 20°C, four days at 16°C, six days at 12°C, eight days at 8°C, and ten days at 1°C.

Product's shelf life stage significantly affects its response to temperature. Quality deterioration proceeded more rapidly when temperature abuse occurred in late, as opposed to early, shelf-life stage (Kou et al., 2014; Kou, Luo, Ingram, Yan, & Jurick, 2015). The observed

acceleration of the detrimental effect of temperature abuse occurring at late shelf life stage may be associated with the physiological condition of the products. In the late stages of product shelf life (after 6 d of storage), the product has already partially senesced, stored carbohydrates have been consumed, cell wall disassembly has progressed, thus the leaves become fully senesced more rapidly once exposed to elevated temperatures (Kou et al., 2014).

The Arrhenius equation we used has also been widely used by others as the basis for predicting loss of food quality or storage life in many processed foods as a function of storage temperature (Piagentini et al., 2005; Rong et al., 2011; Singh, Ruhil, Jain, Patel, & Patil, 2009). The primary assumption made in using the Arrhenius equation is that the rate of quality loss is an exponential function of the reciprocal of absolute storage temperature (Singh et al., 2009). In the Arrhenius equation, as shown in equation 10 above, the pre-exponential factor is the magnitude of reaction rate independent of temperature and the activation energy describes temperature sensitivity of the reaction.

The FDA recommends that leafy greens should be maintained at 5°C or below in transport, storage and retail display in the 2013 Food Code (Kou et al., 2015; U.S. FDA, 2013). There is also a practical lower temperature limit since storage of leafy greens at temperatures that are too low may result in freezing injuries. Freezing injury might result from transport in cold geographical regions, incorrect thermostat settings, refrigeration break-down or a lack of air circulation in refrigerated storage. One common symptom of freezing injury is the presence of water soaked damaged leaves. Leafy vegetables do not have as many dissolved sugars as fruits, so leafy vegetables freeze at -0.5°C, compared to fruits which can freeze between -2°C and -5°C (Jobling, 2000). Therefore our report only includes predictions with an optimized temperature of -0.5°C and above.

5. Conclusions

There is considerable variability in the shelf-life of different leafy greens stored at the same temperature. Fresh-cut Iceberg lettuce has the shortest shelf-life among the leafy greens studied, followed by fresh-cut Romaine lettuce and fresh-cut chicory. Pathogen growth is of greater concern than loss of sensory quality for fresh-cut Iceberg lettuce with a target shelf-life of up to two days. Conversely, browning is a greater concern for fresh-cut Iceberg lettuce with a desired shelf-life of more than two days. Pathogen growth is a greater concern than loss of sensory quality for fresh-cut Romaine lettuce and fresh-cut chicory, with a desired shelf-life of up to four days. Browning and off-odor development are major concerns for fresh-cut Romaine and chicory, respectively when target shelf-life is five days or more.

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Fig. 1. Different components of the graphic-user interface “SHELF” used for the calculations of optimum refrigeration temperature during leafy greens storage

Figure

Table 1

Pre-exponential factor (k_o) and activation energy (E_a) values for sensory quality attributes (general appearance, browning, wilting, and off-odor) for leafy greens

Parameter	Fresh-cut Iceberg lettuce		Fresh-cut Romaine lettuce		Fresh-cut chicory	
	k_o	E_a	k_o	E_a	k_o	E_a
General appearance	3.03×10^{12}	71.1	1.35×10^{12}	69.6	1.21×10^{11}	65.7
Wilting	4.43×10^{11}	66.9	1.39×10^{11}	65.1	1.42×10^{16}	92.9
Browning	1.91×10^8	47.5	4.22×10^6	39.6	8.89×10^{11}	69.0
Off-odor	2.22×10^{11}	65.3	6.58×10^8	51.4	3.38×10^{16}	81.2

k_o : pre-exponential factor

E_a : Activation energy (J mol^{-1})

Table 2

Optimized temperature (°C) for leafy greens for lenient standards (maximum permissible pathogen growth = 1 log CFU/g; Minimum Sensory quality retention = 50% of original)

Type of leafy green	Desired shelf life (days)	Optimized temperature (°C)	Refrigeration cost (relative to 0°C)	Pathogen growth (log CFU/g)			Sensory quality retention (% of original)			
				<i>E. coli</i> O157:H7	<i>Salmonella</i>	<i>L. monocytogenes</i>	General appearance	Wilting	Browning	Off-odor
Fresh-cut Iceberg lettuce	1	14.4	0.27	0.92	0.90	1.00	71	75	65	75
	2	10.3	0.47	0.88	0.96	1.00	64	68	53	68
	3	5.7	0.70	0.33	0.00	0.42	66	69	50	69
	4	1.9	0.90	-0.01	-0.01	0.00	70	72	50	72
Fresh-cut Romaine lettuce	1	14.8	0.27	0.92	0.90	1.00	75	82	77	75
	2	10.3	0.47	0.88	0.96	1.00	69	77	66	66
	3	8.4	0.56	0.85	1.00	0.99	63	72	58	58
	4	7.2	0.62	0.78	1.00	0.94	58	68	51	52
	5	3.9	0.79	-0.01	-0.01	0.29	62	71	50	53
	6	1.0	0.95	-0.01	-0.01	0.00	66	73	50	55

Fresh-cut chicory	1	14.4	0.27	0.92	0.90	1.00	88	84	78	69
	2	10.3	0.47	0.88	0.96	1.00	84	82	73	64
	3	8.4	0.56	0.85	1.00	0.99	80	80	67	58
	4	7.2	0.62	0.78	1.00	0.94	77	78	63	54
	5	6.3	0.67	0.70	0.00	0.87	74	76	59	50
	6	4.8	0.75	-0.01	-0.01	0.58	74	76	58	50
	7	3.6	0.80	-0.02	-0.01	0.34	73	77	58	50
	8	2.6	0.87	-0.02	-0.02	0.00	72	77	57	50
	9	1.7	0.91	-0.02	-0.02	0.00	72	77	56	50
	10	0.8	0.95	-0.02	-0.02	0.00	71	78	56	50
	11	0.1	0.99	-0.02	-0.02	0.00	71	78	55	50

Table 3

Optimized temperature (°C) for leafy greens for stringent standards (maximum permissible pathogen growth = 0.3 log CFU/g;

Minimum Sensory quality retention = 75% of original)

Type of leafy green	Desired shelf life (days)	Optimized temperature (°C)	Relative cost	Pathogen growth (log CFU/g)			Sensory quality retention (% of original)			
				<i>E. coli</i> O157:H7	<i>Salmonella</i>	<i>L. monocytogenes</i>	General appearance	Wilting	Browning	Off-odor
Fresh-cut Iceberg lettuce	1	8.1	0.58	0.25	0.30	0.29	84	86	76	86
	2	4.5	0.76	0.00	0.00	0.16	82	86	75	77
Fresh-cut chicory	1	8.1	0.58	0.25	0.30	0.29	93	93	88	84
	2	5.9	0.69	0.24	0.00	0.30	89	90	82	77
	3	3.4	0.82	-0.01	-0.01	0.12	88	90	79	75
	4	1.1	0.94	-0.01	-0.01	0.00	87	90	79	75