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

Abhinav Mishra [a], Robert L. Buchanan [a, b], Donald W. Schaffner [c], Abani K. Pradhan [a, b, *]

[a] Department of Nutrition and Food Science, University of Maryland, College Park, MD, USA
[b] Center for Food Safety and Security Systems, University of Maryland, College Park, MD, USA
[c] Department of Food Science, Rutgers University, New Brunswick, NJ, USA

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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 temperature 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) models. 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 (Center for Science in the Public Interest, 2009). 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, 1030 hospitalizations, and 19 deaths (Herman, Hall, & Gould, 2015). Between 1973 and 2012 Shiga toxin-producing *Escherichia 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, 1634 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, Aguayo, & Artés, 2004; Szabo, Scurrah, & Burrows, 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; US FDA & USDA, 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,

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[*] Corresponding author. Department of Nutrition and Food Science, University of Maryland, 0112 Skinner Building, College Park, MD 20742, USA.
E-mail address: akp@umd.edu (A.K. Pradhan).

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2015).

The limited shelf-life of fresh processed leafy greens is one of the greatest problems faced by commercial marketers (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.

$$\log N_t = \log N_o + \frac{\mu}{2.303} \times t \tag{1}$$

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).

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

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, Guo, Buchanan, Schaffner, & Pradhan, 2017), and 0.023 and 0.60 for *L. monocytogenes* (Mishra et al., 2017), 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 (≤5 °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.

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

Where, k is die-off coefficient in ln CFU g^{-1} h^{-1}. The mean die-off coefficient for *E. coli* O157:H7 was reported as 0.0130 ln CFU g^{-1} h^{-1} below the storage temperature of 5 °C (McKellar & Delaquis, 2011). Die-off coefficient of *Salmonella* was reported as 0.0128 ln CFU g^{-1} h^{-1} at temperature below 5 °C (Mishra et al., 2017).

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*.

$$\frac{dN_t}{dt} = Rate * N_t \tag{4}$$

For *E. coli* O157:H7,

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

For *Salmonella*,

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

For *L. monocytogenes*,

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

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):

$$COP = \frac{Desired\ output}{Required\ input} = \frac{Q_R}{W} = \frac{T_R}{T_A - T_R} \tag{8}$$

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