Postharvest Biology and Technology 85 (2013) 18–29

Contents lists available at ScienceDirect

Postharvest Biology and Technology

journal homepage: www.elsevier.com/locate/postharvbio

Towards flexible management of postharvest variation in fruit firmness of three apple cultivars

S.G. Gwanpua[a], B.E. Verlinden[b], M.L.A.T.M. Hertog[a], J. Van Impe[c], B.M. Nicolai[a,b], A.H. Geeraerd[a,*]

[a] Division of Mechatronics, Biostatistics and Sensors (MeBioS), Department of Biosystems (BIOSYST), KU Leuven, W. de Croylaan 42, Bus 2428, B-3001 Leuven, Belgium
[b] Flanders Centre of Postharvest Technology, W. de Croylaan 42, 3001 Leuven, Belgium
[c] Chemical and Biochemical Process Technology and Control Section (BioTeC), Department of Chemical Engineering, KU Leuven, W. de Croylaan 46, B-3001 Leuven, Belgium

ARTICLE INFO

Article history:
Received 16 November 2012
Accepted 21 April 2013

Keywords:
Malus × *domestica* (Borkh.)
Biological variation
Stochastic modeling
Monte Carlo
Controlled atmosphere

ABSTRACT

Stochastic modeling provides a useful tool in managing biological variation in the postharvest chain. In the current study, the fruit-to-fruit variability in the postharvest firmness of apples was modeled. Apples from three cultivars ('Jonagold', 'Braeburn', and 'Kanzi') were harvested at different levels of maturity, and stored at different temperatures and controlled atmosphere (CA) conditions. By using a kinetic model describing firmness breakdown as a function of time, temperature, controlled atmosphere conditions and endogenous ethylene concentration, the main stochastic variables were identified as the initial firmness and the rate constants for firmness breakdown and ethylene production. Treating these variables as random model parameters, the Monte Carlo method was used to simulate the propagation of the fruit-to-fruit variability in flesh firmness within a batch of apples during storage under different CA conditions and subsequent shelf-life exposure. The model was validated using independent data sets from apples picked in a different season. The model developed in this study can be used to predict the probability of having apples of certain firmness after long term storage for different scenarios of temperatures and CA conditions.

1. Introduction

Consumers prefer products with uniform quality, based on important quality indicators such as color, size, soluble solids content and firmness. Postharvest handlers are usually faced with the difficult task of dealing with large variations in product quality due to inherent biological variations. Biological variation is a consequence of several factors related to both pre- and postharvest treatments. For instance, apples picked on different dates will ripen differently during storage due to differences in maturity at harvest. Also, even for the same batch of produce, there is quite often fruit-to-fruit variation resulting from factors such as differences in shading, orientation of the fruit on the tree, and types and levels of fungicides (Kingston, 1991). As a result, there is always a large variation in product quality in a postharvest food chain. As illustrated by Carroll (2003) and Tijskens et al. (2003), biological variation cannot simply be treated as disturbances; rather it needs to be properly managed. It is, therefore, important to be able to predict how the initial variations in quality propagate along the whole chain.

Over the last decade, many authors have developed quality models incorporating biological variance to explain the propagation of biological variation in fruit (Tijskens et al., 2000; Hertog, 2002; Hertog et al., 2004, 2007a,b; Scheerlinck et al., 2004; Nicolaï et al., 2006; Mziou et al., 2009). Several approaches have been used in developing these models, such as mixed effects models (Lammertyn et al., 2003a; De Ketelaere et al., 2004), stochastic kinetic models (Hertog, 2002; Schouten et al., 2004; Tijskens et al., 2005, 2008), Monte Carlo simulations (De Ketelaere et al., 2004; Hertog et al., 2009), numerically solving the Fokker–Planck equation (Scheerlinck et al., 2004) and the variance propagation algorithm (Nicolaï et al., 1998; Scheerlinck et al., 2004; Mziou et al., 2009). The use of mixed effects models and stochastic kinetic models depends on the availability of an analytical solution of the model equations describing the process. However, biological systems are usually so complex that even when the process is simplified, the resulting model equations usually do not have an analytical solution. Another prerequisite for obtaining an analytical solution of a set of differential equations is the assumption of constant boundary conditions, such as temperature and gas conditions, which is not realistic for a complete postharvest food chain. Numerically solving the Fokker–Planck equation allows calculation of the propagation of the probability density function of random variables of a stochastic system. However, for equations describing complex systems, such as most biological processes, it is nearly impossible to solve the Fokker–Planck equation, even using numerical methods. In the variance propagation algorithm, which is a first order

* Corresponding author. Tel.: +32 16320591.
E-mail address: annemie.geeraerd@biw.kuleuven.be (A.H. Geeraerd).

0925-5214/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.postharvbio.2013.04.015

approximation of the Fokker–Planck equation, only the propagation of the mean and variance is predicted. Further, a common practice is to assume that for a linear system, if the initial stochastic variables are normally distributed, then the distribution remains normal, such that a normal probability density function can be used to predict the propagation of the probability density function (Mziou et al., 2009; Gwanpua et al., 2012a). In most cases, neither the stochastic variables are initially normal, nor are the equations describing the system linear. The Monte Carlo method is a more robust method when it comes to modeling a stochastic system. It involves repeated simulation of a process characterized by a system with random model parameters, using new values for the random model parameter(s) for each run of the simulations. Although the Monte Carlo method demands a relatively high computation time, it has an advantage over the other methods in that it is neither limited by the number of stochastic variables involved, nor by the complexity of the model equations describing the process. This method has successfully been used extensively in food engineering (Nicolaï et al., 1999; Poschet et al., 2003; Pouillot and Delignette-Muller, 2010; Busschaert et al., 2011; Hoang et al., 2012). In postharvest science, Hertog et al. (2009) used the Monte Carlo method to model variability in the Hue color in tomatoes during different postharvest regimes, while De Ketelaere et al. (2004) used it to predict shelf-life of tomatoes. The Monte Carlo method was also used to predict the firmness of mangoes during storage by De Ketelaere et al. (2006) and to explain softening of individual avocado fruit by Ochoa-Ascencio et al. (2009).

Flesh firmness is one of the most important quality indicators used in apple grading. Like other quality aspects of biological products, there is also a large variation in flesh firmness of apples at harvest. It is very important to be able to understand and predict how this initial variation in the firmness propagates throughout the apple cold chain. Most of the current models for apple firmness are only able to explain changes in the mean firmness (Hertog et al., 2001; Johnston et al., 2001; Gwanpua et al., 2012b). The objective of this study is to use the Monte Carlo method to model and explain the fruit-to-fruit variability in flesh firmness within a batch of apples for three cultivars ('Jonagold', 'Braeburn', and 'Kanzi') during controlled atmosphere (CA) storage and subsequent exposure to shelf-life conditions. Furthermore, the model will be validated by independent data sets. Practical applications of the model will also be discussed.

2. Materials and methods

2.1. Fruit

A total of about 7500 apple fruit (*Malus* × *domestica* Borkh.) from three cultivars ('Jonagold', 'Braeburn', and 'Kanzi') and two seasons (2008–2009 and 2009–2010) were used in this study. Apples were picked at three different stages of maturity corresponding to early, optimally and late picked apples. The early picked apples were picked about 2 weeks before the optimal picking dates, the optimally picked apples were harvested at the optimal picking dates, while the late picked apples were harvested about 2 weeks after the optimal picking dates. The optimal picking dates for the three cultivars were determined by the Flanders Centre of Postharvest Technology (Belgium), using a combination of starch stage, firmness, soluble solid content, background color, and size. The apples were harvested at the experimental station Proefcentrum Fruitteelt, Experimental Garden for Pome and Stone fruit (Sint–Truiden, Belgium).

2.2. Storage experiments

Each batch of apples was stored at 1 °C (and also at 4 °C for the 'Kanzi' apple), under different CA conditions (Fig. 1). CA was applied after pre-cooling for two days, except for the 'Braeburn' apples in which the application of CA was delayed for three weeks to prevent incidents of browning disorders (Elgar and Burmeister Watkins, 1998). Storage was done for either 4 or 6 months and at the end of storage, the apples were placed in shelf conditions (20.8 kPa O_2, 0.03 kPa CO_2 and a temperature of 18 °C) for 18 days. Shelf-life evaluations were performed before storage as well. The data collected for the apples picked in the 2009–2010 season were used for model calibration, while validation was done on the data collected for the apples picked in the 2008–2009 season, except for the Kanzi apples, of which the data set for the 2008–2009 season was more suitable for model calibration (more storage conditions were used).

2.3. Measurements

The initial flesh firmness and ethylene production of eight fruit randomly selected from each batch of apples (i.e., apples of the same cultivar, picked on the same date) were measured immediately after harvest. After 4 months and 6 months of storage, the firmness and ethylene production of eight fruit randomly selected from the fruit stored under the different CA conditions were measured, such that depending on the apple cultivar, between 48 and 80 fruit (eight fruit per storage conditions) were measured at each sampling time. Also, fruit that had been stored for 4 months or 6 months, for all the different storage conditions, were placed in shelf-life conditions for 18 days, during which the firmness and ethylene production of eight randomly selected fruit were measured at 6 day intervals.

Firmness was measured using an LRX Universal Testing Machine (Lloyd Instruments, UK), equipped with a load cell of 500 N. A self-cutting cylindrical plunger with surface of 1 cm^2 (diameter = 11.3 mm) was attached to the load cell and allowed to move at a constant speed of 8 mm s^{-1} towards the fruit. The firmness was taken as the maximum force (N) needed for the plunger to penetrate the fruit to a depth of 8 mm. Two measurements were taken on the equator, one at the blush side and one at the green side, and the average was taken as the firmness value.

Ethylene emission was measured following the protocol described by Bulens et al. (2011). To measure the ethylene emission, each apple was initially enclosed in a separate jar of 1.7 L and flushed with humidified gas with the same composition as the atmosphere and temperature under which the apple was stored. The flushing was done for a period of 24 h, to allow a steady state to be attained between the headspace and the internal atmosphere of the apple. The inlet and outlet of the jars were then closed and 3 mL samples were withdrawn from the jars and analyzed by injecting into a CompactGC (Interscience, Louvain-la-Neuve, Belgium). Calibration was done by ethylene standards ranging from 50 ppb to 50 ppm. The temperature, the free volume of the jar and the pressure inside the jar before sampling, were used to convert ethylene concentration (ppm) to nmol by using the ideal gas law. The ethylene emission (nmol kg^{-1} s^{-1}) was obtained by doing a second measurement after a period of about 18 h. For ethylene emission measurements done at higher temperatures, the time interval between the first and the second measurements was 3 h because of the much higher rate of ethylene production within the fruit.

3. Model development

3.1. Mathematical modeling of firmness breakdown

The model equations used in this study to describe the loss of firmness during storage as a function of storage time, temperature and gas compositions were based on the firmness model developed by Gwanpua et al. (2012b). The assumption made in that