Journal of Food Engineering 206 (2017) 88–97

Contents lists available at ScienceDirect

Journal of Food Engineering

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

A comprehensive simulation program for modified atmosphere and humidity packaging (MAHP) of fresh fruits and vegetables

Ali Jalali [a], [b], Sadegh Seiiedlou [a], [**], Manfred Linke [b], Pramod Mahajan [b], [*]

[a] Department of Biosystems Engineering, University of Tabriz, Tabriz, Iran
[b] Department of Horticultural Engineering, Leibniz Institute for Agricultural Engineering and Bioeconomy (ATB), Potsdam, Germany

ARTICLE INFO

Article history:
Received 17 November 2016
Received in revised form
24 February 2017
Accepted 4 March 2017
Available online 6 March 2017

Keywords:
Respiration
Transpiration
Condensation
Fresh produce
Modeling
Water vapour

ABSTRACT

Modified atmosphere and humidity packaging (MAHP) is used to extend shelf life and maintaining the quality of fresh fruits and vegetables by modifying desired gas concentration and relative humidity (RH) inside fresh produce package. Several factors affect the optimum design of MAHP, most of which are time and or temperature dependent. Hence, there is a vital need for a simulation tool that includes all affecting parameters and their interactive behavior on package gas composition and water vapour. In this study a comprehensive simulation program based on integrative mathematical modeling is presented. A number of validation experiments were conducted to evaluate the robustness of the simulation program under constant and varying temperature conditions during storage period and predict gas composition, humidity and moisture condensation dynamics in packaged strawberry and plum. The simulated results were satisfactory with those obtained experimentally. The validated simulation program was then used for optimization of modified humidity packaging for both plum and strawberry. The predicted equilibrium headspace humidity was 94.0 and 98.8% for strawberries and plums, respectively which was very close to measured values of 93.5 and 94.1%, respectively. Therefore, the simulation program was found to be a convenient tool to virtually test the package under a broad range of environmental conditions such as temperature and RH resembling real supply chain conditions and ensure proper selection of packaging systems for the optimum performance.

1. Introduction

Several factors affect post-harvest quality of fresh produce. Amongst them, some biological phenomena such as respiration and transpiration are of great importance. Respiration is a metabolic process that provides energy for plant biochemical processes (Fonseca et al., 2002). One important consequence of respiration on fresh produce quality is weight loss of produce, due to oxidative breakdown of substrate molecules such as starch, sugars, and organic acids to simpler molecules such as CO_2 and H_2O. This process generates some heat as well, major part of which leaves produce surface by evaporating water vapour from surface layers (Kader and Saltveit, 2003). Also fruits continuously lose water to the atmosphere by transpiration since ambient atmosphere normally has a much lower water potential than produce surface (Rodov et al., 2010). Water loss is one of the main causes of commercial and physiological deterioration of fresh produce, in the form of wilting, shriveling, and decrease of stiffness, turgidity and succulence (Rodov et al., 2010).

Modified atmosphere packaging is an active or passive dynamic process of modifying gaseous composition within a package. Passive approach just relies on natural initial gaseous composition as well as the interaction between the respiration rate of the produce, and the permeation of gases through the packaging material especially packaging film, while in active approach, gases of desired composition are additionally flushed into the package in order to achieve faster equilibrium atmosphere (Caleb et al., 2012; Farber et al., 2003; Mahajan et al., 2007). However, improper control of respiration may lead to undesirable results from low level of O_2 and consequently anaerobic respiration, accelerated physiological decay, and shortened shelf life (Song et al., 2002). Resistance of a plastic film for water vapour permeation usually far exceeds that of produce surfaces. Therefore, most water molecules evaporated from the produce do not escape through the film and remain within the package space, enhancing the water vapour pressure in the package headspace and or condense on fruit and tray wall surfaces,

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[*] Corresponding author.
[**] Corresponding author.
E-mail addresses: seiidloo@tabrizu.ac.ir (S. Seiiedlou), pmahajan@atb-potsdam.de (P. Mahajan).

http://dx.doi.org/10.1016/j.jfoodeng.2017.03.007
0260-8774/

which accelerates spoilage and considerably shortens storage life (Ben-Yehoshua et al., 1998; Kleinhenz et al., 2000; Rodov et al., 2010; Xu and Burfoot, 1999). Hence, modified atmosphere and humidity packaging (MAHP) is used to modify package humidity in addition to gas composition, in order to control the amount of transpiration by decreasing water potential difference and hence preventing water loss (Ben-Yehoshua et al., 1996; Morris and Jobling, 2000; Rodov et al., 2003).

There have been few studies on relative humidity (RH) and condensation in modified atmosphere packaging of fruits and vegetables. Song (1995) presented a mathematical modeling approach based on heat and mass transfer for respiration and transpiration behavior to predict RH in MAP of fresh produce. They could successfully validate the model for blueberry and stated that RH can't be controlled well below 100% using commercial packaging films they used. Song et al. (2001) later modified the model presented by Song (1995) based on respiratory and transpiratory behavior of the fresh produce, the transport phenomena across the package, and the moisture sorption behavior of two commercially available moisture absorbent. Although model predictions agreed well with experimental results, but no further attempts were made to determine the amount of condensation. This can be due to the fact that model predictions showed that the temperature variation was not significant at fruit surface and hence no condensation occurred. Lu et al. (2013) presented a model based on heat and mass transfer for predicting RH within the package. Except for initial period, their model agreed well with experimental data. The package headspace was chosen small; therefore, they neglected the needed time to achieve thermal equilibrium and accordingly condensation occurrence. In contrast, Linke and Geyer (2013) identified the intensity and retention time of condensation on fruit surface, internal film and tray wall surfaces as main determinant of condensation dynamics in fresh produce packaging under fluctuating ambient temperature. However, only experimental approach was used to measure the condensation formation under varying experimental conditions while suggesting mathematical modeling as a future scope. Mathematical modeling approach needs several factors and parameters for simulating condensation dynamics (Table 1), most of which are time and or temperature dependent. Hence the aim of this study was to develop a simulation tool based on integrative mathematical modeling to predict the packaging headspace gas composition and relative humidity (RH), as well as condensation dynamics in fresh produce package headspace. Such a simulation tool was then applied for packaging design for strawberries and plums under varying environmental conditions such as temperature and relative humidity, resembling realistic conditions in fruit supply chain.

2. Model development

2.1. Rate of moisture loss from product

Fresh produce continues to lose moisture after harvest due to both transpiration and respiration (Bovi et al., 2016). Aerobic respiration (i.e., biological oxidation) is the oxidative breakdown of complex substrate molecules such as starch, sugars, and organic acids-to simpler molecules such as carbon dioxide and water and regeneration of ATP from ADP (adenosine diphosphate) and Pi (inorganic phosphate). If hexose sugar like glucose coming from stored simple sugars (e.g., glucose, sucrose) or complex polysaccharides (e.g., starch), is used as the substrate, the overall equation can be written as Eq. (1):

$$C_6H_{12}O_6 + 6\,O_2 + 38\,ADP + 38\,Pi \rightarrow 6\,CO_2 + 6\,H_2O + 38\,ATP + 2816\,kJ \tag{1}$$

For respiratory oxidation of 180 g (1 mol) of glucose, 192 g (6 mol) of O_2 is consumed which diffuses into the tissue from surrounding atmosphere, while 264 g (6 mol) of CO_2 diffuses out. The 108 g (6 mol) of H_2O produced is simply incorporated into the aqueous solution of the cell. From the 2816 kJ that is capable of doing work, around 1176 kJ (41%) is used to produce 38 ATP molecules (38 ATP × 30.96 kJ/ATP) and remaining 1640 kJ (57%) is lost as heat (Kader and Saltveit, 2003). If all of the heat produced leaves the tissue by vaporizing water, the rate of moisture loss due to respiration can be related to produce respiration rate as shown in Eq. (2).

$$\frac{dM_{rr}}{dt} = \frac{R_{CO2}\,W_p}{264} \times \frac{1640}{H_v} = \frac{R_{CO2}\,W_p\,(1640/264)}{(-6.14\times10^{-5}T^3 + 1.58\times10^{-3}T^2 - 2.36T + 2500.7)\times10^{-3}} \tag{2}$$

where the dominator of right hand fraction is equal to H_v as a function of temperature (Yau and Rogers, 1996). Total weight loss is the sum of moisture loss by respiration heat, carbon loss from substrate oxidation minus water produced in respiration reaction

Table 1
Variables affecting design of modified atmosphere and modified humidity packaging for fresh fruit and vegetables.

Fresh produce:
- Physiological properties (respiration and transpiration rate models, water activity)
- Physical properties (weight, density, volume, surface area, geometrical shape)
- Thermal properties (specific heat, thermal conductivity and diffusivity, surface convective heat and mass transfer coefficient)

Package system:
- Physical properties of tray (weight, volume, surface area, geometrical shape)
- Physical properties of lidding film (thickness, surface area, permeability to gases and water vapour, micro and macro-perforations)
- Physical properties of humidity absorbers (absorption kinetic models)
- Thermal properties of packaging materials (specific heat, thermal conductivity and diffusivity, surface convective heat transfer coefficient)

Ambient storage conditions:
- Temperature and relative humidity of air surrounding the package
- Gas composition (O_2 and CO_2)
- Air flow speed around the package