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Real-time monitoring of organic apple (var. *Gala*) during hot-air drying using near-infrared spectroscopy

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ABSTRACT

Dried apple (*Malus domestica* B.) shows a growing trend to its worldwide consumption as raw material used to produce organic snacks, integral breakfast foods, chips, etc. Apple is often dried by conventional methods (e.g. hot-air drying, freeze-drying, etc.), which are usually uncontrolled and then prone to product quality deterioration. Thus, to allow the production of high-value end products, there is a need for developing new drying systems. In this study, it was investigated the feasibility of an implementation of NIR spectroscopy in smart drying systems to non-destructively detect and monitor physicochemical changes in organic apples wedges during 8-h hot-air drying at 60 °C. Moreover, the impact of microwave heating pre-treatment (at 850 W for 45 s) as enzyme inactivators on model performances was also evaluated. Partial least squares (PLS) regression models were successfully developed to monitor changes in water activity ($R^2 = 0.97–0.98$), moisture content ($R^2 = 0.97–0.98$), SSC ($R^2 = 0.96–0.97$) and chroma ($R^2 = 0.77–0.86$) during drying. Classification analysis was performed for the development of discriminant models able to recognise dehydration phases of apple wedges on the basis of their spectral profile. The classification models were computed using K-means and Partial Least Squares Discriminant Analysis (PLS-DA) algorithms in sequence. The performance of each PLS-DA model was defined based on its accuracy, sensitivity and specificity rates. All of the selected models provided a very-good (>0.90) or excellent (>0.95) sensitivity and specificity rates for the predefined drying phases. Feature selection procedures allowed to obtain both regression and classification models with performances very similar to models computed from the full spectrum. Results suggest that effect of microwave heating on both water loss and microstructure of apple tissue was pronounced, mainly affecting the features selection procedure in terms of number of features and selected wavelengths.

1. Introduction

Globalization of markets entails the availability of horticultural products regardless of their harvest date, pursued through innovation in products and processes to obtain fruit and vegetables with improved shelf-life, organoleptic quality, nutritional value, safety and healthiness during the whole agri-food chain. Consequently, market value of perishable commodity mainly depends on the preservation method used to guarantee food stability and, thus, to delay physicochemical, biochemical and microbiological spoilage. In fact, the preservation method directly affects processing, storage, transportation and distribution costs.

Among postharvest operations, drying is one of the oldest, typical, effective and viable preservation processes throughout the world. It consists of three main interlinked steps that can be summarized as: (1) product formulation or treatment selection, (2) dehydration process and (3) quality and properties assessment (Aghbashlo et al., 2015). Drying prevents both food spoilage and decay through moisture removal due to simultaneous heat and mass transfer, allowing foods to be stored for long periods with minimal deterioration occurring (Nadian et al., 2015). Moreover, drying is particularly effective in enabling storability of food at room temperature and in simplifying the handling of the products through their reduction of weight and packaging volume (Liu et al., 2016). Drying technology may vary from simple methods (e.g. sun drying) to relatively advanced techniques (e.g. instant controlled

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pressure drop drying); nevertheless, modern technology schemes are not always paired with good/excellent quality and high commodity value (Chong et al., 2014; Nadian et al., 2015). In fact, drying is a relatively complex, dynamic, unsteady and nonlinear process that may suffer from properties of wet material, scale of production and compliance with regulations, as well as operating and environmental conditions (Aghbashlo et al., 2015). These factors may be responsible for quality degradation, with a reduction of consumer acceptance as a result of the undesirable changes in colour, texture, size and shape as well as the organoleptic, nutritional and functional properties (Brosnan and Sun, 2004; Vega-Gálvez et al., 2012). Last but not least, drying is one of the most energy-intensive processes in food industry (Akpinar et al., 2003); in fact, it adversely effects climate change as most dryers use fossil fuels (Mujumdar, 2012). Consequently, new drying technologies must be designed around the quality attributes of the raw material to ensure valuable products at the highest drying rate and the lowest carbon footprint, which means minimal/optimal energy demand and negligible environmental impact (Mujumdar, 2012; Su et al., 2015). Among emerging drying technologies, smart drying is one of the newest and most promising techniques. It consists in at-/in-/on-line implementation of innovative and reliable sensors, resources, tools and practices, which allow to monitor and control the dryer operating conditions to yield high-value dried products while enhancing energy conservation and environmental sustainability. Smart drying is a multi- and inter-disciplinary sector and its recent developments embrace the following R&D areas: artificial intelligence (Aghbashlo et al., 2015), biomimetic (Ghasemi-Varnamkhasti et al., 2010), computer vision (Brosnan and Sun, 2004), microwave/dielectric spectroscopy (Jha et al., 2011), visible (Vis) and near-infrared (NIR) spectroscopy (Nicolaï et al., 2007), hyper-/multi-spectral imaging (ElMasry and Sun, 2010), magnetic resonance imaging (Clarka et al., 1997; Su et al., 2014), ultrasound imaging (Awad et al., 2012), electrostatic sensing (Chen et al., 2013) and control system for drying environment.

Among commercial fruits, apple shows a growing trend in worldwide consumption. Dried apple in particular plays a major role in food industry as raw material in the production of snacks, integral breakfast foods, chips, etc., which became popular in the diet of modern consumers (Vega-Gálvez et al., 2012; Yi et al., 2015) in parallel with the human consumption of organic products (Sacilik and Elicin, 2006). Despite apple tissue exhibits extensive and not homogeneous discoloration during drying (Fernández et al., 2005), it is nowadays often dried by conventional methods (e.g. hot-air drying, freeze-drying, etc.) which, however, are usually uncontrolled and then prone to product quality deterioration as well as the fact of being affected by a number of drawbacks, such as very long drying time and, of course, high energy demand (Chong et al., 2014; Nadian et al., 2015). Thus, treatment selection before apple drying is a mandatory (but not sufficient) step to obtain a high-value end product. However, since the European Organic Regulation does not allow every conventional drying pre-/treatments on production and labelling of organic products (i.e. EC No. 834/2007 and EC No. 889/2008), drying of organic apples should be carefully optimized in order to obtain comparable results to conventional methods in terms of quality and safety of the final product.

Therefore, the main objective of the proposed study was to investigate the feasibility of near-infrared spectroscopy (NIR) to proactively and non-destructively detect and monitor quality change in organic apple wedges during hot-air drying. Based on authors' best knowledge, apple drying has been widely addressed in literature; nevertheless, little insight is available on smart drying of apples since many authors focused their attention only on monitoring browning development through computer vision (Aghilinategh et al., 2016; Gao et al., 2017, 2016; Wang et al., 2017), while knowledge of its potential use in the organic sector is totally lacking. Consequently, NIR spectroscopy coupled with chemometrics was investigated as a proved and versatile at-/on-/in-line tool with high sensitivity to changes in moisture content, particle size and chemical/physicochemical state of food (Ozaki et al., 2006).

2. Materials and methods

2.1. Sample preparation

Organic apples (*Malus domestica* B. var. Gala) were purchased from an Italian organic farm (La Parrina, Grosseto, Italy), and immediately stored at 4 ± 1 °C until processing. Fruit sampling was performed by selecting sound apples, with uniform size and same ripening stage. Fruits were tempered to room temperature 15 h before starting the experimental activities.

Apple wedges (Fig. 1a), without core and peel, were prepared by washing and cutting fruit into discs (5-mm thick) and subsequently dividing each disc into quarters using a cork borer and a sharp ceramic knife. Samples were visually evaluated for quality assessment and only apple wedges free from decay and/or blemish were used in the experimentation to perform (1) hot-water blanching and microwave heating treatments and (2) hot-air drying tests.

About 100 g of apple wedges were used for both hot-water and microwave treatment experiments, while 270 apple wedges were randomly arranged into 9 batches of 30 samples each for the use in drying experiment. Fruit wedges were subjected to 8-h hot-air drying and batch sampling was performed at 0, 1, 2, 3, 4, 5, 6, 7 and 8 h drying. Each batch was subjected to both NIR spectral data acquisition and determination of CIELab colour, moisture content, water activity (a_w) and soluble solids content.

2.2. Treatment before hot-air dehydration

2.2.1. Hot-water blanching

Hot-water blanching (Fig. 1b) consisted of dipping apple wedges in hot-water with a temperature controlled water bath (Astor 800D, Astori Tecnica, Brescia, Italy). As a control, apple wedges were dipped in distilled water at room temperature. The experimental plan (i.e. 14 different temperature and time combinations) is reported in Table 1. Treated samples were immediately cooled for 3 min in ice-water, and the residual POD enzymatic activity was evaluated.

2.2.2. Microwave heating

A turntable domestic microwave oven (MT243, Whirlpool Co., Michigan, United States) with a continuous output-power (2450 MHz, 1000 W) was used to treat apple wedges (Fig. 1b). An experimental design based on a factorial design (i.e. 15 different power and time combinations) was applied (Table 1). Powers and times of treatment were chosen by taking into consideration the results of preliminary experiments aimed at identifying proper process conditions to allow apple wedges to be uniformly treated. After treatment, apple wedges were removed from the microwave oven and immediately dipped in ice-water for 3 min to accelerate cooling. Residual POD activity was then evaluated.

2.3. Peroxidase activity

Blanching treatments were set up to ensure a peroxidase inactivation of 90%. This level of inactivation was fixed as threshold in order to allow the produce to be stable and, thus, in line with industrial requirements (Benlloch-Tinoco et al., 2013).