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Detection of pits in fresh and frozen cherries using a hyperspectral system in transmittance mode

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A B S T R A C T

The aim of this study was to develop an improved method for detecting internal intrusions (pits and their fragments) in cherries using hyperspectral imaging technique in transmittance mode. Hyperspectral transmission images of pitted and intact cherries of three popular cultivars: ‘Łutówka’, ‘Pandy 103’, and ‘Groniasta’, differing by soluble solid content (SSC), were acquired in the visible and near-infrared (VNIR) range (450–1000 nm). The Correlation-based Feature Selection (CFS) algorithm and 2nd derivative pretreatments of the hyperspectral data were used to construct the supervised classification models. From all the studied classifiers, the best prediction accuracies for whole pit or pit fragment detection were obtained by the backpropagation neural network (BNN) model (94.6% of correctly classified instances for fresh samples and 83.3% for frozen samples). The accuracy of distinguishing between drilled and intact cherries was higher than 87% jointly for fresh and frozen cherries. These results showed that hyperspectral imaging in transmittance mode is an accurate and objective tool for pit detection in fresh and frozen cherries and can be applied in on-line sorting systems.

1. Introduction

Fresh fruits are highly perishable commodities and require special attention to keep their quality and safety for consumption. Cherries can be consumed raw or used in desserts, but they can also be processed into preserves, dried, candied or frozen. Frozen storage is recognized as an effective method of preserving cherries for longer shelf life. Total European production of cherries reaches 655,000 tonnes, with 80% intended for freezing (Gheju et al., 2016). Among the EU member states, the main producers of cherries are Poland, Spain, and Italy, followed by Greece, Hungary, and Germany. For instance, Poland produces up to 188,000 tonnes of cherries per year and about 10,000 tonnes are exported as fresh fruits and 66,000 tonnes as frozen fruit (Rzeźnik et al., 2016). Customers require safe and high quality food products and such products are considered a key factor for success in today's highly competitive markets. Consumers are ready to pay more for fruits and vegetables of superior quality when safety is guaranteed (Grunert, 2005). The food industry is faced with a number of challenges connected with the maintenance of high quality standards and safety assurance during post-harvest processing (Lewis et al., 2007). To meet these challenges, food companies need efficient, low-cost and non-invasive food inspection technologies for fresh and frozen products. These requirements can be accomplished by a hyperspectral imaging system (Sun, 2010) which is recognized as a rapid method to display the chemical structure and physical properties of different types of food (ElMasry and Nakauchi, 2016).

Hyperspectral imaging, also known as imaging spectroscopy, is a technique based on chemical sensing and imaging technologies which provides spectroscopic analysis of each pixel within the image of a sample (ElMasry et al., 2012). This technique allows one to obtain spectral and spatial information from an object in one of the following ranges: ultraviolet (UV), visible and near-infrared (VNIR), and short-wave infrared (SWIR) (Bannon, 2009; Ravikanth et al., 2017). Compared to traditional visible/near-infrared spectroscopy that essentially relies on spot measurement, hyperspectral imaging has more advantages for evaluating the whole surface of individual food items (Feng and Sun, 2013).

Hyperspectral imaging can be carried out in reflectance, interactance or transmittance modes (Nicolai et al., 2007). In reflectance mode, the ratio between the intensities of reflected and incident light is measured. In this mode, the light penetrates several millimeters of the sample, but the measured signal mainly reflects its

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surface properties. In interactance mode, the light is transmitted into the sample and the backscattered light that reaches the surface is measured. In this case, the penetration depth, which can be several millimeters, guarantees spectral information from inside of the sample (Segtnan et al., 2009; Wang et al., 2012). In transmittance mode, the ratio between the intensity of light that crosses through the sample interior and the intensity of light that illuminates the sample is measured (Yoon et al., 2008; Fernandes et al., 2011).

In recent years, hyperspectral imaging has been recognized as a powerful technique for evaluating the quality and safety of agricultural products, including raw and processed fruits (Abbott, 1999; Sun, 2012). The majority of the studies were carried out in reflectance mode and in the VNIR range (900–1100 nm). Hyperspectral imaging was successful in determining the maturity and harvest time of fruits on the basis of some important quality attributes, such as firmness (FI) and soluble solid content (SSC). Peng and Lu (2008) used a hyperspectral imaging system in scatter mode to predict FI and SSC of apples. They used over 20 wavelengths and obtained a prediction of FI and SSC with a correlation coefficient of 0.85. Another important factor which determines the quality and price of fruits is the presence of defects and diseases within their tissues. Qin et al. (2011) developed a multispectral method to inspect citrus canker based on hyperspectral imaging data in the spectral region of 450–930 nm and achieved an overall classification accuracy of 96%. A number of studies have reported using near infrared (NIR) spectroscopic techniques for detection of surface defects, such as bruising in apples (Lu, 2003; ElMasry et al., 2008; Baranowski et al., 2012), pears (Zhao et al., 2010), peaches (Sun et al., 2017), and kiwifruit (Lu et al., 2011). Absorbance images have also been used to distinguish foreign materials (leaves and stems) from blueberries (Sugiyama et al., 2010).

Reflectance mode is used in the majority of applications connected with fruit quality analysis, but more and more interest is focused on transmittance mode to monitor the external and internal features of fruits. A hyperspectral imaging system in transmission mode is more desirable in many cases because in this mode light passes through the fruit and gives information about the internal features of the tissues. A technique based on transmittance mode in the spectral region of 651–1282 nm has been used as a nondestructive method for identifying brown core in pears (Han et al., 2006). The highest classification accuracy of 95.4% was achieved using two optimal wavelengths: 713 nm and 743 nm. Qin and Lu (2005) indicated that the spectral region between 690 nm and 850 nm was most appropriate for cherry pit detection. Transmittance mode has also been used to predict the internal quality of fruits such as mandarins (Liu et al., 2010; McGlone et al., 2003), kiwifruit (Moghimi et al., 2010), and apples (Fan et al., 2009). Leiva-Valenzuela et al. (2014) used a hyperspectral imaging system in reflectance and transmission modes in the spectral region of 400–1000 nm to determine SSC and FI in blueberries. In this research, reflectance mode gave better results (the best correlation for prediction of 0.90 for SSC and 0.78 for FI) than transmittance mode (0.76 for SSC and 0.64 for FI).

Many studies have reported attempts to detect pits and their fragments in cherries. Based on the method developed and patented by Allen et al. (1966), Law (1973) confirmed that near-infrared radiation from 800 to 830 nm was appropriate for detecting pits in cherries. Different methods, including microwave transmission, ultrasound reflection, light-beam interruption, light-beam transmission and machine vision, were studied by Timm et al. (1991). Of these, light transmission coupled with machine vision and image analysis was most effective in differentiating pitted and unpitted cherries; the detection accuracy was close to 95%. Finally, nuclear magnetic resonance (NMR) has been used to identify pits in olives (Zion et al., 1997). The accuracy of this method was 97%, this method however is costly and unlikely to be adapted by the industry. Pit and pit fragments can also be detected using computer tomography (CT). Donis-González et al. (2015) demonstrated that pit fragments as small as 3.01 mm could be detected using CT imaging. The authors showed that CT technique allows distinguishing pit and pit fragment size with a high accuracy rate ($R = 0.99$). Because of its economic cost and lack of speed, CT imaging has proven to be non-practical to be implemented as real time food inspection technology.

Detection of pits in dried fruits has been also studied. For instance, Haff et al. (2005) described a device for nondestructive detection of pits in dried plums. This device compressed the fruit between a roller and a force transducer, but the requirement to restrict the compression of the fruit precludes the possibility of detecting small pit fragments. More recently, Haff et al. (2013) demonstrated the feasibility of using one-dimensional X-ray inspection technique that can identify cherries still containing pits. They obtained recognition rates of 97.3% for pitted and 94% for unpitted cherries with a total error rate of 3.5%. The method described above has a number of disadvantages, including its relatively high cost, the need for radiation shielding and the dangers inherent in using radiation, and the need for high voltage power supplies to generate X-rays (Haff and Toyofuku, 2008).

Only a few devices for pit detection in pitted cherries are available on the market and manual sorting is still being used. Most of commercial pit detection systems use X-ray imaging or the visible range of the spectrum. However, these methods do not guarantee proper accuracy. Therefore, a fast and accurate method for detecting pits and pit fragments in fresh and frozen fruits is a great need.

The objective of this research was to examine the applicability of hyperspectral imaging in the VNIR wavelength range for detecting pits in fresh and frozen cherries of three selected cultivars. The specific aims of this study were:

- to automatically select the optimum sets of wavelengths for supervised classification of fresh and frozen cherries;
- to distinguish between cherries with pits, pit fragments and without pits by using supervised classification models based on VNIR hyperspectral transmission data;
- to investigate how the differentiation in SSC of the three cherry cultivars studied influences the accuracy of detecting pits/pit fragments.

2. Materials

Fruits of three cherry (*Cerasus Mill.*) cultivars: 'Łutówka', 'Pandy 103', and 'Groniasta', were collected from a local fruit and vegetable cold storage plant, Fructosad, Ratoszyn, Poland. Cherries were visually inspected for their surface colour, appearance defects, and size. The cultivars were selected based on the difference in their physical properties, especially SSC (Wojdyło et al., 2014). Only fruits free of visual defects (no bruises, cracks of diseases) were used in the experiment. Skin colour of the cherry fruits was measured using a Lovibond CAM-System 500 imaging colorimeter (Tintometry Ltd., UK). The differences in colour resulted mainly from the natural cultivar-specific differences and no significant differences in colour were observed within each cultivar. It was expected that cherry size differences could strongly influence pit detection (Qin and Lu, 2005) and therefore cherries with a large range of sizes (diameter ranging 15–22 mm) were used in each variant of the experiment, which represented 99% of all available cherries. A total of 1080 fresh and frozen fruits were used in this study. Each cultivar was divided

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