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Review

Use of hyperspectral imaging for evaluation of the shelf-life of fresh white button mushrooms (*Agaricus bisporus*) stored in different packaging films

Masoud Taghizadeh [a,*], Aoife Gowen [a], Patrick Ward [b], Colm P. O'Donnell [a]

[a] *Biosystems Engineering, School of Agriculture, Food Science and Veterinary Medicine, University College Dublin, Belfield, Dublin 4, Ireland*
[b] *Holfeld Plastics Ltd., Avoca River Park, Arklow, Co. Wicklow, Ireland*

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ABSTRACT

The shelf life of mushrooms packaged using different polymer top-films (PVC, PET with different levels of perforations) was investigated using hyperspectral imaging (HSI). Packaged mushrooms were stored at 4 ± 0.2 °C for 14 days and weight loss, Hunter *L*, *a*, *b* values, maturity index and in-pack gas composition (% CO_2 and O_2) were also measured. The results obtained showed that the PET film perforated with small holes (1 mm in diameter) was generally superior in terms of maintaining overall mushroom quality. Regression models were built to correlate HSI data with measured quality parameters. Prediction maps were generated from hyperspectral data to show the model performance at pixel level. Results presented in this work show hyperspectral imaging can be used to evaluate the effect of different packaging systems on mushroom quality and that perforated PET packaging film is a viable alternative to the conventional PVC packaging, facilitating an increase in shelf life from 10 to 14 days.
Industrial relevance: The present study demonstrates HSI can be used for rapid evaluation of mushroom quality facilitating non-destructive evaluation of the effect of packaging systems on mushroom shelf-life. In addition, this work suggests an effective packaging solution to extend shelf life of mushrooms during storage. The proposed solution potentially improves the packaging recyclability as the same polymer material (PET) is used for the tray and top film, compared to conventional mushroom packaging where PVC is used for the top film and polypropylene (PP) for the tray.

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* Corresponding author. Tel.: +353 1 7167364; fax: +353 1 7167415.
E-mail address: masoud.taghiza@ucd.ie (M. Taghizadeh).

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1. Introduction

Mushrooms (*Agaricus bisporus*) have a short shelf life of less than 3 days at ambient temperature (Lee, 1999) and from 8 to 10 days under refrigeration conditions (Burton, 1989). They are highly perishable due to their thin and porous epidermal structure resulting in high respiration rates which induce deterioration immediately after harvest. More importantly, the high tyrosinase and phenolic content of mushrooms makes them prone to enzymatic browning (Brennan, Le Port, & Gormley, 2000) which is the major cause of quality losses that accounts for reduction in market value (Mohapatra, Frias, Oliveira, Bira, & Kerry, 2008). Therefore, mushrooms need special attention to retain freshness (Kim, Ko, Lee, Park, & Hanna, 2006). There are several indicators that determine the quality of mushrooms, such as visual appearance, size, colour, maturity stage, development stage, microbial growth and weight loss (Aguirre, Frias, Ryan, & Grogan, 2008). Gormley and O'Sullivan (1975) reported the relationship between different quality levels in mushrooms (*A. bisporus)* and Hunter *L*-value; mushrooms with an *L*-value greater than 93 were classified as excellent, an *L*-value between 90 and 93 as very good, an *L*-value between 86 and 89 as good, an *L*-value between 80 and 85 as reasonable and *L*-value between 69 and 79 as poor. This criterion can be used as an indicator of mushroom shelf life; for example mushrooms with an *L*-value less than 80 would not be acceptable at wholesale level. This grading method is the most frequently used indicator of mushroom shelf-life, both in the industry and research (Aguirre et al., 2008). Although there is no such defined level of acceptability for WL as there is for *L*-value, from a producer's point of view it is desirable to retain the maximum weight possible.

Hyperspectral imaging (HSI) is a novel technique which combines conventional imaging and spectroscopy to simultaneously acquire both spatial and spectral information from an object. This technology has recently been applied as a powerful process analytical tool for rapid, non-contact and non-destructive inspection of internal and external attributes of food and agricultural products including mushrooms (Taghizadeh, Gowen, & O'Donnell, 2009). HSI offers many advantages over conventional analytical methods. It is a non-contact, non-destructive method, which enables multi component information to be obtained from a sample. Moreover, the ability to identify the spatial distribution of multiple chemical and physical components in a sample makes HSI stand out over traditional analytical methods (Gowen et al., 2008; Qin, Burks, Ritenour, & Bonn, 2009).

Packaging, coating, refrigeration and dipping in sorbitol are the most common methods used for extending the shelf life of mushrooms (Eissa, 2007; Gormley & O'Sullivan, 1975; Mau, Miklus, & Beelman, 1993; Roy, Ramaswamy, Shenk, Westerhaus, & Beelman, 1993). Appropriate packaging can delay development of deterioration and senescence of mushrooms after harvest. Nichols and Hammond (1973) reported that over-wrapping with polyvinyl chloride (PVC) film increased the shelf life of mushrooms by retarding cap opening, discoloration and reducing weight loss. Although different films have been utilized, PVC is still the most commonly employed commercial packaging film for mushrooms (Simon, Gonzalez-Fandos, & Tobar, 2005). Xing, Wang, Feng and Tan (2008) studied the effect of different packaging films on post harvest quality of *Hypsizygus marmoreus* mushrooms. They studied 5 different non-perforated packaging films: PVC, 2 types of polyethylene with different thicknesses (PE6 and PE11), polyoletin (PO) and biaxially oriented polypropylene (BOPP) to over-wrap mushrooms. They reported that the selection of packaging film is critical in optimising postharvest quality and shelf life of *H. marmoreus* mushrooms, finding BOPP film to be superior in terms of maintaining overall quality. However, for highly respiring products such as mushrooms, packaging in some non-perforated polymer films (e.g. polyethylene polypropylene) may encourage anaerobic conditions within the packaged goods in a short period of time. This enhances production of off-flavours and the potential growth of anaerobic pathogens.

Some researchers have investigated the effect of modified atmosphere packaging (MAP) on fresh mushrooms (Kim et al., 2006; Barron, Varoquaux, Guilbert, Gontard, & Gouble, 2002; Roy, Anantheswaran, & Beelman, 1995; Lopez, Varoquaux, Bureau, & Pascat, 1993). Active MAP involves modification of the gas composition through initial gas flushing or the introduction of a gas scavenging system within the package; in passive MAP the gas composition is altered due to the combined effects of product respiration and permeability of the packaging film (Charles, Guillaume, & Gontard, 2008). Active MAP has been demonstrated to be beneficial for some products; however it may not be suitable for mushrooms due to their high respiration rates (Halachmy & Mannheim, 2006). Perforated polymer films have been developed to improve gaseous diffusion of O_2 and CO_2 across the film (i.e. passive MAP), which prevents anaerobic respiration of the packaged produce (Deepark & Shashi, 2007; Mahajan, Oliveira, Montanez, & Frias, 2007).

Simon et al. (2005) investigated the effect of passive MAP on the quality of sliced mushrooms using different packaging films including perforated and non perforated PVC, and 2 types of micro perforated PP with O_2 permeabilities of 45,000 and 2400 $cm^3\ m^{-2}\ day^{-1}\ 0.1\ MPa^{-1}$ (film thickness 35 μm) respectively. Analysis of variance showed that film type had no significant effect on the CIE *L*-value (luminosity) in the slices, while the measured texture parameter (i.e. shear force) was considerably affected by film type. Overall, the PP film with lower O_2 permeability was found to be the best film for maintaining quality attributes of fresh sliced mushrooms. The authors stated that an in-pack gas composition of 2.5% CO_2 and 10–20% O_2 resulted in reduced microbial growth and improved mushroom appearance.

Although polyethylene terephthalate (PET) is frequently used as a food packaging material (Mutsuga, Tojima, Kawamura, & Tanamoto, 2005), the use of PET for mushroom packaging has not been reported. PET is becoming increasingly utilized because of its excellent barrier, appearance and mechanical properties, low weight and price (Kucuk & Caner, 2005) and enhanced potential for recycling (Hopewell, Dvorak, & Kosior, 2009). Due to current pressure on retailers to remove PVC from their packaging (CHEJ, 2009) and the potential of PET trays to be converted to low grade plastics (Fortelný, Michalkova, & Kruliš, 2004), adoption the packaging used in this study (i.e. PET top film and PET trays) would help the industry to move towards a more sustainable packaging alternative. The objective of this study was to use hyperspectral imaging to investigate the effect of PET top film with different levels of perforations on the shelf life of white button mushrooms as compared with the conventional PVC top film.

2. Materials and methods

2.1. Sample preparation

A. bisporus spp. mushrooms were grown in plastic bags and tunnels in Kinsealy Teagasc Research Centre (Malahide, Co. Dublin, Ireland). Spawn running and casing took place throughout the 6 weeks prior to mushroom cropping. A total of 720 damage free mushrooms, each with a diameter of 3–5 cm, were harvested in January–February 2009. Harvesting was carried out at 3 different times (January 27th, February 3rd and February 10th) with 240 mushrooms per harvest. For each harvest 240 mushrooms were subdivided into 40 PET trays (6 mushrooms in each tray). The 40 trays were subdivided into 4 groups of 10 trays; each group being wrapped with a different packaging film. The following film types were investigated: non-perforated plasticised PVC (Linpac Plastics Ltd. UK, thickness = 18 ± 1 μm) and 3 types of PET (Dupont Plastics Ltd. UK, thickness = 30 ± 1 μm) packaging film: non-perforated PET (PET_nh), perforated PET with holes of 9 mm in diameter (PET_bh, 170 holes per m^2) and perforated PET with holes of 1 mm in diameter (PET_sh, 140 holes per m^2). Typical oxygen transmission rates

for PVC (plasticised) and PET are 500 $cm^3\ m^{-2}$ 0.1 $MPa^{-1}\ day^{-1}$ and 110–130 $cm^3\ m^{-2}$ 0.1 $MPa^{-1}\ day^{-1}$ for films of 25 μm thickness measured at 25 °C (Blakistone, 1999). Samples were stored at 4± 0.2 °C, evaluated at 5 different time points (days 1, 4, 7, 10 and 14 of storage) and at each time point, 2 packages (i.e. 12 mushrooms) of each film type were analysed.

2.2. Hyperspectral imaging system

A hyperspectral imaging system (DV optics, Padua, Italy) in the Vis–NIR range (400–1000 nm) was employed in this study. The main components of this system are: objective lens, spectrograph, detector, acquisition system, moving table, and illumination via fiber optic line lights (schematic of hyperspectral imaging system used can be found in Gowen et al., 2008). Hyperspectral images were obtained in the aforementioned wavelength range with a spectral resolution of 5 nm. The effective resolution of the charge-coupled-device (CCD) detector was 580×580 pixels by 12 bits. Hyperspectral images of mushrooms were obtained at each sampling point. A black sample holder was designed to provide contrast between mushrooms and their background and mushrooms of each batch then were placed on it; with 6 mushrooms being scanned in each image (Fig. 2), each scan taking approximately 1 min.

The noise characteristics of the sensor were investigated by acquiring 50 scans of the calibration tile over a time period of 1 h. Signal to noise ratio was lowest at the upper (950–1000 nm) and lower (400–445 nm) wavelength ranges; in these regions the noise level exceeded 2% of the signal. This is due to the decreased CCD detector sensitivity in these wavelength regions. Due to this noise, subsequent analysis of spectra was performed only on data in the 445–945 nm range. In order to account for the non-linear sensitivity of the CCD camera a two point reflectance calibration was performed (Ariana, Lu, & Guyer, 2006). The bright response ('W') was obtained by acquiring a hypercube from a uniform white ceramic tile (the reflectance of which was pre-calibrated against a tile of certified reflectance (Ceram Research — UK); the dark response ('D') was acquired by turning off the light source, completely covering the lens with its cap and recording the camera response. This was done prior to image acquisition at each time point. The corrected reflectance value (R) was calculated from the measured signal ('I') on a pixel-by-pixel basis as shown below (Ariana et al., 2006):

$$R_i = (I_i - D_i) / (W_i - D_i)$$

where i is the pixel index, i.e. $i = 1, 2, 3, \ldots, n$ and n is the total number of pixels.

The average reflectance (R) spectrum from the total surface of each mushroom was calculated using MATLAB 7.0 (The Math Works, Inc. USA). In order to separate the mushroom from the image background, the hyperspectral images at each wavelength were pre-processed by masking. The mask was created by thresholding the mushroom image at 800 nm (images at this wavelength provided good contrast between mushroom and background) and setting all background regions to zero. Non-zero elements of the image were then extracted and the mean spectrum was calculated for each mushroom image.

2.3. Measured experimental parameters

2.3.1. Weight loss (WL)

Weight loss for each package was measured using a mass balance and presented as percentage of weight loss compared to initial weight.

2.3.2. Colour

Hunter L, a and b values of individual mushrooms were measured using a Minolta Chromameter (CR-400, Minolta Corp., Japan). Three readings of L, a and b values were obtained from different regions covering the top of the mushroom cap and averaged for each sample.

2.3.3. Maturity index (MI)

The maturity index was assigned to mushrooms based on the extent of cap opening on a 7 point scale described by Guthrie (1984).

2.3.4. Digital image acquisition

RGB images were acquired for samples using a digital camera (Canon PowerShot A560, Japan).

2.3.5. Gas composition

Carbon dioxide and oxygen concentrations inside the packages were determined using a gas analyser (PBI-Dansensor, Ringsted, Denmark — Sample volume: approx. 15 ml). Samples were taken with a syringe inserted through a septum placed on the exterior of the film. Determinations were carried out on two trays of each packaging film type on days 1, 4, 7, 10 and 14 of storage.

2.4. Data processing and analysis

To study the effect of different packaging films on quality attributes of mushrooms, analysis of variance (ANOVA) was carried out on the measured parameters for different groupings of the data (R Development Core Team, 2007).

Partial least square regression (PLSR) was applied to the mean spectra using the PLS package in R (R Development Core Team, 2007) to investigate the correlation between the spectral response and measured quality parameters of mushroom samples and thereby predict mushroom quality attributes. Leave-one-out (LOO) cross validation was applied to the calibration set and root mean square error of cross validation and prediction (RMSECV and RMSEP) were obtained by calculating the square root of the mean of the sum of squared differences between predicted and measured values of the calibration and test sets respectively. The ratio of percentage deviation (RPD) which is the ratio of the standard deviation to RMSECV or RMSEP was also calculated to select the best predictive model (Williams, 1987).

Scattering effects are frequently encountered when obtaining diffuse reflectance spectra of solid and semi-solid materials (Burger & Geladi, 2007). To reduce the influence of scatter effects and other sources of variations (e.g. differences in mushroom sample height and shape), spectral pre-processing methods were used. These methods were: Multiplicative Scatter Correction (MSC), Standard Normal Variate (SNV), first and second order Savitsky–Golay derivative smoothing (Savitzky & Golay, 1964). MSC aims to reduce the effects of scattering in a set of spectra by performing linear regression on a reference or target spectrum; in this case the mean spectrum of the mushroom was used as the target spectrum (Geladi, MacDougall, & Martens, 1985).

A method for detection of mechanical injury on white mushrooms using hyperspectral imaging was recently reported (Gowen and O'Donnell, 2009). This method involves applying MSC to the entire mushroom hyperspectral image, using the mean mushroom reflectance as a target spectrum, followed by application of a PLS-DA regression vector, built to optimally segregate between undamaged and mechanically damaged mushrooms. It was found that this model could distinguish between different damage levels on the mushroom surface, leading to a prediction map of mushroom quality. This model was applied to the hyperspectral images obtained in this study, for comparison with the other quality measurements (i.e. L, a, b, WL and MI) used and to investigate whether this model was suitable for monitoring of mushroom quality during storage. To reduce processing time, hypercubes were reduced to 20% of their original size using bi-cubic interpolation. Then non-zero elements of the image cube were removed and the proposed model was applied to the image.

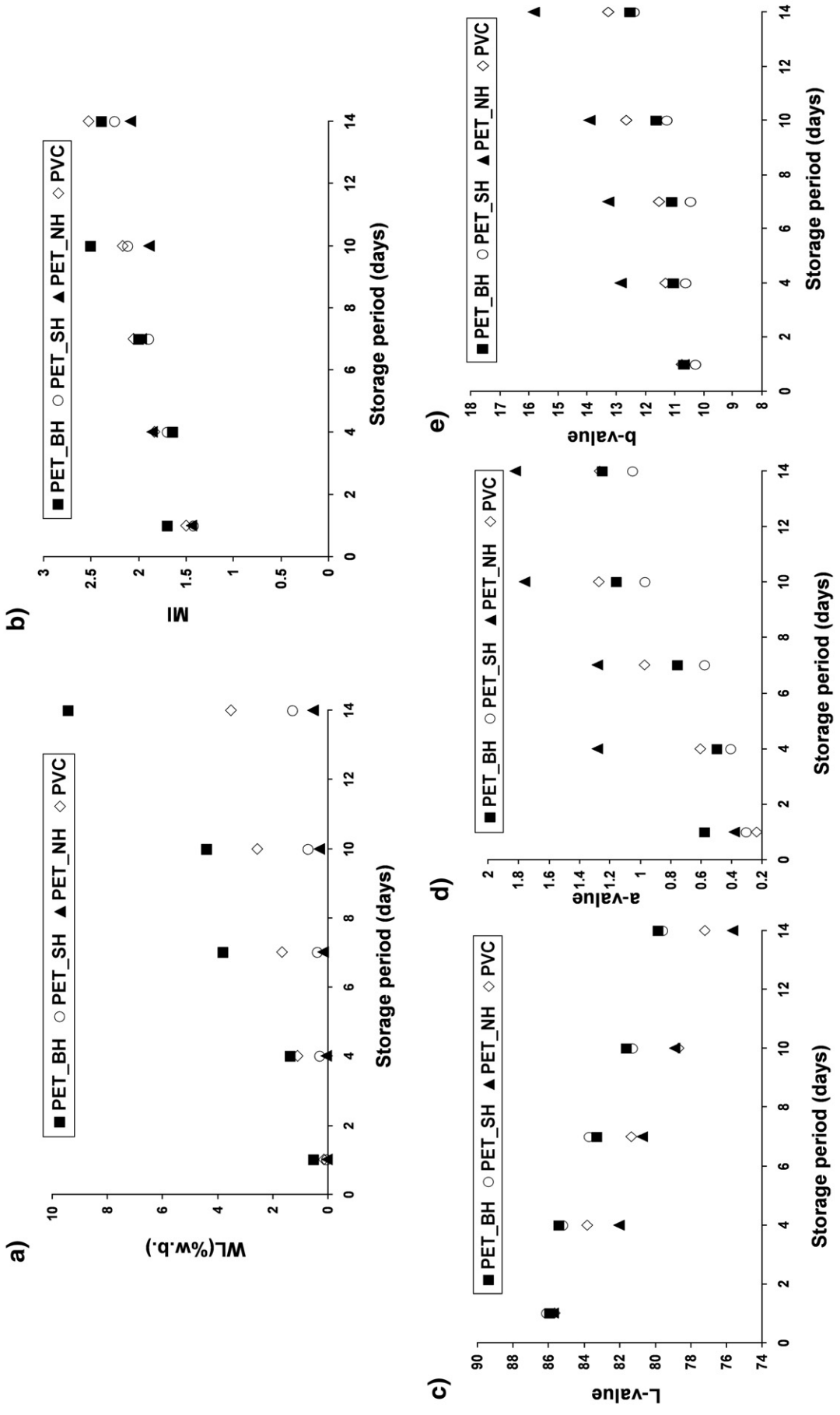

Fig. 1. Effect of packaging film on different quality parameters of mushrooms: a) WL, b) MI, c) *L*-value, d) *a*-value, e) *b*-value (each marker for WL is average value for 6 mushroom packages and each marker for the other plots is average value for 36 mushrooms).

3. Results and discussion

3.1. Quality parameters

Fig. 1 shows the effect of different packaging films on the measured quality parameters (averaged over replicates) over the storage time. Mushrooms over-wrapped in PET_bh had the highest WL among all samples studied (Fig. 1a) and ANOVA results showed that their WL was significantly higher than mushrooms packaged in the other films. This can be related to the presence of larger sized holes and the higher distribution of such holes on the PET_bh film compared with the other packaging types. PVC over-wrapped samples experienced significantly a higher WL in comparison to PET_sh and PET_nh over-wrapped samples. WL in PET_nh over-wrapped samples was significantly lower than the other packaging types. WL in PET_sh over-wrapped samples was also low but no significant difference was found between PET_sh and PET_nh over-wrapped samples. A reduced weight loss during storage is desirable from a commercial perspective; the PET_nh and PET_sh were the best performing films in this respect.

Overall, maturity index (MI) increased over storage time as was expected, ranging from 1 to 3 (Fig. 1b) indicating early stages of maturation (Guthrie, 1984). No significant difference in MI was found among the different packaging films.

L-values in this experiment ranged from 90 to 70 (Fig. 1c), which represents quality ranging from very good to unacceptable according to Gormley and O'Sullivan (1975). *L*-value generally decreased over the storage period, indicating a loss of luminosity in the samples over the storage period. PET_nh over-wrapped samples showed the highest variation in *L*-value during the storage period and their *L*-value was significantly lower than samples over-wrapped with the other films, indicating their poor quality. This could be due to water aggregation inside the package related to the reduced weight loss which results in conditions favourable for enzymatic browning leading to a decrease in *L*-value. Also, PVC over-wrapped samples had low *L*-values at day 14 and on that day no significant difference in *L*-value was found between PVC and PET_nh over-wrapped samples. PET_bh and PET_sh over-wrapped samples exhibited *L*-values significantly higher than those of PET_nh and PVC over-wrapped samples from days 4 to 14 of storage. By day 10 of storage, the mean *L*-values for mushrooms packaged in either PET_nh or PVC film were below the above-mentioned *L*-value quality threshold of 80; whereas samples packaged in the perforated PET films did not reach this threshold until day 14 of storage. This indicates an extension of shelf life of up to 4 days using the perforated PET film.

Similar results were obtained for *a* and *b* values measured for mushrooms over-wrapped with different packaging films. The *a* and *b* values, which refer to redness and yellowness of mushrooms respectively, represent obvious signs of enzymatic browning and other deteriorative reactions. Generally, the highest variation in *a* and *b* values was observed in PET_nh over-wrapped samples. The low permeability of the PET_nh film results in water and CO_2 aggregation inside the package which induces enzymatic browning and other chemical reactions. This is in agreement with the results obtained for WL as PET_nh over-wrapped samples showed the lowest WL among all samples. Unlike *L* and *a* values, *b*-value, which is associated with yellowness, was significantly higher in PET_nh over-wrapped samples in comparison to samples over-wrapped with PVC. Mushrooms over-wrapped with PET_sh, generally showed the best results in *L*, *a* and *b* value measurements; i.e. low *a* and *b* values, high *L*-values, meaning low levels of discoloration.

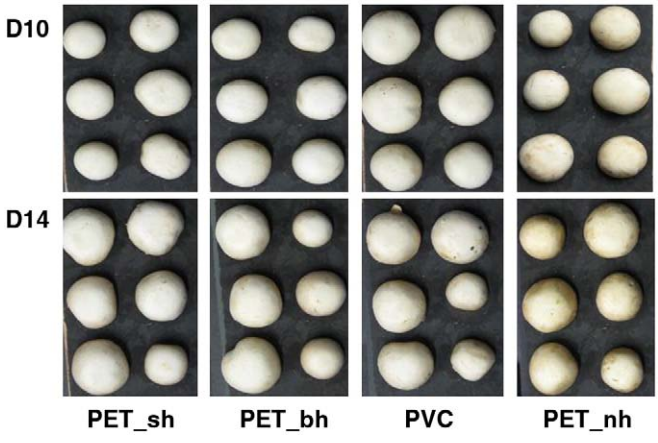

Fig. 2. RGB images of mushroom at days 10 and 14 of storage.

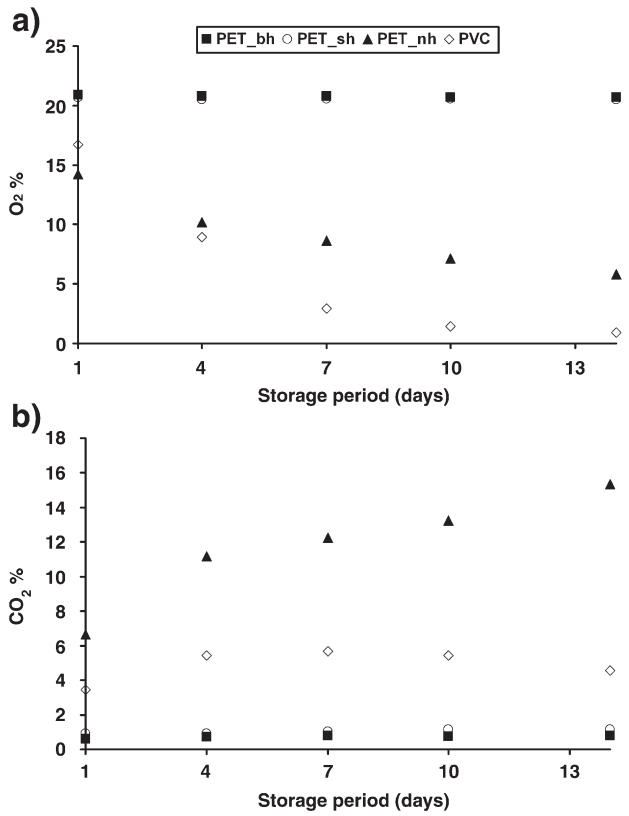

Fig. 3. Effect of packaging film on oxygen (a) and carbon dioxide (b) concentrations in mushrooms (each marker is average value of 2 mushroom packages).

Fig. 2 shows digital images of the mushroom samples studied at days 10 and 14 of the experiment. A major visible difference in colour can be observed between PET_nh samples and the other samples on these 2 days of storage. PET_nh samples tended to become yellow after 10 days which is due to enzymatic browning. This agrees with the reported results obtained for WL, *L*, *a* and *b*-values.

The results obtained from analysis of gas composition are shown in Fig. 3a and b. The 4 types of packaging films generated significantly

Table 1
Average RPD value for untreated and pre-treated PLSR models where n = number of mushrooms.

Pre-treatment	RPD	
	Calibration set (n = 480)	Validation set (n = 240)
No pre-treatment	1.53	1.38
First derivative	1.52	1.44
Second derivative	1.50	1.46
SNV	1.64	1.79
MSC	1.35	1.31

Table 2
RMSEP and RPD for 4-component PLSR models developed for different quality parameter where n = number of mushrooms.

Parameter	Calibration set (n = 480)		Validation set (n = 240)	
	RMSECV	RPD	RMSEP	RPD
WL	2.605	1.012	2.271	1.011
MI	0.747	1.141	0.846	0.934
L	1.737	2.247	1.362	2.533
a	0.374	1.685	0.348	2.657
b	0.949	2.118	0.833	1.794

different atmospheres ($P \leq 0.001$) in terms of CO_2 and O_2 concentrations. The atmospheres generated with PET_bh film were barely modified over the storage period and were very similar to air. PET_sh film generated CO_2 levels of around 1.15% (Fig. 3a) which is below the maximum tolerance level recommended for mushrooms by other authors (2.5%) (Lopez et al., 1992; Simon et al., 2005). O_2 levels for this film did not exceed from 20.5% which is similar to air and within the optimum range (10–21%) recommended by Thompson (1998) and Simon et al. (2005). PET_nh generated the highest amount of CO_2 which was significantly higher than those of other film type ($P \leq 0.001$) and those of PVC film ($P \leq 0.01$). O_2 levels of approximately 5.8% were achieved with PET_nh, whereas very low levels of O_2 (0.9%) were obtained for PVC after 14 days of storage. CO_2 levels achieved with PVC were significantly higher than those of PET_bh and PET_sh and reached to values around 4.55% at the end of the experiment. Overall, results obtained from analysis of O_2 and CO_2 measurements confirm the results for *L*, *a* and *b* values, i.e. highest quality for PET_bh and PET_sh and poorest quality for PET_nh and PVC. High CO_2 levels coupled with O_2 depletion lead to anaerobic respiration in mushrooms which results in quality degradation (Wilson, 2007).

3.2. Hyperspectral image analysis

RPD for PLSR regression models applied to non pre-treated and pre-treated reflectance data with different numbers of latent variables was calculated for both the calibration and test sets. Table 1 shows the average RPD (averaged over all quality indices) for PLSR models developed on reflectance and pre-treated spectra to predict studied quality indicators for calibration and validation sets. Although different spectral pre-treatments showed similar performance in terms of RPD, SNV was the optimal method resulting in the highest RPD for both calibration and validation sets; therefore this pre-processing method was used for further investigations in this study.

Indicators of model performance, i.e. RMSECV, RMSEP and RPD for the 4-component PLSR models developed for different quality parameters are shown in Table 2. The best correlation result was obtained for *L*-value with an RPD of 2.3 and 2.5 for the calibration and validation sets, respectively. The lowest RPD was obtained for models predicting WL and MI with the respective values of 1.0 and 1.1 for the calibration set and 1.0 and 0.9 for the validation set. Rossel, Taylor and McBratney (2007) reported that RPD values < 1.0, between 1.0 and 1.4, between 1.4 and 1.8, between 1.8 and 2, between 2 and 2.5 and greater than 2.5 indicate very poor, poor, fair, good, very good and excellent model performance respectively. Using this classification, it seems that the predictive ability for the MI model was poor. Low RPD values obtained for MI could be due to the fact that MI determination is a subjective measurement and is not as reliable as the other quality parameters measured in this study. Also, MI is measured by observation of the region underneath the mushroom cap which was not measured by the hyperspectral imaging system. The regression model for prediction of WL from hyperspectral data also performed poorly. High RMSECV and RMSEP and consequently low RPD values obtained for WL could be interpreted by high variations in WL within a package as it was not possible to measure the individual WL of a mushroom in this study. Fig. 4 shows the predicted *L* values plotted against the measured values respectively for both calibration and test sets. The reasonably high R^2 obtained for PLSR models shows the appropriate performance of the developed models to predict *L*, *a* and *b* values of mushrooms.

L-value prediction maps of mushrooms stored in the different packaging films investigated were constructed by applying the 4-component PLSR model to SNV pre-treated hyperspectral images. This was carried out in order to demonstrate model performance over the surface of the mushroom. In order to apply the procedure, it was necessary to first 'unfold' the hypercube into a two-dimensional matrix in which each row represented the spectrum of one pixel. The SNV transformation was applied to the unfolded spectra, after which the 4-component PLSR model (built on the calibration set) was applied. The resultant matrix was refolded to form a prediction image shown in Fig. 5. Overall, the prediction maps show that the model preformed well for prediction of *L*-value of mushrooms packed with different packaging

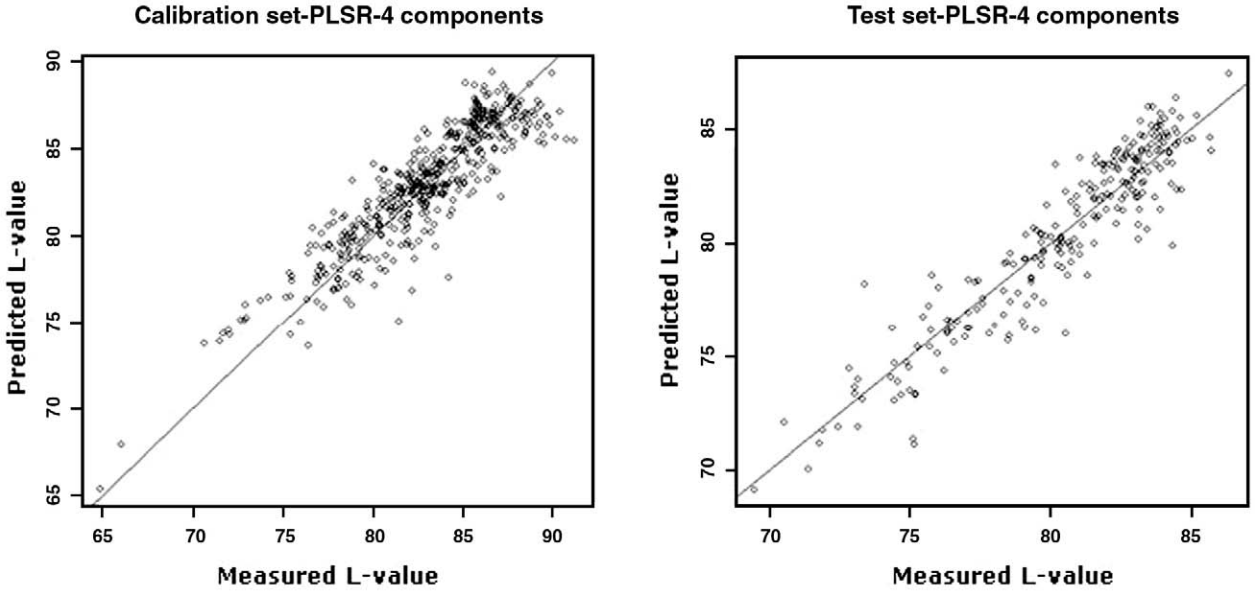

Fig. 4. The measured *L*-value against predicted *L*-value obtained by the 4-component PLSR model (Calibration set: $R^2 = 0.80$, Test set: $R^2 = 0.87$) (where n = 480 mushrooms for calibration set and n = 240 mushrooms for test set).

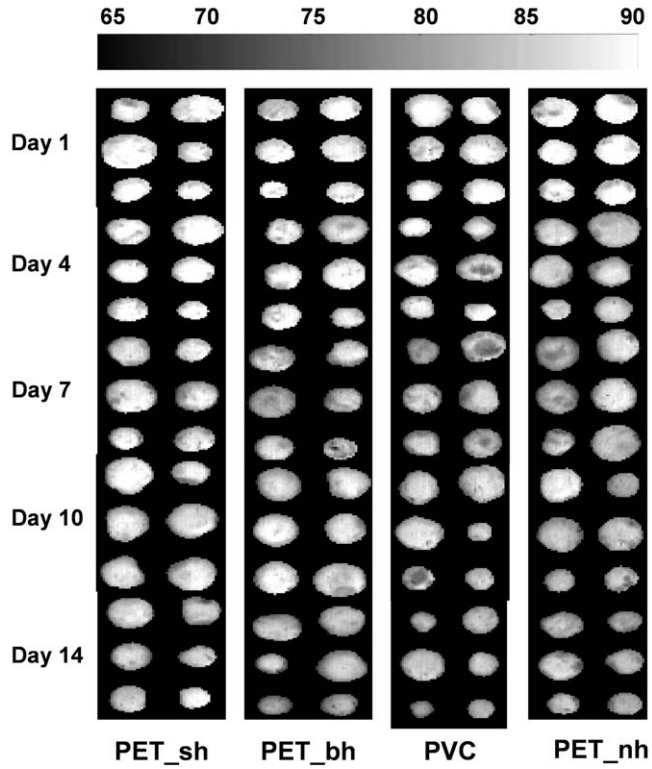

Fig. 5. *L*-value prediction maps for PLSR predictive model applied to mushroom hyperspectral data for mushrooms over-wrapped with different packaging types.

films. It can be seen that at day 1, all samples are bright showing the high level of *L*-value. For mushrooms over-wrapped in PET_nh, samples start rapidly to become dark from day 4; this demonstrates the progress of enzymatic browning resulting in a darkening or loss of luminosity on the mushroom surface. In contrast, for samples stored in PET_sh, the images remained quite bright until the end of the storage period, indicating high *L*-values. Using HSI in this way enables better understanding of *L*-value distribution on the mushroom surface, which is not possible by conventional point colour measurements, and also demonstrates clear mushroom to mushroom variability. It also shows the effectiveness of SNV pre-treatment to overcome mushroom curvature.

To investigate the effect of different packaging films over the storage period on reflectance properties of mushrooms and the applicability of the model proposed by Gowen and O'Donnell (2009), the average pixel value for predicted damage level was also calculated which is shown in Fig. 6.

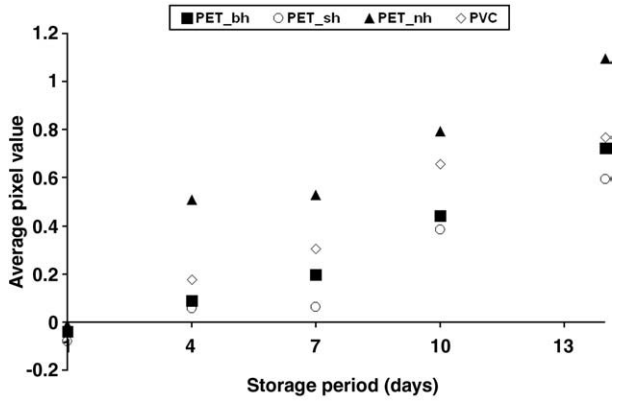

Fig. 6. Average predicted damage level from hyperspectral images for 4 different packaging films during storage (each marker is average value for 36 mushrooms).

Table 3
Analysis of variance for mean pixel values calculated for different experimental treatments during storage period where n = number of mushrooms.

Group	*P*
PET_nh and other 3 films ($n=720$)	***
PET_sh and other 3 films ($n=720$)	***
PET_bh_sh and PVC_PET_nh ($n=480$)	***
PET_bh and PET_sh ($n=480$)	*
PET_nh and PVC ($n=480$)	***
PET_bh and PVC ($n=480$)	*

$^{*}P \leq 0.05$; $^{**}P \leq 0.01$; $^{***}P \leq 0.001$.

The highest increase in average pixel value (which corresponds, based on the model proposed by Gowen and O'Donnell (2009), to a decrease in mushroom quality) over the storage period was observed in mushrooms over-wrapped with PET_nh films. This confirms the results obtained from *L*, *a* and *b* value measurements mentioned earlier in the text. A significant difference was found between predicted pixel values for PET_nh over-wrapped samples and samples over-wrapped with other films. Table 3 shows the analysis of variance for average pixel values in different treatments over the storage period. According to this analysis, the highest quality (i.e. the lowest mean pixel value) was found for PET_sh over-wrapped samples. Mushroom quality as predicted from hyperspectral images for PET_sh and PET_bh over-wrapped samples was better compared to PET_nh and PVC over-wrapped mushrooms. These findings are in agreement with the results presented earlier for measured quality attributes (*L*, *a* and *b* values).

The average pixel values from the predicted images of individual mushrooms over-wrapped with different packaging films were plotted against measured *L*-values (Fig. 7). A reasonably high correlation coefficient of 0.74 was found between average predicted damage level and original *L*-values respectively for all mushrooms studied. This indicates the effectiveness of the model proposed by Gowen and O'Donnell (2009) for quality monitoring of mushrooms during their shelf life. As shown in Fig. 7, it is possible to relate an *L*-value of 80 (as the minimum *L*-value for the end of shelf life) to a predicted pixel range of 0.5–0.6. This range could be used as an effective threshold to identify sub-standard mushrooms at the end of their acceptable shelf life.

By day 10 of storage, the mean predicted pixel values for mushrooms packaged in either PET_nh or PVC film were above the threshold of 0.5; whereas samples packaged in the perforated PET films did not exceed this threshold until day 14 of storage. This further

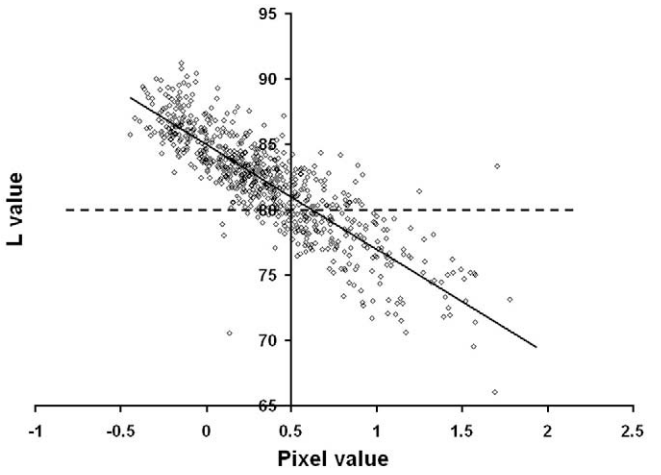

Fig. 7. Average pixel values of predicted mushroom images versus the measured mushrooms *L*-values (dotted line represents lower threshold for acceptable mushroom quality) ($n=3$).

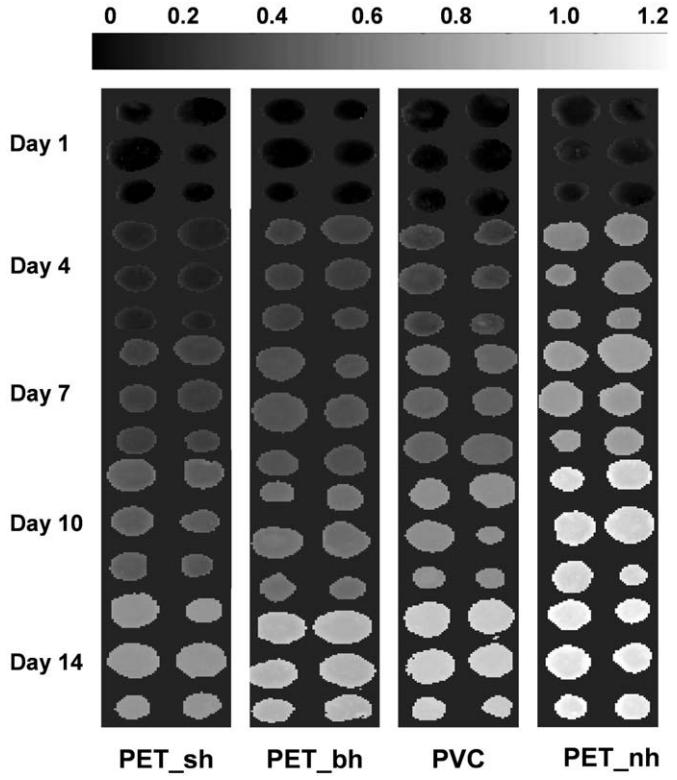

Fig. 8. Prediction maps for PLS model applied to mushrooms over-wrapped with 4 different packaging films during storage.

indicates an extension of shelf life of up to 4 days using the perforated PET film.

In order to demonstrate the effectiveness of proposed procedure, maps of predicted quality level of mushrooms stored in the different packaging films were obtained. In Fig. 8; it can be seen that PET_sh over-wrapped mushrooms had the lowest mean pixel value (the darkest prediction maps) at all experimental days which can be related to the high *L*-values reported in Fig. 7. The highest average pixel values (the brightest prediction maps) at all experimental days were observed in PET_nh over-wrapped samples. This corresponds well with their low *L*-value and high *a* and *b* values in comparison to the samples over-wrapped with other packaging films. In comparison to the *L*-value prediction maps (Fig. 5), the prediction maps shown in Fig. 8 show more uniformity over the mushroom surface; this is a consequence of applying MSC in the model, which normalizes all spectra in the image towards the mean spectrum. This approach may be more useful to illustrate the overall damage level in the sample sets while *L*-value prediction maps enables mapping of the distribution of damage level in individual mushrooms.

4. Conclusions

Results presented in this work show that perforated PET packaging film is a viable alternative to the conventional PVC film, facilitating an increase in mushroom shelf life from 10 to 14 days. PLSR models were developed to correlate mushroom quality indicators to mean spectra obtained by hyperspectral imaging. The SNV transformation was found to be the optimal spectral pre-treatment out of those tested. Hyperspectral data correlated well with *L*-value, a commonly employed quality indicator in the mushroom industry. While colour measurement for a mushroom package will take approximately 3 min and contact with the colourimeter could destruct the samples, a hyperspectral imaging system can scan the whole tray in less than 1 min without touching the samples. HSI can also show the distribution of quality within a batch of sample whereas this is not feasible by using the traditional point measurements such as coulorimeters. This study demonstrates the potential use of hyperspectral imaging as an analytical tool for evaluation of shelf-life of fresh mushrooms. Moreover, this research shows how HSI can be used to evaluate the effect of different packaging solutions on mushroom quality.

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