UNIVERSITI PUTRA MALAYSIA

CHARACTERIZATION OF OPTICAL PARAMETERS IN SEEDED AND SEEDLESS WATERMELON USING LASER-INDUCED BACKSCATTERING IMAGING

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By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

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CHARACTERIZATION OF OPTICAL PARAMETERS IN SEEDED AND SEEDLESS WATERMELON USING LASER-INDUCED BACKSCATTERING IMAGING

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Monitoring of watermelon fruit quality is essential in order to regulate proper postharvest handling and yield production. Problems arise in forecasting the quality parameters of watermelon during storage as the shelf-life of the fruit is only lasts for three weeks. The non-climacteric nature of the fruit is also related to high perishability which does not undergo a continuous process to ripen after being harvested. In the present study, laser-induced backscattering imaging was used to determine the firmness, soluble solids content (SSC), pH, moisture content (MC), and colour changes of watermelons in seven interval days starting from storage day 0 after harvesting (day 0, day 4, day 8, day 12, day 15, day 18, and day 21). Two types of watermelon cultivars were used in this study; seeded watermelon (Black Beauty) and seedless watermelon (Red Seedless). The backscattered images of the fruit surface were obtained at six different locations using laser diodes emitting at 658 nm wavelength. The backscattered images were analysed and the feature information was extracted based on the backscattering image parameters which are minor length, major length, perimeter, maximum intensity, minimum intensity, and mean intensity. The standard reference methods were carried out after the image acquisition process in order to determine the quality parameter measurements.

The multivariate analysis was used to optimise the classification between seeded and seedless watermelons, as well as the regression models between backscattering data and quality parameters, were also discussed. Principal component analysis (PCA) was used to classify the seeded and seedless watermelons into two different classes according to the physicochemical changes. Partial least squares (PLS) regression with full cross-validation method was used to establish the regression models between the backscattering data and quality parameters. The firmness values obtained were 5.07 to 3.24 kg/cm^2 and 4.78 to 3.03 kg/cm^2, whereas the SSC values achieved 9.06 to 5.66 Brix and 8.52 to 6.41 Brix for the seeded and seedless watermelons, respectively. The pH values were 5.27 to 7.10 pH and 5.60 to 6.42 pH while the moisture content values revealed 95.46 to 82.79 % w.b. and 94.53 to 86.43 % w.b. for the seeded and seedless watermelons, respectively. For colour parameters, the L* values ranged from 24.08 to 51.06, whereas the b* values ranged from 11.52 to 36.84. The chroma and hue values were also increased from 12.41 to 38.95 and 104.55º to 111.60º, respectively. The a* value reduced significantly ($P<0.05$) from -4.32 to -13.06 for both seeded and seedless watermelons. For seedless watermelon, the colour prediction (L*, a*, b*, chroma, and hue) gave the highest coefficient of determination (R^2) with all of them above 0.90. Meanwhile, the firmness prediction gave the highest R^2 of 0.92 for seeded watermelon. On the whole, it is concluded that the application of laser-induced backscattering imaging is a promising technique for assessing quality parameters of watermelons during storage. The proposed approach has significant potential as a well-controlled system for developing automated sorting and grading system in the future.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

PENCIRIAN PARAMETER OPTIK DALAM TEMBIKAI BERBIJI DAN TIDAK BERBIJI MENGGUNAKAN PENGIMEJAN LASER PEMBALIKKAN

Oleh

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Pemantauan kualiti buah tembikai adalah penting dalam usaha untuk mengawal pengendalian lepas tuai yang betul dan hasil pengeluaran buah. Masalah timbul dalam meramal parameter kualiti tembikai semasa dalam simpanan kerana kitaran buah ini hanya bertahan selama tiga minggu. Sifat bukan klimakterik buah ini juga berkaitan dengan kadar mudah rosak yang tidak menjalani proses berterusan untuk masak sepenuhnya selepas dituai. Dalam kajian ini, pengimejan laser pembalikkan telah digunakan untuk menentukan ketegasan, kandungan pepejal larut (SSC), pH, kandungan kelembapan (MC), dan perubahan warna tembikai dalam tempoh tujuh hari interval berrmula dari hari 0 selepas penuaian (0, 4, 8, 12, 15, 18, 21). Dua jenis tembikai telah digunakan dalam kajian ini; tembikai berbiji (Black Beauty) dan tembikai tidak berbiji (Red Seedless). Imej-imej yang dibalikkan di permukaan buah pada enam lokasi berbeza daripada tembikai berbiji dan tidak berbiji menggunakan diod laser yang dipancarkan pada gelombang 658 nm. Imej-imej yang dibalikkan telah dianalisis dan maklumat ciri diekstrak berdasarkan parameter imej pembalikkan iaitu panjang kecil, panjang utama, perimeter, intensiti maksimum, intensiti minimum, dan purata intensiti. Kaedah rujukan standard telah dijalankan selepas proses pengambilan imej untuk menentukan ukuran kualiti parameter.

Analisis multivariat digunakan untuk mengoptimumkan klasifikasi antara tembikai berbiji dan tidak berbiji, serta model regresi antara data pembalikkan dan parameter kualiti, juga telah dibincangkan. Analisis komponen utama (PCA) telah digunakan untuk mengelaskan tembikai berbiji dan tidak berbiji kepada dua kelas yang berbeza mengikut sifat-sifat perubahan kualiti. Regresi separa kuasa dua terkecil (PLS) dengan kaedah pengesahan silang penuh telah digunakan untuk mewujudkan model regresi antara data pembalikkan dan parameter kualiti. Nilai ketegasan diperoleh adalah 5.07-3.24 kg/cm^2 dan 4.78-3.03 kg/cm^2, manakala nilai SSC adalah 9.06-5.66 Brix dan 8.52-6.41 Brix untuk tembikai berbiji dan tidak berbiji. Nilai pH adalah 5.27-7.10 pH dan 5.60-6.42 pH, manakala nilai kandungan lembapan adalah 95.46-82.79% w.b. dan 94.53-86.43% w.b. untuk tembikai berbiji dan tidak berbiji. Untuk parameter warna, nilai L* diperoleh di antara 24.08 hingga 51.06, manakala nilai b* adalah di antara

11.52 hingga 36.84. Nilai kroma dan hue juga meningkat daripada 12.41 hingga 38.95 dan 104.55º hingga 111.60º. Nilai a* berkurang dengan ketara ($P < 0.05$) daripada -4.32 hingga -13,06 untuk tembikai berbiji dan tidak berbiji. Untuk tembikai tidak berbiji, ramalan warna (L*, a*, b*, kroma, dan hue) memberikan pekali tertinggi penentuan (R^2) dengan nilai 0.90. Sementara itu, ramalan ketegasan memberikan nilai tertinggi R^2 sebanyak 0.92 untuk tembikai berbiji. Secara keseluruhannya, penggunaan pengimejan laser pembalikkan adalah teknik yang berkesan untuk menilai parameter kualiti tembikai semasa penyimpanan. Pendekatan yang dicadangkan mempunyai potensi yang besar sebagai satu aplikasi yang terkawal untuk membangunkan system automatik pengasingan dan penggredan buah pada masa hadapan.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

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- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

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LIST OF ABBREVIATIONS

a*	Greenness
ANOVA	Analysis of variance
b*	Yellowness
C	Chroma
CCD	Charge-coupled device
CMOS	Complementary metal-oxide-semiconductor
CV	Cross validation
GL	Gaussian-Lorentzian
h	Hue angle
HSI	Hue-saturation-intensity
kNN	k-nearest neighbours
L*	Lightness
LDA	Linear discriminant analysis
LDV	Laser Doppler vibrometry
LLBI	Laser light backscattering imaging
MC	Moisture content
MLR	Multiple linear regression
NIR	Near infrared
PC	Principal component
PCA	Principal component analysis
PLS	Partial least squares
PLS-DA	Partial least squares discriminant analysis
QDA	Quadratic discriminant analysis
r	Correlation coefficient
R^2	Coefficient of determination
RGB	Red-green-blue
RMSEC	Root mean square of calibration
RMSEP	Root mean square of prediction
ROI	Region of interest
SEP	Standard error of prediction
SSC	Soluble solids content

TSS	Total soluble solids
VIS/NIR	Visible/near-infrared
μ_a	Absorption coefficient
μ_s	Scattering coefficient
μ'_s	Reduced scattering coefficient

CHAPTER 1

INTRODUCTION

1.1 Background Study

Watermelon (*Citrullus lanatus*) is an edible and beneficial fruit which is available all year round. The fruit is the world's second most produced fruit with approximately 109.28 million metric tonnes in global production in 2013 (FAO, 2015). The fruit belongs to the family of *Cucurbitacea* and well-known for its sweet and juicy flesh. Moreover, the fruit is also denoted as a pepo; a special type of berry that has a thick rind and deep flesh inside it (Ajuru & Okoli, 2013). The pepo is also developed from the inferior fruit which is distinctive for every crop in the *Cucurbitaceae* family. Normally, the colour of watermelon flesh of most commercial cultivars is red or yellow. Meanwhile, the watermelon rind colour varies from light to dark green with yellow spots, stripes, or marbles. As an added value, the entire fruit is edible and frequently being eaten raw or consumed as fruit juice, stir-fried, salad, and pickled watermelon.

Apart from that, watermelon differs in terms of shape and size from circular to oblong. The fruit has high water content and another source of vitamins and minerals such as carbohydrates, calcium, phosphorus, and ascorbic acid (Tlili et al., 2011). Other than that, watermelon is also proven to be one of lycopene and citrulline sources (Perkins-Veazie & Collins, 2004; Rimando & Perkins-Veazie, 2005). Citrulline is a non-essential amino acid whereas lycopene is a type of carotenoid that gives the distinct property of red colour (Liu et al., 2010). In addition, watermelon is a non-climacteric fruit which does not undergo a continuous process to ripen after being harvested (Wechter et al., 2008).

Watermelon consists of numerous cultivars, including seeded, seedless, and disorder-resistant cultivars. At the moment, the watermelon seeds are mostly imported from Taiwan or Japan. The seeded cultivars which are Black Beauty, Sugar Baby, New Dragon, Empire No. 1, and Cina Dragon are grown in Malaysia. On the other hand, seedless cultivars such as Fengshan No. 1, Red Seedless, Gold Rush 1663, and Felicity Orchid Sweet which are the combination of F1 hybrids are imported from Taiwan and Japan. The seedless cultivars have characteristics of short-term maturity phase, high yield, as well as better-quality compared to the seeded cultivars (Nunes, 2009).

The evaluation of internal and external qualities in the past has been difficult and time-consuming due to the subjective form of assessment and the use of destructive measurements. Most aspects of the evaluation have always been based on the visual appearance and inspection of the fruit which could lead to inaccuracies in the results. Further, assessment by manual sorting depends very much on human labour and time management which is liable to subjectivity (Hashim et al., 2014). For watermelon, the conventional technique for choosing a good-quality fruit is usually done by thumping the skin of the fruit in order to check its sound, as it is used to detect a hollow heart defect in the fruit. The other technique is searching for yellow spots on the surface which is not practical when dealing with a huge number of fruits, especially during the harvesting season. Thus, since the demand for good-quality fruit is increasing, an automated system using non-destructive techniques is desirable.

The advanced technology in non-destructive and fibre optics applications has been developed rapidly in the agricultural sector to fill in the requirement for high yield production. In recent years, non-destructive techniques have been used for monitoring quality changes externally and internally of various crops and agricultural produce. The most recommended techniques are generally based on the food properties including optical, vibration, sound, and electrical properties. These assessments are very much related to the relationship of physicochemical properties and the features of the non-destructive method. For instance, non-destructive applications have been tested on watermelon using acoustic impulse response (Armstrong et al., 1997; Diezma-Iglesias et al., 2004; Mao et al., 2016), laser Doppler vibrometry (Abbaszadeh et al., 2011; Abbaszadeh et al., 2014; Taniwaki et al., 2009), image-based methods (Abdul Rahman et al., 2009; Koc, 2007; Syazwan et al., 2012), infrared spectroscopy (Jie et al., 2014; Lohumi et al., 2013; Yao et al., 2013), and dielectric spectroscopy (Nelson et al., 2007a; 2007b). Nevertheless, the techniques involving vibration property are sensitive to the noise of surrounding and mechanical vibration (Tian et al., 2007). Saito et al. (1996) have investigated the application of nuclear magnetic resonance imaging (MRI) in detecting soluble solids content of watermelon. However, the equipment used in MRI is quite expensive and more complex since this technique is not dependent on the difference between internal flesh and external surface of the fruit. Therefore, effective non-destructive techniques are needed to increase the commercial value of agricultural produce.

Light backscattering imaging is one of the novel methods which has recently arisen as an alternative to machine vision by combining imaging and spectroscopic approaches for quality control and safety assessment of crops and agricultural produce (Mollazade et al., 2012). The technique of light backscattering imaging is categorised into three categories based on the usage of the light source and imaging unit: laser light backscattering imaging (LLBI), hyperspectral backscattering imaging, and multispectral backscattering imaging (Adebayo et al., 2016; Mollazade et al., 2012). In addition, the application of LLBI has been used for monitoring fruit quality such as firmness, soluble solids content (SSC), pH, moisture content, colour, total acidity, and maturity level.

Results indicated promising and reliable potential on its application for in-line determination of moisture content changes during drying process of bell peppers (Romano et al., 2012), optimisation and control process equipped with sensors for in-line system in various food processing (Udomkun et al., 2014), as well as detection of water content values to obtain chilling injury in bananas (Hashim et al., 2015). The method offers a non-destructive and low-cost assessment along with advanced processing analysis for predicting quality parameters of various agricultural produce. The fundamental research studies have also proven promising results demonstrating the versatility and simplicity of the LLBI as an innovative approach for quality assessment of food quality of agricultural produce.

1.2 Problem Statements

Nowadays, consumers are demanding for fresh food and agricultural produce which has longer shelf-life. The postharvest handling and storage of the agricultural produce vary in terms of the physiological state as well as the harvest time (Tirkey et al., 2014). There has been a limitation due to the effect of storage on quality parameters of the agricultural produce. The effect of storage is also associated with the loss of nutrition, chemical, and microbiological changes, deterioration of food quality, and detection of defects (Falah et al., 2015). Therefore, optimal storage condition is important to preserve the quality of the fruit and minimise postharvest losses.

Since the current assessment in sorting and grading watermelons involves manual labour, there has been a strong call for the application of automatic and non-destructive devices. The application of manual assessment in sorting and grading processes may lead to non-uniform results as the size-based sorting system may varied in terms of fruit density (Omid et al., 2010). Apart from that, manual sorting also causes slight damage in fruit product such as bruising and mechanical injuries, due to the deterioration of the external defects. Another important factor in manual sorting is the impracticality of the process which is subjected to the subjective assessment according to the surface appearance, texture, and thumping sound (Sun et al., 2010). Besides, the manual sorting is quite labourious which depends very much on the competency of manpower and human skills. Hence, the effective non-destructive approach is needed to replace the application of conventional methods which apparently are not so practical in the modern days.

Watermelon production depends on the various conditions and postharvest handling. The shelf life of seedless watermelon is expected to be longer than seeded watermelon since the seeds produce hormones that generate deterioration. The seedless watermelons have a soft texture and become overripe later than seeded watermelons. Besides, seedless watermelons have immature small seeds and should be free of hard seeds. The selection of seeded and seedless watermelons must have adequate yield and suitable with the production demand according to the market acceptability. Thus, the development of laser-induced backscattering imaging delivers a novel method to classify between the seeded and seedless watermelons. Apart from that, the potential use of backscattering imaging system evaluates the sensing and classification abilities as an indicator for developing automated machine system.

Choosing a suitable watermelon variety is one of the most important decisions by a watermelon producer. The backscattering imaging system classifies the watermelon according to the type of cultivars (seeded vs seedless) and storage day (after harvest). Unlike other agricultural produce, the variation of watermelons in terms of shapes and sizes presents challenges for non-destructive applications during storage. The ability of the system to classify between the storage day is necessary to obtain information on the condition and quality attributes of the fruit. Accurate analysis based on the classification of the fruit also provides minimal postharvest losses and maintains good fruit quality. The future of classifying watermelons based on the type of cultivars and storage days in possible automated systems might be useful with the progression on multivariate pattern recognition algorithms and suitable device detectors.

The non-destructive methods are recommended due to its rapid process, objective measurements and reliable results (Wu & Sun, 2013). The ability of non-destructive techniques in terms of fast data processing and handling contributes to the high anticipation of good food products for the consumers. A lot of studies have been conducted on the application of LLBI in various crops and conditions such as kiwifruits (Baranyai & Zude, 2009), bananas (Dénes et al., 2013; Hashim et al., 2014, 2013, 2012), apples (Baranyai et al., 2009; Lafuente et al., 2013; Qing et al., 2007, 2008), papayas (Udomkun et al., 2014), citrus fruits (Lorente et al., 2013; Lorente et al., 2015; Lorente et al., 2014), and bell pepper (Romano et al., 2012). Nonetheless, the facts and information on the feasibility of this technique are still inadequate for evaluating quality changes of tropical fruits such as watermelon. Hence, the potential of light scattering in quantifying the quality of seeded and seedless watermelon is investigated.

1.3 Importance of Study

The cultivation of watermelon in Malaysia has been massively developed especially in the East Coast Region for domestic use and export. According to the Food and Agriculture Organization Corporate Statistical Database (FAOSTAT), Malaysia has produced 227 thousand tonnes production of watermelon in 2013. In the agricultural society, much research effort has been put into developing a seedless strain as well as seeded watermelon. Hence, there has been an increased concern in the application of non-invasive computer-aided image processing methods to evaluate fruit properties, chemical constituents, and qualities of both cultivars. Laser-induced light backscattering imaging offers computationally inexpensive technology that might change the production scenarios in fruit industries. Besides that, information about the interaction between seeded and seedless properties and the quality changes during storage could be a baseline study to the development of optimal storage condition not only to watermelon but also to other agricultural produce. The laser backscattering approach has been evaluated on a limited and small scope of agricultural produce. Hence, it is advisable that the effectiveness of laser backscattering approach is investigated over a vast range of agricultural produce for the new database.

1.4 Objectives

The goal of this research is to determine the quality changes of seeded and seedless watermelons during storage non-destructively by means of backscattering imaging. The specific objectives are:

i) To establish the changes of physicochemical properties in seeded and seedless watermelons during storage.

ii) To evaluate the interaction between backscattering parameters and physicochemical properties of watermelons.

iii) To develop a prediction model of quality deterioration during storage using LLBI system.

iv) To classify the watermelons based on the type of cultivars and storage days.

1.5 Scope and Limitations

The present study aims at exploring the potential use of backscattering imaging for monitoring quality parameters of watermelons. This study was conducted to determine the seeded and seedless properties of watermelon non-destructively by means of backscattering imaging. The samples only cover one variety from each type of the fruit which is Black Beauty (seeded) and Red Seedless (seedless) cultivars of watermelon. Besides, this investigation focuses on one type of LBI which is LLBI using a solid-state laser diode emitting light at 658 nm. The backscattering image is obtained in the two-dimensional (2D) image with the dimension measured in pixel (1392 x 1040 pixels).

1.6 Thesis Overview

The thesis is organised as follows. Chapter 1 describes the background study driving this work. This chapter also outlines the research objectives, scope, and limitation as well as the importance of the study. Chapter 2 provides a literature review of cultivation and quality evaluation of watermelons. This chapter also describes the postharvest handling of the fruit, application, and future prospect of laser-induced backscattering system. Chapter 3 explains the experimental set-up for image acquisition process using backscattering imaging system as well as the procedure of physicochemical and optical properties measurements. Image processing and data analysis are also discussed in this chapter. Chapter 4 discusses the results and findings obtained for each research objective. Chapter 5 summarises the conclusions and achievements of this research, alongside recommendations for future studies.

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