UNIVERSITI PUTRA MALAYSIA

EVALUATION OF BANANA AND PEAR FRUIT MATURITY STAGES USING LASER BACKSCATTERING IMAGES, ARTIFICIAL NEURAL NETWORK AND SUPPORT VECTOR MACHINE TECHNIQUES

ADEBAYO SEGUN EMMANUEL

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By

ADEBAYO SEGUN EMMANUEL

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

June 2017

DEDICATION

This work is dedicated to my wife and children:

Adebayo Olanike Oluwabusayomi (Mrs), Iyanuoluwa Aduke and Oluwabunmi Ajike

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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Chairman : Norhashila Hashim, PhD
Faculty : Engineering

Consumers considered ripeness of fruit as a very important factor in making choices of purchase. Ripeness in fruit generally affects their eating quality and market price. Quality attributes of fruit determined the extent of its acceptability and satisfaction by the consumers. Many quality attributes have been used for the determination of fruit quality, among them are colour, firmness and soluble solid contents (SSC). Majority of the techniques used to determine the maturity stages are destructive involving the removal of little quantity of fruit tissue especially for the measurement of SSC, total acidity and nutritional content. These techniques resulted in large amount of postharvest losses, inability to measure the whole batch and laborious. However, over the last decades several attempts have been made to develop optical techniques for monitoring quality indices of fruits via non-destructive approach. Laser light backscattering imaging (LLBI) system is one of the emerging optical techniques which is inexpensive and easy to use.

Bananas samples at six ripening stages i.e. from ripening stage 2 to 7 and pear samples at different days after full bloom (dafb) were obtained from a ripening facility at Potsdam Bornim and Sachsenobst orchard Germany respectively. The samples were kept at 14 °C with 79 to 89 % relative humidity (RH). Laser light backscattering imaging (LLBI) with 5 laser diodes wavelengths in the visible and near infrared region i.e. 532, 660, 785, 830 and 1060 nm were employed to acquire the backscattering images of the samples and features were extracted from the backscattering images of both fruit using transform-based textural techniques viz: Wavelet transform, Gabor transform, Tamura texture and optical properties i.e. absorption and reduced scattering coefficients with Farrell's diffusion theory. The reference measurements of index of chlorophyll, elasticity, firmness and SSC were measured with ΔA meter, texture analyzer, penetrometer and refractometer respectively immediately after backscattering images acquisition.

The extracted features and optical properties at individual and combined wavelengths were used as an input into the prediction and classification models in the predictions and classification of quality attributes and maturity stages of both fruit. Two computational intelligence techniques, artificial neural network (ANN) and support vector machines (SVM) were used to build the prediction and classification models. Root mean square error of calibration (RMSEC), root mean square error of cross-validation (RMSECV), coefficient of determination (R^2) and bias were used to evaluate the performance of the prediction models while overall classification accuracy was used to evaluate the classification models.

The results showed that there was a very strong correlation between the absorption and reduced scattering coefficients with ripening stage of banana and pear development. The range values of absorption coefficient and reduced scattering coefficient of bananas at 532 nm were between 0.312 and 0.963, and 2.637 and 4.893 for ripening stages 2 to 7 respectively. The result shown a decreasing trend of optical properties with increasing wavelength. For pear at 532 nm, the range of absorption coefficient was between 0.033 and 0.308 while reduced scattering coefficient was between 3.160 and 6.741. For banana, analysis using ANN with visible wavelength region of 532, 660 and 785nm resulted in high R^2 values ranging from 0.977 to 0.981 for the prediction of index of chlorophyll and 0.955 to 0.976 for elasticity; while near infrared region of 830 and 1060nm resulted in R^2 range between 0.964 and 0.980 for SSC prediction when absorption and reduced scattering coefficients at individual and combined wavelengths were used. For the classification of banana into ripening stages 2 to 7, visible wavelength region using ANN gave the highest classification accuracy of 98.77% with combined wavelengths while the highest overall classification accuracy of 96.30 % was recorded at 830nm with SVM. For pear the highest R^2 of 0.947 and 0.818 were obtained for firmness and SSC respectively using ANN while R^2 values of 0.890 and 0.808 for firmness and SSC using SVM. For pear classification into different maturity stages, the highest classification accuracy of 90.42 % was achieved with both ANN and SVM. Similar results though lower were obtained when transform-based textural techniques were used for the prediction of banana and pear quality parameters and classification of banana and pear into different ripening and maturity stages. This study has shown that transform-based textural techniques and optical properties of banana and pears with ANN and SVM as prediction and classification models can be employed to predict the quality parameters and classify banana and pears into different ripening and maturity stages non-destructively.

Abtsrak tesis dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENILAIAN TAHAP KEMATANGAN BUAH PISANG DAN PEAR MENGGUNAKAN KAEDAH PENGIMEJAN PENGHAMBURAN LASER, RANGKAIAN NEURAL BUATAN DAN MESIN SOKONGAN VEKTOR.

Oleh

ADEBAYO SEGUN EMMANUEL

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Pengguna menganggap kematangan buah sebagai satu faktor yang sangat penting dalam membuat pilihan pembelian. Kematangan buah secara amnya memberi kesan kepada kualiti pemakanan dan harga pasaran. Ciri-ciri kualiti buah menentukan tahap penerimaan dan kepuasan pengguna. Pelbagai ciri-ciri kualiti telah digunakan bagi menentukan kualiti buah-buahan, antaranya ialah warna, ketegasan dan kandungan pepejal larut (SSC). Kebanyakan teknik-teknik yang digunakan untuk menentukan tahap kematangan adalah bersifat musnah melibatkan pembuangan sedikit kuantiti tisu buah terutama untuk mengukur SSC, jumlah keasidan dan kandungan nutrien. Teknik-teknik ini menghasilkan kerugian lepas-tuai dalam jumlah yang besar, ketidakbolehan mengukur seluruh kumpulan dan menggunakan tenaga buruh yang tinggi. Walau bagaimanapun, sejak beberapa dekad yang lalu, beberapa percubaan telah dijalankan untuk membangunkan teknik optik bagi pemantauan indeks kualiti buah-buahan melalui pendekatan tanpa-musnah. Sistem cahaya laser penghamburan adalah salah satu teknik optik yang muncul, yang mempunyai kos yang murah dan mudah untuk digunakan.

Sampel buah pisang pada enam tahap kematangan iaitu daripada tahap kematangan 2 hingga 7 dan sampel buah pear pada hari-selepas-mekar (dafb) yang berlainan telah diperolehi masing-masing daripada pusat pemeraman di Potsdam Bornim dan dusun Sachsenobst, Jerman. Sampel kajian telah disimpan pada suhu 14 °C dengan kelembapan bandingan 79 hingga 89% (RH). Cahaya laser pengimejan penghamburan (LLBI) dengan 5 gelombang diod laser dalam rantau nampak dan berhampiran inframerah iaitu 532, 660, 785, 830 dan 1060 nm telah digunakan untuk mendapatkan imej-imej penghamburan sampel dan ciri-ciri imej diekstrak daripada imej-imej tersebut menggunakan teknik berasaskan-ubahan tekstur iaitu: ubahan Wavelet, ubahan Gabor, tekstur Tamura dan sifat-sifat optik iaitu pekali penyerapan dan penyebaran-berkurang dengan teori penyebaran Farrell's. Pengukuran rujukan indeks klorofil, keanjalan, ketegasan dan SSC diukur masing-masing dengan ΔA

meter, penganalisa tekstur, *penetrometer* dan *refractometer* sebaik selepas pengukuran pngimejan penghamburan.

Ciri-ciri yang diekstrak dan sifat-sifat optik pada gelombang individu dan gabungan telah digunakan sebagai input kepada model-model ramalan dan pengelasan ciri-ciri kualiti dan tahap kematangan kedua-dua buah. Dua teknik kecerdasan pengkomputeran, teknik rangkaian neural buatan (ANN) dan mesin sokongan vektor (SVM) telah digunakan untuk membina model-model ramalan dan pengelasan. Punca kuasa dua ralat penentukuran (RMSEC), punca kuasa dua ralat pengesahan-silang (RMSECV), pekali penentuan (R^2) dan kecenderungan telah digunakan untuk menilai prestasi model ramalan manakala ketepatan keseluruhan pengelasan digunakan untuk menilai model klasifikasi. Hasil kajian menunjukkan bahawa wujud hubungan yang sangat kuat antara pekali penyerapan dan penyebaran-berkurang dengan tahap kematangan buah pisang dan pembentukan buah pear.

Nilai julat pekali penyerapan dan penyebaran-berkurang buah pisang pada 532 nm adalah masing-masing antara 0.312 dan 0.963, dan 2.637 dan 4.893 bagi tahap kematangan 2 hingga 7. Keputusan menunjukkan gaya menurun oleh sifat optik dengan peningkatan gelombang. Bagi buah pear pada 532 nm, julat pekali penyerapan adalah antara 0.033 dan 0.308 manakala pekali penyebaran-berkurang adalah antara 3.160 dan 6.741. Bagi buah pisang, analisis menggunakan ANN dengan rantau gelombang nampak iaitu 532, 660 dan 785nm menghasilkan nilai R^2 yang tinggi antara 0.977 hingga 0.981 bagi ramalan indeks klorofil dan 0.955 hingga 0.976 bagi keanjalan; sementara gelombang berhampiran inframerah iaitu 830 dan 1060nm menghasilkan R^2 berjulat antara 0.964 dan 0.980 untuk ramalan SSC apabila pekali penyerapan dan penyebaran-berkurang pada gelombang individu dan gabungan digunakan. Bagi pengkelasan buah pisang ke tahap kematangan 2 hingga 7, rantau gelombang nampak menggunakan ANN memberikan ketepatan klasifikasi tertinggi iaitu 98.77% dengan gelombang gabungan manakala ketepatan klasifikasi keseluruhan tertinggi sebanyak 96,30% dicatatkan pada 830nm dengan SVM. Bagi buah pear, nilai R^2 tertinggi masing-masing 0.947 dan 0.818 telah diperolehi untuk keanjalan dan SSC menggunakan ANN manakala nilai R^2 0.890 dan 0.808 diperolehi untuk keanjalan dan SSC menggunakan SVM. Bagi pengelasan buah pear ke tahap kematangan berbeza, ketepatan klasifikasi tertinggi sebanyak 90.42% telah dicapai dengan ANN dan SVM. Keputusan yang sama walaupun rendah diperolehi apabila teknik berasaskan-ubahan tekstur digunakan untuk ramalan parameter kualiti buah pisang dan pear dan pengelasan buah pisang dan pear ke tahap kemasakan dan kematangan berbeza. Kajian ini telah menunjukkan bahawa teknik berasaskan-ubahan tekstur dan ciri-ciri optik pisang dan buah pear dengan ANN dan SVM sebagai model ramalan dan pengelasan boleh digunakan untuk meramalkan parameter kualiti dan mengelaskan buah pisang dan pear ke tahap kemasakan dan kematangan yang berbeza secara tanpa musnah.

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Thank you all!

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

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Declaration by Members of Supervisory Committee

This is to confirm that:

- 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) were adhered to.

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LIST OF ABBREVIATIONS

ABR	Acid-Brix Ratio
ANN	Artificial neural network
AOTF	Acousto-optic tunable filter
AU	Auxilliary unit
BIL	Band-interleaved-by-line
CCD	Charge-coupled device
CMOS	Complementary metal oxide semiconductor
CMY	Cyan, magenta and yellow
CT	Computed Tomography
DA	Discriminant analysis
DAFB	Days after full bloom
DM	Dry Matter
EM	Electromagnetic spectrum
EN	Electronic Nose
FF	Flesh firmness
FN	False negative
FP	False positive
GLCM	Gray level co-occurrence matrix
GLRLM	Gray level run length matrix
GUI	Graphical user interface
HSI	Hue, saturation and intensity
LBP	Local binary pattern
LED	Laser emission diode
LCTF	Liquid crystal tunable filter
LDA	Linear discriminant analysis
LLBI	Laser Light Backscattering Imaging
LR	Linear regression

LS-SVM	Least square support vector machine
MC	Monte Carlo
MLR	Multiple linear regression
MLP	Multilayer perceptron
MSI	Multispectral Imaging
MRI	Magnetic resonance imaging
NB	Naïve bayes
NIR	Near Infrared
NIRS	Near infrared reflectance spectroscopy
NMR	Nuclear Magnetic Resonance
QDA	Quadratic discriminant analysis
RBF	Radial-basis function
RGB	Red, green, blue
RMSE	Root mean square error
RP	Ripening stage
SIMCA	Soft independence modelling of class analogy
SSC	Soluble solids content
SVM	Support vector machine
SVLA	Support vector learning algorithm
SWNIR	Short wave near infrared
TA	Titratable acidity
TN	True negative
TP	True positive
TSS	Total soluble solids
UV	Ultra Violet
VC	Vapnik-Chervonenkis
μ_a	Absorption coefficient
μ'_s	Reduced scattering coefficient

CHAPTER 1

INTRODUCTION

1.1 Background of study

The quality, shelf life, and storage are principles that determine the time which fruit and vegetables are harvested. According to Barbosa-Cánovas (2003), there are three distinct stages in the life span of fruit and vegetable and these are maturation, ripening, and senescence. At maturity, the fruit is fully developed to be harvested. This is due to an edible portion of the fruit that has been completely developed in size, though it may not be available for consumption immediately. The stage following or sometimes overlapping with maturation is ripening. At this stage, the fruit has undergone biochemical processes marked by taste and aroma and it is ready for immediate consumption. The final stage is senescence, where this stage is marked by an essential decline in the quality parameters such as texture, flavour, etc of the fruit and vegetable. Senescence is often described as the death of fruit tissue.

Fresh fruit quality has been defined as the sum total of attributes, properties, or characteristics that enhance or attract them for consumption (Achilleas and Anastasios, 2008; Giusti et al., 2008; Schreiner et al., 2013). For instance, the concept of fruit quality changes along the supply chain. To producers or farmers, quality is defined in terms of high yield, ease of harvest, and long transportation without/with minimal damage, storability, ratio of soluble solids content (SSC) to acidity, as well as attractive appearance (Narrod et al., 2009; Van der Vorst et al., 2009). Subsequently to the wholesalers and retail marketers, fruit quality is defined in terms of good appearance, firmness, and extended shelf life, while the consumer of fruit looks at quality from the perspective of freshness, firmness, flavour attributes, nutritional quality, and appearance in terms of absence of defects or decay (Punan et al., 2000; Zúñiga-Arias, 2007).

1.2 Statement of problem

Discrimination of fruit into maturity stages with deployment of non-destructive assessment is critical because it assist in proper grading of fruit for handling and storage. As such various non-destructive techniques such as multispectral, hyperspectral, spectrophotormeters as well as machine vision systems have been deployed for variety of fruit.

In a number of researches carried out on the non-destructive fruit quality assessments, light intensity-based features in the space domain has been utilized to build calibration models between the acquired images from the various systems and the reference measurements to be studied. Features such as the area of the captured image regions (Qing et al., 2007), radial averaging (Lu, 2004) wherein the photon scattering region is partitioned into several circular rings and the average value of the pixels within the ring is used as features to determine the quality of interest. Employing the radial averaging, various mathematical functions such as Lorentzian, Modified Lorentzian and Gompertz functions were fit into one-dimensional scattering profile as a function of distance. Other approaches used to process backscattering images is using one dimensional features of pixel brightness using colour models such as RGB, HSI, L*a*b* and others and using the colour features to assess or predict fruit quality of interest.

Consequent utilizing the one dimensional features focus solely on the pixel values neglecting pixel intensity pattern or location from the overall two-dimensional captured scattering images. Therefore, employing the two-dimensional scattering images i.e using the pixel values and location could help in improvement of the performance of backscattering images processing to study or assess the quality parameters of fruit and discriminating them into maturity stages.

Image texture is a two-dimensional processing approach which takes into account the pixels values and locations (Zheng et al., 2006). Though, a number of image texture-based analysis techniques has been used in image processing problems, majority has been done individually with different fruits, very few studies has reported comparative studies of these techniques. Therefore, this study investigates the comparative study of transform-based textural techniques to analyze backscattering images of banana and pear for prediction of the fruit quality parameters and discrimination into maturity stages.

Furthermore, processing of backscattering images using light propagation in tissues by extracting absorption and reduced scattering coefficients otherwise known as optical properties which is guided by the radiative transport theory has been employed sparingly. Few studies has reported the use of optical properties extracted from backscattering images for assessment of quality parameters of fruit and discrimination into maturity stages. Therefore, this study investigate the use of optical properties of banana and pear to assess/predict their quality parameters and discriminate them into maturity stages.

1.3 Objectives of the study

The main objective of this study is to evaluate quality parameters of banana and pear fruit related to the development and ripening by means of backscattering imaging coupled with computational intelligence techniques. The specific objectives are:

1. To evaluate banana and pear quality parameters using backscattering imaging and standard reference measurements i.e. firmness, elasticity, SSC, and index of chlorophyll.
2. To analyse the capability of transform-based processing techniques (wavelet, Gabor and Tamura) and diffusion theory (Farrell) features extraction methods for prediction of quality attributes of banana (index of chlorophyll, elasticity and SSC) and pear (Firmness and SSC) and classification of the fruit into maturity stages.

3. To develop intelligent models for bananas and pears quality parameters prediction and classification into maturity stages by artificial neural network and support vector machine.

1.4 Scope and limitation of the study

This study focuses on the evaluation of quality parameters of two climacteric fruits which are banana (Cavendish) and pear (*Pyrus communis* 'Conference'). The optical technique employed is LLBI system with five laser diodes 532, 660, 785, 830, and 1060 nm to capture the images of the fruit. Measurements were carried out on samples of banana at six ripening stages and on pears at different days after full bloom once a week for eight weeks. The quality parameters of interest were elasticity, firmness, index of chlorophyll and SSC and these were determined destructively using standard methods.

Optical properties and textural features were extracted from the backscattered images of both fruit using Farrell diffusion approximation and transform-based techniques (Wavelet, Gabor and Tamura). Labview and Matlab were used to develop a program to extract optical properties and textural features respectively.

The optical properties and textural features serve as input for neural networks and support vector machines models to predict the quality parameters of banana and pear, and also to classify banana into six ripening stages. Statistica 12, WEKA and Unscrambler x were used in the data analysis. This work is limited to two climacteric fruit that are banana and pear and one variety each for the two fruit, with three quality parameters for banana and two for pear. Pear sample collection is from one orchard.

1.5 Significance of the study.

Feasible applications of the method include packinghouse sorting of bananas into different ripening stages for effective postharvest handling to prolong shelf-life and pears for similar postharvest handling and effective sorting into ripe and unripe pears and banana. Using this technique banana and pears may be sorted into six ripening stages and pears into two classes of ripe and unripe fruits. The technique may also potentially be extended to other climacteric fruits.

The industrial relevance of the method presented in this research is immediate and high. The methods are simple to implement therefore its applicability in the industry can be undertaken with minimal expertise. Likewise, the system set-up is less cumbersome so it can be easily assembled for use in the industry. Due to low processing time per object with laser backscattering imaging system, time for image processing will be greatly reduced thereby enhancing the sorting and grading of fruit in the industry.

Since the techniques are non-destructive, samples which usually would have been destroyed with destructive technique will be saved thereby reducing waste and subsequently maximum numbers of samples can be assessed to have a fair representation of the entire lots. Less man power will be required as the technique can be automated thereby few hands will be needed to run the system with good accuracy for maturity stages discrimination of fruit.

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