UNIVERSITI PUTRA MALAYSIA

MODELLING OF PUNCTURE RESPONSES IN PAPAYA USING FINITE ELEMENT ANALYSIS

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By

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MODELLING OF PUNCTURE RESPONSES IN PAPAYA USING FINITE ELEMENT ANALYSIS

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Monitoring of impact damage of papaya due to punctures and cuts caused by excessive loading is a significant problem in papaya production. Therefore, this study aims to develop a finite element (FE) model to determine the puncture responses of Exotica papayas during storage.

As a first step to modelling the puncture responses of papaya during storage, the physiochemical and puncture properties were analysed. The fruits were used to measure the physicochemical properties (i.e colour, weight, dimensions, density, moisture content (MC), total soluble solids (TSS), pH) and puncture properties (i.e., bioyield force, apparent elastic modulus, and mean force). The colour and TSS were best regressed with all puncture properties with the coefficient of determination (R^2) more than 0.85.

Through the combination of FE analysis and optimisation procedure, the constitutive properties of flesh and skin were obtained. The FE data showed strong agreement with experimental data with R^2 values obtained of 0.87 and 0.88 for FE compression and tensile models, respectively. Throughout the 16 days' storage durations, the FE model was able to predict a decrease of 54.28% and 71.24% in failure stress of flesh and skin, respectively.

A three-dimensional (3D) FE model to simulate the probe-papaya interaction during the puncture test was then developed. The fruit model was presented as a multi-body system, and the constitutive properties of skin and flesh were used for the material model. The resulting force-deformation of the FE data was compared with the experimental data for the validation of the FE puncture model. Sensitivity checks were also done to evaluate the robustness of the FE model using the different values of constitutive properties of flesh and skin. Results

indicated that the model was able to predict the decrease in bioyield force of 39% when the papaya was stored at 12 ± 1°C for 16 days. This study also suggested that the skin contributes more than 20% to the overall stiffness of the whole papaya. The extreme values of 22.3N proved this detection for the bioyield force measured in the FE model when performing the sensitivity checks on skin properties, instead of 16.8N obtained during the sensitivity checks on flesh properties.

In conclusion, the FE model developed in this study potentially serves as a reliable prediction method to predict the puncture properties of papaya. The simulation and modelling of the different loading cases using the FE method can be beneficial to predict failure stress in papaya, which can occur during postharvest handling operations.

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

PEMODELAN TINDAK BALAS TEBUK-TEMBUS DI DALAM BETIK MENGGUNAKAN ANALISIS ELEMEN TERHINGGA

Oleh

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Pemantauan kerosakan akibat beban hentaman betik akibat tebuk-tembus merupakan masalah yang ketara dalam pengeluaran betik. Oleh itu, kajian ini bertujuan untuk membangunkan model elemen terhingga (FE) untuk menentukan tindak balas tebuk-tembus betik Esotika semasa penyimpanan.

Sebagai langkah pertama untuk memodelkan tindak balas tebuk-tembus betik semasa penyimpanan, sifat fisiokimia dan tebuk-tembus telah dianalisis. Sampel digunakan untuk mengukur sifat fisiokimia (iaitu warna, berat, dimensi, ketumpatan, kandungan lembapan (MC), jumlah pepejal larut (TSS), pH) dan sifat tebuk-tembus (iaitu daya biohasil, modulus anjal, dan daya min). Sifat warna dan TSS boleh digunakan untuk menjangkakan perubahan pada daya biohasil, modulus anjal, dan daya min dengan pekali penentu (R^2) lebih 0.85.

Melalui gabungan analisis FE dan prosedur pengoptimuman, properties juzuk isi dan kulit betik diperolehi. Data FE menunjukkan persetujuan yang kukuh dengan data eksperimen dengan nilai R^2 yang diperolehi masing-masing 0.87 dan 0.88 untuk model mampatan dan tegangan FE. Sepanjang tempoh penyimpanan 16 hari, model FE dapat meramalkan penurunan masing-masing sebanyak 54.28% dan 71.24% dalam tekanan kegagalan isi dan kulit betik.

Model FE tiga dimensi (3D) untuk mensimulasikan interaksi kuar-betik semasa ujian tebuk-tembus telah dibangunkan. Model buah dibentangkan sebagai sistem skala berbilang badan, dan properties juzuk kulit dan isi digunakan sebagai input kepada model FE. Untuk pengesahan model FE, perbandingan antara data yang diperolehi daripada model FE dibandingkan dengan data eksperimen. Pemeriksaan sensitiviti juga dilakukan untuk menilai keteguhan model FE menggunakan nilai properties juzuk isi dan kulit yang berbeza.

Keputusan mencadang bahawa model FE berupaya menjangkakan penurunan nilai daya biohasil sebanyak 39% apabila betik disimpan selama 16 hari pada suhu 12 ± 1°C. Penemuan juga menunjukkan bahawa sumbangan kulit sebanyak lebih 20% dalam meramalkan kekakuan keseluruhan betik. Nilai ekstrem 22.3N telah membuktikan pengesanan ini untuk daya biohasil yang diukur dalam model FE apabila melakukan pemeriksaan sensitiviti pada sifat kulit, bukannya 16.8N yang diperoleh semasa pemeriksaan sensitiviti pada sifat isi.

Kesimpulannya, model FE yang dibangunkan dalam kajian ini berpotensi berfungsi sebagai kaedah ramalan yang boleh dipercayai untuk meramalkan sifat tebuk-tembus di dalam betik. Simulasi dan pemodelan kes pemuatan yang berbeza menggunakan kaedah FE boleh memberi manfaat untuk meramalkan tekanan kegagalan di dalam betik, yang boleh berlaku semasa operasi pengendalian lepas tuai

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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 Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

ALE	Arbitrary Lagrangian Eulerian
ANOVA	Analysis of variance
CA	Controlled atmosphere
CI	Chilling injury
C*	Chroma
FD	Force-deformation
FDM	Finite difference method
FEA	Finite element analysis
FEM	Finite element modelling
FVM	Finite volume method
h°	Hue angle
MAP	Modified atmosphere packaging
MC	Moisture content
R2	Coefficient of determination
RMSE	Root mean square error
RMSEC	Root mean square error of calibration
RMSEP	Root mean square error of prediction
SDG	Sustainable Development Goal
TSS	Total soluble solids
VCP	Ventilated corrugated paperboard
2D	Two-dimensional
3D	Three-dimensional

CHAPTER 1

INTRODUCTION

1.1 Background study

Papaya is a non-seasonal fruit and is available throughout the year. It contains nutrients such as vitamin A and vitamin C, polyphenols, carotenoids, potassium, folate, niacin, thiamine, riboflavin, iron, carbohydrates, calcium, and fibre (Nieto Calvache et al., 2016). Also, the digestive enzyme of papaya, namely papain is used as an industrial ingredient in brewing, tenderizer in cooking and applications in the food industry, pharmaceuticals, textile, beauty products, and cosmetics (Esti et al., 2013).

Based on the recent report (FAO, 2022), The world production of papayas grew by 2.7% to 353 000 tonnes in 2020. Malaysia is the fourth world- leading supply of papaya exporting 22 500 tonnes to the markets. However, in the face of a new market dynamic, the industry faced various challenges. Among many, one of them is the significant number of post-harvest losses due to the mechanical impact damage. A reduction in these losses would increase the number of fruits available for consumption and thus leads to growing consumer demand. This can be achieved by maintaining the fruit quality and extending the shelf-life of the papaya, mainly during the distribution from farm to retail.

This current decade has seen the development of non-destructive techniques for determining the mechanical damage resistance of agricultural products, such as the thermo-acoustic ultrasound (Vasighi-Shojae et al., 2018), electronic and spectroscopy devices (Figueiredo Neto et al., 2017). For instance, Doosti-Irani et al. (2016) used thermal maps, while Che et al. (2018) used the hyperspectral imaging to determine the bruise region in apples. However, these techniques require extensive research to anticipate real-time monitoring, especially when the damaged fruit progressively and continuously softens throughout the handling processes. Furthermore, the systems also require a standard set up for a particular type of real-fruit, which is even more challenging to develop a practical and portable system usage. The phenomena observed in fruits under load are generally described using the constitutive approaches (Komarnicki et al., 2016; Stopa et al., 2018a; Stropek & Gołacki, 2016). Mathematical models such as the Maxwell model (Saeidirad et al., 2013; Zhao et al., 2017), the Kelvin–Voight model (Xu & Chen, 2013), or the Burgers model (Ji et al., 2019), were often used to describe the mechanical behaviour of fruit.

Finite element analysis (FEA) can be used to solve these constitutive model equations. For example, the formulation of the system equation was developed to express the conservation of between mass, applied force, and energy in mechanised fruit processing (Fadiji et al., 2018). Through FEA, one should be able to estimate the fruit responses based on the number of applied loadings, making it possible to determine the influence of post-harvest handling systems that affect the susceptibility of the fruit to mechanical damage. The practicability of FEM is that it can reduce the number of physical experiments by replacing it with a simulation study before developing any related design prototype.

1.2 Problem statement

The accessibility of consumers to papaya must be increased by reducing the number of post-harvest losses. A reduction in these losses would increase the number of fruits available for consumption and thus leads to the growing consumer demand. MAFI (2020) reported that in 2018, papaya production in Malaysia was reduced to 36.8% while the export value declined up to 38% from 2017. Papayas are often exposed to deterioration of physical structure caused by rough handling during post-harvest operations. The area or spot of impact can then serve as infection site for numerous wound pathogens that result in many severe diseases (Habib et al., 2020). These spots, even without infection by pathogens, are unsightly and cause moisture loss and excessive shrivelling (Ayón-Reyna et al., 2017). Besides, the quality of fruits may decline greatly during the postharvest supply chain. Since most of the recent literature describes the appeared physical and mechanical damages among other climacteric fruits except for papayas, this thesis addresses the existing gap by evaluating the connection between the changes in quality properties and the susceptibility level of papaya towards mechanical damage.

The impractical implications of puncture probe-sample-related variables also make it challenging to compare puncture test data from different puncture setups. Plus, to this date, there are limited studies on the finite element modelling (FEM) related to papaya have been proposed. Therefore, this study aims to develop a three-dimensional (3D) model to simulate the probe-papaya interaction without having to perform the actual puncture test that could destruct the physical of the fruit. This thesis also addresses the importance of defining the material model as the accuracy of finite element (FE) models is depending on the material inputs. To select these inputs, the constitutive material model was developed to describe the non-linear, elastic-plastic, and failure deformation. However, the consideration of the nonlinearity in part contact and plasticity in material models in these types of studies is still limited for fruit's stress analysis. Through FE analysis and the combination of optimisation procedures, the constitutive properties of flesh and skin were obtained.

1.3 Significance of study

Reducing food loss is critical to creating a zero Hunger world and reaching the world's Sustainable Development Goals (SDGs). SDG 2 aims to achieve food security and SDG 12 to ensure sustainable consumption and food production patterns.

Since papaya is consumed after peeling, not only its freshness is reduced but it also becomes prone to desiccation leading to spoilage. To counter this problem, researchers have strived to develop measures that kept the convenience of consumers in mind as well as helped in preserving the fruit for a longer duration. Hence, determining the mechanical properties is essential to achieve these aims.

By adopting the experimental, numerical and FE modelling approaches, the mechanical damage in papaya can be predicted in real-time. Plus, this study exploited some prior knowledge about the characterisation of the multi-mechanical properties of papaya. In this study, the different aspects in terms of simulation case study i.e type of puncture loading, and the suggested material model to predict the mechanical behaviour of papaya upon the impact loading are provided. In this study, localised tissue failure along the maximum width of papaya was simulated.

The output of this research is beneficial to fresh produce producers, agricultural industries, and inventors to be used that it can reduce the number of physical experiments of the real testing on the site, by replacing it with a simulation study before developing any related design prototype

1.4 Research objectives

The main objective of the thesis is to develop a finite element model to predict the puncture responses in papaya. The specific objectives of the study are listed below:

1. To determine the relationship between physicochemical and puncture properties of papaya at different storage durations.

2. To evaluate the constitutive properties of papaya flesh and skin through the combined finite element analysis and optimisation procedure.

3. To validate the finite element model for the predictions of the puncture impact at different storage period.

1.5 Scope and limitations

The study only focused on the established commercial variety of Exotica papayas, stored at 12 ± 2 °C with 75 ± 5% of relative humidity (RH) for 16 consecutive days. The main essence of this study is the development of finite element modelling that predicts the mechanical responses of papaya during puncture impact loading at 1.5mm/s. The puncture was performed along the maximum width of each fruit. The ANSYS software (ANSYS Incorporation, Canonsburg, PA, USA) was used for developing the geometrical model and FE analysis.

1.6 Thesis outline

This thesis content is organised into five chapters, which are presented as follows:

Chapter 1 begins with an overview of the background study. The broad issue concerning the fruit losses and the occurrence of mechanical damage throughout post-harvest handling are highlighted. The overview section helps to develop the problem statement and research objectives which are also represented in this chapter.

The main focus of Chapter 2 is to report a review of the literature, considering the application of FEM to determine the mechanical damage in fruits. The objective is to identify the state of the art in FE analysis by considering the recent trends in geometrical modelling approaches, constitutive models, and the relevant method that is required for FEM validations. Furthermore, the discussion on the FEM-related future research possibilities is proposed where comments are made regarding the potential for the practical implementation of FEM in the agricultural industry.

Chapter 3 describes the empirical test to evaluate the effects of storage duration on the physicochemical and puncture properties of the Exotica papaya. The method to identify the constitutive properties of flesh and skin of the papaya using FE analysis and optimisation procedure is presented. This chapter also covers the customary method to develop the FE model for the prediction of the puncture response of papaya with the effect of storage conditions.

Chapter 4 is devoted to findings obtained in the experimental tests and FEA. The effect of different storage conditions on the physical and puncture properties of the Exotica papaya are discussed. Constitutive properties of flesh and skin of papaya which had been obtained through FE analysis were presented. Using the constitutive multi-scale s, the performance of the FE model to predict the puncture response of papaya was then compared with the experimental results.

Finally, Chapter 5 will provide the summary and conclusion of the study. Besides that, several recommendations are given based on the findings discussed in previous chapters.

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