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Modeling the Mechanical Behavior of Fruits: A Review

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ABSTRACT: According to the significance of postharvest processes in increasing the life of agricultural produce and preserving their nutrition, industrial, and economic values, as well as identifying damage factors in order to reduce products' damages and losses, it is essential to acknowledge and evaluate the mechanical behavior of agricultural produce for designing and optimizing machineries. This behavior includes such determined and defined parameters as modulus of elasticity (E), shear modulus (G), and bulk modulus (K), Poisson's ratio, and viscosity, as well as imposed forces and factors effective in damages. Accordingly, rheological models (spring and dashpot), finite element, discrete elements, regression, and mass estimation using image processing are among the methods being used for this purpose. In doing so, reviewing the literature background on fruits' mechanical behavior modeling, their modeling methods were highlighted and the characteristics, capabilities, and necessary requirements of each modeling technique were discussed.

Keywords: Rheology, Mechanical Behavior, Post-harvest, Fruit.

INTRODUCTION

Generally, the mechanical damage to fruits, during harvest and transportation chain, leads to early deterioration, quality degradation, and decreasing fruits' market value. Therefore, it is necessary to design and develop machineries which do not impose any physical damage to fruits during harvest. Also, given the importance of transportation and storage cycle of products before processing as well as the importance of designing and developing transportation machineries and packages, it is essential to perform extensive research on identifying the mechanical behavior of fruits during this relatively long process. Therefore, there are methods for measuring the mechanical behavior of products. Some of which are as Fundamental methods, Empirical methods, Emulative methods

The above-mentioned methods are used to measure the rheological and tissue properties of products. The following is the description of each method (Bourne, 1982):

A. Fundamental methods

The fundamental methods have physical and mathematical basis and fully defined and determined physical and rheological properties (such as modulus of elasticity, shear modulus, and bulk modulus, Poisson's ration, and viscosity) are measured. In these methods, the rheological behavior of foods could be defined using mathematical models and the units could be interconverted. The major flaw of fundamental methods is their relatively low correlation with sensory evaluation methods. That is, the results from fundamental measurements might be inconsistent with what is tasted inside the mouth during chewing. The measured rheological parameters in fundamental methods are defined and developed by engineers of materials science who might have a completely different view from food industry engineers. Materials science engineers measure the rheological and mechanical parameters so that they would be able to design materials which are resistant against imposed forces and are not easily broken. While, determining the ease of breakage for foodstuff during chewing and swallowing is the purpose for measuring most of the mentioned properties.

The following hypotheses are in fundamental rheological tests:

(i) The developed strain is small (1-3% maximum).

(ii) The material is continuous and isotropic, i.e. the material has identical physical properties along all axes.

(iii) The test sample has a uniform and orderly shape.

The disadvantages of fundamental methods are as follows:

(i) Weak correlation with sensory methods (unlike empirical methods).

(ii) Are easy to use and performed with a high speed.

(iii) The equipments of this method are expensive and not used extensively in food manufacturing plants and are limited to specific laboratories.

B. Empirical methods

In empirical methods, the measured rheological and tissue properties are not properly defined and could not convert the data from these methods to each other or to fundamental data.

Advantages of empirical methods are as follows:

(i) Good correlation with sensory methods.

(iI) Easy to use and relatively high speed.

(IIi) Relatively inexpensive equipments.

According to the advantages mentioned above, these methods are extensively used in plants. Specially, equipments working with empirical methods are widely used in cereal industries.

Disadvantages of empirical methods are as follows:

(i) The measured parameters have no clear or weak physical definition and are not interconvertible.

(ii) The equipments are only used for a limited number of foodstuffs.

(iii) The calibration of equipments is difficult.

(iv) There is no absolute standard in most cases.

Due to the above-mentioned drawbacks and the extensive application of such methods, more study and development are needed for empirical methods so that they could be converted to methods with stronger scientific basis.

C. Emulative methods

These methods are designed based on simulation of imposed forces and deformations of foods under such forces during processing or chewing and swallowing. Sometimes these methods are supposed as a subset of empirical methods since the measured parameters are not fundamental properties. For example, the dough mixture process is emulated in farinographs and the force required for chewing is measuring using a device similar to human jaws with sensors on its synthetic teeth. Considering the introduction of the aforementioned methods and papers on fruits modeling, this topic is further studied relying on software-mathematical modeling and empirical modeling. Papers on such topic are discussed below.

LITERATURE REVIEW

Hassan *et al* (2005) studied stress relaxation models of Maxwell, Nussinovitch, and Peleg in order to predict dates maturity time and used a texture analyzer to measure the laboratory data. Data related to modulus of elasticity were extracted based on stress-strain diagrams of different date varieties. The results were then compared with those from modeling. It was concluded that according to the viscoelastic texture of dates, the results from stress relaxation models are in good accordance with the empirical results. Also, it was acknowledged that the Maxwell model is more capable and accurate than the other models (Hassan *et al.*, 2005).

Wang (2003) used the generalization of viscoelastic properties of materials to spring and dashpot elements for fruits transportation as well as obtaining a proper time for preserving fruits inside packages. In this study, the Maxwell's model was used to obtain stress parameters against time. Non-isotropic properties of pear fruit was studying through the stress relaxation phenomenon, rheological properties of pear fruit was measured along different axes using Instron equipments, and the results were capered with modeling under spring and dashpot elements. The results from this study showed that the loading axis has a significant effect on modulus of elasticity and other rheological properties. Therefore, its results could be used to improve transportation and storage of products along the proper axis, from harvest to supply.

Dintwa *et al* (2011) studied the finite element analysis of a tomato tissue cell. According to this study, a tomato cell was considered as a sphere containing liquid which its wall was membrane-like and the liquid could secrete through under force and pressure. Then this cell was loaded using a special probe and the deformation was measured using image processing MATLAB software. An elastic behavior was assumed. Then, the results were compared by simulation using the COMSOL software. This study indicates the quiet proper closeness of results from the laboratory method and those from the finite element method. Also, it could be concluded that using the results obtained from the molecular and cellular simulations, the properties of a whole fruit could be achieved. These data could be used in improving the post-harvest methods.

Dintwa *et al* (2008) modeled the process of impact and apples being rubbed against each other and hitting the storage packages using the finite element of the MENTAT software. The nonlinear parameter analysis of materials is the feature of this software. In doing so, first a 2D model of apple was introduced to the software, and then it was meshed and using the "Duplicate" feature of the software, a whole fruit was simulated and studied under fruits hitting each other and the box's walls. To do so, the fruit's properties were assumed similar in all axes (isotropic material). Also, the numerical values related to modulus of elasticity, shear modulus, density, and Poisson's ratio of apple were introduced to the software.

Then, two conditions were studied: apple-package wall contact and apple-apple contact. The result of this study was the diagram of deformation and force variations against time in both theoretical state and using the finite element software. Also, the diagrams of viscosity, elasticity, and viscoelasticity coefficients were obtained. This study showed the closeness of theoretical data to modeling process data using the finite element method. This method could be applied to the modeling of mechanical behavior of fruits.

Lu *et al* (2006) used both the empirical and finite element methods in measuring of apple's firmness and compared their results. In this experiment, a loading device was used for measuring firmness, and then the loading was performed within the elastic range and the data were recorded. It is worth mentioning that the tip of the penetrator was covered by a plastic layer. Next, both the fruit and the penetrator were simulated using the simulation software, MARK. The loading operations were conducted based on the equipment's test features and the results from both methods were statistically analyzed. The results showed a coefficient of correlation equal to 0.828 between the data from both methods.

Jancso'k *et al* (2001) modeled the effect of pear fruit shape on the acoustic response of the fruit using the finite element method and the results were compared with the laboratory method of acoustic impact. This method was based on capturing the sound of hitting pears through a microphone and then processing and correlating the obtained signal to the pear fruit's firmness. For the finite element method, parameters such as length, maximum diameter and the ratio of fruit's length to diameter were used and finally the modulus of elasticity was correlated to the fruit's firmness. The analysis was conducted using the CADA-X software. According to the very good fitness of data obtained from the finite element method with the laboratory method within the linear elastic range, the software method could be used for determining the physical properties of pear fruits.

Celik *et al* (2001) modeled apple's falling-induced deformation using the finite element method. In doing so, the image of apple was captured by a 3D camera. Next, the image was modeled by the Solidworks software and the meshing and the finite element analysis operations were performed using the same software. Then, the parameters corresponding to the same apple variety were introduced to the software as the finite element analytic data. The falling-induced deformations from different heights as well as the forces imposed to the apple were calculated. The results from the deformation measured using the finite element method and their comparison with those from the deformation measured using the high-speed camera images showed that applying the finite element method to measure the deformation caused by impact load is reliable.

The 3D modeling of fruit mechanical behavior using the modeling of the tiniest components could contribute to the better understanding of the mechanical behavior of different parts of a fruit and consequently its total cellulose structure under compression loads. Accordingly, Wu *et al* (1999) modeled the finite element loading for an apple's cell. In doing so, first a primary loading of cell was simulated, and then the main loading within the elastic range was simulated. This modeling was performed by the finite element software, CAE. The results showed the close relationship between the results from the finite element method with those from the empirical data of other authors.

Chen *et al* (1996) measured the firmness of honeydew through a nondestructive test using the finite element method. In this method, the modulus of elasticity was statically obtained from data pertaining to stress-strain and loading-deformation obtained from the Universal Testing Machine (UTM). Next, the ANSYS software was used for the dynamic and resonance frequency simulation of the honeydew. The application of resonance frequency is in determining the firmness and finally the ripeness of fruits. The results from this study showed the high accuracy of fruits' finite element simulation and the reliability of the resonance frequency in estimating the maturity level of fruits, as a nondestructive test.

Van Zeebroeck *et al* (2007), using regression equation and the discrete element method, investigated the effect of some of the physical parameters of apple on its sensitivity against impact. The results from four studied parameter, namely time of harvest, sphericity, temperature, and firmness, showed that the effect of impact decreases as a result of increased sphericity. Higher firmness leads to more effective impacts, and also the effect of impact is decreased in higher temperatures. Finally, later harvests decreases the effect of impact on products during storage and transportation.

Van Zeebroeck *et al* (2006) used discrete elements method to simulate the process of apple's transportation and the impact-induced effects during transportation, including bruises. Then they compared these results with the actual state. The discrete element simulation was carried out using the C++ software for parameters such as number of elements (apples inside a box), element radius, density, box dimensions, time of impact, apples' initial speed, apples' initial position inside box, and the contact force between apples.

In order to investigate the effects of bruises from the obtained data, the contact force duration and the depth of bruises were studied by MATLAB and the results were then compared with an empirical model with similar number of apples and box size. The close relationship between the results of both methods showed that by using the discrete element method, the mechanical behavior of apple during transportation could be studied with high reliability.

Van Linden *et al* (2006) calculated the bruises in 5 varieties of tomatoes using the impact test. In this method, an encoder-equipped pendulum with different angles applied impact forces on a tomato and the data from this experiment were recorded by force and time measurement sensors installed on the pendulum. On the other hand, a synthetic electronic tomato was as well under actual impacts from the transportation operation. The data from this experiment, including time and the imposed energy were recorded and analyzed using the SAS software. The study results are applicable for determining impact resistance varieties.

DISCUSSION AND CONCLUSION

The literature review showed that the mechanical behavior modeling of fruits is one the major topics of the post-harvest engineering. Since the post-harvest engineering encompasses the transportation of products from farms and orchards to the product processing stage, studying the mechanical behavior of fruits has led to important progresses in developing transportation, packaging, grading, and quality measurement machineries. The reports other references show that the objective of modeling the mechanical behavior of fruits is to understand their physical and mechanical properties at the shortest time possible and with high accuracy, as well as the ability to study the different depths and layers of fruits without the limitations imposed by laboratory instruments and tools and as a nondestructive test with less cost and higher accuracy. The results of the modeling from the reviewed papers are as follows:

Reviewing rheological models for mechanical behavior modeling of fruits using stress relaxation and creep compression modeling which are based on the generalization of viscoelastic properties of materials to spring and dashpot elements showed that the Maxwell, Kelvin, and Burger models could be used in determining strain and stress against time. The results from each model were compared to the laboratory method and validated. The findings of this method might lead to optimized designing of dimensions and depth of transportation boxes. The suitable preservation time of fruits inside the designed box could be determined, as well. The cited references showed the close relationship between data and results from the modeling method and the laboratory method. Thus, this is a reliable method in modeling of fruits' mechanical behavior.

The finite element modeling enjoys several specific features including the ability of modeling and analysis of the finest components of a fruit, e.g. cells. The mechanical behavior modeling of fruits using the finite element method, in the mentioned studies, was performed using the following software: ALGOR, ANSYS, MARK, COSMOS, CADA-X, CAE, and MENTAT COMSOL. The use of such software in analysis and modeling of fruits' mechanical behavior is only reliable only within the linear range since the mentioned software is technical and engineering by nature and their responses are within the elastic range while biological materials such as agricultural produce and fruits also indicate nonlinear behaviors. However, considering what was discussed in the literature review, the MENTAT software is capable of modeling the mechanical behavior within the nonlinear range; therefore, it is suitable and accurate for modeling of biologic materials.

In the discrete element modeling method, the modeling of mechanical behavior was performed using differential equations under initial and boundary conditions of each fruit as an element. The boundary conditions were considered as the conditions governing the contact location of fruits with each other or with the box's walls. Then, MATLAB and C++ were applied to the analysis of matrices containing information related to the discrete elements (fruits) including number of elements, radius of elements, density, time of contact, initial speed, and contact force. C++, SAS, and MATLAB are among the software used in this method. In terms of the speed of analysis and calculation during the modeling process, C++ provides the fastest data processing because of its similarities with the machine code. Based on the performed validation between parameters obtained from the experiments and results from the discrete element method, it was indicated that this method enjoys a good capability and accuracy in simulating the mechanical behavior of fruits.

In the literature review, it was also highlighted that mass modeling of fruits was performed using the image processing technique with parameters related to fruit dimensions. In this method, the fruit's dimensions were calculated and its mass was determined using the fruit's density and volume. This technique is used in determining the physical properties of fruits related to the qualitative and quantitative grading.

Similarly, the image processing technique is applied to determining the mechanical behavior of fruits under impact loading. Using this method, the approximate amount of impact and pressure on a fruit under falling conditions from different elevations and using impact-sensitive films or color ink was determined.

Also, another modeling method for mechanical behavior of fruits is the regression modeling in which the mechanical behavior under different loads and speeds, parameters related to stress-strain, force-deformation, and so forth are extracted using laboratory tools and instruments. Data are afterwards analyzed using statistical analysis software and the corresponding relations for each mechanical behavior are presented. Expensive laboratory equipments and tools, slow testing and modeling process, and being destructive are some of the drawbacks of this method. Equipments such as texture analyzer, rheometer, impact test device, vibrometer, and so forth are among the necessary equipments for performing such experiments, which are all expensive and costly.

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