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Review Article

Reliability of Finite Element Analysis to Determine the Mechanical Responses in Fruits and Root-Vegetables

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Abstract: Maintaining the quality of fresh fruits and root-vegetables (FV) is still a very challenging task due to its susceptibility to physical damage. The quantification of damage depends on the mechanical behaviour of FV subjected to either static or dynamic impact loading. This work aims to provide readers with the background information regarding the applicability of finite element (FE) modelling to predict the mechanical properties, yield strength and failure of FV subjected to any given load, specifically during post-harvest operations. Therefore, the relations between the reverse engineering approaches, mechanical tests and FE method were discussed. A brief description of geometrical modelling, material model and validation techniques that allow for a more accurate FE model was also reviewed. This article presents the recent developments in FE model, highlighting the applications and their contributions to the agricultural field as well as identifying open issues where extensive research is needed.

Keywords: Finite element method; mechanical model; fruit; root-vegetable

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1. Introduction

The reduction of post-harvest losses has significantly increased the accessibility of consumers to good quality agricultural produces. For that, the handling operations need to be improved so that the reduction in these losses would increase the number of the produces available for consumption and thus leads to the fulfilment of growing consumer demand. This can be achieved by improving the commercial handling process and also the distribution process from farm into retail (Chegere 2018).

The management of agriculture produces in distribution begins with understanding the nature of the distribution chain, from production to consumption, and defining the components that make up the chain input. An understanding of the nature of post-harvest management practice is important for it largely determines the final quality of the produces; whether it is safe for fresh consumption or as minimally processed fruit or to be as an ingredient for a processed product. Numerous research was found investigating the resistance of fresh fruits and root vegetables (FV) under the impact loads, for example, during grading (Aliasgarian *et al.,* 2015); transportation (Jung & Park 2012; Soleimani & Ahmadi 2014); and packaging (Albaar *et al.*, 2016). Mechanical damages occurred during these operations may not immediately be visible, but will rapidly deteriorate the FV quality over a definite time. For instance, an affected spot due to damage would have eventually become an entrance site for pathogens that results in a much larger damage area. Even without infection by pathogens, the spot is unsightly and causes moisture loss and shrivelling of skin (Opara & Pathare 2014).

FV is characterized by a complex mechanical behaviour. In the case of only one level of impact load, there are several mechanical testing such as the use of the pendulum, puncture or compression tests which can be performed to investigate the effects of load, yield stress, failure and deformation in FV (Li *et al*., 2017). However, in practice, it is difficult to study every possible combination of critical stresses because each test is expensive, and a large number of samples are required. Finite element (FE) modelling is one of the numerical methods that has been applied successfully in many areas of engineering sciences related to mechanic studies (Tanadrob & Suvanjumrat 2017). The method has been found useful in the research field of agricultural engineering in the context of the yield, strength, failure and deformation in FV (Zulkifli *et al*., 2020). The FE model is developed using multiple choices of FE software such as ABAQUS, ANSYS and COMSOL Multiphysics. These software choices contain pre-and post-processing facilities to solve even the complicated geometrics and multiphysics phenomena.

This paper reports a review of the literature, considering the application of FE modelling to determine the mechanical responses in FV. The objective was 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 was required for FE modelling validations. Furthermore, the discussion on the FE modelling related future research possibilities was proposed where comments were made regarding the potential for the practical implementation of FE analysis in the agricultural industry.

2. FE Modelling for Stress Analysis in FV

Multiple impact loads that occur during handling operations could cause physical stress and injury to fresh agricultural produces. In the last 10 years, researchers have developed FE models to assess the mechanical responses in these produces under the influence of static and dynamic loads (Manetto *et al.*, 2017; Salahuddin *et al.*, 2019). Based on the previous works, the FE simulation of FV under static load was more effective at defining the simple yield stress limit, for example, during compression. However, the simulation under dynamic load was more effective at assessing the factors that caused the FV to bruise (Shafie *et al*., 2017).

The most common FE model for the prediction of mechanical damage in FV is carried out by drop test simulation. Stress distribution within the contact area at the time of the collision can be determined, as the severity of the damage was suggested to be related to the drop heights, orientation, and the conditions of the contact surfaces (Shafie *et al.*, 2016; Stropek & Gołacki 2013). Such a model has been established for peach (Kabas & Vladut 2015), apple (Celik *et al.*, 2011), and kiwi (Du *et al.*, 2019). Figure 1 presents the drop test results for pear, carried out at different drop orientations and heights (Yousefi *et al.*, 2016). The severity level of mechanical damage in FV was also proven to have significantly influenced by the physiological state of FV, for instance, due to the changes in its properties under the influence of natural ripening (Hussein *et al*., 2018). In previous studies, FE simulations were performed to predict the mechanical strength of an orange (Namdari *et al*., 2020) and a watermelon (Abbaszadeh *et al.*, 2014), at different ripening stages under the influence of free vibration condition. However, both authors have opted for the modal analysis, hence the magnitude of stress and displacement results were assumed to be meaningless as there was no definite force applied onto the fruit (Jancsók *et al.*, 2001).

FE modelling was performed for the quantification of mechanical damage in FV, without having to perform laborious works. Earlier, FE modelling has been utilized to compare the different designs of ventilated corrugated paperboard packages to reduce the probability of an apple to compression damage (Fadiji *et al.*, 2016; Opara & Fadiji 2018). As illustrated in Figure 2, FE models developed by Fadiji *et al.* (2019) investigated the role of geometrical configurations of ventilated holes to provide better ventilation of the packaged apples, without compromising the compression strength of the paperboard package.

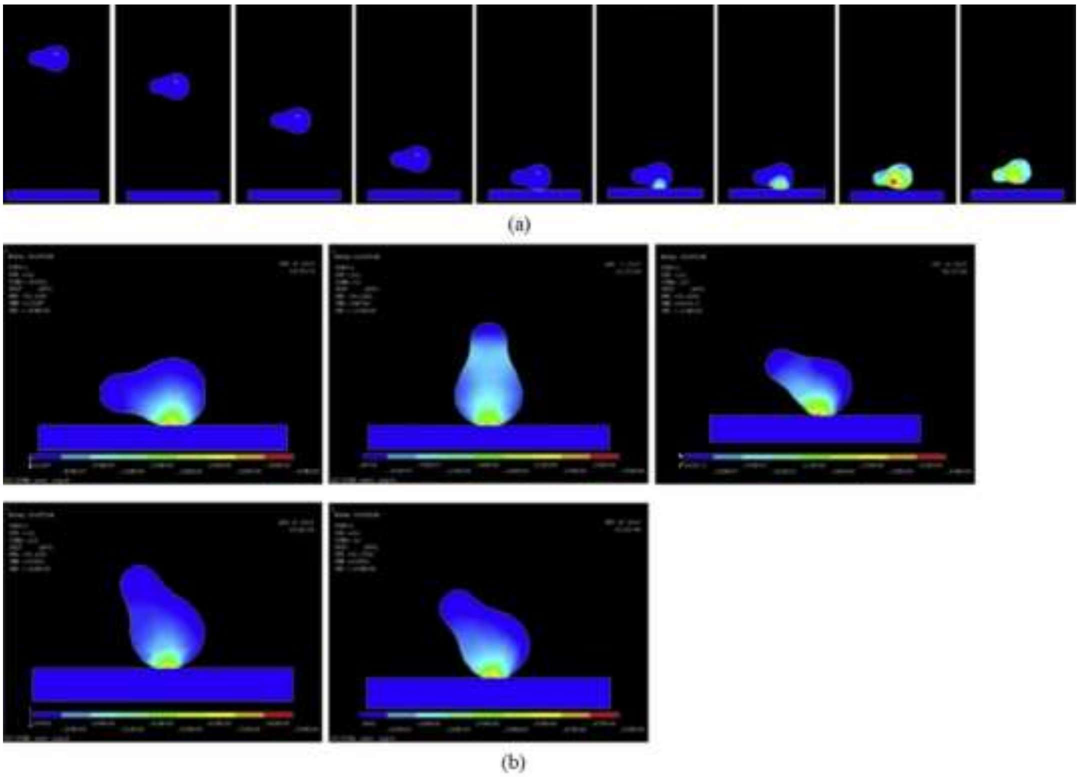

Figure 1. The FE-dynamic model: (a) Drop simulation; (b) The drop tests carried out at different orientations, from the horizontal line of the contact surface. Adapted from (Yousefi *et al*., 2016).

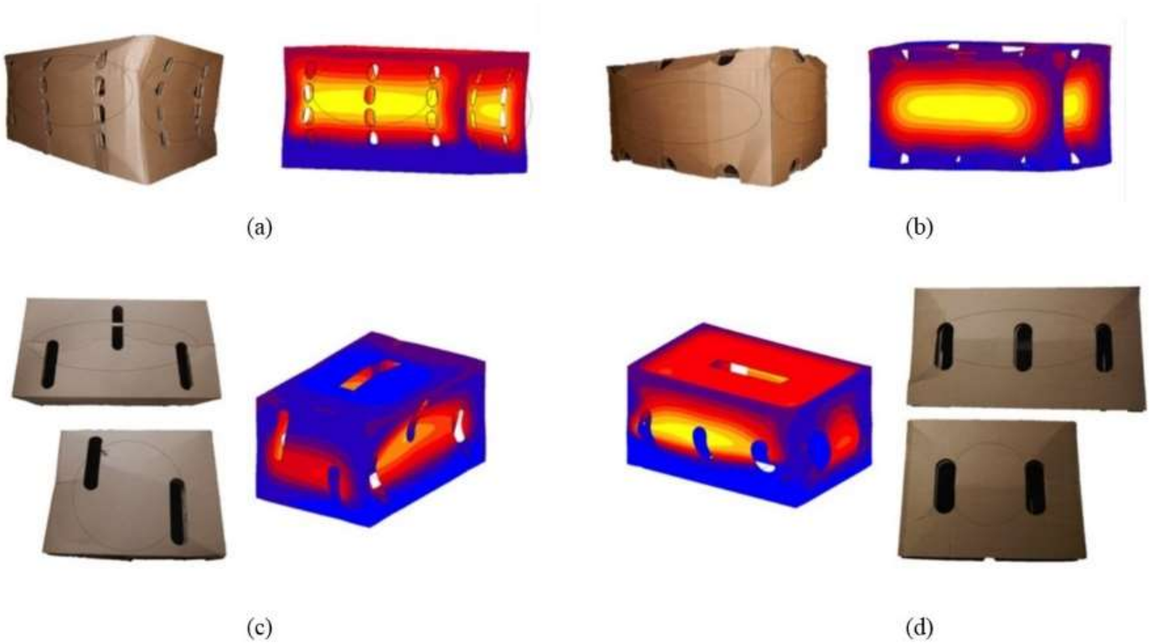

Figure 2. Comparisons of the FE results showing the compression stress distribution of different vent hole designs of corrugated paperboard packages: (a) Multi vent; (b) Edge vent; (c) Alt vent and (d) Standard vent. Adapted from (Fadiji 2019).

3. Geometrical Attributes and Meshing Techniques

In FE analysis, the geometrical model can be simplified in two-dimensional (2D) or three-dimensional (3D) depending on the type of element that is selected accordingly. A 2D-planar element is used when two of the dimensions are large in comparison to the third dimension (Petrů *et al*., 2014). For bulk FV with complex geometry, a simplified 2D model have the advantage of lower computational memory and processing time (Ihueze & Mgbemena 2017), whereas, the 3D element is used when all three dimensions are comparable. FE-3D model is used to simulate the rigid and flexible behaviour of the solid, surface and line bodies (Abera *et al*., 2016). Each element is connected to the nodes with the nodal degree of freedom.

FE modelling is essentially a multiscale model that can be used to describe the material behaviour at different spatial scales, which are indicated by the total number of elements. The advantage of multiscale modelling is the macroscale level behaviour that can be predicted based on the cumulative responses of the underlying structure of matter at the microscale level (Mebatsion *et al.*, 2008). Usually, a multiscale modelling is required for the characterization of mechanical properties in FV which relates to the physiological responses of the comprised cells and tissues. According to Ho *et al.* (2013), the heterogeneous material at the microscopic level combines with the stiff reinforcing elements and the binding medium to assemble into a composite material that is homogenous at the macroscopic level.

Recently, Nikara *et al.* (2020) developed a geometrical model which comprised of a set of potato cells in a FE modelling environment to investigate micro- mechanical changes in the tissue and cells in response to impact load. In the study, scanning electron microscopy technique was adapted for the better representation of the geometrical model comprised of cells and tissues of the potato. Earlier, Dintwa *et al.* (2011) proposed the use of a FE model of a single cell of tomato to predict the deformation of plant tissues at the macroscopic level. In addition, Li and Wang (2016) found that the microscale properties of a single cell measurement can be used to simulate the compressive response of whole tomato fruit. However, in all of these studies, the microscale properties were identical, homogeneous and orthotropic.

Alternatively, the microscale properties can also be incorporated through averaging procedures so that the simulation can be performed at the mesoscale and macroscale level simultaneously. Fewer assumptions are required for the macroscale properties when physical constants of microscale properties are known. Earlier, both Celik (2017) and Salarikia *et al*. (2017) proposed a single scale geometrical model of the whole fruit to limit the uncertainties caused by irregular geometric properties of cells for both skin and flesh tissues. On the other hand, in another study, Li *et al.* (2013) developed a 3D FE model representing the exocarp, mesocarp and locular gel tissues of a whole tomato. The author suggested that the different geometrical characteristics of the different tissue types had effects on the deformation and the yield stress under the compression load (Figure 3).

For an accurate FE analysis, meshing should be employed by selecting the appropriate type, shape and size. It is important to make sure that the appropriate number of elements is used. For mesh convergence analysis, the optimum number and type of elements chosen must not affect the accuracy of the FE model (Celik 2017) (Figure 4). Usually, the higher density meshes would give a better approximate solution to the problem (Guessasma *et al*., 2011). However, a longer computational time may be required if the element size is inappropriately small, especially for multiple iterations of the nonlinear and dynamic stress analyses (Li *et al*., 2013). Alternatively, the uses of the different types and sizes of elements can also be used to mesh the more complex geometrical model.

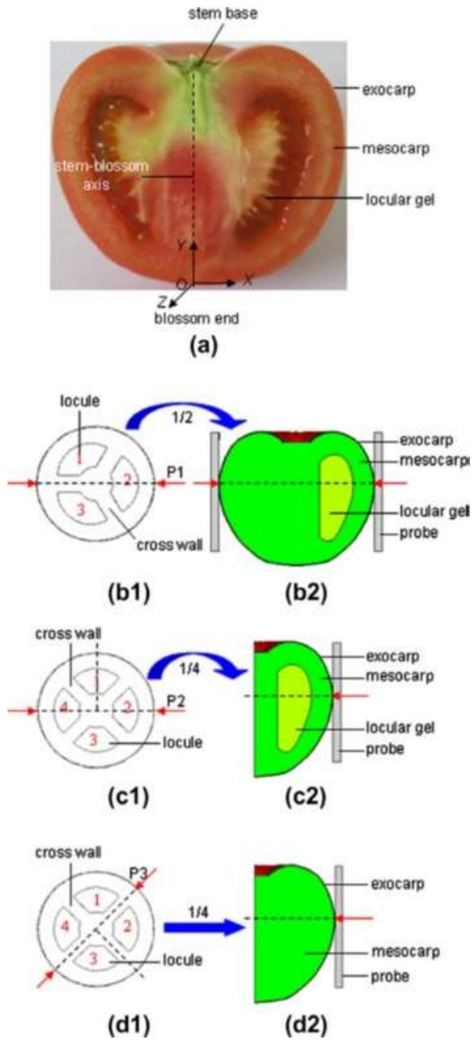

Figure 3. Geometrical models: **(a)** Different regions of the exocarp, mesocarp and locular gel of a tomato. Considering the different contact geometries: **(b1)** Equatorial section of a three locular tomato; **(b2)** Half-geometric model; **(c1, d1)** Equatorial section of a four locular tomato; **(c2, d2)** A quarter geometric model of a four locular tomato. Adapted from Li *et al*. (2013).

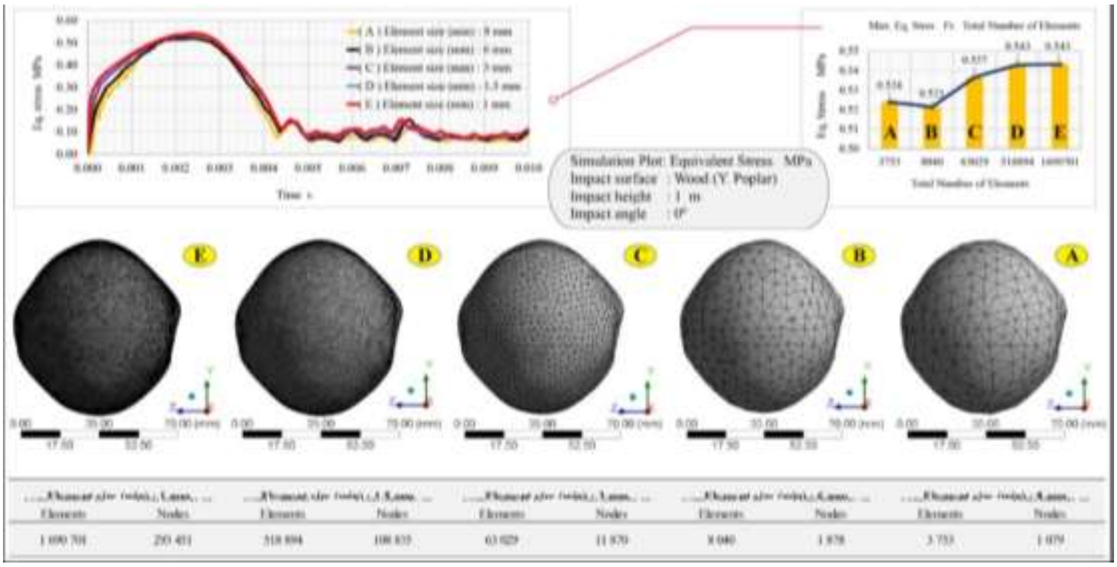

Figure 4. Mesh convergence study: Effects of different sizes of elements on the resulted impact stress in fruit (Top); The respective numbers and sizes of elements: **(a)** 8 mm; **(b)** 6 mm; **(c)** 3 mm; **(d)** 1.5 mm and **(e)** 1 mm. Adapted from Celik (2017).

4. Constitutive Material Models

In general, the material model is used to describe the FV responses to the various types of loadings. The model was either used to define the strength or the failure of the FV, based on the simulation of the mechanical system (Guo *et al*., 2020). The characterization of whether it is the isotropic, orthotropic or anisotropic properties should be first defined for the different material model to simulate the different yield stress, deformation and failure in FV.

The selection of material models covers a wide range of mechanical behaviours, which can be formulated either based on the equation of state, material strength model or material failure model. The most commonly used is the linear elastic of constitutive model by specifying the elastic modulus and Poisson's ratio of the assumed homogenous material (Yousefi *et al.,* 2016; Celik *et al.,* 2011). In an attempt to model the linear force-deformation behaviour of a cell under a compression load, Dintwa *et al.* (2011) experimented on a single tomato cell of suspension cultures. The cell was compressed between the flat end of an optic fibre probe and a glass surface. For orthotropic elastic material, the elastic modulus, Poisson's ratio and shear modulus in the direction of x-axis, y-axis and z-axis of the local coordinate system need to be assigned (Stopa *et al.,* 2019).

The plasticity model is often used for large strain analysis, where significant changes in geometrical features are expected during deformation. Earlier, Pieczywek and Zdunek (2014) proposed the isotropic hardening model to simulate the elongation of the onion epidermis. For the quantification of the severity of bruising, Celik (2017) and Du *et al*. (2019) proposed the use of a bilinear isotropic hardening model to predict the bruise susceptibility in pear and kiwi, respectively. In another research, Tian *et al.* (2017) predicted the bruises in kiwi fruit subjected to axial and radial compression, by assigning the elastic modulus, tensile strength and tensile force of skin and flesh, respectively.

Over time, the effort to establish the FE model to simulate the time dependent-viscoelastic behaviour for FV has also been done. Based on Prony's series, Ji *et al.* (2019) investigated the viscoelastic behaviour of an apple during static compression loading. Meanwhile, the viscoelastic model can also be considered to predict the time-dependent stress and strain distribution in FV under dynamic impact loading (Gao *et al.,* 2018). Ahmadi *et al.* (2016) developed a model by assigning elastic properties to peel and viscoelastic properties to both cortex and core of an apple. The relaxation functions were used to represent the viscous force generated by the flow inside the core and cortex.

Several works of literature are also available to model failure in FV. In order to predict the failure, Li *et al.* (2021) developed an extended FE damage model to predict the local yield stress and the ultimate failure of tomato under compression load. The properties of elastic modulus, Poisson's ratio, failure stress, failure strain, tensile elastic modulus and fracture energy were calculated and used as the inputs of the material model. In another research, Stropek and Gołacki (2020) predicted the mechanical responses in pear as a result of internal damage energy. In general, most studies showed the possibility to simulate fruits that underwent various impact loads by combining the different constitutive material models. Through the progressive development of constitutive models used in FE modelling, the simulation results will become more accurate.

5. Verification and Validation of the FE Models

It is important to note that FE modelling only gives an approximate solution to the variational formulation of the partial differential equation problem. This approach provides several assumptions and uncertainties in terms of domain discretization and element shape function, and system equation. Besides the solver problem, common errors in FE modelling can be the result from the uncertainties of choice of element types, geometrical domain, material model and boundary constraint (Celik 2017; Fadiji *et al*., 2019)

Essentially, the element equation U^h can be expressed by Equation 1 (Liu & Quek 2014)

$$U^h = (x, y, z) = \sum_{i=1}^{nd} N_i\,(x, y, z)di \tag{1}$$

where N_i is the sub-matrix of element equation in the direction of x, y and z axes, nd is the number of element's nodes, di is the nodal displacement at the i-th node. The element equation uses to govern the FE system equation is formulated by the following Equation 2

$$[R] = [K][u] - [F] \tag{2}$$

where $[R], [K], [u], [F]$ are the reaction matrix, stiffness matrix, displacement matrix, and load matrix respectively.

An experimental test is required to validate the FE model. Usually, the FE results indicated to have differed significantly from the experimental results due to the variability of experimental factors. Therefore, replication and randomization are important to increase the reliability and reducing the bias of the FE and experimental results. With the combination of the optimization method and the design of experiments (DOE) approach, experimental verification is performed to evaluate the multifactor effects on the mechanical damage in FV (Celik 2017; Khodabakhshian & Emadi 2015). In order to solve the optimization problem, the mechanical parameter is selected based on the defined objective function. The solution should be able to satisfy the objective function, which can be described by Equation 3

$$\phi \ (d^{opt}) = \frac{\| X_S \ (d^{opt}) - \ X_E \ (d^{opt}) \|}{\| X_E \ (d^{opt}) \|} \tag{3}$$

where ϕ is the objective function, X_S and X_E is the parameter value from FE and experimental data respectively and d^{opt} is the optimum value of the parameter.

For the validation of the FE compression model, a series of experiments were performed to measure the relationship between the elasticity, failure stress, deformation and compressibility level of FV (Li *et al.*, 2013; Li &Wang 2016). Ji *et al.* (2019) formulated a mathematical equation to relate the differences in grasping velocity to the maximum stress in apple. The simulation data were well fitted into a curve with the coefficient of determination (R^2) of 0.99.

For the dynamic loading test, the prediction of stress distribution at the time of collision can be done by validating the FE results with the effect of different drop heights, drop orientation, mechanical properties of the contact surfaces (Kabas &Vladut 2015). The damaging height can be determined with reference to Equation 4

$$h = \frac{1.5^5 \sigma \varepsilon \ R^3}{mg} \tag{4}$$

where h is the damaging height (mm), σ is the mean stress (N/mm^2), ε is the percentage of elongation (%), R is the radius of curvature (mm), m denotes the mass (kg), and g is the gravitational acceleration (m/s^2).

According to Li and Thomas (2014), mechanical damage is usually described by the presence of bruising which is a type of subcutaneous tissue failure resulting from the action of excessive impact load. The external damage of a fruit is visible and therefore can be quantified either the damage surface area or volume (Stropek & Gołacki 2013). Energy analysis is common for the quantification of damage under the effect of dynamic impact load (Dintwa *et al*., 2008; Ahmadi *et al*., 2016). During the impact, the decrease in kinetic energy that was transferred in the internal energy and contact energy were observed (Du *et al*., 2019) (Figure 5).

With the combination of sophisticated image processing technique, it is possible to quantify the external and internal damage in FV (Yousefi *et al*., 2016; Celik 2017). By means of the scanning electron microscopy (SEM) technique, Nikara *et al*. (2020) estimated damage area by measuring section area, perimeter, and the roundness of the impacted potato cell. The relation between cell parameters can be described based on the following Equation 5

$$R_c = \frac{(4\pi \quad x \quad A_C)}{P_C^2} \tag{5}$$

where R_c is the cell roundness, A_C is the area of cell section μm^2 and P_C is the perimeter of cell. Whereas, the volume of the impact damage was calculated as Equation 6

$$VD = \frac{\pi d}{24}(3w_1w_2 + 4d^2) \tag{6}$$

where VD is the volume of impact damage (μm^3), w_1, w_2 is the major and minor width of impact damage (μm), respectively; and d is the depth of the impact damage (μm).Table 1 shows some of the current applications of FE modelling for mechanical responses in FV.

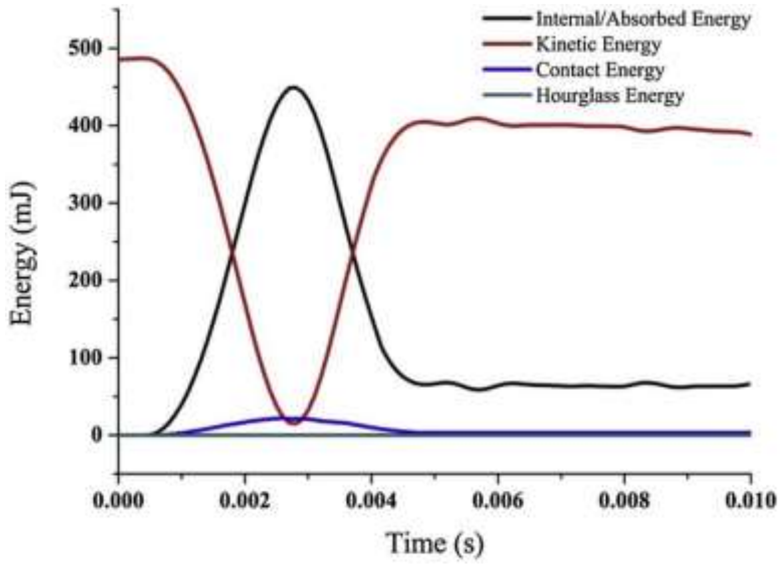

Figure 5. Energy analysis used in FE modelling. Adapted from Du *et al*. (2019).

Table 1. Quantifications of mechanical responses in FV using FE modelling.

Fruit	Simulation case	Loading factor	Parameter	Reference
Potato	Pendulum test	Contact force, displacement, displacement rate	Length, width, depth of damage region	(Nikara *et al*., 2020)
Carrot	Compression	Load, displacement, contact area	Surface pressure	(Stopa *et al*., 2019)
Apple	Stress-relaxation	Load, displacement rate, impact velocity,	von-Mises deformation, von-Mises stress	(Ji *et al*., 2019)
Kiwi	Drop test	Drop height, fruit's orientation	Contact force, von-Mises stress, volume of damage region, absorbed energy, susceptibility level	(Du *et al*., 2019)
Grapefruit	Compression	Load, fruit's orientation	Von-Mises stress, deformation	(Miraei Ashtiani *et al*., 2019)

6. Conclusions and Recommendations

For the scope of this study, the reliability of FE modelling in predicting the mechanical damages of FV under the effects of impact loads were discussed. The FE simulation data will be beneficial to predict the mechanical behaviour of FV under the influence of different experimental factors. It should also be highlighted that most of the previous studies were conducted on the assumed isotropic properties with the effects of static or quasi-static loading cases and small strain deformation. Consideration of the orthotropic and anisotropic properties is still limited. For a better representation of the geometrical model, the selection of size and shape of the elements is recommended. In conclusion, the potential of FE modelling should be further explored in terms of its validation aspects. The combination of the empirical-non-destructive approaches for FE model validation should be considered. Further complexities of the mechanical system can be built on to address the extensive range of impact scenarios that could be possible during post-harvest operations.

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