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Physical and mechanical properties of biological materials

Propriedades físicas e mecânicas dos materiais biológicos

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ABSTRACT - A relevant characteristic of agricultural products is the close association between their complex geometry and material constitution. A study of the mechanical behavior of biological materials should involve a detailed analysis of the laws of solid mechanics, particularly of hereditary integrals and analogical models. Moreover, volume, surface, and shape surveys of plant organs support, on a fundamental level, the development of equipment capable of processing and handling these products with adequate precision. Quality determination of agricultural products is a dynamic process, as part of which interactive and non-invasive techniques are relevant. Accordingly, this review targets pertinent literature associated with the analysis of physical as well as mechanical properties of vegetative materials. Following this, the review covers scientific advances associated with techniques employed to study the physical and mechanical behavior of vegetative tissues and how these techniques can support engineering projects. Finally, the conclusions present an analysis of the importance of these new techniques and their applications to the agricultural sciences.

Key words: Characterization of biological materials. Optical techniques. Moiré techniques. Biospeckle.

RESUMO - Uma característica importante dos produtos agrícolas está intimamente associada à geometria complexa e também do material que os constituí. O estudo do comportamento mecânico dos materiais biológicos merece uma análise detalhada das leis da mecânica dos sólidos, particularmente das integrais hereditárias e dos modelos analógicos. O levantamento do volume, superfície e forma dos órgãos das plantas podem fornecer suporte fundamental para o desenvolvimento de equipamentos capazes de manusear esses produtos com precisão adequada. A determinação da qualidade dos produtos agrícolas é um processo dinâmico, para o qual técnicas interativas e não invasivas são de relevante importância. Este trabalho tem como objetivo revisar a literatura pertinente associada à análise das propriedades físicas e mecânicas de materiais vegetativos. A seguir os avanços científicos associados às técnicas para estudar o comportamento físico e mecânico dos tecidos vegetativos e como elas podem dar suporte a projetos de engenharia. As conclusões deste artigo incluem a análise da importância destas novas técnicas e suas aplicações para as ciências agrícolas.

Palavras-chave: Caracterização dos materiais biológicos. Técnicas ópticas. Técnica de moiré. Biospeckle.

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INTRODUCTION

Bruising on agricultural products mainly results from the mechanical handling of vegetative organs. Vegetable production processes include several mechanized operations, ranging from seedling to harvesting and commercialization. The development of transportation, sorting, and storage equipment and selection of appropriate food processing operation parameters require accurate determination of the viscoelastic and mechanical properties of vegetative tissues (MAHIUDIN *et al*., 2020). These mechanical interactions, involving the plant organs and machine elements, should be interpreted using adequate solid mechanics equations, such as those for linear and non-linear elasticity and linear and non-linear viscoelasticity (MASE, 1970; CHRISTENSEN, 1971), as well as the failure theories (MENDELSON,1965).

In many situations, failure must be avoided; however, in some cases, it should be induced. Vegetative tissue should be characterized as a mechanical entity associated with a biological system exhibiting a specific behavior that does not meet the conditions of material and geometrical linearity (DAL FABBRO; GAZZOLA, 2018). Despite the fact that the experimental mechanical impositions do not satisfy the real conditions imposed by the machine elements, they can induce the identification of the constitutive mechanical laws applied to vegetative materials. Recently, pertinent studies have emphasized the application of optical techniques, such as moiré and classical photoelasticity, to serve as technical support to the stress and strain distribution analysis of the vegetative body under study (MOHSENIN, 1970; TIMOSHENKO; GOODIER, 1970). Dynamic laser speckle imaging has also been employed to identify bruising as well senescence, beyond the typical objectives of experimental investigations of vegetative tissues. Nuclear magnetic resonance, ultrasound, and near-infrared techniques are also being reported to support mechanical tests on vegetative bodies. The fundamental background of this study concerns experimental tests on vegetative bodies of regular geometry, exhibiting homogeneous, continuous, and isotropic conditions as established by Mechanics of Continuous Media.

VEGETATIVE MATERIAL MODELING

The mechanical modeling of biological materials can also be supported via classical viscoelastic models, which describe the stress and strain mathematical relationships. These models can be defined as analogical models or even by constitutive equations through operators of integral order (DAL FABBRO; GAZZOLA, 218; MAHIUDIN *et al*. 2020). This chapter presents the analogical as well as analytical viscoelastic models based on pertinent literature.

LINEAR ELASTIC MODEL

The stress σ_{ij} and strain ε_{ij} tensors are included in Hooke's general law, where the four constants **E** (modulus of elasticity), **G** (shear modulus), **ν** (Poisson's ratio), and **K** (bulk modulus), take part in the linear equation that describes the law. However, it should be emphasized that Hooke's law supports linear associations between stress and strain. The same pair of tensors can also take part in any other elastic law, emphasizing that a non-linear association is being considered, which is not interpreted by Hooke's Law. Elastic laws do not include the time parameter **t** (MASE, 1970).

$$\sigma_{ij} = \frac{E}{1+\nu}\left(\varepsilon_{ij} + \frac{\nu}{1-2\nu}\delta_{ij}\varepsilon_{kk}\right) \tag{1}$$

$$\varepsilon_{ij} = \frac{1+\nu}{E}\sigma_{ij} - \frac{\nu}{E}\delta_{ij}\sigma_{kk} \tag{2}$$

LINEAR VISCOELASTIC ANALYTICAL MODEL

If the time parameter **t** takes part in the stress–strain relationship, elastic laws are no longer applicable. These two tensors are then referred to as σ_{ij} **(t)** and ε_{ij} **(t),** both time dependent entities, while the former constants are transformed into time-dependent parameters, namely, **E(t), G(t), ν(t)**, and **K(t).** These time-dependent parameters are further transformed into the well-known creep Ψ**(t)** and relaxation Φ**(t)** functions. These functions can be related to each other via the Laplace transform. However, these two tensors are also termed *total tensors*, which are subdivided into two components: *hydrostatic* and *deviatoric* stress and strain tensors. The relationship between these two components involves the deviatoric creep function ψ_d**(t)**, deviatoric relaxation function ϕ_d**(t)**, hydrostatic creep function ψ_H**(t)**, and hydrostatic relaxation function ϕ_H**(t).** All these functions compose a set of hereditary integrals that govern the linear viscoelastic behavior as follows (FINDLEY *et al*., 1976):

$$\varepsilon_{ij}(t) = \int_0^t \frac{d\sigma_{ij}(t')}{dt'}\psi(t-t')dt' \tag{3}$$

$$\sigma_{ij}(t) = \int_0^t \frac{d\varepsilon_{ij}(t')}{dt'}\phi(t-t')dt' \tag{4}$$

$$S_{ij}(t) = \int_0^t \frac{d\varepsilon_{ij}(t')}{dt'} \phi_d(t-t')dt' \quad (5)$$

$$e_{ij}(t) = \int_0^t \frac{dS_{ij}(t')}{dt'} \psi_d(t-t')dt' \quad (6)$$

$$\sigma_{kk}(t) = \int_0^t \frac{d\varepsilon_{kk}(t')}{dt'} \phi_H(t-t')dt' \quad (7)$$

$$\varepsilon_{kk}(t) = \int_0^t \frac{d\sigma_{kk}(t')}{dt'} \psi_H(t-t')dt'. \quad (8)$$

COMPLEX ANALYTICAL MODEL

In certain situations, the harvesting, selection, and transportation operations involve vibrational input. Laurenti (2003) explained that a complex model is generated when an oscillatory strain function ε_{ij}**(t)** is imposed, resulting in an oscillatory stress history σ_{ij}**(t)** that is out of phase by δ**,** as determined by equations (9) and (10). These equations can also be expressed in the complex form, as indicated by equations (11) and (12):

$$\varepsilon_{ij}(t) = \varepsilon_0 sin(wt) \quad (9)$$

$$\sigma_{ij}(t) = \sigma_0 sin(wt-\delta) \quad (10)$$

$$\varepsilon^* = \varepsilon_0 e^{iwt} \quad (11)$$

$$\sigma^* = \sigma_0 e^{i(wt-\delta)} \quad (12)$$

The complex modulus ε^* **(w)** can be split into two components: a real term in phase associated with energy storage and an imaginary term out of phase associated with the energy loss (MOHSENIN, 1970).

$$\varepsilon^* = \varepsilon' + i\varepsilon'' \quad (13)$$

The complex modulus ε^* can be experimentally obtained through the ratio of maximum stress to maximum strain, as described by equation (14), and the angle of phase as represented by equation (15):

$$(\sigma_{max}/\varepsilon_{max}) = |\varepsilon^*| = (\varepsilon'^2 + \varepsilon''^2)/2 \quad (14)$$

$$\delta = w.\Delta t \quad (15)$$

where **w** denotes the angular velocity (rad/s), and Δ**t** is the time between the maximum stress and the maximum strain. Thus, the following relationships are also obtained:

$$\varepsilon' = \varepsilon^* \cos(\delta) \quad (16)$$

$$\varepsilon'' = \varepsilon^* \sin(\delta) \quad (17)$$

$$\varepsilon''/\varepsilon' = \tan(\delta) \quad (18)$$

The function ε^*, as described earlier, depends on the angular velocity **w**, which is also related as

$$\sigma^*/\varepsilon^* = \varepsilon^*(iw) = (\sigma_0/\varepsilon_0)e^{i} = \varepsilon' + \varepsilon'' \quad (19)$$

The inverse is denominated as *complex compliance*, which is divided into complex compliance (J_1) and storage (J_2) modulus (MASE, 1970).

$$[\varepsilon^*/\sigma^*] = J^*(iw) = (\varepsilon_0/\sigma_0)e^{-i\delta} = J_1 + iJ_2 \quad (20)$$

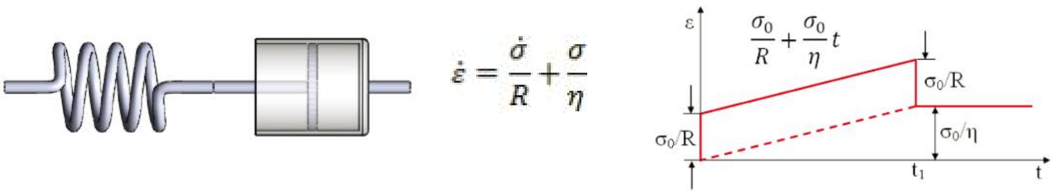
ANALOGIC MODELS

The analogic models are generated via the combinations of springs, whose constants are denoted by $\mathbf{E_n}$), and dashpots, whose constants are denoted by $\boldsymbol{\eta_n}$, where **n** represents integer numbers. The associations of the springs and dashpots constitute the models known as the Maxwell model (Figure 1), Kelvin model (Figure 2), Burger model (Figure 3), a result of all their combinations), and the Maxwell and Kelvin generalized models. All these combinations are constructed to achieve agreement with experimental results (LU *et al.*, 2015; DAL FABBRO; GAZZOLA, 2018). This paper considers analogic models as historic study objects that have been supplanted by analytical models. However, the researchers that developed these models deserve outstanding merit.

CONTACT STRESS PROBLEMS

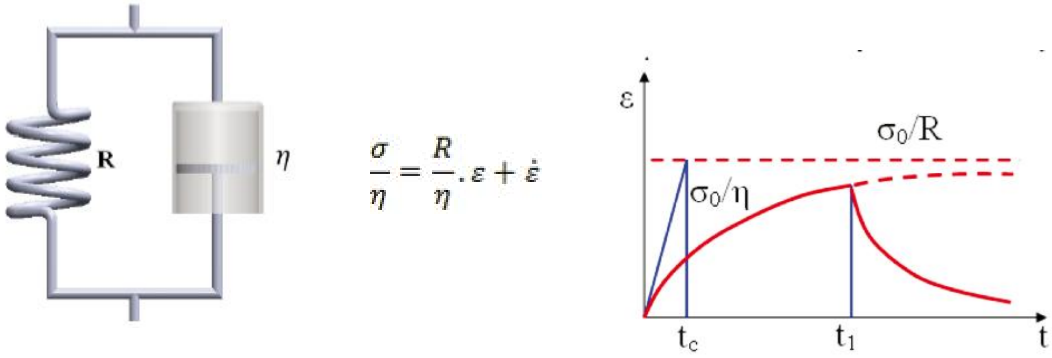
Bodies exhibiting near-spherical shapes show non-linear stress–strain relationships, because of which the Hooke equations are not applicable. In such a situation, the diametrical compression of cylindrical spheres and spheroids is considered. Agricultural products exhibit geometrical as well as material non-linearity. The contact stress theory developed by Hertz provided theoretical support for several cases of mechanical loading of bodies exhibiting near-spherical or cylindrical surfaces. An important case of this type is defined by the compression of spheres or solid ellipsoids and others with similar shapes, such as compression of spherical or ellipsoid fruits between two parallel rigid

Figure 1 - Maxwell model: a) Analogic representation; b) Viscoelastic equation; c) Strain rate. Source: Dal Fabbro; Gazzola, 2018



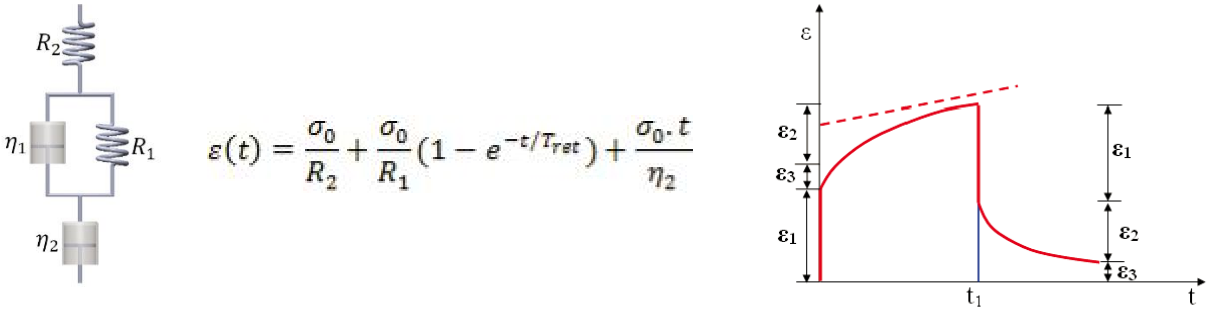
(a) (b) (c)

Figure 2 - Kelvin model: a) Analogic representation; b) Viscoelastic equation; c) Strain rate. Source: Dal Fabbro; Gazzola, 2018



(a) (b) (c)

Figure 3 - Burger model: a) Analogic representation; b) Viscoelastic equation; c) Strain rate. Source: Dal Fabbro; Gazzola, 2018



(a) (b) (c)

and flat plates. The final equation involves the contact area, modulus of elasticity, Poisson’s ratio, applied force, and diametrical deformation. The contact area can be captured by means of a moiré experimental setup or paint printing. Finally, the elastic constants **E** and **ν** can be determined (LAURENTI, 2003; TIMOSHENKO; GOODIER, 1970).

The application of the Brazilian test refers to the diametrical compression of cylindrical bodies such as wood, concrete, soil, rubber, and sugar specimens. The final equation includes the contact area, diametrical applied force, diametrical deformation, modulus of elasticity, and Poisson’ s ratio. This test allows for obtaining the elastic constants in the diametrical direction, mainly when these differ from those in the longitudinal direction, as is the case with sugarcane stalks. The moiré method can also be useful for capturing the contact area (DI RAIMO, 2020).

SCIENTIFIC ADVANCES ASSOCIATED TO THE MECHANICAL CHARACTERIZATION OF BIOLOGICAL MATERIALS

The application of optical techniques facilitates studies on the mechanical behavior of vegetative bodies; this assistance is required because the three-dimensional geometries of these bodies are quite complex (SILVA *et al*., 2015; RODRIGUES *et al*., 2015). Mohsenin (1970) discussed the potential of applying optical techniques to qualitative studies on the mechanical behavior of biological materials due to the complexity of the material constitution. Volume and surface determination of agricultural products provides important technical support to projects focusing on the mechanical handling of these products during their harvest and selection. Agricultural products are very perishable and sensitive to weather and time, and thus, can result in dynamic quality losses. Fast quality determination requires non-invasive and rapid methods. In this chapter, recent techniques that facilitate the understanding of the physical and mechanical characteristics of biological materials are discussed.

APPLICATION OF OPTICAL TECHINIQUES FOR STUDYING THE MECHANICAL BEHAVIOR OF BIOLOGICAL MATERIALS

Moiré optical techniques have been developed based on the phenomenology involved when two screens with similar mesh densities are superposed—moiré fringes are generated. The primary moiré techniques are the *shadow moiré method* and *phase-shifting*. The moiré techniques gained attention because they require a simple and low-cost experimental setup to realize an easy digitalization of the shape characteristics and mechanical properties of vegetables (COSTA *et al*., 2016; RODRIGUES, 2015). Figure 4 shows the application of the moiré techniques in the digital modeling elevation of vegetable products.

Silva *et al*. (2015) applied the moiré techniques to determine the volume of a few horticultural products; they compared the results obtained with those obtained via conventional techniques. The results yielded by the moiré methods were adequate for generating the three-dimensional geometry of vegetables while causing no bruising. Similar results were reported by Costa *et al*. (2016) when they reconstructed the macaw palm fruit, claiming an error of 12%. However, the proposed method precisely determines the correlation between fruit mass and volume.

Lino (2008) reported a three-dimensional survey of a few products such as pears, potatoes, tomatoes, and guava with healthy and bruised surfaces. The correlation between surface equations and experimental data exhibited acceptable R^2 values. Individuals exhibiting high R^2 had a healthy surface, while the one with low R^2 had superficial bruises. The analysis allowed us to conclude that the applied moiré method is viable in supporting the automation process for fruit selection and discarding bruised individuals and fruits showing congenital defects.

Silva *et al*. (2011) reported the application of moiré methods for analyzing eggshell topography, which is useful for estimating the mass of the egg, its yolk, the egg white, and the eggshells. The data showed that the proposed method yielded an error close to 5.5%. Their research work also concludes that an independent calibration would lead to more precise data, discarding calibrating tools.

Optical techniques are effective for visualizing the complete stress and strain fields. The difference between the moiré fringes in the deformed and non-deformed bodies allow for the generation of a displacement field, in turn, allowing for the qualitative determination of its mechanical behavior (CARDOSO *et al*., 2014). Figure 5 illustrates the determination of a deformation field via a moiré method.

The pertinent literature discloses several studies to understand the mechanics of nut shell failure. Rodrigues *et al*. (2015) used the shadow moiré method to determine the isodeformation maps of cashew nuts (*Anacardium Occidentale*, L.) (Figure 5). The results clearly demonstrated the regions suffering large deformation. Following a similar procedure, Albiero *et al*. (2012) analyzed the mechanical behavior of an integral cashew nut as well as its endocarp via the pixel intensity in order to analyze its deformation field. The results demonstrated a high correlation between the whole nut and its endocarp. The results showed no agreement with the Hertz contact stress theory. The lack of agreement is supposedly due to the anisotropy exhibited by biological materials. Kuninari

Figure 4 - Digital reconstruction of fruits via moiré techniques. A) papaya; b) potato with superficial bruising; and c) guava with superficial bruising. Source: Lino, 2008

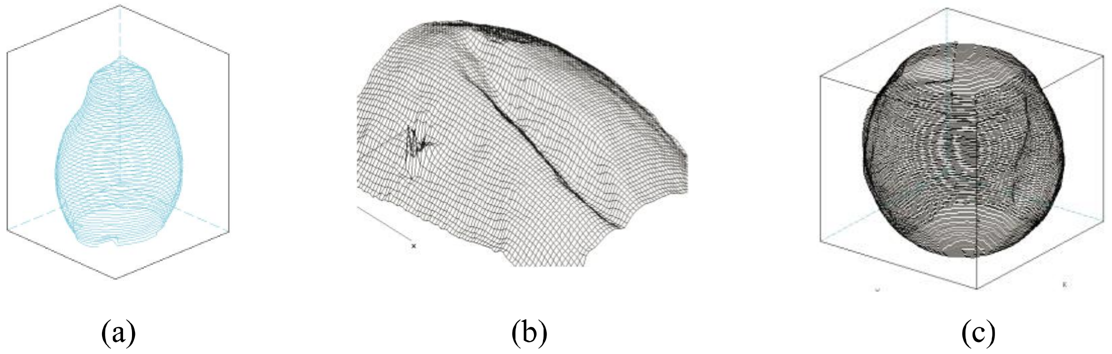
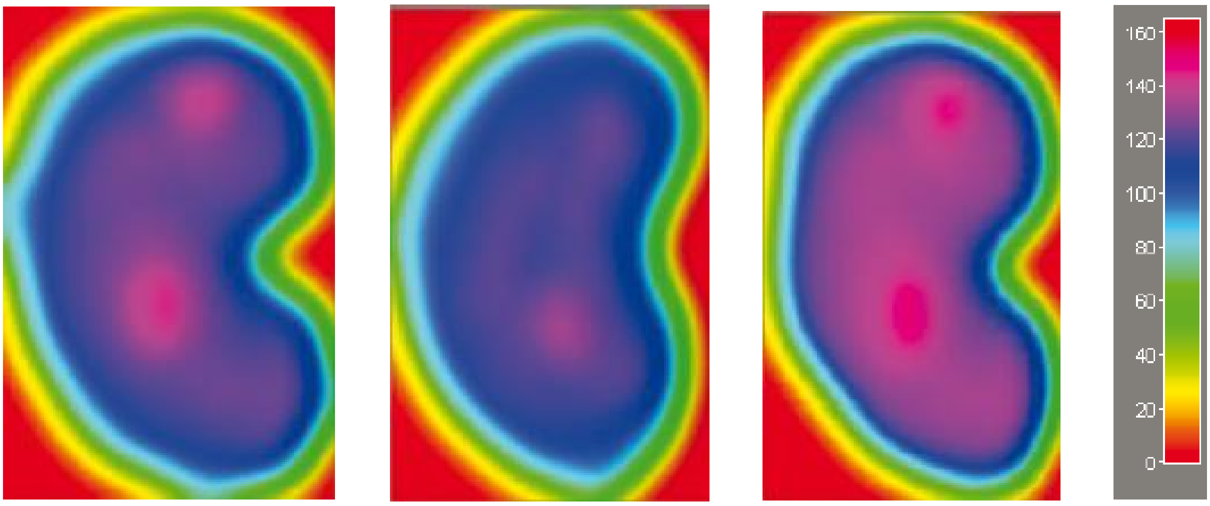


Figure 5 - Isodeformation map generated on cashew nuts. Source: Rodrigues *et al*., 2015



et al. (2010) determined the deformation history of the Brazilian nut (Bertholletia excelsa) via the phase-shifting moiré method.

Gazzola *et al*. (2012) determined the mechanical behavior of a eucalyptus beam under flexural loading via the shadow moiré method. The results allowed for the identification of regions subject to traction and compression efforts as well as neutral lines. Because wood is an orthotropic material, a high correlation could be observed between the fiber slope and neutral line slope. Further, the data showed the dynamics of the beam load absorption as the load increased. Beraldo *et al*. (2007) analyzed the isodeformation field for two different bamboo specimens. The data clearly showed the possibility of identifying the specimens. Gazzola *et al*. (2010) applied a moiré technique to examine the mechanical behavior of biological material and how the stress field varies with the internal constitution. Fringe analyses showed clear variations between bodies with integral constitution and bodies of non-continuous material distribution.

Di Raimo (2020) analyzed the application of Brazilian tests on sugarcane internodes as well as rubber cylinders supported by the moiré methods. The results demonstrate how the lack of ideality influences fringe contrasts. This can be evidently observed from a comparison between sugarcane and rubber cylinder results. Rubber cylinders showed zones of high and low stress concentrations and well-defined stress directions. The inner fibers of the sugarcane samples presented a uniform overall cross-sectional area. However, the external fibers exhibited stress concentrations. In addition, in the sugarcane testing bodies, stress directions were not well defined.

APPLICATION OF BIOSPECKLE LASER OPTICS IN THE STUDY OF VEGETABLE PRODUCTS QUALITY

The terms biospeckle and dynamic speckle refer to a phenomenon observed when a highly coherent light inside a surface exhibits a certain dynamic behavior, resulting in patterns of interference (CARDOSO *et al*., 2012; SILVA *et al*., 2020; SILVA, 2000). Such an activity could originate from biological processes or even from non-biological dynamic activities, such as evaporation or mechanical vibrations (ENES *et al*., 2012). Biospeckle techniques are classified into several categories, such as Fujii, generalized differences (DG), moment of inertia (MI), contrast, and autocorrelation. When the objective is to monitor biological materials, an index must be established to indirectly correlate to biological, chemical, and physical movements exhibited by the scattering particles. The identification of these elements is of fundamental importance for practical applications as fruit quality determination to support their classification and sorting. These differentiations facilitate fast, automatic, non-destructive, and objective analyses, such as bruising generated by impact during mechanical handling, insect attack, and areas infected by fungi (ENES *et al*., 2012).

These techniques were applied to image processing owing to their potential to generate maps of distinct activities in fruits, allowing for the identification of phenomena that can compromise fruit quality. Dynamic speckle is frequently noted in the laser interaction with seeds (BRAGA JÚNIOR, 2000; RODRIGUES, 2003), fruits (RABELO, 2000), soil samples (SHIMABUKURO *et al*., 2005), and sperm samples. Oliveira (2018) reported the application of biospeckle techniques to monitor Aspergillus and Penicillium biological activities during the initial development period.

Skic *et al*. (2016) indirectly determined an optimum harvesting period for apples by correlating quality patterns and physiological parameters with biospeckle results. Ansari *et al*. (2018) reported the evaluation of healthy and non-healthy areas of leaves using biospeckle tests. Biospeckle tests are applied to correlate fruit color, taste, and texture with the moment of inertia (RETHEESH *et al*., 2016). Silva *et al*. (2020) reported the application of the moment of inertia to generate moisture curves of agricultural products. Rahmanian *et al*. (2020) considered the ability of biospeckle methods to identify freezing physiological disturbances in oranges.

Rabello *et al*. (2011) applied biospeckle methods to analyze fungal contamination of seeds, demonstrating that the moment of inertia value was higher for contaminated seeds. Sutton and Punja (2017) reported the application of biospeckle methods to monitor fungi-contaminated bruised wheat seed germination. The activity level could identify bruised seeds.

The objective of this research is to carry biospeckle tests in the field. However, the encountered difficulties are associated with light and mechanical vibrations.

CONCLUSION

This paper helps conclude that the proposed optical methodologies, as a set of alternative techniques of analysis, are crucial for supporting and comprehending the physical and mechanical characterization of biological materials that are useful for machine design, vegetable processing, development of prototypes, rural construction material quality analyses, and wood classification. Moiré techniques allow for the determination of vegetable organ volume, surface, and stress–strain relationships. Further, biospeckle methods are important to support the analysis of product quality, which help obtain dynamic and non-invasive characteristics.

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