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Modeling of Mechanical Damage to Apples at Various Stages of Ripening Using the Finite Element Method

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Abstract

Existing studies on the mechanical properties of apples often lack the comprehensive data needed for accurate finite element method (FEM) model construction and validation. Moreover, many rely on store-bought apples, which are unsuitable for industrial purposes due to the treatments they undergo before reaching consumers. This study introduces a novel method for developing 3D discrete models of apple tissue at various ripening stages using FEM, focusing on the new Polish apple variety, Chopin. Detailed mechanical property measurements of the apple flesh and skin were conducted, along with physicochemical analyses. For model validation, force-displacement curves and pressure-force relationships were examined, and micro-computed tomography was used to determine bruise volumes in fruits subjected to 20%, 50%, and 80% of the destructive force. The results indicate that, depending on the application, apple flesh can be modeled as either an elastic or elastoplastic material. Consequently, parameters were established for numerical models at different stages of developmental maturity, ripening, and senescence maturity. Model validation, based on displacement-load relationships and changes in contact area under loading force, showed that elastic models achieved a minimum of 82% compliance with empirical data, while elastoplastic models exhibited at least 91% compliance. In the final phase, a method was developed to determine the stresses causing damage to apple flesh by integrating microtomographic images of damaged fruits with von Mises stress images from discrete models. This involved compression tests on fruits at 20%, 50%, and 80% of their destructive force capacity.

Keywords: FEM, fruit, internal stress, mechanical properties, microtomography