Modeling Mechanical Property Changes During Heating of Carrot Tissue - a Microscale Approach

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Abstract

Plant tissue comprises of a group of cells with defined cell wall enclosing cell vacuole. The water present in vacuole builds pressure inside causing the cell membrane to exert pressure on the cell wall which is known as turgor pressure. Turgor pressure plays an important role in the rigidity and firmness of the plant based materials. During cooking, with increasing temperature, the breakdown of cell membranes result in tissue softening brought about by loss of turgor pressure. In addition, heating causes thermal degradation of middle lamella pectins which leads to further loss of texture (Figure 1). Pectin is one of the most important components of the cell wall that provides rigidity to the material. In carrot, for example, texture is closely related to enzymatic or non-enzymatic pectin degradation. In this work, changes in texture of carrot at cellular level during thermal processing were studied using the reaction based approach. At elevated temperatures, pectin is highly prone to non-enzymatic degradation via β-eliminative depolymerization that lead to tissue softening. The β-elimination reaction follows a zero-order kinetics during thermal treatments. Kinetic parameters were obtained using Arrhenius fitting of release of pectic substances (Uronic Acid) at different temperatures (75C, 80C, 85C, 90C, 95C and 100C) and treatment times (0, 3h, 6h, 9h, and 12h). Changes in carrot texture follow an exponential relationship with Uronic Acid release. For the present study, Young's Modulus of the carrot tissue was taken as a measure of texture. A simultaneous heat transfer, microscale moisture transfer, pectin degradation in the cell wall material and solid mechanical model was developed at the microscale using finite elements to predict the homogenized Young's Modulus of the carrot tissue during heating at different time-temperature combinations. The tissue was modelled as a thin walled liquid-filled honeycomb structure using COMSOL Multiphysics® software. Temperature distribution and turgor pressure loss were solved using Heat Transfer in Solids and Mathematics interfaces using Coefficient Form of PDEs, respectively. Pectin degradation reaction kinetics was solved using domain ODE again of Mathematics interfaces while small deformation was modeled using the Linear Elastic Material model in the Structural Mechanics Module. The model developed was validated by predicting the Young's Modulus at different temperatures and treatment times and comparing them with experimental data. Simulated trends in changes of modulus agreed favorably well with experimental results. The homogenized modulus of the carrot tissue was found to be equally sensitive to changes in cell size and elastic modulus of the cell wall material and cell membrane permeability. The efficacy of the model developed above lies in the fact that the framework can be used to simulate texture changes during cooking root vegetables.

Figures used in the abstract

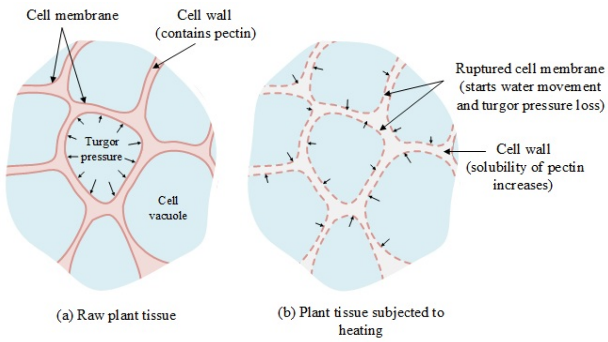

Figure 1: Problem description.