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

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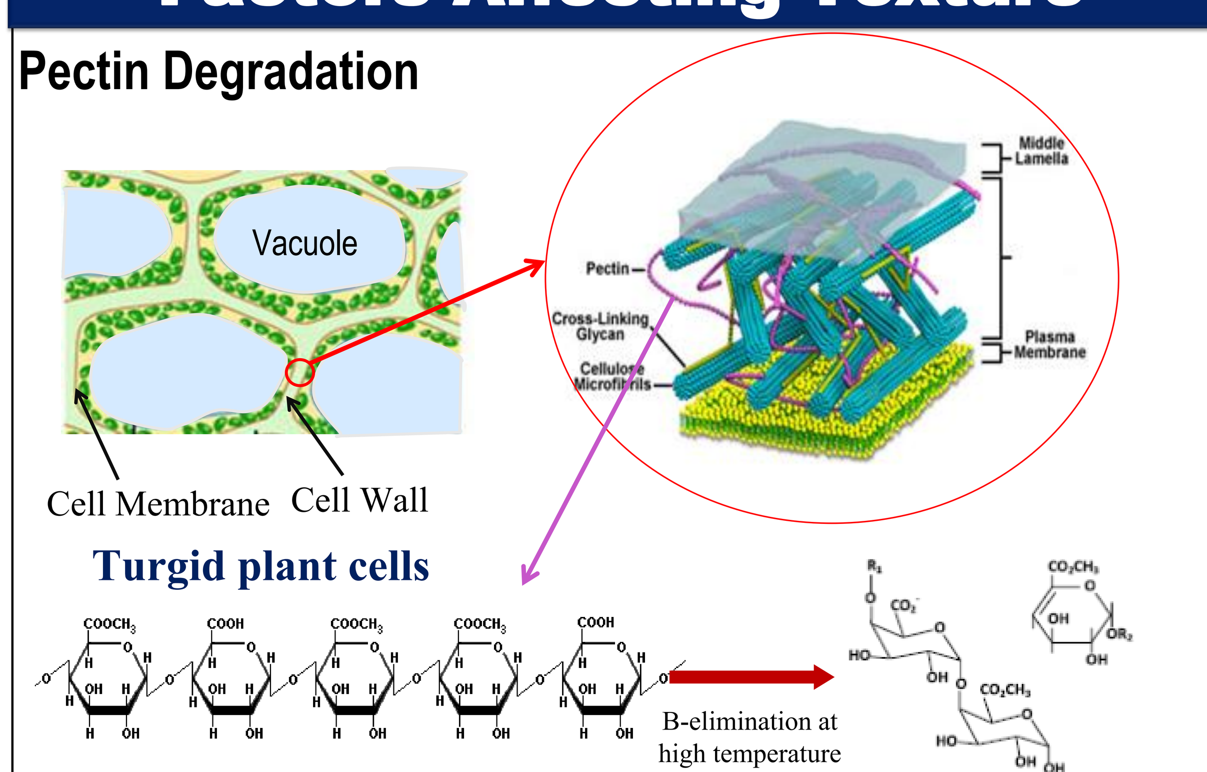
Overview

Multiscale modeling approaches help to describe mechanical behavior of materials at different scales. Going down in scales, there is increasing difficulty in developing suitable model. Building micro-scale models has been confined by the lack measurement techniques at such scales and computational complexity due to structural heterogeneity. But development of such models are necessary as many properties that contribute to the quality depends on local properties that originates from tissue heterogeneity.

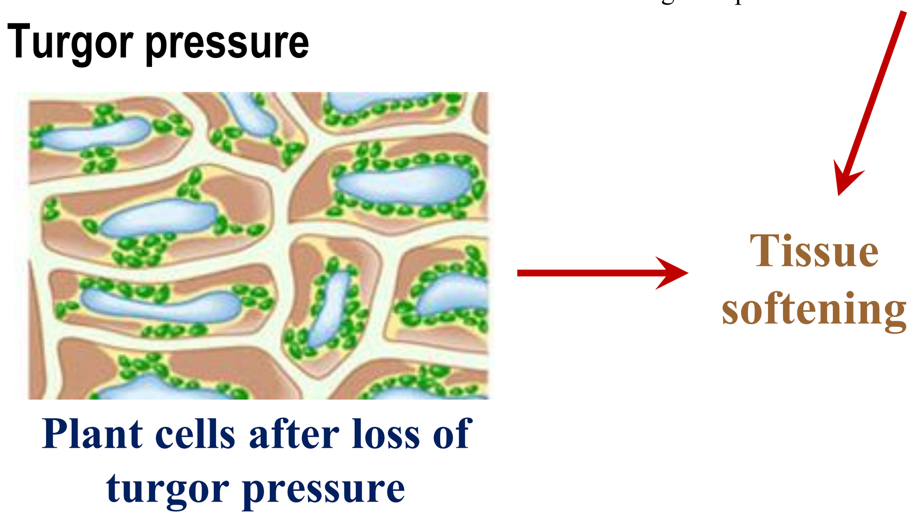
Therefore, the goal of this study is to develop a quality model of plant tissue deformation which incorporates micro-scale geometrical features using carrot as an example. A framework to derive the dependence of quality with process parameters and reaction kinetics is developed and discussed.

Factors Affecting Texture

Pectin Degradation

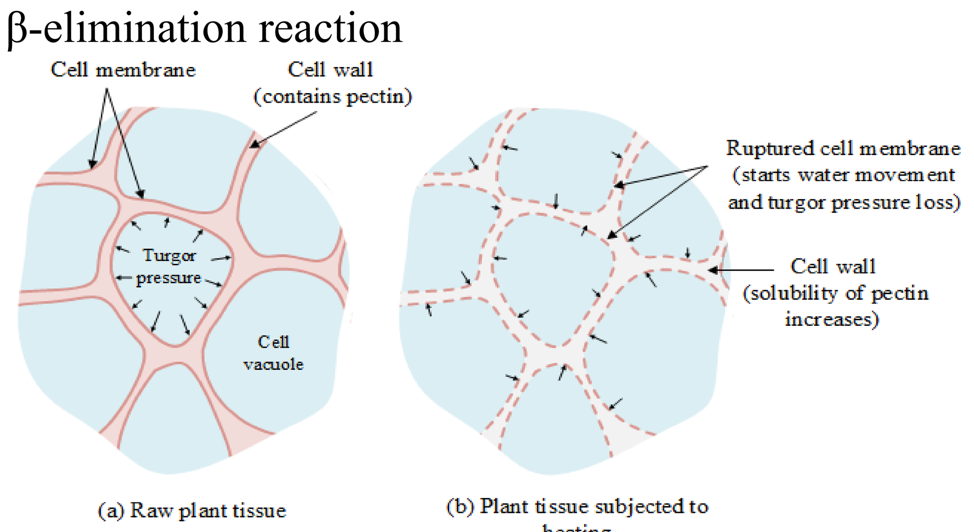


Turgor pressure

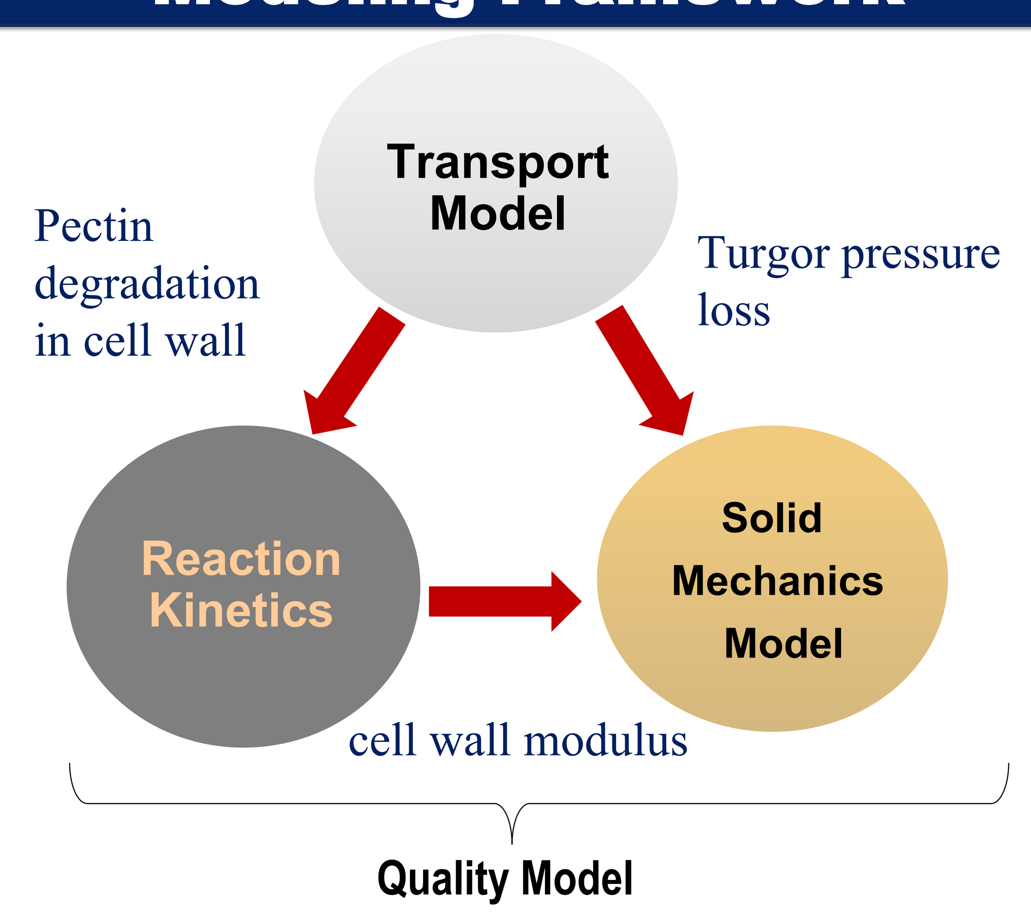


Factors Affecting Texture

- 90% water is present inside the vacuole of the cell which is surrounded by cell membrane and cell wall. Initially cell membrane is semi-permeable. As the temperature increases, cell membrane permeability starts to increase due to formation of holes in the membrane surrounding the vacuole that leads to turgor pressure loss
- Heating causes thermal degradation of middle lamella pectin via β-elimination reaction



Modeling Framework



Transport Model

Heat Transfer

Cell wall $$\rho_c C_{pc}\frac{\partial T_c}{\partial t} = \nabla\cdot(k_c\cdot\nabla T_c) \quad (1)$$

Cell vacuole $$\rho_w C_{pw}\frac{\partial T_w}{\partial t} = \nabla\cdot(k_w\cdot\nabla T_w) \quad (2)$$

Moisture Transfer

Cell vacuole $$c_{\Psi c}\frac{\partial \Psi_c}{\partial t} = \nabla D_c \frac{c_{\Psi c}}{1+x_c}\nabla\Psi_c \quad (3)$$ ← Water potential

Cell wall $$c_{\Psi w}\frac{\partial \Psi_c}{\partial t} = \nabla D_w c_{\Psi c}\nabla\Psi_w \quad (4)$$

Cell membrane $$J = \rho_w \frac{k_p}{\mu_w}\frac{(\Psi_c - \Psi_w)}{\Delta x} \quad (5)$$

$$\Psi_c = \Psi_s + \Psi_p \quad (6)$$ ← Turgor pressure

Reaction Kinetics

Pectin degradation

Solubility of pectin increases as increase in temperature and cooking time via β-elimination reaction which follows zero order kinetics

$$\frac{\partial P_n}{\partial t} = k \quad (7)$$

Reaction rate constant → $$k = k_{ref}\times exp\frac{E_a}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right) \quad (8)$$

Linear relationship between pectin degradation and cell wall modulus was assumed

Cell wall modulus → $$E_{cw} = \frac{P}{P_o}\times E_o \quad (9)$$ ← Initial cell wall modulus

Solid Mechanics Model

Effective Young's Modulus

Under uniaxial loading Young's modulus is obtained by homogenization

$$-\nabla\sigma = 0 \qquad \boldsymbol{\sigma} = \mathbf{D}\boldsymbol{\varepsilon} \qquad E_{eff} = \frac{\int\sigma dA}{\varepsilon A} \quad (10)$$

Methodology

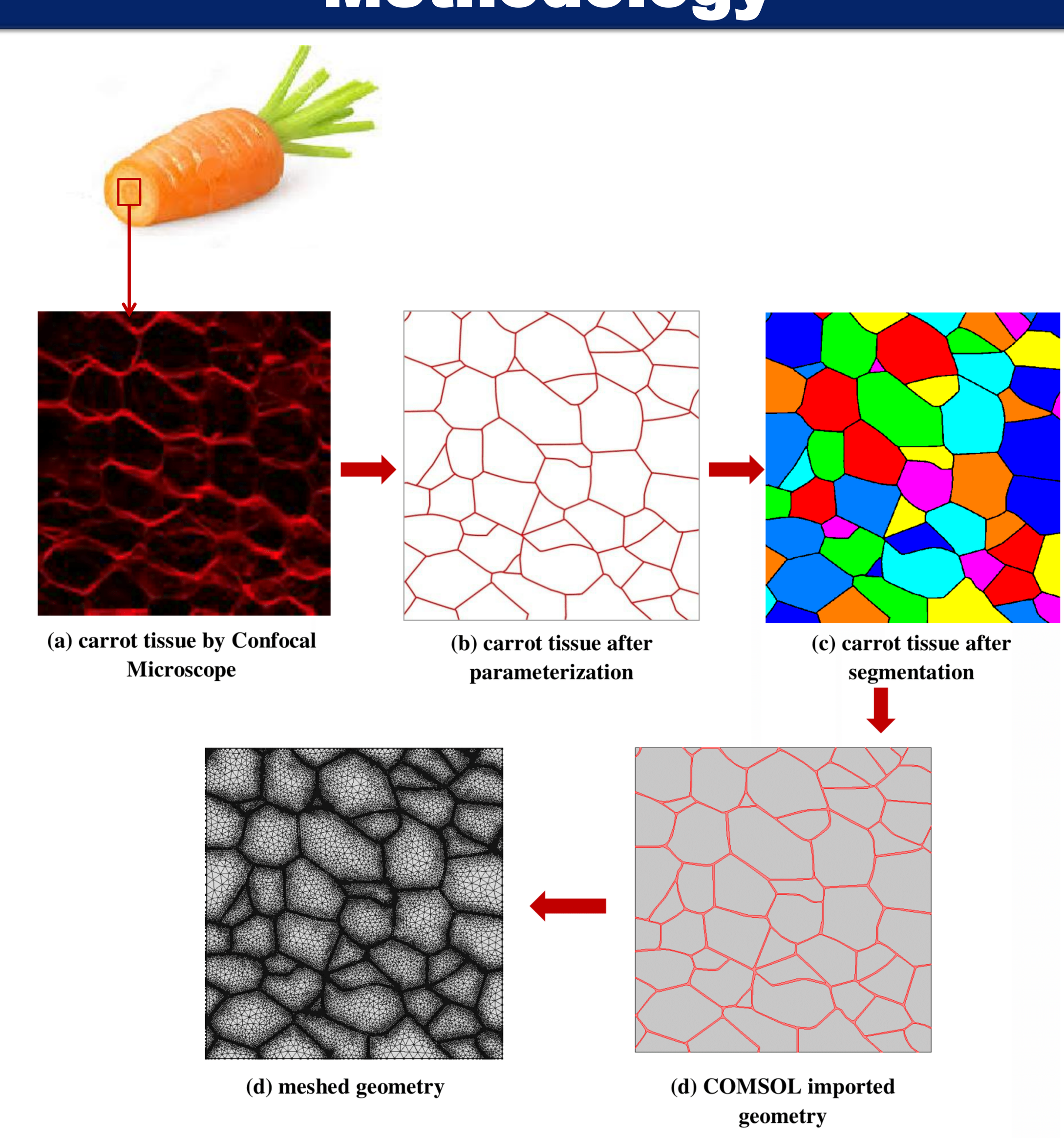
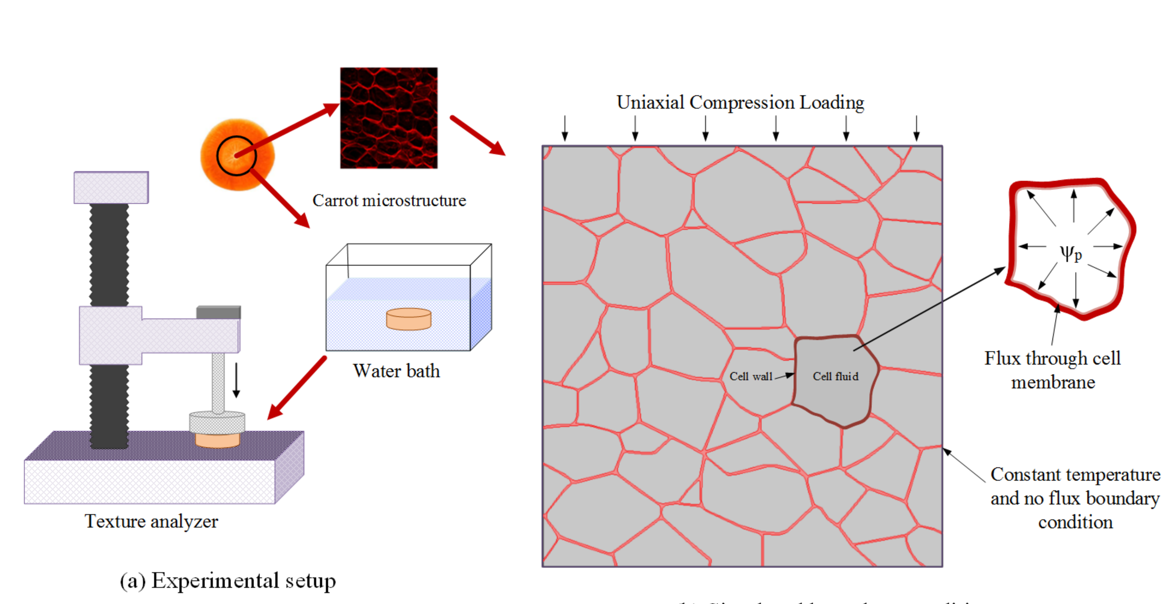


Image acquisition and analysis



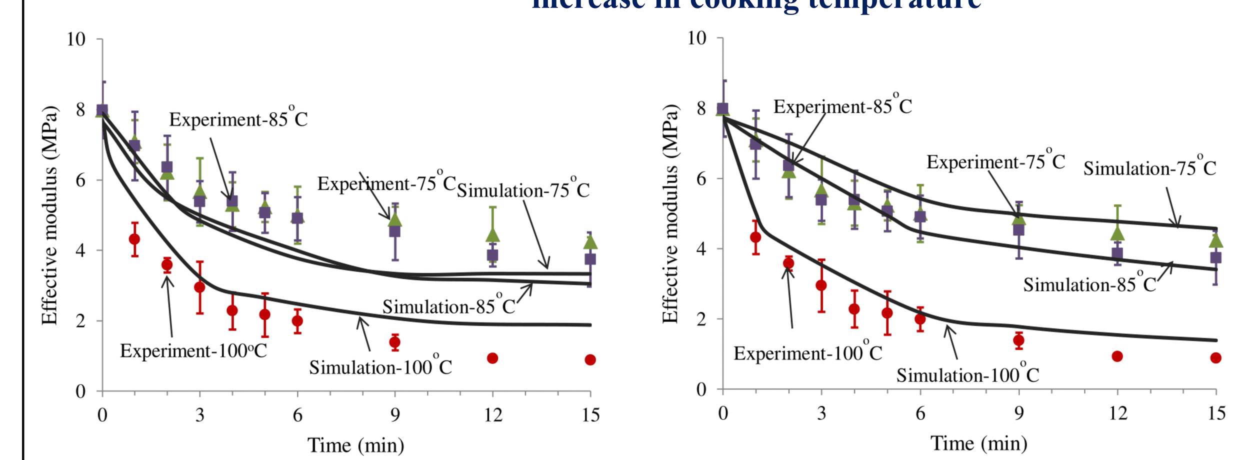
Simulated geometry and Boundary conditions

Results

Model Validation

The model was validated for effective Young' modulus at different temperatures

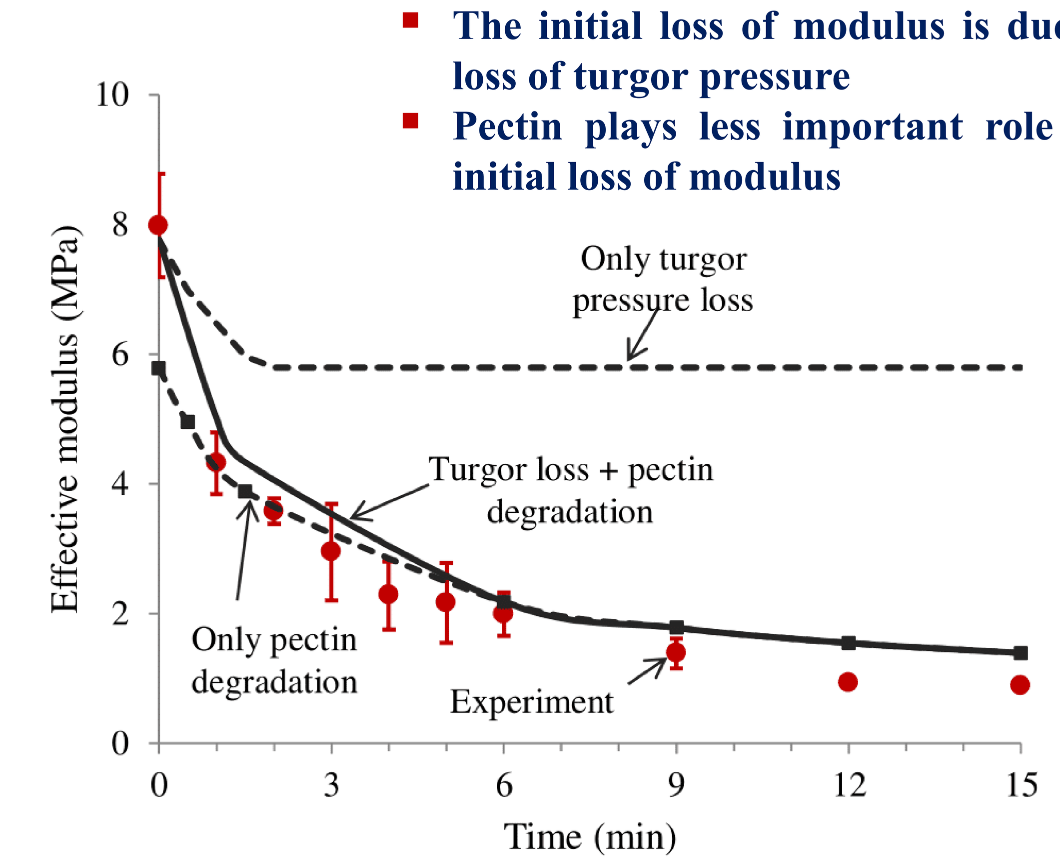
- The rate decrease in modulus decreases with increase in cooking temperature



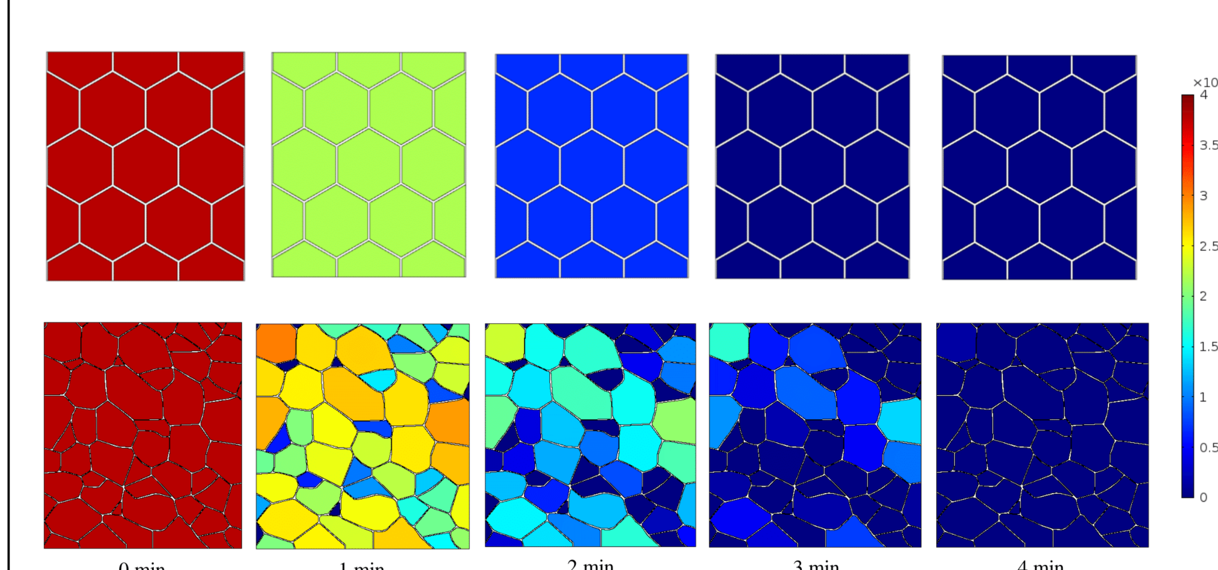
(a) real tissue geometry (b) uniform honeycomb geometry

Effect of turgor pressure and pectin degradation

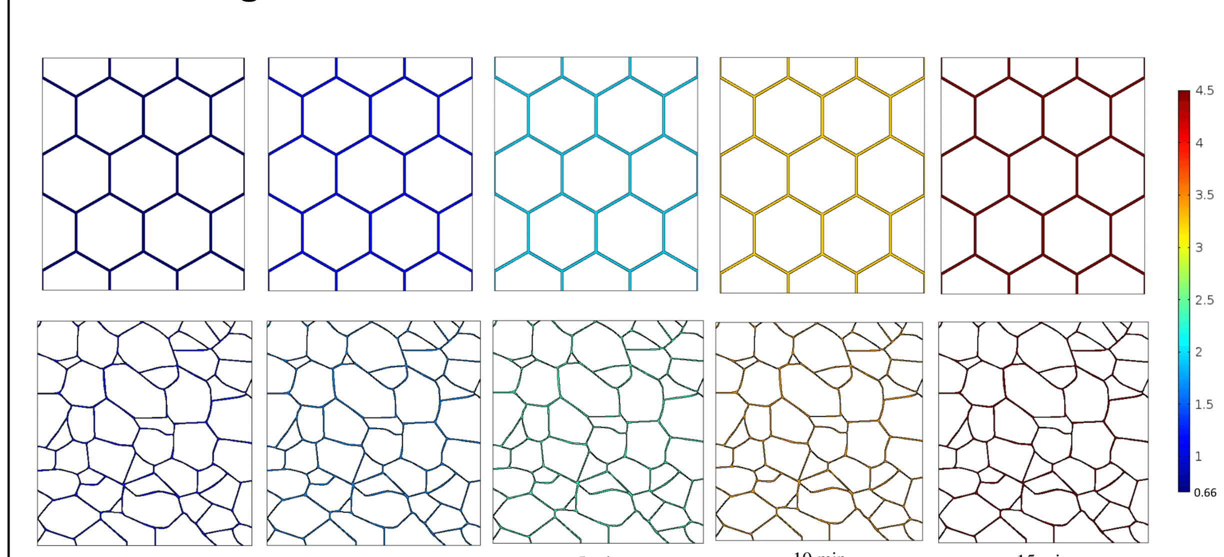
- The initial loss of modulus is due to the loss of turgor pressure
- Pectin plays less important role during initial loss of modulus



Water potential prediction



Pectin Degradation



Summary and Conclusions

- A cooking model that predicts the effective Young's modulus was developed using micro-scale geometrical features
- Initial texture loss is due the loss in turgor pressure
- Pectin degradation in cell wall could predict the texture loss over time and its contribution to the initial loss is small compared with turgor pressure loss

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