Reduction of Energy Consumption During Prune Drying: Modeling, Super Absorbent Polymers, and Ultrasound Techniques

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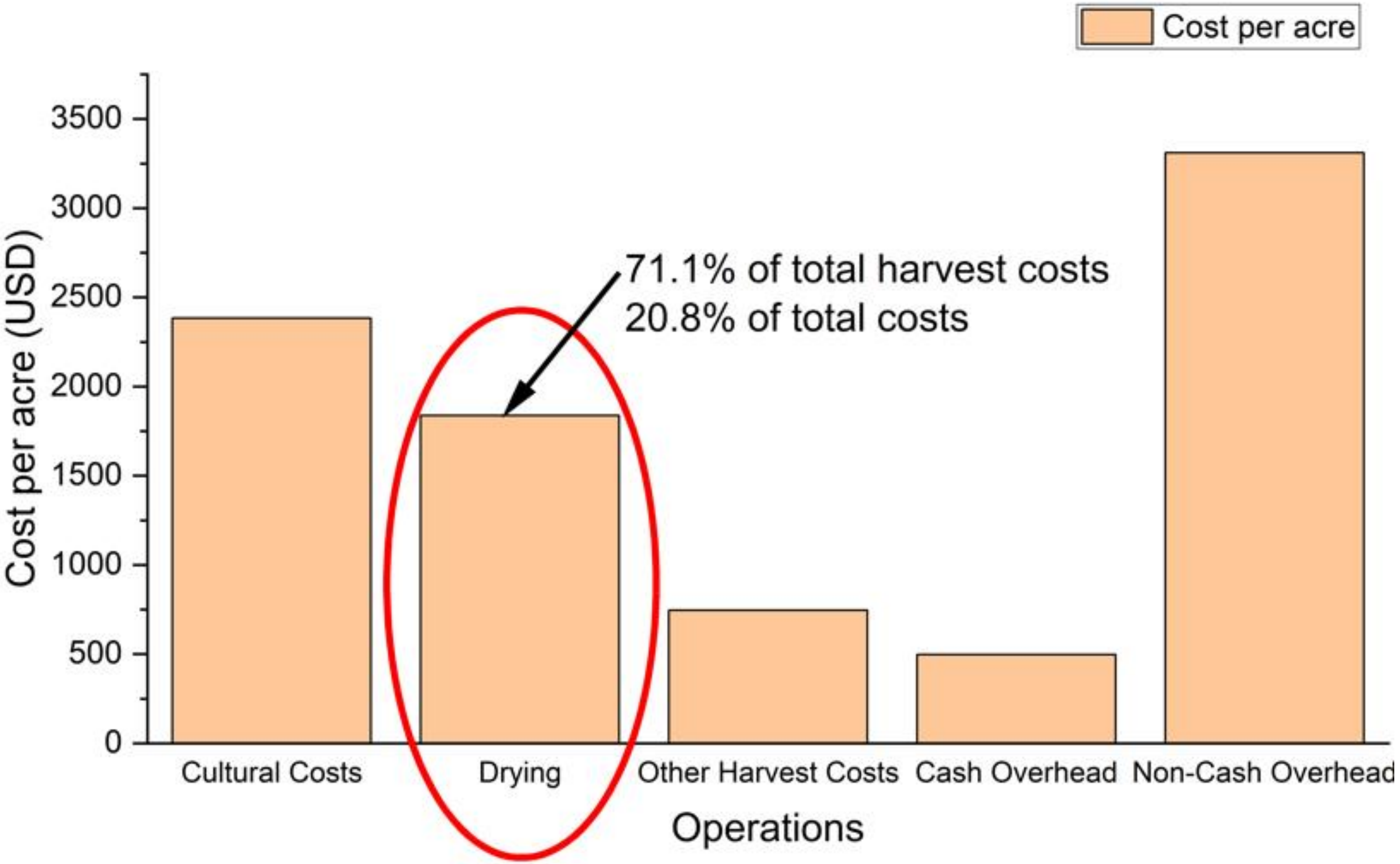
Cost Structure for Prune Production in California



Plotted using data from Niederholzer, F., Milliron, L., Fichtner, E., Murdock, J., & Goodrich, B. (2022). Sample costs to establish a prune orchard and produce prunes.

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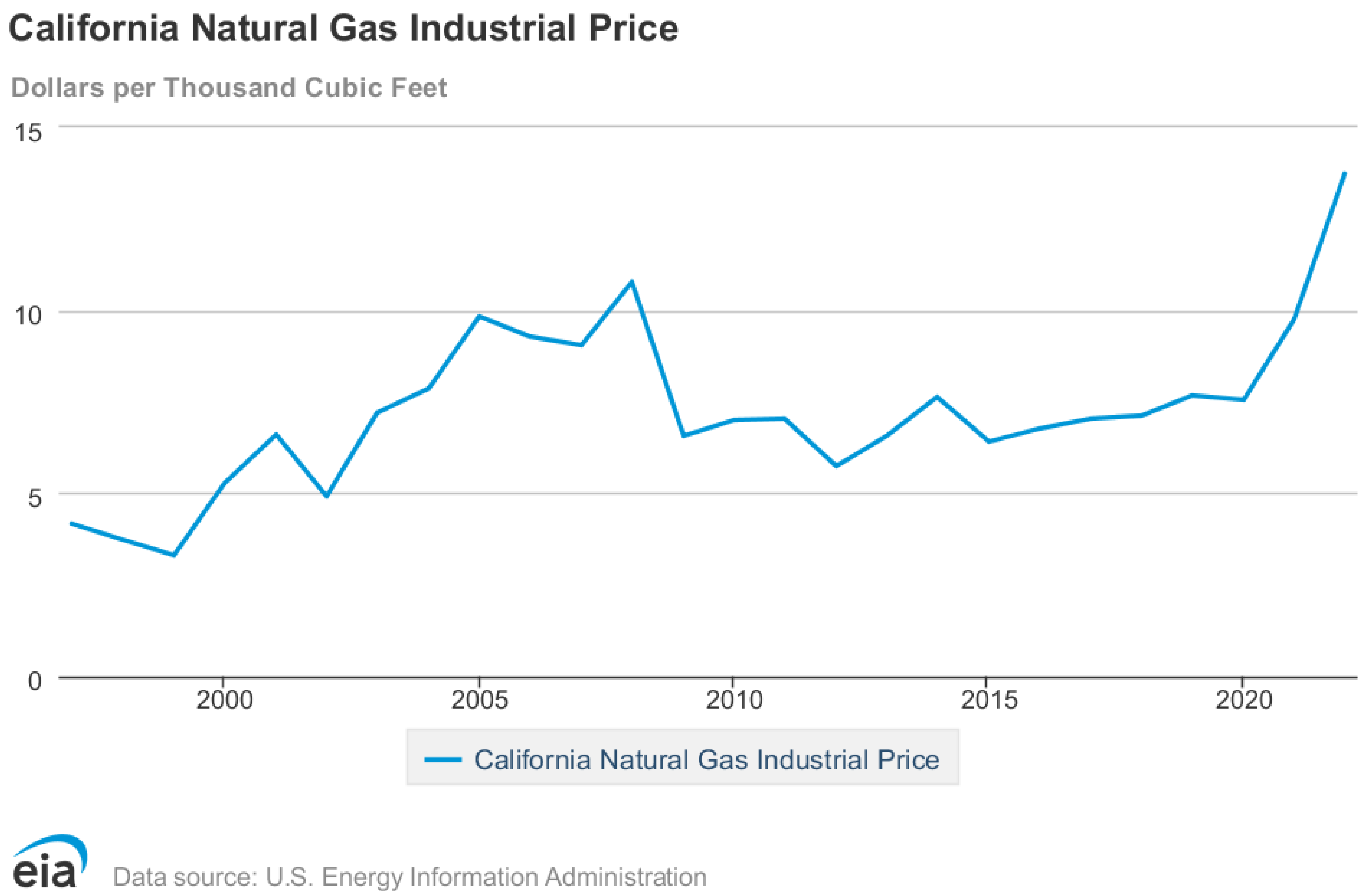
Trends in Natural Gas Prices in California: A Twenty five-Year Review



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Key Determinants of Energy Consumption During the Drying of Prunes

- Long effective drying time

- High drying temperature

50 – 70^{o}C

24 – 36 hours

Approach for Reducing Energy Consumption During Convective Drying

$$Q_w = -h_m \left(\frac{M_w \times P_{sat}}{R_u T} \right) (\boldsymbol{a_w - RH})$$

Q_w : Moisture flux
$\boldsymbol{a_w}$: Water activity at the prune surface
RH : Relative humidity of the drying air

- Maintaining the lowest possible **RH** in the dryer during the drying process
- Keeping surface water activity $\boldsymbol{a_w}$ as high as possible throughout drying

↓

Reduction of effective drying time

↓

Reduction in energy consumption

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Research Objectives

1. Identify the bottleneck for energy consumption during prune drying through mathematical modeling and on-site experimentation.

2. Evaluate experimentally the effect of super absorbent polymers on reducing ambient air relative humidity and effective drying time.

3. Evaluate the effect of Ultrasounds pretreatment followed by convective drying on drying kinetics and energy consumption.

4. Conduct a techno-economic analysis (TEA) to evaluate efficiency and costs of innovations.

Research Methodology

Preliminary Data

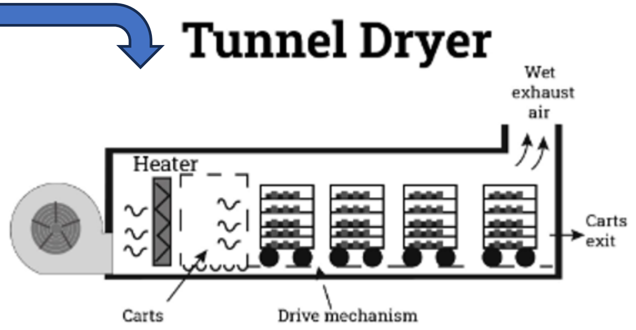
Single prune drying model

$$\frac{D^s(\varepsilon^w\rho^w)}{Dt} + j^{-1/3}\nabla_L.(\varepsilon^w\rho^w v_L^{w,s}) - \left(\varepsilon^w\rho^w \frac{\dot{\varepsilon}^s}{\varepsilon^s}\right) = 0$$

Proposed Research

Computational Fluid Dynamics (CFD) modeling

In-field measurements



Integrate the air flow dynamics within a full-scale dryer into the drying model

Identify zones where humidity builds up

Obj 1. Bottleneck for energy consumption

Lab/Pilot-scale experiments

RH

Super absorbent polymers

Obj 2. Effect on drying time and energy consumption

a_w

Ultrasounds pretreatment

Obj 3. Effect on energy drying time and energy consumption

Full-scale models

Include the effect of super absorbent polymers into the model

Obj4. Conduct a TEA

Include the effect of the US pretreatment into the model

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Objective 1: Identify the bottleneck for energy consumption during prune drying through mathematical modeling and on-site experimentation

Activities

- Characterization of prunes before and after drying : Laboratory activity
- Lab-scale drying measurements
- In-field measurements: Tunnel dryer measurement, air flow velocity, relative humidity, temperature, drying duration and energy consumption.
- Modeling: Integrating Computational Fluid Dynamics (CFD) to simulate air flow inside the dryer with the heat and mass transfer processes occurring within prunes.
- Computer simulation: Evaluate various scenarios such as intermittency of the heater and changes in air humidity levels.

Objective 1: Identify the bottleneck for energy consumption during prune drying through mathematical modeling and on-site experimentation

Outcome

- A model capable of predicting the spatiotemporal distribution of moisture content in prunes, the characteristics of air inside the dryer, and the overall energy consumption.
- Comprehensive mapping of regions within the dryer where humidity tends to accumulate.

Impact

- Enhanced energy efficiency of the drying process using current tunnel dryers.
- Identification of zones within dryers for targeted interventions aimed at enhancing energy efficiency and reducing drying time.

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Objective 2: Evaluate experimentally the effect of super absorbent polymers (SAP) on reducing ambient air relative humidity and effective drying time

Activities

- Material selection (SAP): Crosslinked Polyacrylamide, Crosslinked Polyvinyl Alcohol, Silica gel, Crosslinked sodium polyacrylate, Polyvinylpyrrolidone
- Setup construction: Design and assembly of experimental apparatus for SAP testing.
- Testing SAP moisture absorption capacity
- Testing SAP effectiveness: controlled drying with prunes, both with and without SAPs to establish a baseline for comparison.
- SAP regeneration testing: Evaluating the ability of SAP to be regenerated for repeated use.
- SAP longevity testing: Assessing the long-term effectiveness of SAPs over multiple drying cycles.

Objective 2: Evaluate experimentally the effect of super absorbent polymers (SAP) on reducing ambient air relative humidity and effective drying time

Outcome

- Optimized SAP material selection: Identification of the SAP material with the highest moisture absorption efficacy for prune drying applications.
- Regeneration protocol for SAP: Assessment of the potential for SAP regeneration (cost efficiency).
- Durability data for SAP: Analysis of the long-term usability of SAP.

Impact

- Increased drying efficiency with the optimal use of SAP, thus saving energy and reducing costs.
- Reduced environmental footprint of the prune drying process.

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Preliminary Data: Single Prune Drying Model

$$\frac{D^s(\varepsilon^w\rho^w)}{Dt} + j^{-1/3}\nabla_L\,.\,(\varepsilon^w\rho^w v_L^{w,s}) - \left(\varepsilon^w\rho^w\frac{\varepsilon^{.s}}{\varepsilon^s}\right) = 0$$

Mass balance

$$\sum_{\alpha=s,w}\varepsilon^\alpha\rho^\alpha C_p^\alpha\left(\frac{\partial T}{\partial t} + v_L^\alpha . j^{-1/3}\nabla_L T\right) - j^{-1/3}\nabla_L\,.\,j^{-1/3}\left(\sum_{\alpha=s,w}(\varepsilon^\alpha k^\alpha)\nabla_L T\right) = 0$$

Energy balance

$$v_L^{w,s} = -\varepsilon^w\left(D^w j^{-1/3}\nabla_L\varepsilon^w + B_c j^{-1/3}\nabla_L\sigma\right)$$

Momentum balance

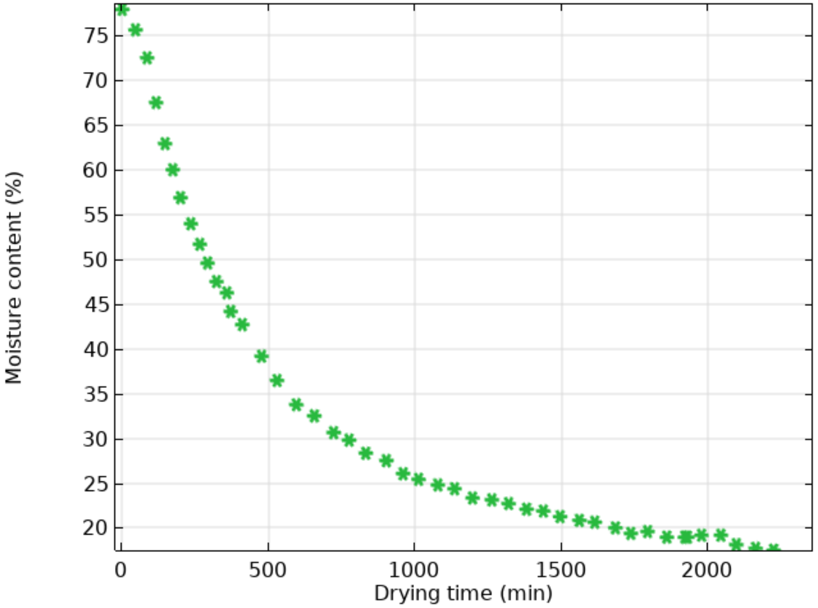
$$\sigma(t) = \sum_{\mathrm{m}=0}^{p}\int_0^t G_m\exp\left(-\frac{t-\varphi}{\lambda_m{}'}\right)\frac{\partial E_{MM}}{\partial\varphi}\,d\varphi$$

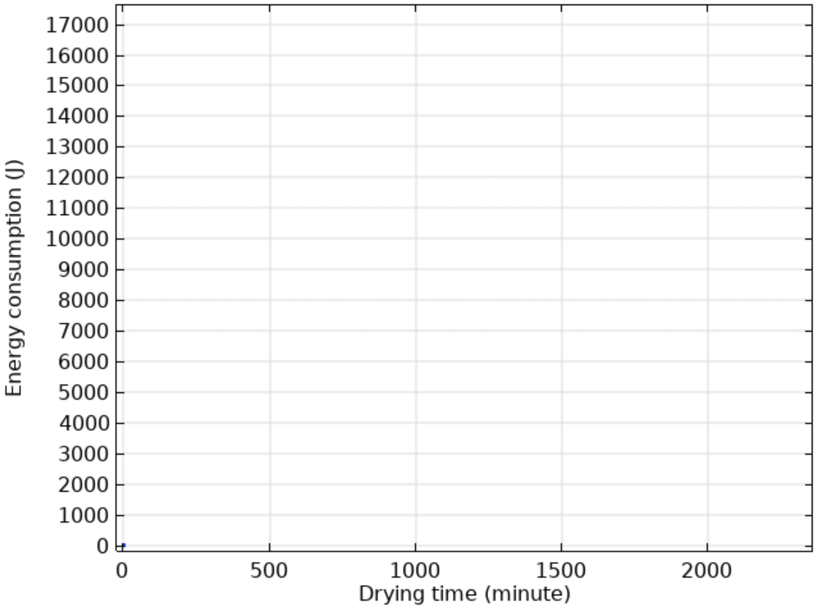
Stress equation

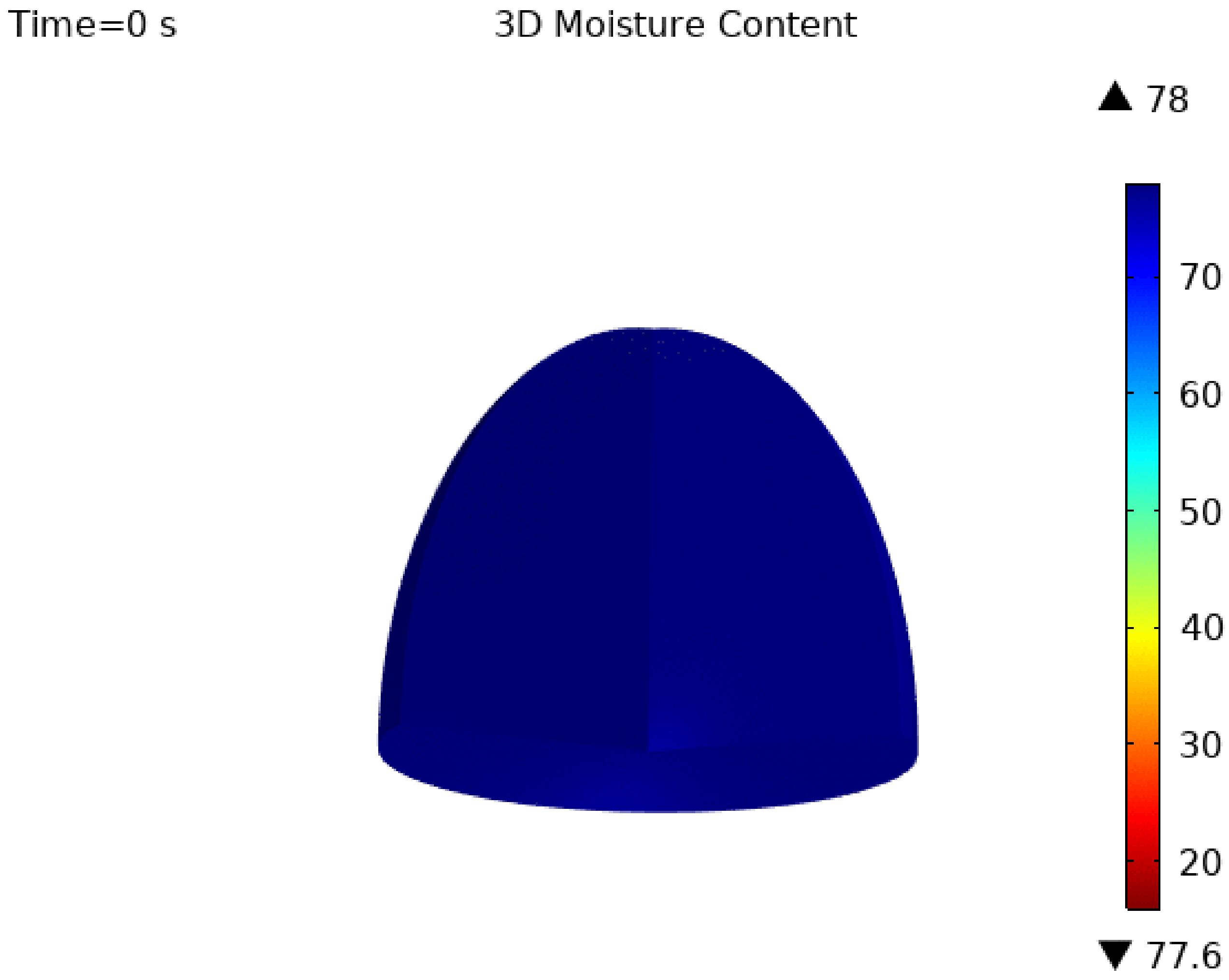
Main Parameters Predicted by the Single Prune Drying Model

- Moisture content
- Temperature
- Energy consumption
- Plum deformation
- Stress
- Strain (deformation)

Single Prune Drying Model Validation: Comparison of Model Prediction with Experimental Data at 50C







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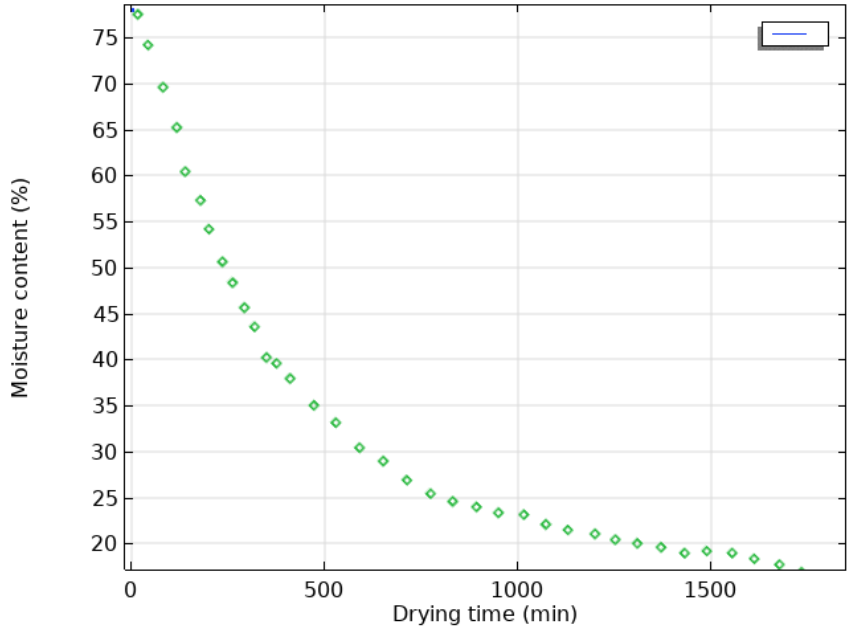
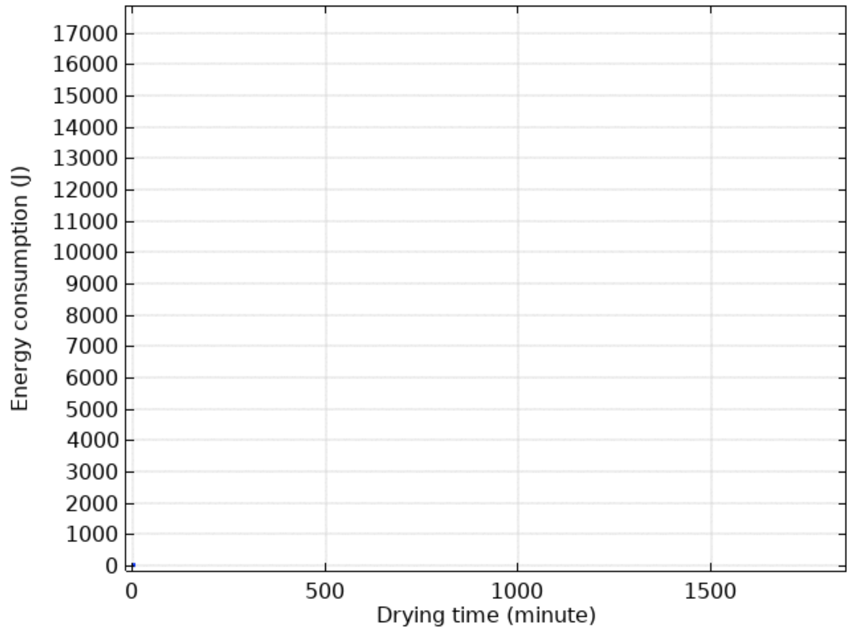
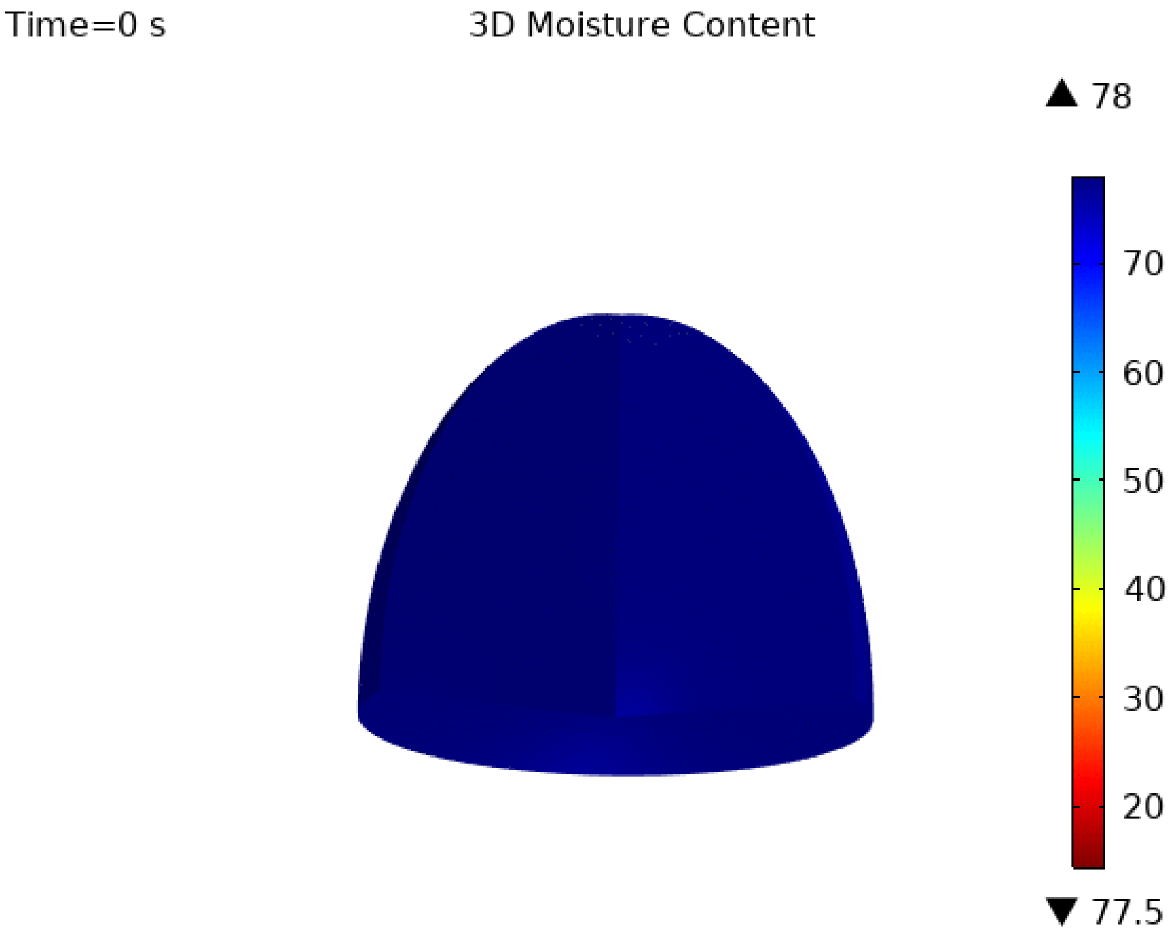
Single Prune Drying Model Validation: Comparison of Model Prediction with Experimental Data at 60C







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Expected Outcome and Benefits of the Research

- A comprehensive mathematical model capable of predicting the moisture content within the prune, air characteristics inside the dryer, and overall energy consumption during the drying process.

- Identification of the optimal combination of ultrasound pretreatment, superabsorbent polymer selection and placement, and a drying strategy (non-stationary air conditions) to minimize energy consumption.

- Utilization of the drying model for testing numerous drying scenarios via computer simulation, offering cost-effectiveness and minimal operational interference.

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Timeline

Activities	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan
Obj. 1: Identify the bottleneck for energy consumption during prune drying through mathematical modeling and on-site experimentation												
Prunes characterization							■	■				
Lab-scale drying measurements							■	■				
In-field measurements	■	■					■	■				
CFD Modeling			■	■	■	■	■	■				
Computer simulation									■	■	■	
Obj. 2: Evaluate experimentally the effect of super absorbent polymers on reducing ambient air relative humidity and effective drying time												
Material selection (SAP):	■	■	■									
Setup construction		■	■	■								
SAP moisture absorption capacity					■	■						
Testing SAP effectiveness							■	■	■			
SAP regeneration testing					■	■						
SAP longevity testing							■	■	■			
Obj. 3: Ultrasounds pretreatment												
Obj. 4: Techno-economic analysis												

Requested Budget

- $40,000 for 12 months
  - $25,000 : Partial support for postdoctoral scholar
  - $10,000 : Drying chamber for conducting controlled drying experiments
  - $5,000 : Materials and supplies for measuring air flow rate, relative humidity, and temperature