Innovative Applications of Infrared Heating for Food Processing

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Needs in Food and Agri Processing

- Quality and new products
- Sustainability
  - Energy
  - Water
  - Other natural resources
Why Infrared Heating?

- Infrared *radiant* heat transfer is often more efficient than convective heat transfer
- *Large amount* of controlled heat for heating food materials
- Improved final product quality
Infrared Radiation Research
IR for Dehydration

- Conventional drying
  - Low quality
  - Low drying rate

- IR drying
  - Improved quality and drying rate
  - Sequential IR and Freeze Drying (SIRFD) (patent pending)
IR for Dehydration - Onion

DRYING RATES – 70°C

Drying Rate (g h2o/kg Onion Min)

Moisture Content (d.b.)

- 70°C
- 70°C No Recirculation
- 70°C Fluff
- 70°C FAC
IR for Dehydration - Onion

Color Comparison

CFGIR

Retail
Commercial Demonstration Project – Walnut Drying

- Demonstration and Commercial Implementation of Energy Efficient Drying for Walnuts
- Expected at least 35% energy saving
- Capacity 10-15 T/h

Wizard Manufacture Inc.
Emerald Farms Inc.
SIRFD for Strawberry

Cross sections

- Regular FD Strawberry
- SIRFD Strawberry
- SHAFD Strawberry

SIRFD Strawberries
Blanching and Dehydration

- Hot water and steam blanching
  - Wastewater, nutrient loss
- IR blanching
  - No water is needed
  - Fast
- Simultaneous IR dry-blanching and dehydration (SIRDBD) (patent pending)
  - More energy efficient
  - Simplified equipment and process
SIRDBD for Fruit Bars

Whole fruit frozen bars (apple and strawberry bars)

Moisture content (% w.b.)

90.11 89.01 87.64 85.87 83.52 80.22 75.28

92.70 91.42 89.59 86.75 81.78 70.84

(Patent Pending)
Samples Fried at 160°C

C – 160°C, 1 min
C – 160°C, 3 min
C – 160°C, 5 min
C – 160°C, 7 min

IR – 160°C, 1 min
IR – 160°C, 3 min
IR – 160°C, 5 min
IR – 160°C, 7 min
At the end of 7 min frying:

- 37.5% reduction at 146°C
- 32.0% reduction at 160°C
- 30.0% reduction at 174°C
Sensory Analysis

Average frying times at different frying temperatures

<table>
<thead>
<tr>
<th>Frying Temperature</th>
<th>Control (min)</th>
<th>IR (min)</th>
<th>Oil Content (IR)</th>
<th>Oil Content (Control)</th>
</tr>
</thead>
<tbody>
<tr>
<td>146°C</td>
<td>7 min 27 s</td>
<td>5 min 30 s</td>
<td>13.93</td>
<td>22.77</td>
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<tr>
<td>160°C</td>
<td>5 min 33 s</td>
<td>4 min 30 s</td>
<td>15.30</td>
<td>21.74</td>
</tr>
<tr>
<td>174°C</td>
<td>4 min</td>
<td>3 min 48 s</td>
<td>14.23</td>
<td>20.79</td>
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</tbody>
</table>

· 77 panelists attended.

· Differences in texture, color, appearance and overall were asked.
## Sensory Analysis

P-value of sensory attributes and percentage preferring infrared blanched samples

<table>
<thead>
<tr>
<th>Sensory Attribute / Frying Temperature (°C)</th>
<th>Taste</th>
<th>Texture</th>
<th>Color</th>
<th>Appearance</th>
</tr>
</thead>
<tbody>
<tr>
<td>146</td>
<td>P=0.168</td>
<td>P=0.0003</td>
<td>P=0.118</td>
<td>P=0.017</td>
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<tr>
<td></td>
<td>N/A</td>
<td>59.1%</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>160</td>
<td>P=0.113</td>
<td>P=0.0003</td>
<td>P=0.113</td>
<td>P=0.0003</td>
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<tr>
<td></td>
<td>N/A</td>
<td>46.4%</td>
<td>N/A</td>
<td>39.3%</td>
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<tr>
<td>174</td>
<td>P=0.149</td>
<td>P=0.0020</td>
<td>P=0.0001</td>
<td>P=0.0001</td>
</tr>
<tr>
<td></td>
<td>N/A</td>
<td>59.3%</td>
<td>55.6%</td>
<td>51.9%</td>
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</tbody>
</table>
Industrial IR Equipment for Demonstration

- Runs with the state-of-the-art catalytic emitters powered with natural gas.
- Weighs 4500 lbs.
- $H \times L \times W = 77'' \times 240'' \times 77''$
Dry-blanching & Dehydration Tests

Tested Commodities

Bell pepper
Carrot
Onion
Potato

Parameters Evaluated

• Weight loss
• Temperature Profile
• Color
• Enzyme Inactivation
  • Polyphenol Oxidase
  • Peroxidase
Potatoes - Sliced

Test 2
Section 2: OFF
Speed: 1.0 m/min

Test 3
Section 2: OFF
Speed: 0.7 m/min

Test 4
Section 2: 50%
Speed: 1.1 m/min
Potatoes - Diced

- After 4 minutes exposure to IR radiation, the MC decreased to 66.31%.

- Dipping into water for 1 minute after blanching increased the MC to 70.2%.

- Dipping after blanching improved the final appearance of diced potatoes.
Green Bell Pepper

Color of IR treated green bell peppers did not change significantly.

Untreated 1.224 m/min
4.017 ft/min 1.428 m/min
4.686 ft/min 1.935 m/min
6.350 ft/min

Untreated
White Onions

- Color of IR treated white onions did not change significantly.

Untreated 1.224 m/min 1.428 m/min 1.935 m/min
Carrots - Sliced

No significant change in appearance after 4 min IR exposure.

Dipping the samples into water after blanching eliminated the dry-look.
Carrots - Pomace

- Color of carrot pomace became lighter as the weight loss increased.
- IR drying of carrot pomace was successful.
Commercial Demonstration Project

- Commercial Demonstration of Innovative, Energy Efficient Infrared Processing of Healthy Fruit and Vegetable Snacks.
- Treasure Brands Inc., Innovative Foods Inc.
Almond Pasteurization and Roasting

- Raw almond pasteurization
  - Maintain quality characteristics
- Roast almonds and pasteurization
  - Reduce processing time
  - Meet pasteurization requirement
Effect of maximum kernel surface temperature on decontamination

Before IR

100.6 104.1 108.6

1.06% weight loss during treatment

0.98% weight loss during treatment

Log (cfu/g kernel)

Surface temperature (°C)

Time (sec)

Detection threshold: 2 cells/g kernel

Maximum kernel surface temperature (°C)

4.2-log

5.3-log

>7.5-log
Quality of IR-treated Raw Almonds

IR + 30-min holding (104°C max.)

CONTROL
Almond Roasting

Roasting methods

- Infrared roasting (IR)
- Sequential IR and hot air roasting (SIRHA)
- Hot air roasting (HA)

Temperatures

- 130°C
- 140°C
- 150°C
## Roasting Time Reduction

<table>
<thead>
<tr>
<th>Roasting degree (ΔE)</th>
<th>Method</th>
<th>HA</th>
<th>SIRHA</th>
<th>IR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Temp. (°C)</strong></td>
<td>130</td>
<td>140</td>
<td>150</td>
<td>130</td>
</tr>
<tr>
<td>Light (5.7)</td>
<td>Time (min)</td>
<td>22</td>
<td>14</td>
<td>9</td>
</tr>
<tr>
<td>Reduction (%)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>45</td>
</tr>
<tr>
<td>Medium (11.5)</td>
<td>Time (min)</td>
<td>34</td>
<td>18</td>
<td>13</td>
</tr>
<tr>
<td>Reduction (%)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>38</td>
</tr>
<tr>
<td>Dark (21.4)</td>
<td>Time (min)</td>
<td>72</td>
<td>30</td>
<td>19</td>
</tr>
<tr>
<td>Reduction (%)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>28</td>
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</table>
Reduction of Bacteria

<table>
<thead>
<tr>
<th>Methods</th>
<th>SIRHA</th>
<th>HA</th>
<th>IR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp. (°C)</td>
<td>150</td>
<td>140</td>
<td>130</td>
</tr>
<tr>
<td>Dark</td>
<td>8.55</td>
<td>7.41</td>
<td>7.45</td>
</tr>
<tr>
<td>Medium</td>
<td>6.96</td>
<td>5.82</td>
<td>4.10</td>
</tr>
<tr>
<td>Light</td>
<td>3.33</td>
<td>3.17</td>
<td>3.59</td>
</tr>
</tbody>
</table>
Infrared Heating for Improved Drying Efficiency, Food safety and Quality of Rice
Background – Rice Drying

- **Hot air drying**
  - Air temperature at 43 °C
  - Tempering

- **Disadvantages**
  - Low drying efficiency
    - 1.5% -2% moisture removal during 15-20 min
  - High energy consumption
  - Low temperature results in ineffective
    - Disinfestation
    - Disinfection
    - Stabilization

Quick and energy efficient drying technology is needed.
Research Goals

- To achieve simultaneous
  - Drying
  - Disinfestation
  - Stabilization
  - Disinfection
Drying - Materials and methods

- **Rough rice**
  - Freshly harvested medium grain rice, M202 IMC of 20.6% and 25.7 % (wb)

- **Infrared heating treatment**
  - Samples were dried as single-layer bed
  - The drying bed was preheated to 35°C
  - Four exposure times (15, 40, 60, 90 s) and (25, 40, 60, 90 s)

- **Tempering and cooling treatments**
  - Tempering by placing samples in an incubator with a temperature as the same as the heated rice for 4 h.
  - Cooling by natural cooling or forced air cooling at room temperature
Drying - Materials and methods

- **Milling Quality**
  - Total rice yield (TRY)
  - Head rice yield (HRY)
  - Whiteness index (WI)

Yamamoto Rice Mill  
Yamamoto Husker

Whiteness Tester  
Graincheck
Drying – Results: Temperature and moisture removal under different heating durations

\[ T = 21.066^{0.26} \times t \]

\[ R^2 = 0.9969 \]

Drying - Results:

Heating rate - (IMC 23.8%)

\[ y = 20.75 \times t^{0.2619} \quad R^2 = 0.9978 \]

\[ y = 9.2078 \times t^{0.4258} \quad R^2 = 0.9869 \]

\[ y = 8.184 \times t^{0.4349} \quad R^2 = 0.9981 \]

Drying - Results:
Moisture removal- IR heating only - (IMC 23.8%)

Drying - Results

Total moisture removals - (IMC 23.8%)

Quality of milled rice dried with different conditions with initial moisture content of 20.5 %.  (DBT = drying bed thickness)

<table>
<thead>
<tr>
<th>Heating time (s)</th>
<th>Rice temperature (°C)</th>
<th>Total moisture removal (%)</th>
<th>DBT and control [a]</th>
<th>Milled rice quality [b]</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Control</td>
<td>TRY 68.61 a</td>
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<tr>
<td></td>
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<td></td>
<td></td>
<td>HRY 64.11 a</td>
</tr>
<tr>
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<td></td>
<td></td>
<td>WI 41.90 a</td>
</tr>
<tr>
<td>15</td>
<td>42.6</td>
<td>2.0</td>
<td>Single-layer</td>
<td>TRY 68.39 ab</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>HRY 64.45 a</td>
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<td></td>
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<td>WI 41.50 a</td>
</tr>
<tr>
<td>30</td>
<td>40.6</td>
<td>1.9</td>
<td>5 mm</td>
<td>TRY 68.11 bc</td>
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<tr>
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<td></td>
<td></td>
<td>HRY 62.67 b</td>
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<td>WI 41.80 a</td>
</tr>
<tr>
<td>30</td>
<td>37.0</td>
<td>1.2</td>
<td>10 mm</td>
<td>TRY 67.78 cd</td>
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<td>Control</td>
<td>HRY 62.84 b</td>
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<td></td>
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<td>WI 41.60 a</td>
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<tr>
<td>40</td>
<td>54.5</td>
<td>2.4</td>
<td>Single-layer</td>
<td>TRY 68.68 a</td>
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<tr>
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<td></td>
<td></td>
<td>HRY 64.71 b</td>
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<tr>
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<td></td>
<td>WI 41.67 a</td>
</tr>
<tr>
<td>60</td>
<td>53.4</td>
<td>2.3</td>
<td>5 mm</td>
<td>TRY 68.38 a</td>
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<td>HRY 62.91 c</td>
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<td></td>
<td>WI 41.80 a</td>
</tr>
<tr>
<td>60</td>
<td>46.2</td>
<td>1.6</td>
<td>10 mm</td>
<td>TRY 68.42 a</td>
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<td>Control</td>
<td>HRY 63.97 a</td>
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<td>WI 41.60 a</td>
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<tr>
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<td>61.0</td>
<td>2.7</td>
<td>Single-layer</td>
<td>TRY 69.26 b</td>
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<td>WI 41.60 a</td>
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<tr>
<td>90</td>
<td>60.2</td>
<td>2.6</td>
<td>5 mm</td>
<td>TRY 69.49 bc</td>
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<td>Control</td>
<td>HRY 65.05 b</td>
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<td>WI 42.06 a</td>
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<td>53.4</td>
<td>2.2</td>
<td>10 mm</td>
<td>TRY 68.82 ab</td>
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<td></td>
<td>Control</td>
<td>HRY 65.40 b</td>
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<td>WI 41.60 a</td>
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<tr>
<td>90</td>
<td>69.1</td>
<td>4.1</td>
<td>Single-layer</td>
<td>TRY 68.51 a</td>
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<td>HRY 63.52 a</td>
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<td>WI 41.80 a</td>
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<td>120</td>
<td>71.4</td>
<td>3.8</td>
<td>5 mm</td>
<td>TRY 67.91 b</td>
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<td>Control</td>
<td>HRY 62.77 b</td>
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<td>WI 42.00 a</td>
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<td>2.5</td>
<td>10 mm</td>
<td>TRY 69.20 c</td>
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<td></td>
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<td>WI 41.70 a</td>
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</table>

## Comparison of sensory flavor and texture attributes of IR treated rice and control

<table>
<thead>
<tr>
<th>Flavor Attributes</th>
<th>Initial MC 20%</th>
<th>Texture Attributes</th>
<th>Initial MC 20%</th>
<th>Initial MC 25.1%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control</td>
<td>Treated</td>
<td>Control</td>
<td>Treated</td>
</tr>
<tr>
<td>Sewer Animal</td>
<td>1.0 a</td>
<td>0.9 a</td>
<td>2.2 a</td>
<td>2.2 a</td>
</tr>
<tr>
<td>Floral</td>
<td>0.0 a</td>
<td>0.0 a</td>
<td>6.9 a</td>
<td>7.3 a</td>
</tr>
<tr>
<td>Grain/Starchy</td>
<td>3.4 a</td>
<td>3.5 a</td>
<td>5.6 a</td>
<td>5.4 a</td>
</tr>
<tr>
<td>Hay-like Musty</td>
<td>0.6 a</td>
<td>0.5 a</td>
<td>10.2 a</td>
<td>9.5 b</td>
</tr>
<tr>
<td>Popcorn</td>
<td>0.3 a</td>
<td>0.5 a</td>
<td>5.6 a</td>
<td>5.2 a</td>
</tr>
<tr>
<td>Corn</td>
<td>0.8 a</td>
<td>1.0 a</td>
<td>4.0 a</td>
<td>4.0 a</td>
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<tr>
<td>Alfalfa</td>
<td>0.0 a</td>
<td>0.3 a</td>
<td>5.3 a</td>
<td>5.4 a</td>
</tr>
<tr>
<td>Dairy</td>
<td>0.9 a</td>
<td>0.5 a</td>
<td>5.8 a</td>
<td>5.7 a</td>
</tr>
<tr>
<td>Sweet Aromatic</td>
<td>0.4 a</td>
<td>0.4 a</td>
<td>6.9 a</td>
<td>7.5 a</td>
</tr>
<tr>
<td>Water-like Metallic</td>
<td>0.8 a</td>
<td>1.1 a</td>
<td>5.8 a</td>
<td>6.0 ac</td>
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<tr>
<td>Sweet Taste</td>
<td>1.3 a</td>
<td>1.2 a</td>
<td>5.3 b</td>
<td>5.2 b</td>
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<tr>
<td>Sour</td>
<td>0.3 a</td>
<td>0.3 a</td>
<td>4.7 a</td>
<td>4.8 a</td>
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<tr>
<td>Astringent</td>
<td>1.0 a</td>
<td>1.2 a</td>
<td>4.1 a</td>
<td>4.0 a</td>
</tr>
</tbody>
</table>

Moisture gradient (% dry basis per mm) distribution in the rough rice after 5 min

Infrared drying: Moisture gradients
Infrared drying: Moisture gradients

Head rice yield (HRY) and moisture gradients at bran-endosperm interface (P1) and bran-husk interface (P2) during infrared heating for different time period.
Disinfestation - Materials and methods

- **Insects**
  - Lesser grain borers (beetles) and moths (S. cerealella)

- **Effectiveness of disinfestation treatment**
  - Incubator was set at 28°C and 64% RH
  - Surviving and emerged live adults insects were visually counted during 35 days after treatment
Disinfestation – Results: Numbers of live moths in the rice samples

<table>
<thead>
<tr>
<th>Harvest MC (%)</th>
<th>Heating time (s)</th>
<th>Rice temperature (°C)</th>
<th>Days of storage after treatment</th>
<th>Tempering</th>
<th>1[b]</th>
<th>5</th>
<th>8</th>
<th>15</th>
<th>27</th>
<th>32</th>
<th>34</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.6%</td>
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<td></td>
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<td></td>
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<td></td>
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<tr>
<td>90</td>
<td>69.4</td>
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<td>0</td>
<td>0</td>
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</tr>
<tr>
<td>60</td>
<td>61.3</td>
<td>No</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
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<td>0</td>
</tr>
<tr>
<td>25.7%</td>
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<td>90</td>
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</table>

## Disinfection - Results: Numbers of live beetles in the rice samples

<table>
<thead>
<tr>
<th>Harvest MC (%)</th>
<th>Heating time (s)</th>
<th>Rice temperature (°C)</th>
<th>Tempering</th>
<th>Days of storage after treatment</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1[b]</td>
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<tr>
<td>20.6%</td>
<td>90</td>
<td>69.4</td>
<td>Yes</td>
<td>0</td>
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<tr>
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<td>90</td>
<td>69.4</td>
<td>No</td>
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<td>61.3</td>
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<td>61.3</td>
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<td>0</td>
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<td>40</td>
<td>54.3</td>
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<td>26</td>
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<td>54.3</td>
<td>No</td>
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<td>49.0</td>
<td>Yes</td>
<td>45.5</td>
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<td>25</td>
<td>49.0</td>
<td>No</td>
<td>50.0</td>
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<td>25.7%</td>
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<td>90</td>
<td>68.0</td>
<td>No</td>
<td>0</td>
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<td>60</td>
<td>59.1</td>
<td>Yes</td>
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<td>55.5</td>
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<td>58.5</td>
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<td></td>
<td>25</td>
<td>49.0</td>
<td>No</td>
<td>29.5</td>
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</tbody>
</table>

Stabilization - Materials and methods

- **IR heating (one and two passes)**
  - Single-layer drying
  - Heating to 60 ºC (surface)
  - Medium grain M206
  - Harvest MC 32.5% (db)
    - Test initial MC
      - 32.5%, 25.5% and 20.1% (db)

- **Tempering treatment**
  - Incubator @ 60 ºC
  - Durations (4 h)
  - Natural cooling

- **Control samples (ambient air drying)**

- **Moisture content (db) and moisture loss**
  - Oven method (130°C, 24 h)
Stabilization - Results: IR & tempering treatments

FFA Concentration: IMC = 32.5%
Disinfection - Materials and methods

Microorganism

Aspergillus flavus NRRL 3357 spore suspension (105 cfu/mL)

Rice samples

Fresh rice (M 206): IMC=14% - 27% (wb)
Surface rewetted storage rice: MC=15%-19% (wb)
To simulate different rice source
Disinfection - Materials and methods

25 g inoculated rice  IR 35-38 s to 60°C  Tempering in oven at 60 °C

Cooling  25 g rice + 225 mL water  Series dilution  Spread on agar
**Disinfection - Results:** Effect of IR heating and tempering treatment on log reduction of *A. flavus* spores for fresh rice and surface rewetted rice samples

![Graph showing log reduction of spores over tempering time]

- ▲ fresh rice MC=27.0%; ▗ surface rewetted rice MC=16.4%; ◇ surface rewetted rice MC=19.4%.

Disinfection results:

- MR 5.8 (% point)
- MR 5.3 (% point)
- MR 4.8 (% point)
- MR 4.5 (% point)
- MR 3.3 (% point)

- Fresh rice MC:
  - MC=21.1%: ■
  - MC=25.0%: ●
  - MC=27.0%: ▲

- Surfacerewetted rice MC:
  - MC=16.4%: ▼
  - MC=19.4%: ◇
Rice Drying and Disinfestations

- Current heated air drying
  - 15-20 min to remove about 2% MC

- IR drying
  - 1 min heating to 60°C
  - Remove 4% MC during heating and cooling
  - Improved head rice yield
  - Kill insects and microbials
  - Stabilization

Lungberg Farms, California Rice Research Board
IR Dry-Peeling

- California needs alternative peeling methods
  - Reduce and avoid water and lye
  - Bring environmental benefit
  - Improve product quality
  - Improve energy efficiency
Processing Tomatoes

- Produce over 14 million tons of tomatoes each year
- Peel tomatoes for canning products

California is the largest processing tomato producer in the U.S.

Graph from http://www.heinzketchup.com/
Tomato Anatomy

- Skin
- Red layer
- Pericarp
- Columella
- Locule

Skin (~50 µm)

Red layer

Cuticle

Epidermal cells
Hypodermal cells

Pericarp cells

Tomato Internal Structure

Tomato Anatomy
Tomato Peeling Process

- Commercial peeling methods
  - Hot lye peeling
    - 8%~25% NaOH/KOH
    - 80°C~100°C
    - 30~75 seconds
  - Steam peeling
    - 120°C~215°C
    - 120~480 kPa

- Disadvantages
  - Water- and energy-intensive
  - Wastewater disposal problems
  - High salinity related issues
  - Long-term water supply concern
  - High peeling loss (up to 50%)

Developing Sustainable Non-Chemical Peeling Method
IR Experimental Setup
IR Peeled Tomatoes

Raw tomato

IR peeled tomato

IR peeled skin
Peeling Outcomes

Peeling Performance

Peelability:
• FDA standard: 21CFR 155.190
• Un-removed peel per gram of the raw product should less than 0.015 cm²/g

Peeling loss:
• The weight change of tomato before and after peeling in terms of percentage

Peeled skin thickness

Ease of Peeling:
• Subjective grading scale 1-5.
• Grade 1 = unable to peel; grade 5 = easy to peel;
• acceptable level >4
Peeling Outcomes

Quality of peeled products

- Col or
- Firmn

Final surface temperature

Color Measurement

Fruit Texture Analyzer

Infrared Thermometer
Peeling Methods

- IR Peeling
- Regular lye peeling
- Lye-IR Peeling
- Enzyme-IR peeling

*Experimental configuration for A) IR heating of tomatoes, B) Lye peeling, C) Enzymatic peeling*
Mechanical Property of Tomato Peel

Young’s Modulus of Tomato Peels

After 60s IR heating
90mm emitter gap with rotation
n=10
Adhesive Energy for Pulling Peel Off

After 60s IR heating
90mm emitter gap with rotation
n=10
Dynamic Mechanical Analysis

DMA 8000 (PerkinElmer) with tension clamps

- Temperature ramp test
- Frequency sweep test
Temperature Ramp Test

IR heated peels

Lye heated peels

Temperature Ramp Test

Storage Modulus (MPa)

Temperature (°C)

Temperature Ramp Test

Temperature Ramp Test

Storage Modulus (MPa)

Temperature (°C)

Fresh control
IR-30s
IR-45s
IR-60s
IR-75s

Fresh control
Lye-30s
Lye-45s
Lye-60s
Lye-75s
Storage Modulus of Frequency Spectra

IR heated peels

Lye heated peels

- Fresh control
- IR-30s
- IR-45s
- IR-60s
- IR-75s
- Lye-30s
- Lye-45s
- Lye-60s
- Lye-75s
Observed Skin Separation

- Thickness
- Layer separation

1 mm
Microstructural Changes on Surface

- Clearly defined contours
- Concave surfaces

**Fresh Tomato**

**Lye Heated**

- Increased cell contour visibility

**IR Heated**

- Damaged epidermal layers
- Redistribution of cuticular wax
- Different mechanisms
  - Chemical diffusion and reaction
  - Radiation damage
Microstructural Changes in Pericarp Tissue

- Fresh control
  - Thicken cell walls
  - Icy crystals

- IR heated
  - Loss of cell integrity
  - Layer separations

- Lye heated
  - Thermal expansion of cell walls

- IR heated
  - 200um
Measurements of Skin Rupture

Rupture stress of IR heated skin:

\[ \sigma_r = \frac{F_p}{2R_p \sin \theta} \]
Transient Skin Stress Development and Peel Cracking Susceptibility

Temperature from heat transfer model → Vapor Pressure from Antoine equation → Stress in skin membrane from shell model

IR heating for 60s

Stress > Rupture stress
IV. Geometric Modeling of Tomatoes

- Specially bred for processing operations
- Effects of tomato geometry on peeling
  - Peeling and heating performance
  - Design of IR emitter configuration
- Important tomato geometric features
  - Uniform elongated oval shape
  - Axial symmetric in stem-blossom direction
  - Circular symmetric in its cross-section
  - Intended feature at stem end
Tomato Shape Equations

\[
\begin{align*}
\begin{cases}
x = R(\theta) \sin(\theta) \cos(\varphi) \\
y = R(\theta) \sin(\theta) \sin(\varphi) \\
z = R(\theta) \cos(\theta)
\end{cases}
\end{align*}
\]

in which

\[
R(\theta) = \frac{1 + c_1 \sin(\theta) + c_2 \sin^3(\theta)}{\sqrt{\left[\frac{\cos(\theta)}{b}\right]^2 + \left[\frac{\sin(\theta)}{a}\right]^2}}
\]

Where
- \(a\) = the semi-major axis
- \(b\) = the semi-minor axis
- \(c_1\) = shape coefficient
- \(c_2\) = shape coefficient

Where
- \(R(\theta)\) = radius function of distance from the origin to the boundary
- \(\theta\) = zenith angle, \([0, \pi]\)
- \(\varphi\) = azimuth angle, \([0, 2\pi]\)
Experimental Measurements

- Dimensional parameters: $H$, $s$, $W$, $P$, $R_{90}$
- Physical parameters: mass, density, surface area

Dimensional Measurements and Geometric Relationship
Mathematical relationship within tomato geometric profile

\[ R(\theta) = \frac{1 + c_1 \sin(\theta) + c_2 \sin^3(\theta)}{\sqrt{\left(\frac{\cos(\theta)}{b}\right)^2 + \left(\frac{\sin(\theta)}{a}\right)^2}} \]

\[ R(a, b, c_1, c_2) = g(H, s, W(\theta), P, R_{90}) \]
# Results of Determination of Coefficients

- Five necessary measurements of tomato dimensions
  - H, W, P, s and R90
- Coefficients calculated from each tomato measurements

<table>
<thead>
<tr>
<th>Descriptions</th>
<th>Formulas</th>
<th>Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>$a = \frac{H - s}{2}$</td>
<td>H and s</td>
</tr>
<tr>
<td>b</td>
<td>$b = a \frac{W}{2d} \sqrt{c_1 \sin[\arctan(\frac{2d}{W})]}$, where $d =</td>
<td>P + R_{90} - H</td>
</tr>
<tr>
<td>c1</td>
<td>$c_1 = \frac{4(H - P - R_{90})^4 \cos^2[\arctan(\frac{2d}{W})] + (H - P - R_{90})^2 W^2 \cos^2[\arctan(\frac{2d}{W})]}{\left(\frac{H - s}{2}\right)^2 W^2 \sin^2[\arctan(\frac{2d}{W})]}$</td>
<td>H, W, P, s and R90</td>
</tr>
<tr>
<td>c2</td>
<td>$c_2 = \frac{2R_{90}}{L} - c_1 - 1$</td>
<td>R90, H and s</td>
</tr>
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</table>
Shape and Size Variations

Tomato size changes

\[ c_1 = 0.24; \ c_2 = 0.38; \]

- \( a = 31, \ b = 26 \)
- \( a = 29, \ b = 22 \)
- \( a = 26, \ b = 18 \)

Tomato shape variations

\[ a = 26; \ b = 18; \]

- \( c_1 = 0.25, \ c_2 = 0.45 \)
- \( c_1 = 0.4, \ c_2 = 0.38 \)
- \( c_1 = 0.25, \ c_2 = 0.38 \)
Linear Regression Analysis

Dimensional parameters: $a$ vs. mass and $b$ vs. height

Shape coefficients: $c_1$ and $c_2$ vs. mass and height
Simplified Tomato Geometric Model

\[
\begin{align*}
x &= R(\theta) \sin(\theta) \cos(\varphi) \\
y &= R(\theta) \sin(\theta) \sin(\varphi) \\
z &= R(\theta) \cos(\theta)
\end{align*}
\]
in which
\[
R(\theta) = \frac{1 + c_1 \sin(\theta) + c_2 \sin^3(\theta)}{\sqrt{\left(\frac{\cos(\theta)}{b}\right)^2 + \left(\frac{\sin(\theta)}{a}\right)^2}}
\]

<table>
<thead>
<tr>
<th>Descriptors</th>
<th>Formulas</th>
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<tr>
<td>a</td>
<td>0.498×height-1.304</td>
</tr>
<tr>
<td>b</td>
<td>0.12×mass+13.40</td>
</tr>
<tr>
<td>c1</td>
<td>0.12 ~ 0.54</td>
</tr>
<tr>
<td>c2</td>
<td>0.30 ~ 0.38</td>
</tr>
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# Tomato Geometric Characterization

<table>
<thead>
<tr>
<th>Geometry Characteristics</th>
<th>Derived Formulas</th>
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<tbody>
<tr>
<td>Mass</td>
<td>( m = \frac{2\pi R^3}{3} \int_{\theta_1}^{\theta_2} (\cos(\theta))d\theta )</td>
</tr>
<tr>
<td>Volume</td>
<td>( V = \frac{2\pi R^3}{3} \int_{\theta_1}^{\theta_2} (\cos(\theta))d\theta )</td>
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<tr>
<td>Surface area</td>
<td>( S = 2\pi \int_{\theta_1}^{\theta_2} R(\theta) \sin(\theta) \sqrt{R(\theta) + \left(\frac{dR}{d\theta}\right)^2} d\theta )</td>
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<tr>
<td>Projected area</td>
<td>( A = \frac{1}{2} \int_{\theta_1}^{\theta_2} R(\theta) d\theta )</td>
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<tr>
<td>Circumference length</td>
<td>( C = \int_{\theta_1}^{\theta_2} \sqrt{R(\theta) + \left(\frac{dR}{d\theta}\right)^2} d\theta )</td>
</tr>
</tbody>
</table>

- Quantify a group of tomato geometric attributes
- Validated model in determining tomato mass and surface area
Model Validation

- A rapid estimation of tomato mass and surface area
- Good agreement of linear correlation
- Reasonable goodness-of-fit criteria

<table>
<thead>
<tr>
<th>Prediction</th>
<th>Sample size</th>
<th>Predicted Values</th>
<th>Measured Values</th>
<th>$R^2$</th>
<th>RMSE</th>
<th>Relative Error (%)</th>
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<tbody>
<tr>
<td>Mass</td>
<td>96</td>
<td>56.4-169.6 g</td>
<td>59.7-148.2 g</td>
<td>0.9987</td>
<td>1.688 g</td>
<td>1.2</td>
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<tr>
<td>Surface area</td>
<td>96</td>
<td>72.7-156.1 cm²</td>
<td>66.4-142.7 cm²</td>
<td>0.8745</td>
<td>9.776 cm²</td>
<td>6.7</td>
</tr>
</tbody>
</table>
Model Application — Design and Simulation

• Heating performance affected by shape and size
  - Over-heating vs. loss in texture and nutritional values
  - Under-heating vs. insufficient degree of peel loosening

• Facilitate configuration design of infrared heating system
  - Complex radiation heat transfer
  - Heating rate vs. heating uniformity
  - High surface temperature vs. low interior temperature

Need to understand the IR heating process affected by various engineering parameters
Scheme of IR Heating Configuration

- Flameless catalytic gas-fired emitters
- Emitter emissivity: 0.97
- Emitter surface temperature: 450°C
- Emitter surface area: 300×460mm
- IR heating duration: up to 60s
- Distance between emitters: 90mm

Tomato model and contours of three size levels: 42, 49, 54±1mm
Temperature Measurements

- Multiple locations in a tomato
  - Four surface locations (S1-S4): top, bottom, side S1, side S4
  - Four interior locations (I1-I4): 1, 4, 8, 16mm under skin

- Hypodermic miniature thermocouples
  - Tiny tip (0.3mm) and fast response time (60ms)
  - Five replicates at each location

Positions of thermocouples
Model Development
— Radiation Heat Transfer

- Gray-diffuse radiation exchange based on enclosure theory
Model Development — Combined with Conduction and Convection

1) Moisture loss <2~3%
2) Respiration

Conduction

Radiation $q_{rad}$

Convection $q_{cov}$

BC on tomato surface:

$$-\mathbf{n} \cdot (-k \nabla T) = h(T_{amb} - T_{sur}) + q_{rad}$$

BC at tomato center:

$$-\mathbf{n} \cdot k \nabla T = 0$$

IC : $T = T_{ini}(x,y,z)$ at $t=0$

Temperature depend properties

$$k_p \nabla T = 1 - \xi \sigma y_i k_i \nabla T + \xi k_{air} \nabla T$$

Water evaporation effect

$$\rho_{ap} \nabla T = 1 - \xi \rho_t \nabla T = \frac{1 - \xi}{\sum_{i=1}^{\sigma} x_i \rho_i(T)}$$

Function of chemical compositions

Water evaporation effect

$$\rho_{ap} \nabla T = \rho_{ap} \nabla T + \frac{\rho_{ap} \nabla T}{\xi} \exp\left[\frac{\rho_{ap} \nabla T}{\xi \cdot 2} \right]$$
Simulation Results — 60s IR Heating

Facing toward the emitter
Simulation Results — 60s IR Heating

Facing away from the emitter
Simulation Results — 60s IR Heating

Surface Temperature Uniformity Index (STUI)

Facing towards emitter

Facing away from emitter

\[
STUI = \frac{1}{T_{sur}} \frac{s \int [T_{sur} - \bar{T}_{sur}]^2 dA}{A_{sur}}
\]
Model Validation

- Compare temperature at multiple locations for tomatoes of different sizes
  - Good agreement of linear correlation ($R^2 > 0.9$)
  - Reasonable Standard error of estimate criteria

\[
\text{SEE} = \frac{1}{N} \sum_{i=1}^{N} [T_{\text{pre}i} - T_{\text{exp}i}]^2
\]

Smaller SEE value
Better goodness-of-fit

<table>
<thead>
<tr>
<th>Tomato Size</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>I1</th>
<th>I2</th>
<th>I3</th>
<th>I4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large</td>
<td>5.2</td>
<td>3.6</td>
<td>3.3</td>
<td>5.9</td>
<td>2.7</td>
<td>1.9</td>
<td>1.6</td>
<td>1.1</td>
</tr>
<tr>
<td>Medium</td>
<td>3.9</td>
<td>4.6</td>
<td>3.9</td>
<td>2.9</td>
<td>0.8</td>
<td>3.1</td>
<td>2.6</td>
<td>1.1</td>
</tr>
<tr>
<td>Small</td>
<td>2.3</td>
<td>1.9</td>
<td>1.5</td>
<td>3.1</td>
<td>2.1</td>
<td>0.7</td>
<td>0.8</td>
<td>0.7</td>
</tr>
</tbody>
</table>
Model Validation
—Medium Size Tomatoes

Surface temperature:
*Top, bottom, two sides*

Interior temperature:
*1, 4, 8, and 16 mm beneath skin*
Model Validation  
—Small and Large Size Tomatoes

Surface temperature:  
*Top, bottom, two sides*

Interior temperature:  
*1, 4, 8, and 16 mm beneath skin*
Sensitivity Analysis — Tomato Size Effects

<table>
<thead>
<tr>
<th>Tomato Size</th>
<th>Surface Area to Volume Ratio (1/mm)</th>
<th>Maximum Temperature (°C)</th>
<th>Surface Averaged Temperature (°C)</th>
<th>STUI</th>
<th>Energy Absorption (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large</td>
<td>0.10</td>
<td>101.21</td>
<td>89.06</td>
<td>0.0846</td>
<td>8331</td>
</tr>
<tr>
<td>Medium</td>
<td>0.11</td>
<td>100.82</td>
<td>89.76</td>
<td>0.0782</td>
<td>6903</td>
</tr>
<tr>
<td>Small</td>
<td>0.12</td>
<td>100.67</td>
<td>90.54</td>
<td>0.0736</td>
<td>5605</td>
</tr>
</tbody>
</table>

- Similar average and maximum surface temperature
- Different STUIs and overall energy absorption
- Sorting tomatoes according to their size or weight
Sensitivity Analysis
—Initial Temperature of Tomatoes

Medium size tomato for 60s IR heating of 90mm emitter gap
Medium size tomato for 60s IR heating

Emitter Gap (mm)
- 60mm
- 90mm
- 120mm

Temperature (°C)
- Maximum temperature
- Average temperature
- STUI

Emitter Gap (mm)
Sensitivity Analysis
— Emissive Power of the Emitters

Medium size tomato under IR heating of 90mm emitter gap
Pilot Scale Infrared Dry-Peeling System
Reducing water use in tomato processing

“The tomato processing industry has long been interested in finding a better way of peeling tomatoes,” says Zhongli Pan, a USDA-ARS research engineer at the Western Regional Research Center in Albany, Calif., and an adjunct professor in the Department of Biological and Agricultural Engineering at UC Davis. He and his colleagues found that peeling tomatoes with infrared heat eliminates by use, greatly reduces water use, and results in better quality tomatoes.

Infrared heat is similar to heat from the sun. It allows for efficient heat transfer from the source to the product. “The real advantage is that infrared heat doesn’t penetrate the product very deeply, so the tomato skins can be heated and removed easily while maintaining firmer, higher-quality peeled tomatoes,” Pan explains. Another advantage is that the removed peel is purer and more concentrated, allowing it to be used in other ways, such as added back into tomato paste or as a new food additive. Infrared heat has promising potential not only for dry-peeling tomatoes, peaches, and other produce, but also for Blanching many fruits and vegetables before freezing, such as apples and “baby” carrots.

With financial support from the California League of Food Processors, the California Energy Commission, and six tomato
Tomato Peeling Demonstration

• Olam Tomato Processor Inc.
• H.J. Heinz Co.
IR and Steam Peeled Tomatoes
Results: IR Peeled Inmatured Tomatoes

Before peeling
Small size tomatoes (42-46mm)

After peeling
Peeled under 130 s infrared heating
Conclusions

Advantages

- Various applications in food and agricultural product processing
- Environmentally Friendly
- Improved processing efficiency
- Improved energy efficiency
- Improved product quality
- Improved food safety
New IR Book

*Infrared Heating for Food and Agricultural Processing*