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Innovative Applications of Infrared Heating for Food Processing

Zhongli Pan Ph.D.
USDA-ARS-WRRC, USA
Dept. of Biological and Agricultural Engineering, UC Davis



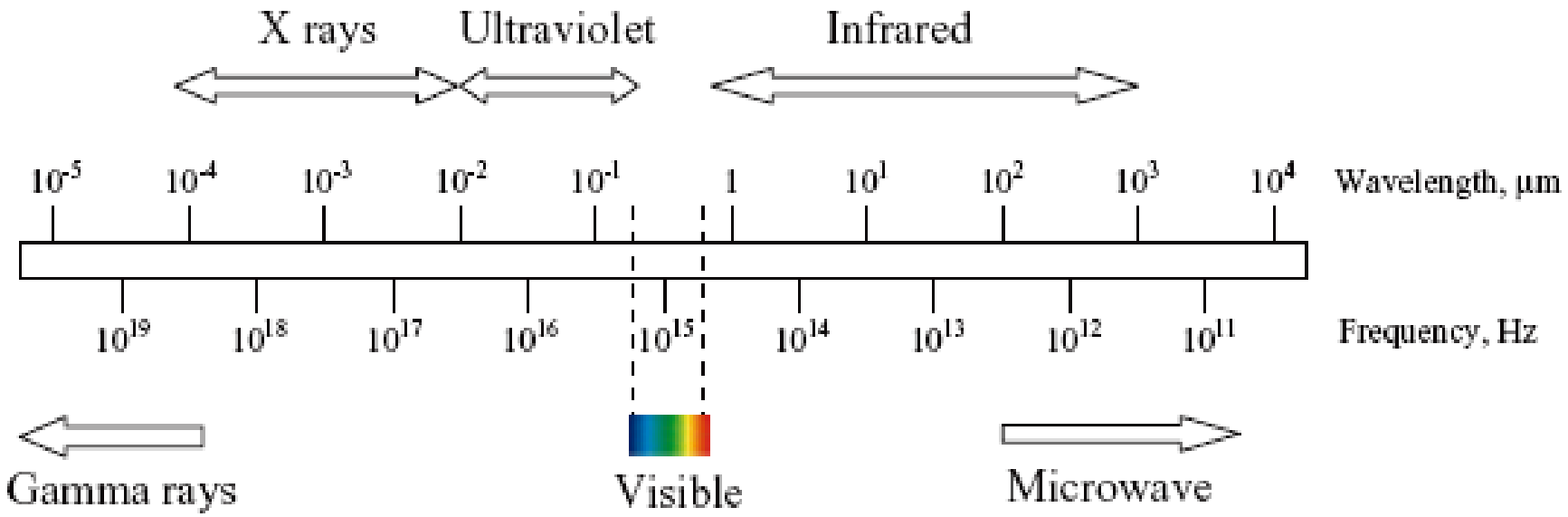


Email: zlpan@ucdavis.edu

Needs in Food and Agri Processing

- Quality and new products
- Sustainability
  - Energy
  - Water
  - Other natural resources

Infrared Radiation



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

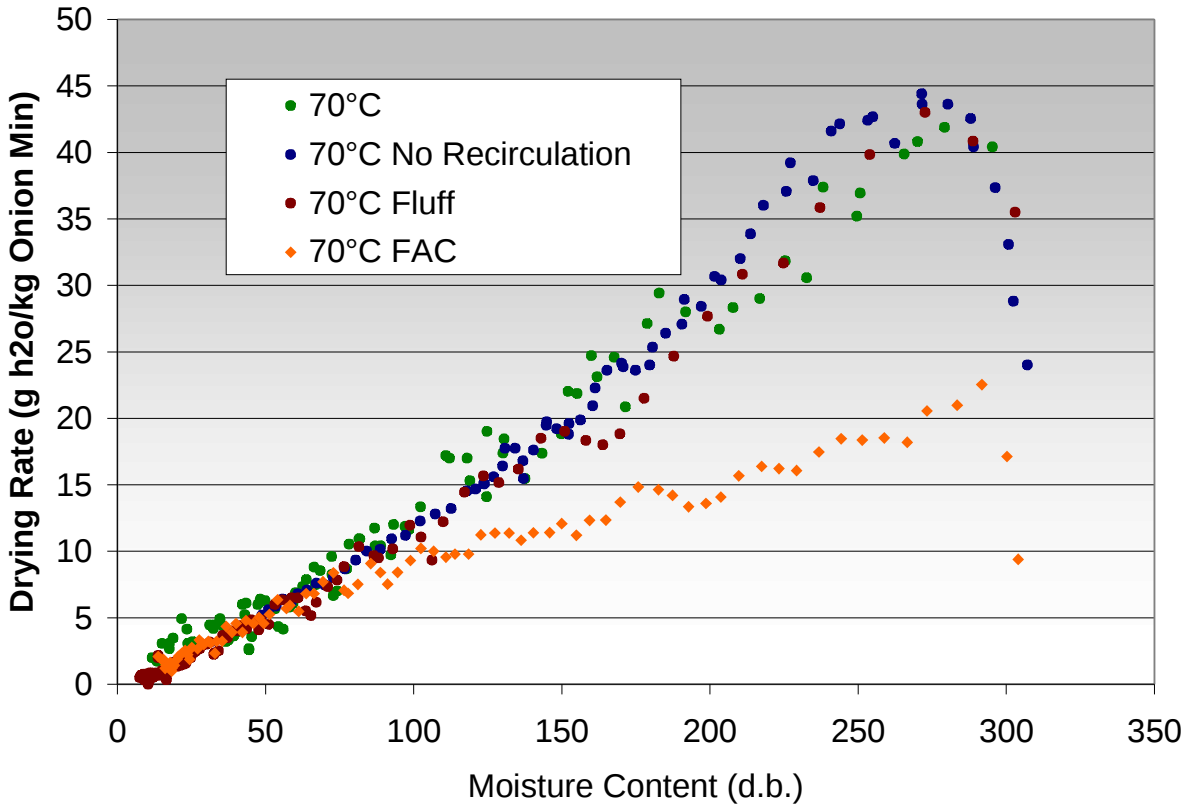


IR for Dehydration

- 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



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

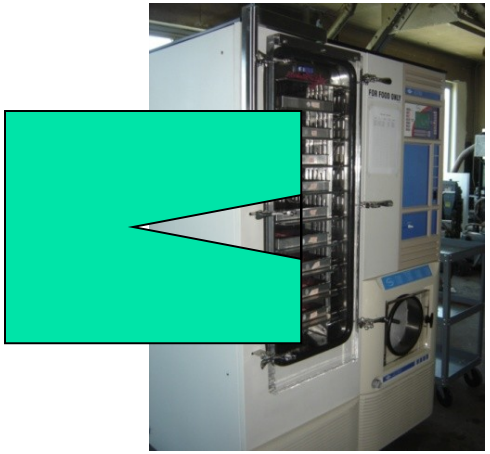


Wizard Manufacture Inc.
Emerald Farms Inc.

SIRFD for Strawberry

IR drying

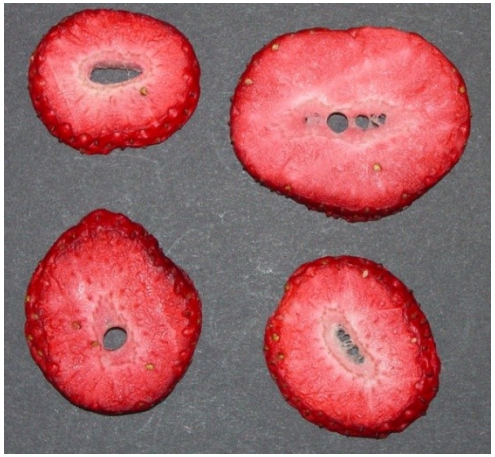




Freeze drying

Regular FD Strawberry



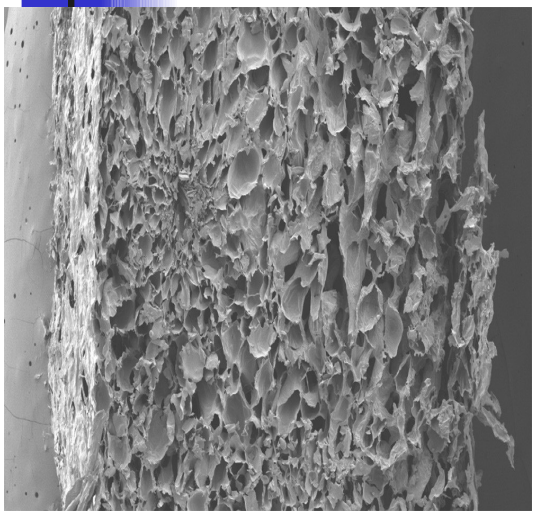


SIRFD Strawberry

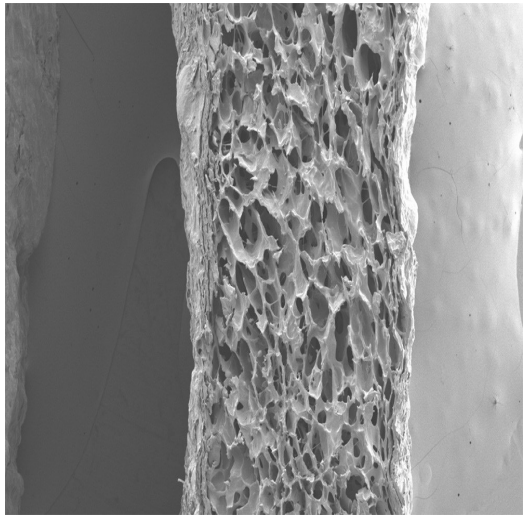
Shih, C., Z. Pan, T. H. McHugh, D. Wood, and E. Hirschberg. 2008. Sequential infrared radiation and freeze-drying method for producing crispy strawberries. Transactions of the ASABE. 51(1): 205-216.

Cross sections

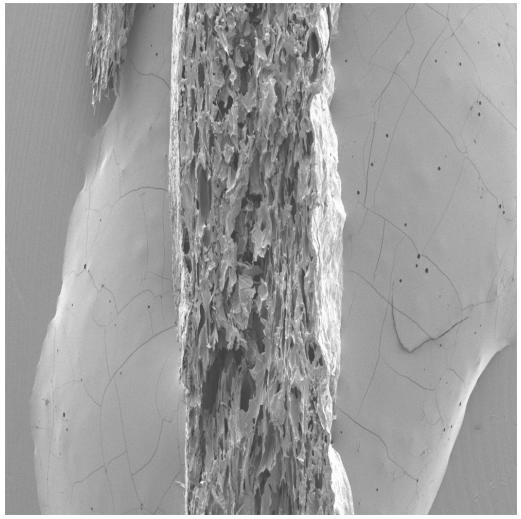
SIRFD Strawberries



- Regular FD Strawberry



- SIRFD Strawberry



- SHAFD Strawberry

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)



90.11 89.01 87.64 85.87 83.52 80.22 75.28

Moisture content (%, w.b.)



92.70% 92.41% 89.59% 86.75% 81.78% 70.84

92.70 91.42 89.59 86.75 81.78 70.84

Moisture content (%, w.b.)

(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

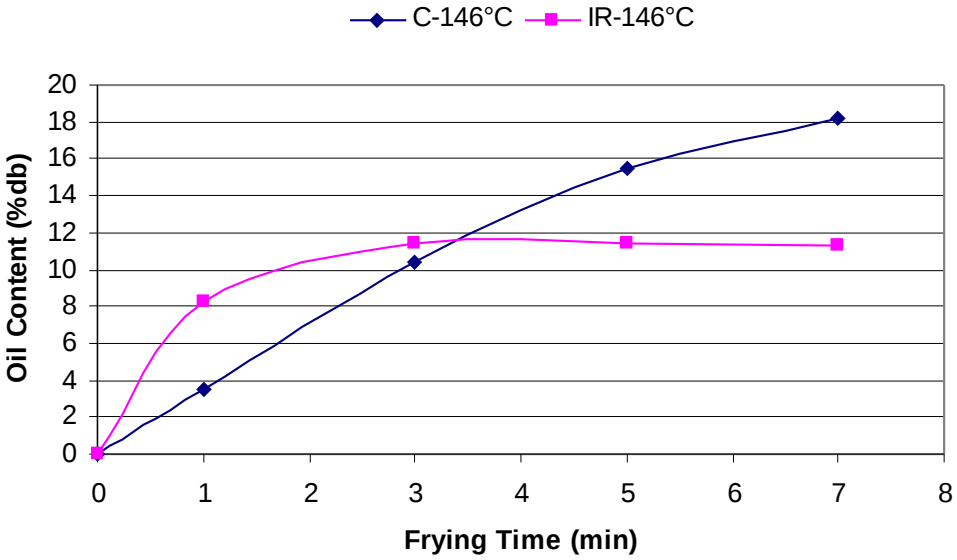


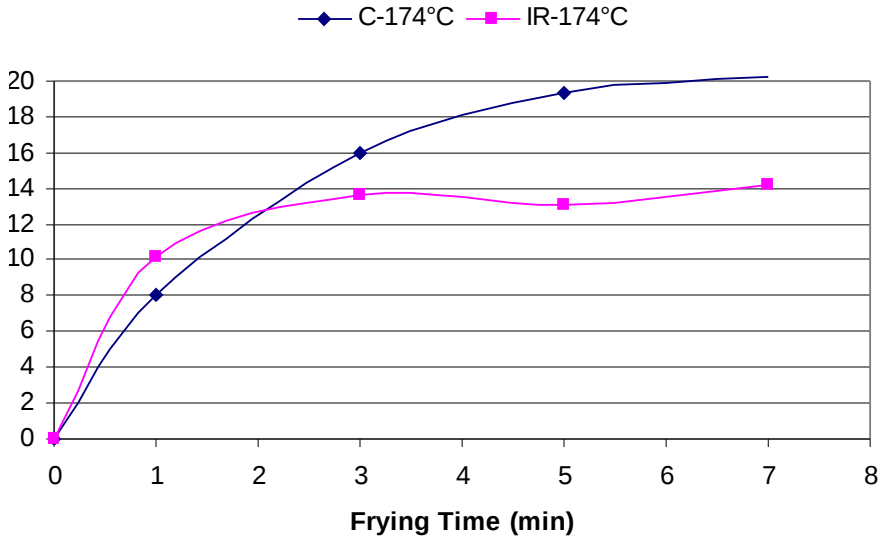
IR – 160°C, 5 min

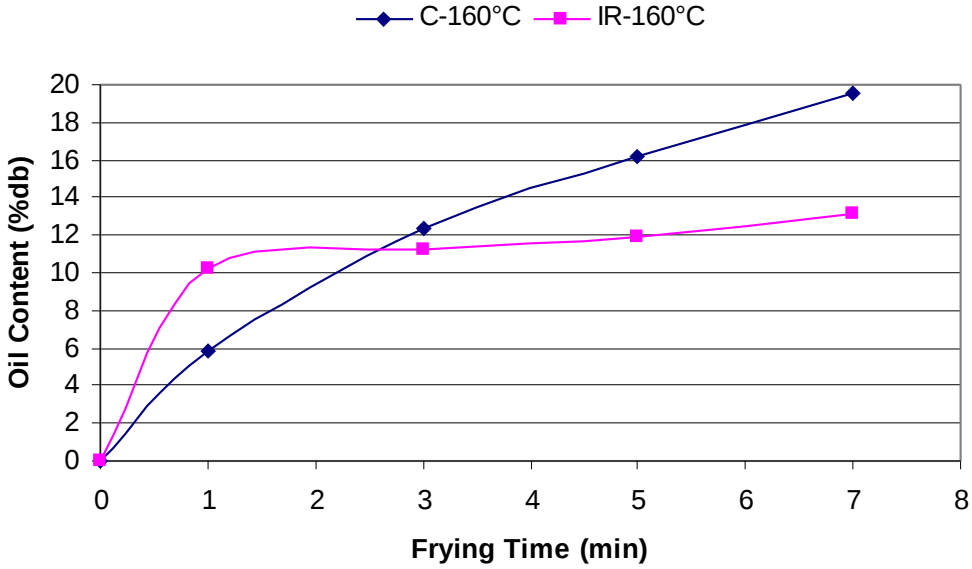


IR – 160°C, 7 min

Oil Content







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

Frying Temperature	Control (min)	IR (min)	Oil Content (IR)	Oil Content (Control)
146°C	7 min 27 s	5 min 30 s	13.93	22.77
160°C	5 min 33 s	4 min 30 s	15.30	21.74
174°C	4 min	3 min 48 s	14.23	20.79

· 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

Sensory Attribute / Frying Temperature (°C)	Taste	Texture	Color	Appearance
146	P=0.168	P=0.0003	P=0.118	P=0.017
	N/A	59.1%	N/A	N/A
160	P=0.113	P=0.0003	P=0.113	P=0.0003
	N/A	46.4%	N/A	39.3%
174	P=0.149	P=0.0020	P=0.0001	P=0.0001
	N/A	59.3%	55.6%	51.9%

Industrial IR Equipment for Demonstration





· Runs with the state-of–the-art catalytic emitters powered with natural gas.

· Weighs 4500 lbs.

· H × L × W 77”× 240” × 77”

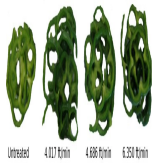
Southern California Gas Company



Dry-blanching & Dehydration Tests

Tested Commodities

Bell pepper



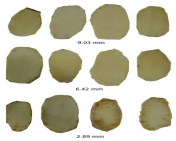
Carrot



Onion



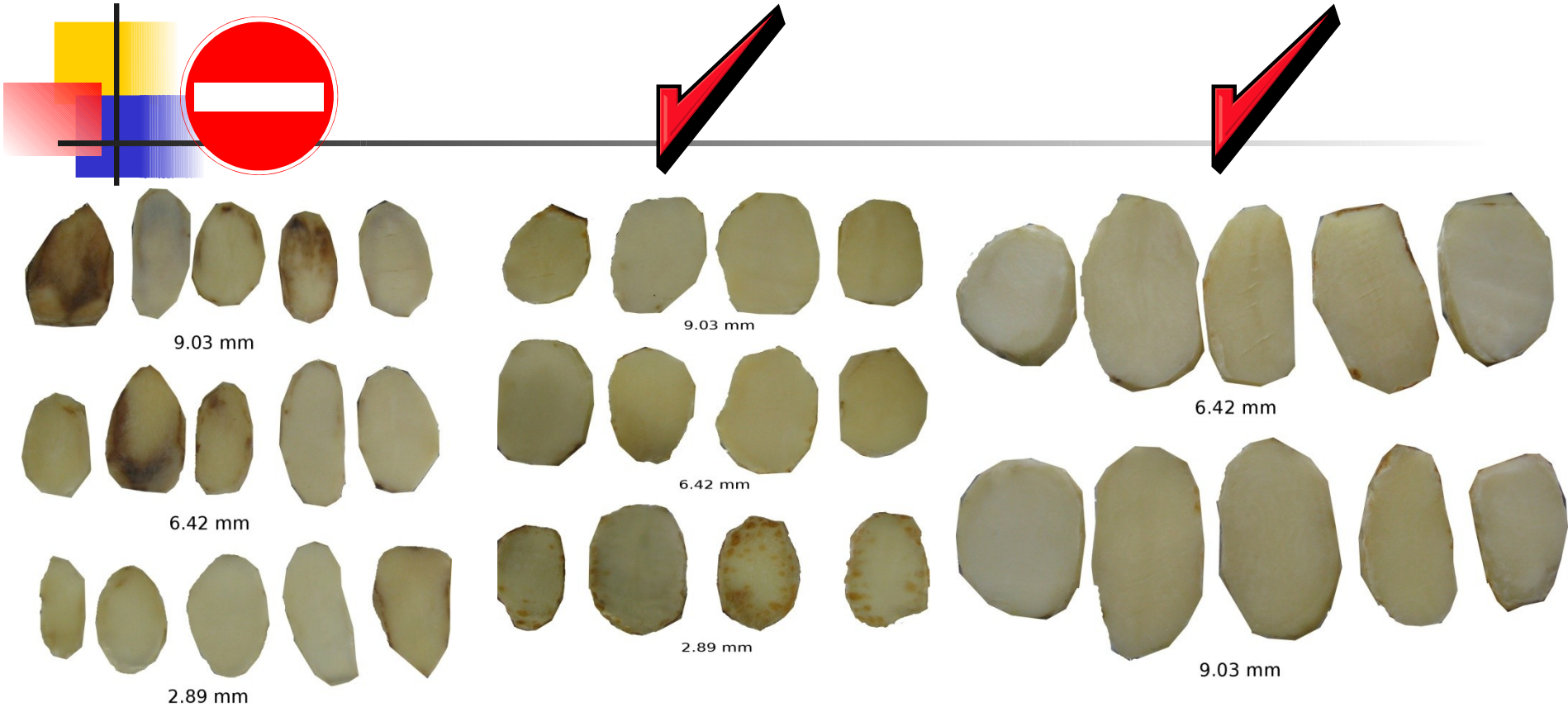
Potato



Parameters Evaluated

- Weight loss
- Temperature Profile
- Color
- Enzyme Inactivation
  - Polyphenol Oxidase
  - Peroxidase

Potatoes - Sliced



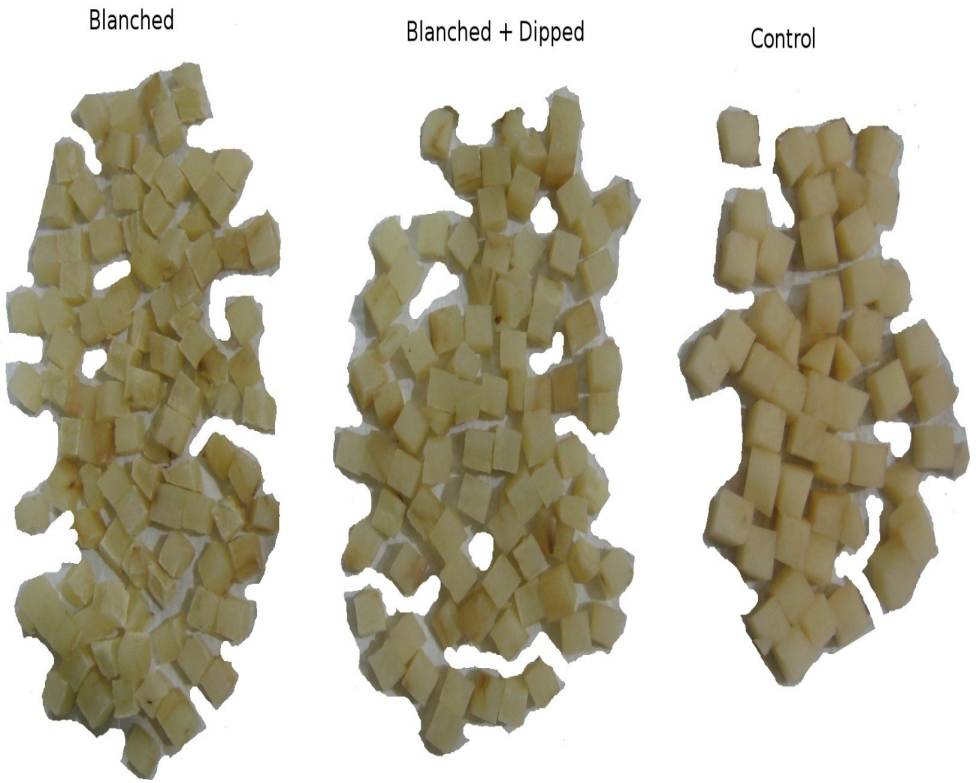
Test 2
Section 2: OFF
Speed: 1.0 m/min

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

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

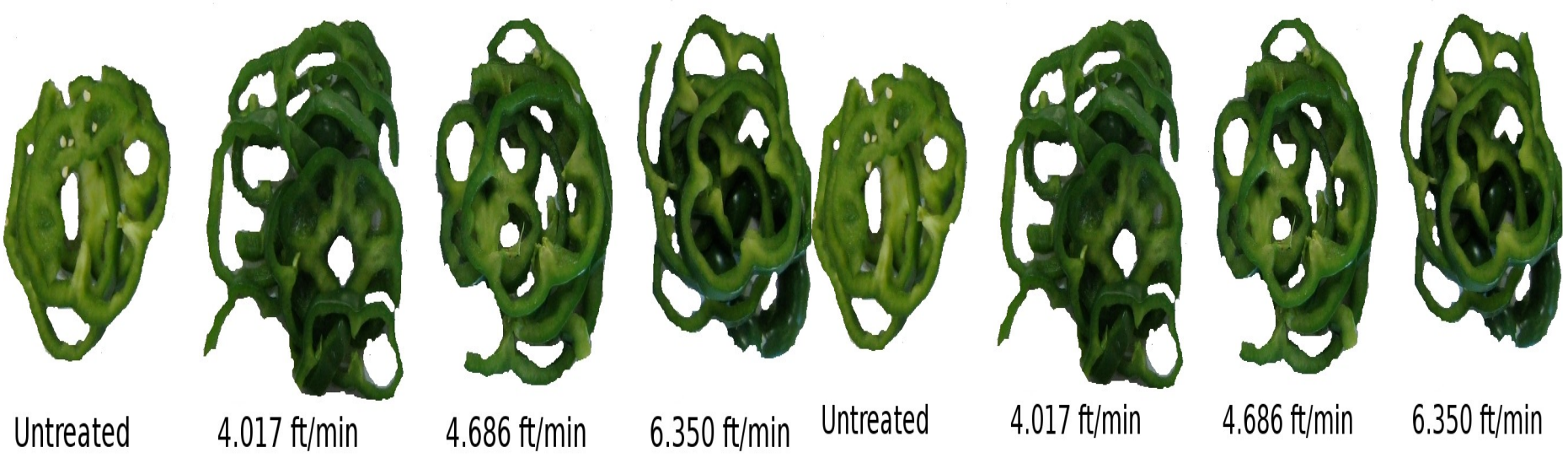
Potatoes - Diced

- 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

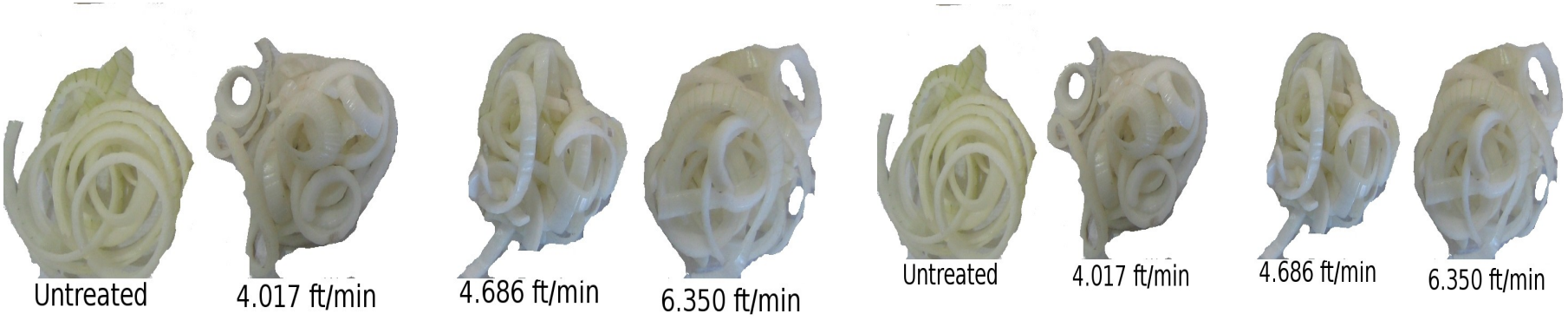
- Color of IR treated green bell peppers did not change significantly.



Untreated 1.224 m/min 1.428 m/min 1.935 m/min

White Onions

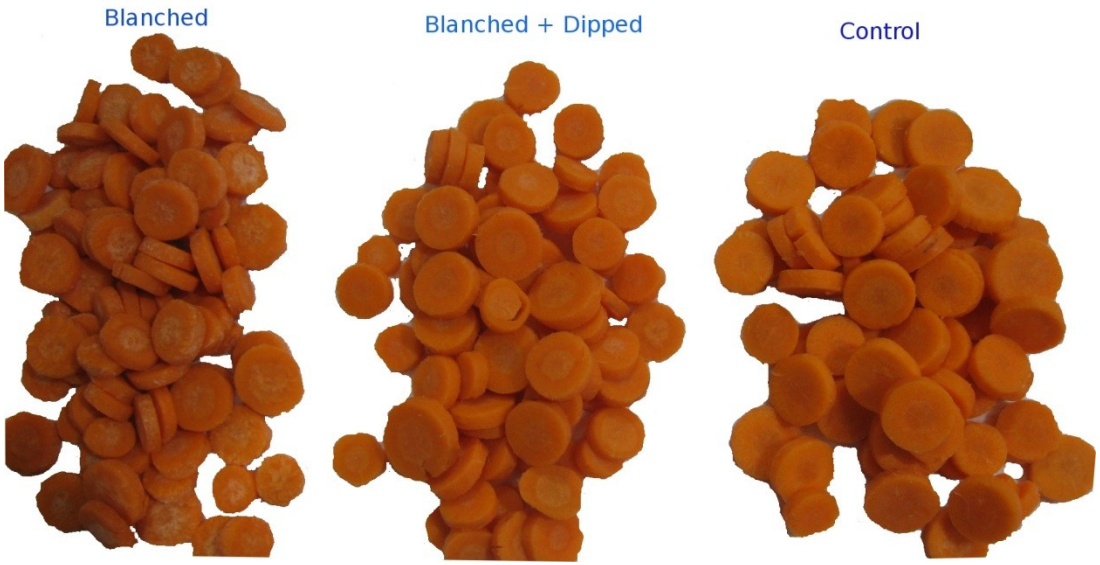
- Color of IR treated white onions did not change significantly.



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





Wet





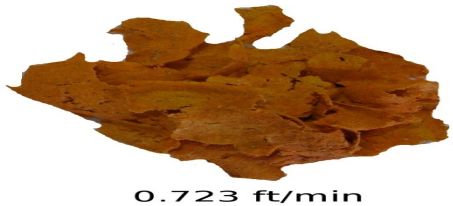
0.274 m/min





0.504 m/min





0.220 m/min

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











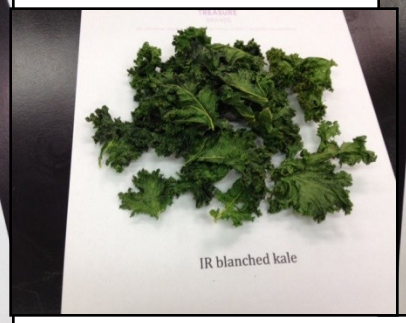
Commercial Demonstration Project

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









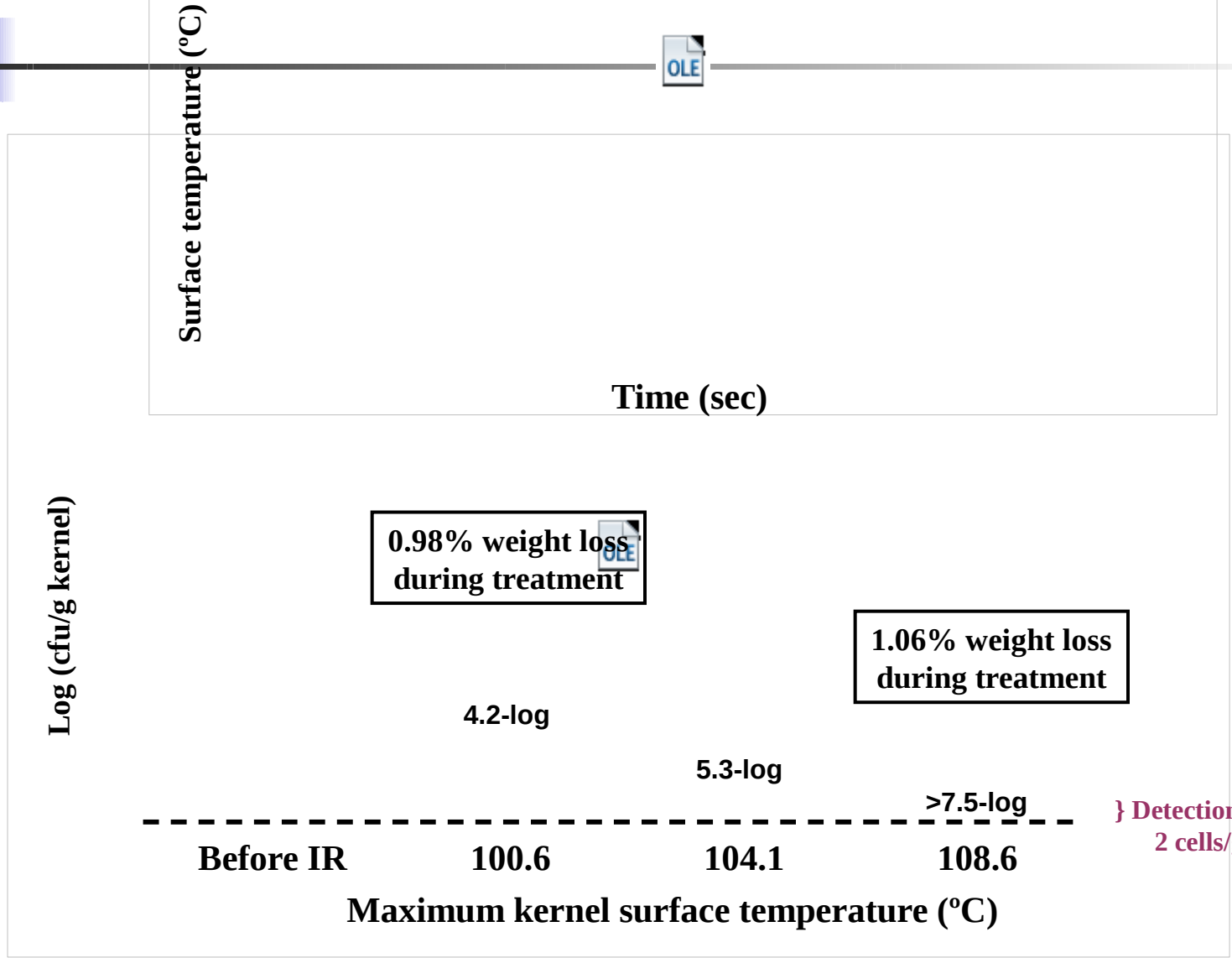


Almond Pasteurization and Roasting

- Raw almond pasteurization
  - Maintain quality characteristics
- Roast almonds and pasteurization
  - Reduce processing time
  - Meet pasteurization requirement



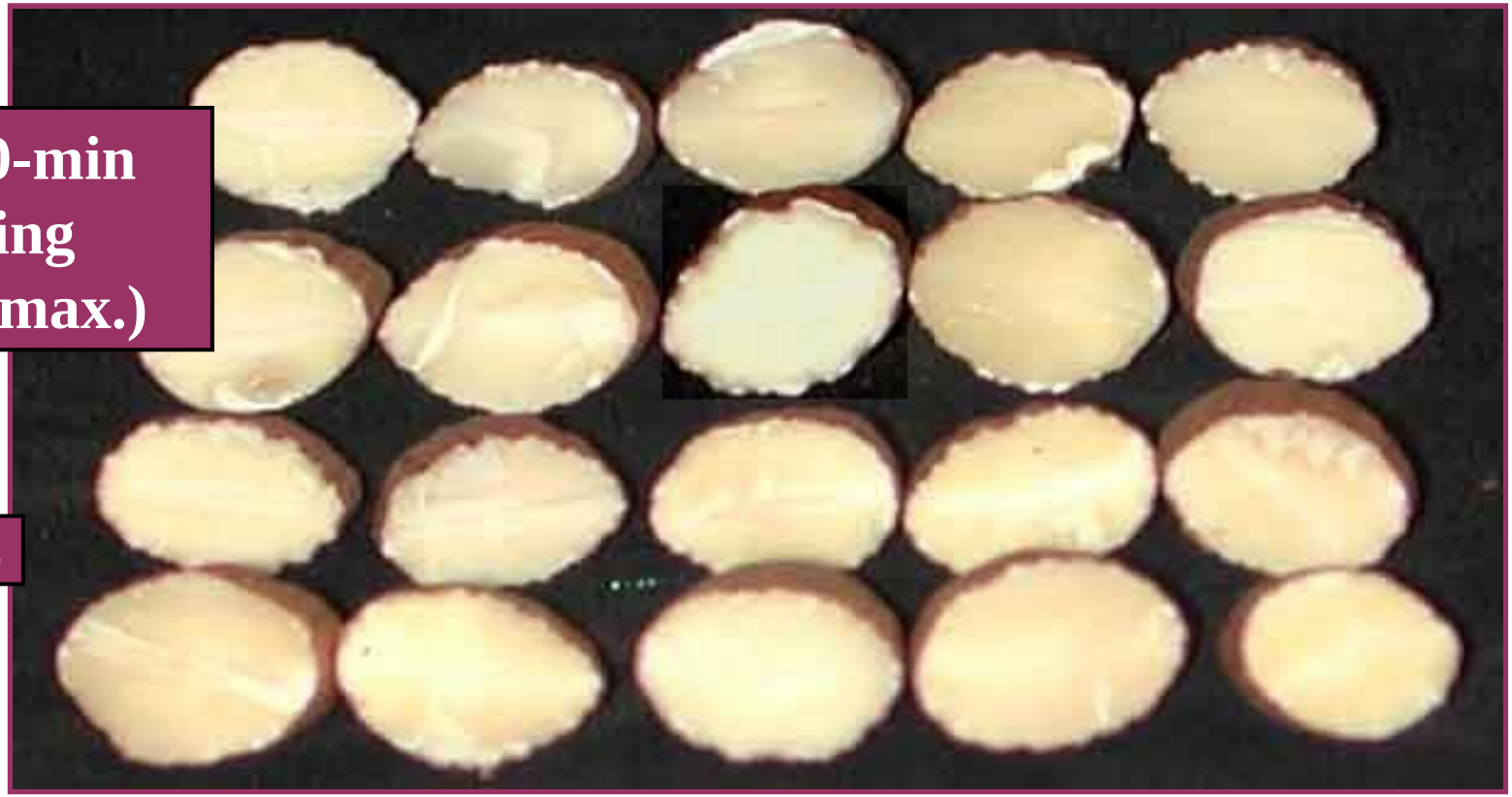
Effect of maximum kernel surface temperature on decontamination



Quality of IR-treated Raw Almonds

IR + 30-min holding (104°C max.)

CONTROL

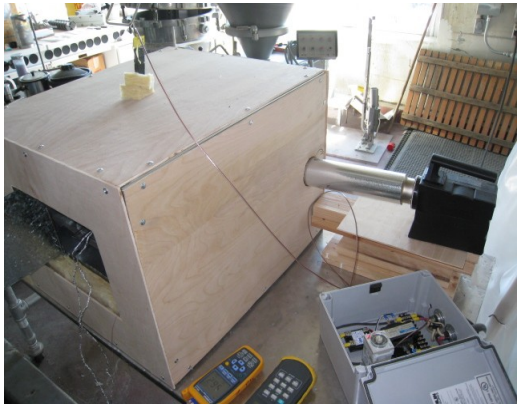


Almond Roasting





- **Roasting methods**
  - Infrared roasting (**IR**)
  - Sequential IR and hot air roasting (**SIRHA**)
  - Hot air roasting (**HA**)
- **Temperatures**
  - 130℃
  - 140℃
  - 150℃





Roasting Time Reduction



Roasting degree (ΔE)	Method	HA			SIRHA			IR		
	Temp. (°C)	130	140	150	130	140	150	130	140	150
Light (5.7)	Time (min)	22	14	9	12	5	2	6	3.5	2
	Reduction (%)	-	-	-	45	64	78	73	75	78
Medium (11.5)	Time (min)	34	18	13	21	11	5	11	6	4
	Reduction (%)	-	-	-	38	39	62	68	67	69
Dark (21.4)	Time (min)	72	30	19	52	24	12	20	14	7
	Reduction (%)	-	-	-	28	20	37	72	53	63

Reduction of Bacteria



Methods	SIRHA			HA			IR		
Temp. (°C)	150	140	130	150	140	130	150	140	130
Dark	8.55	7.41	7.45	8.48	8.21	7.87	4.53	4.35	3.56
Medium	6.96	5.82	4.10	5.39	4.62	3.58	4.12	3.21	2.94
Light	3.33	3.17	3.59	1.58	1.89	1.96	2.82	2.91	2.19

Infrared Heating for Improved Drying Efficiency, Food safety and Quality of Rice

Background – Rice Drying

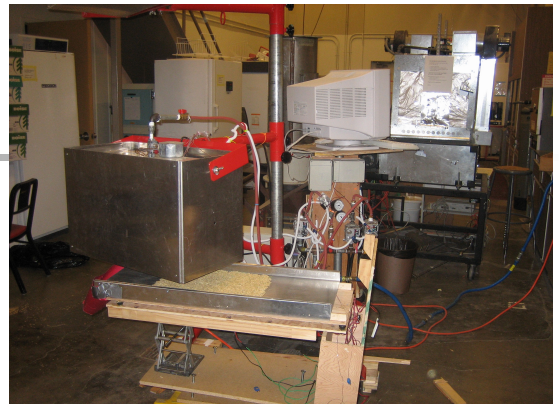
- Hot air drying
  - Air temperature at 43 ºC
  - Tempering
- Disadvantages
  - Low drying efficiency
    - 1.5% -2% moisture removal during 15-20 min
  - High energy consumption
  - Low temperature results in ineffective
    - Disinfestation
    - Disinfection

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



Infrared heating



Tempering treatment

Drying - Materials and methods

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



Yamamto Rice Mill



Yamamoto Husker

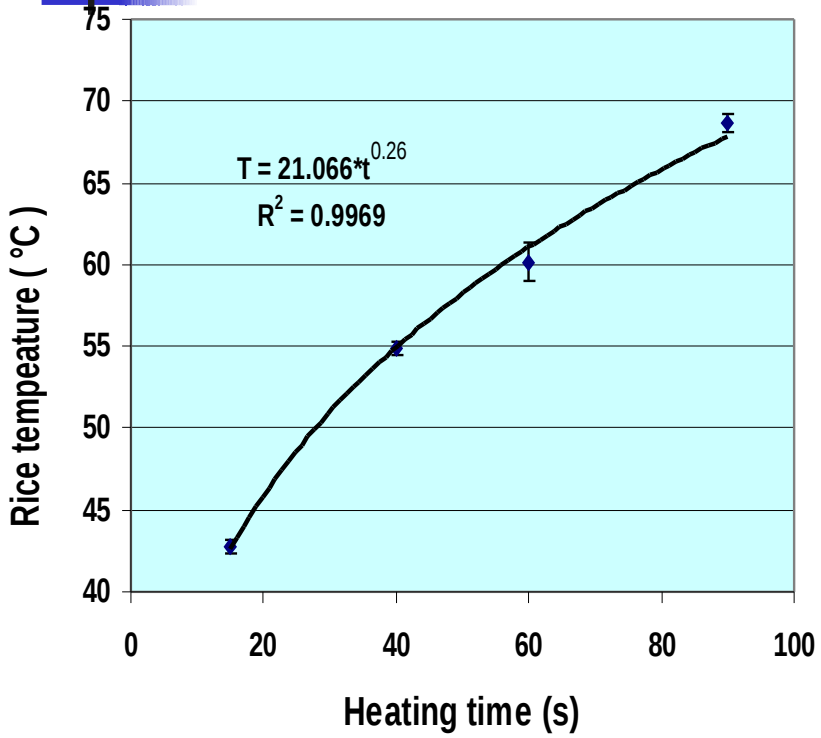


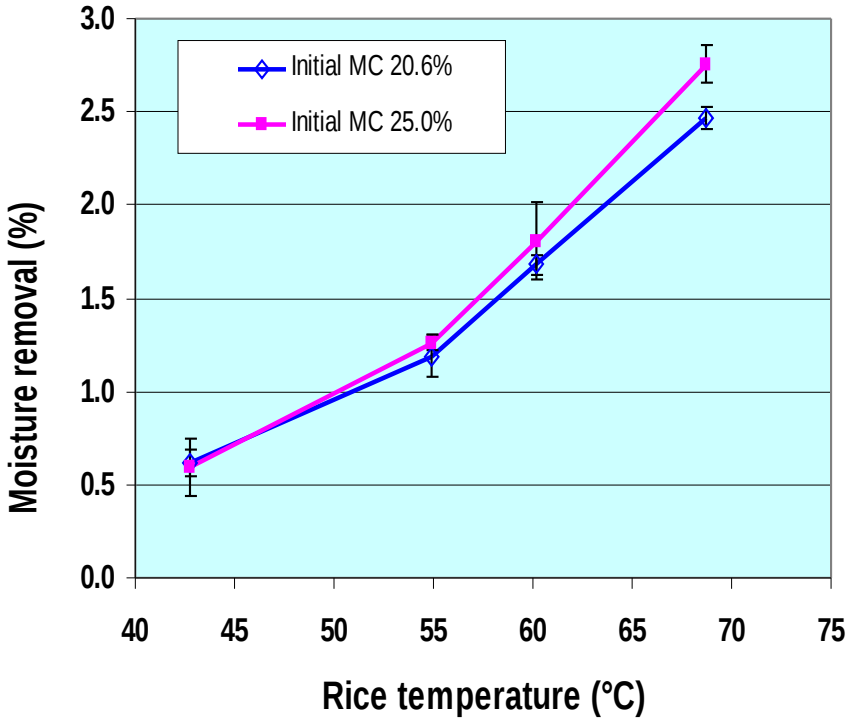
Whiteness Tester



Graincheck

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

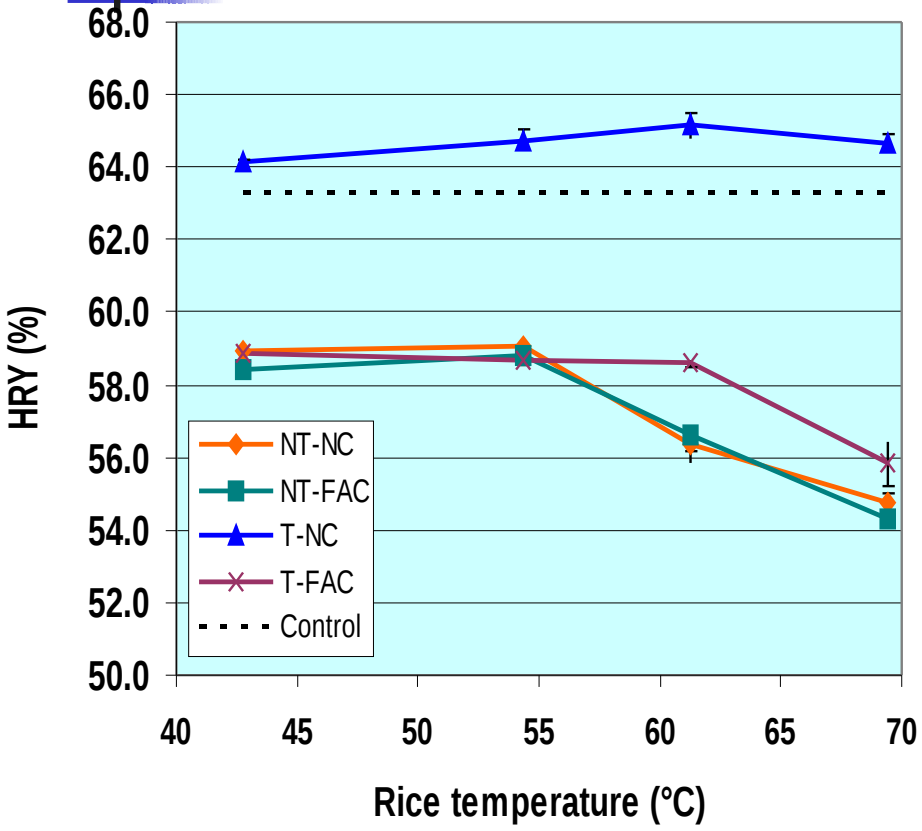




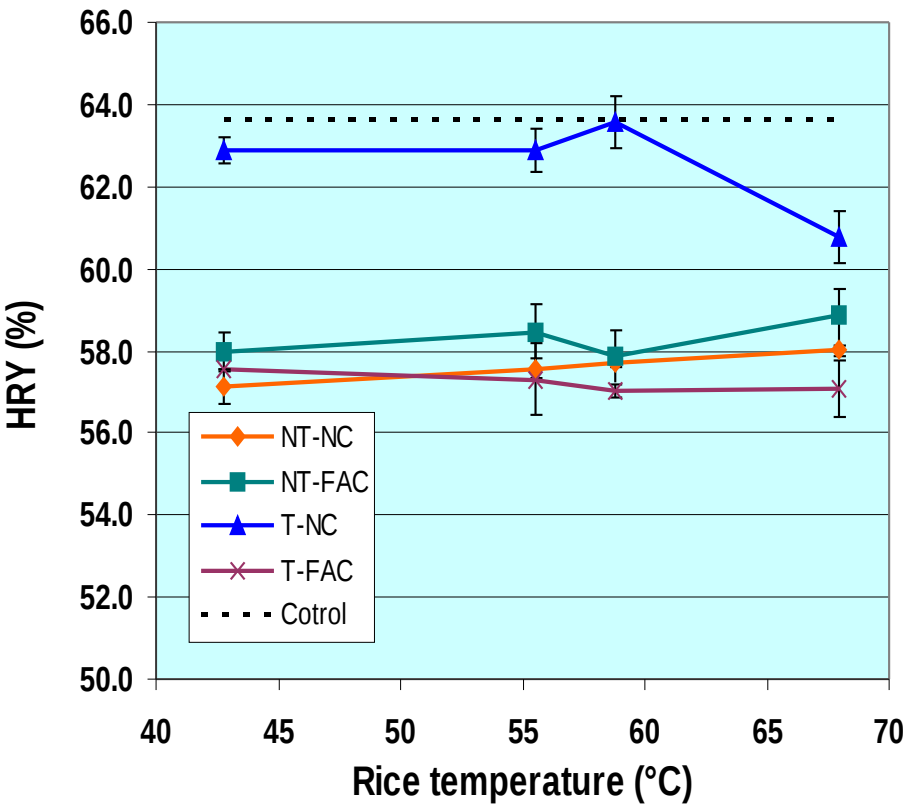
Pan et al. (2008). Journal of Food Engineering 84, 469-479.

Results - Milling quality- HRY

MC = 20.6 %

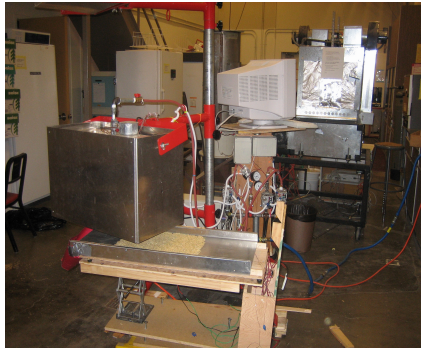


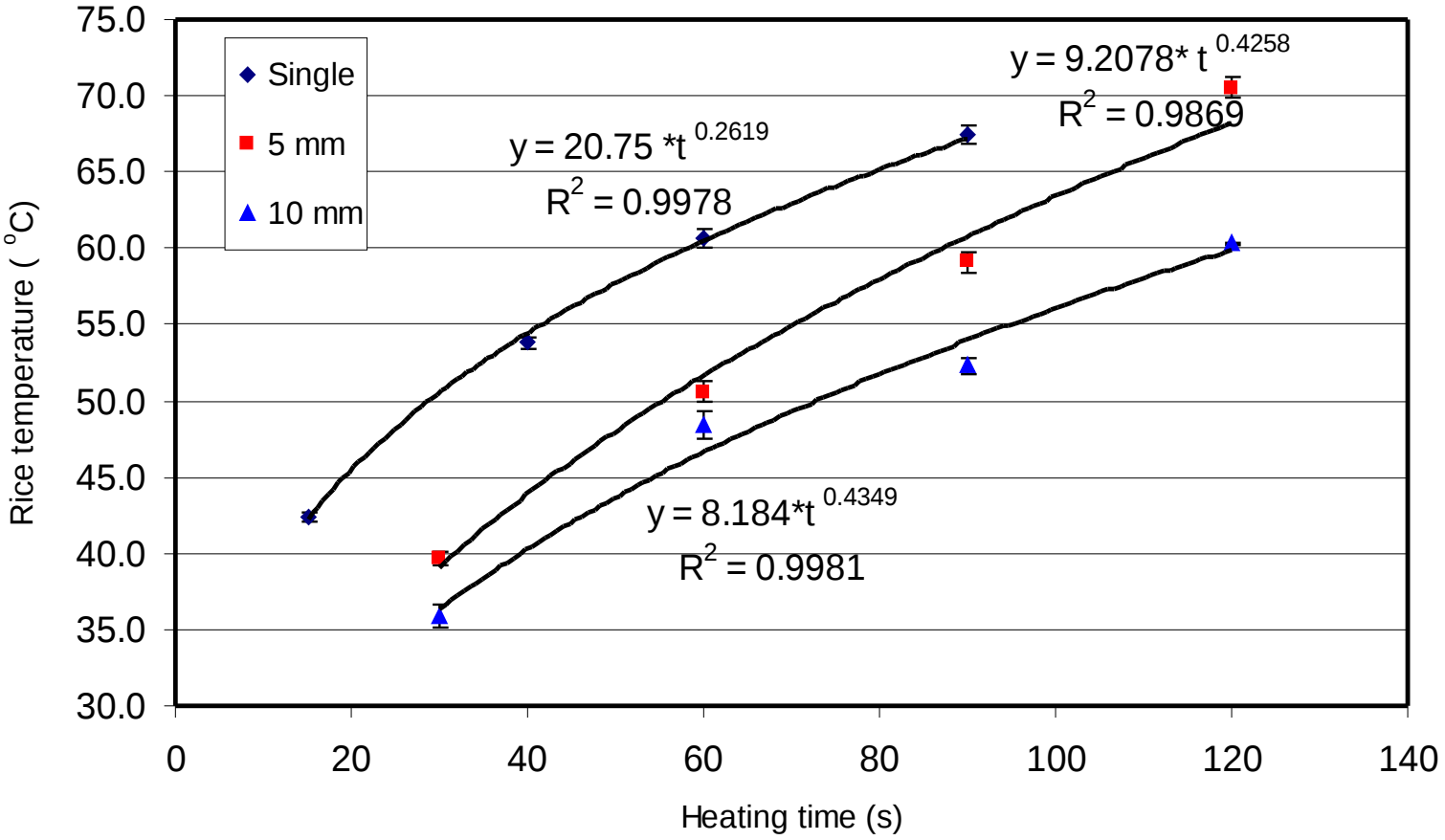
MC = 25.7 %



Pan et al. (2008). Journal of Food Engineering 84, 469-479.

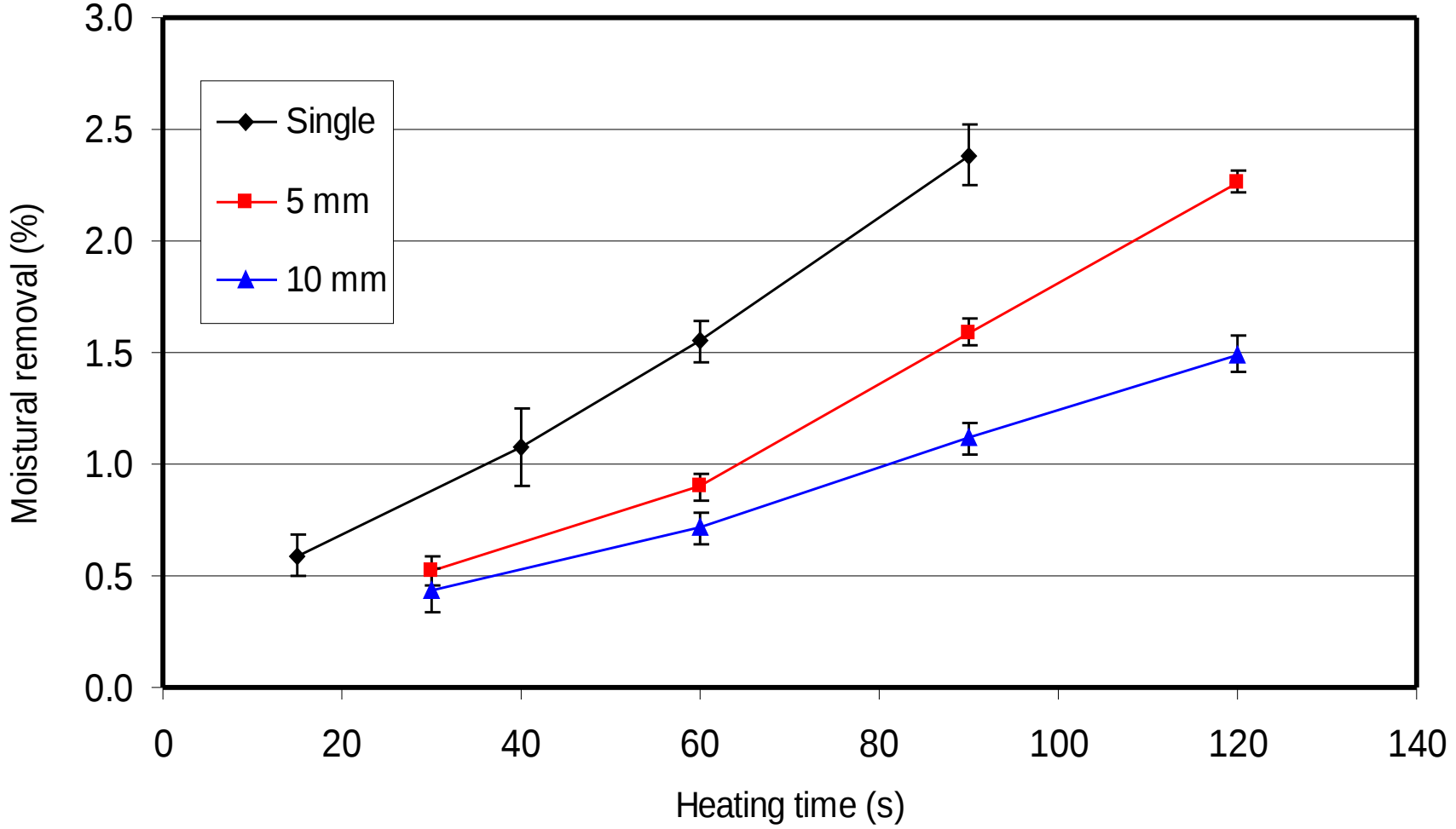
Drying - Results :
Heating rate - (IMC 23.8%)





Pan et al. (2011). Transactions of the ASABE 54, 203-210.

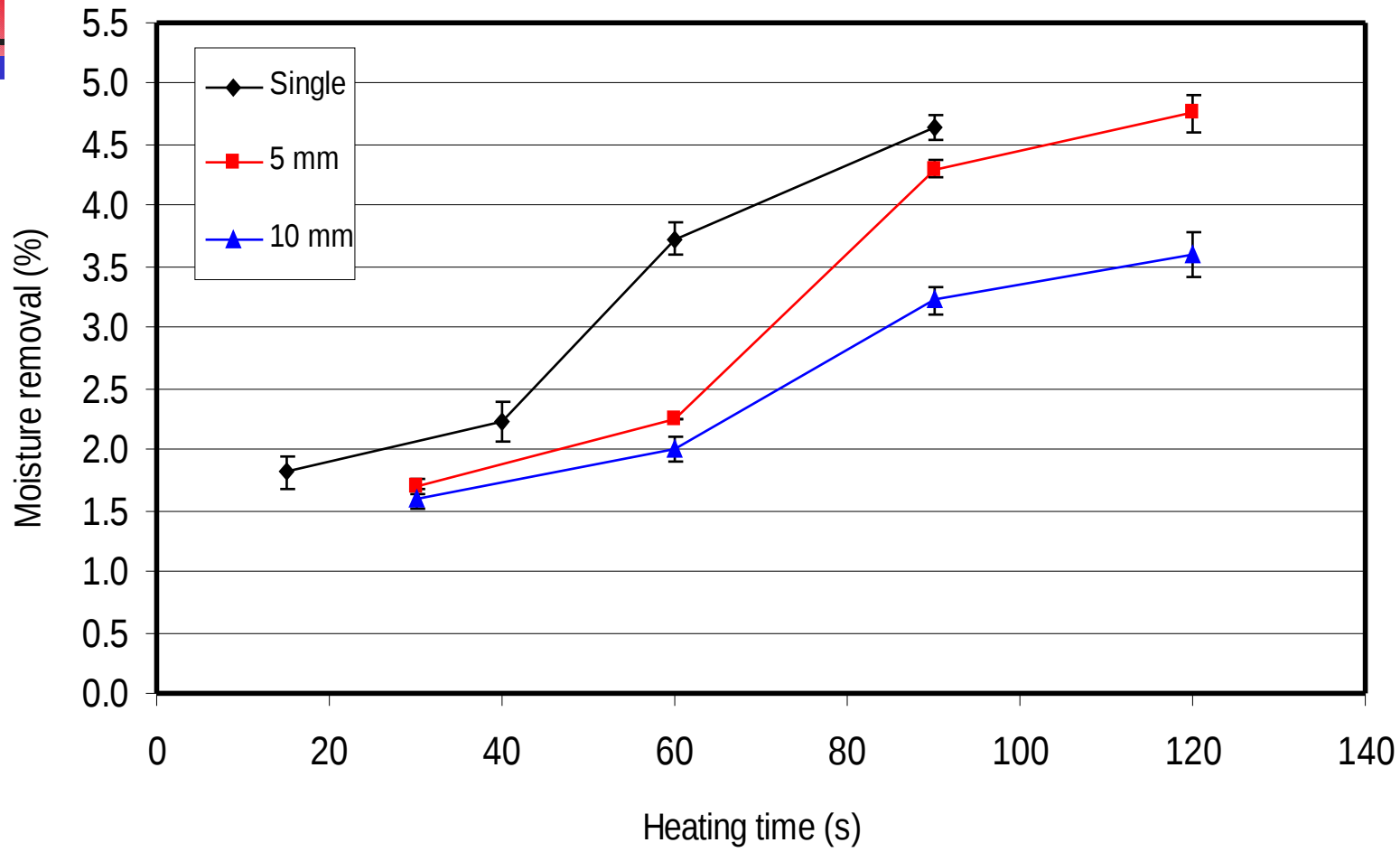
Drying - Results:
Moisture removal- IR heating only - (IMC 23.8%)



Pan et al. (2011). Transactions of the ASABE 54, 203-210.

Drying -Results

Total moisture removals - (IMC 23.8%)



Pan et al. (2011). Transactions of the ASABE 54, 203-210.

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

Heating time (s)	Rice temperature (ºC)	Total moisture removal (%)	DBT and control [a]	Milled rice quality [b] TRY	HRY	WI
			Control	68.61 a	64.11 a	41.90 a
15	42.6	2.0	Single-layer	68.39 ab	64.45 a	41.50 a
30	40.6	1.9	5 mm	68.11 bc	62.67 b	41.80 a
30	37.0	1.2	10 mm	67.78 cd	62.84 b	41.60 a
			Control	68.61 a	64.11 a	41.90 a
40	54.5	2.4	Single-layer	68.68 a	64.71 b	41.67 a
60	53.4	2.3	5 mm	68.38 a	62.91 c	41.80 a
60	46.2	1.6	10 mm	68.42 a	63.97 a	41.60 a
			Control	68.61 a	64.11 a	41.90 a
60	61.0	2.7	Single-layer	69.26 b	65.63 b	41.60 a
90	60.2	2.6	5 mm	69.49 bc	65.05 b	42.06 a
90	53.4	2.2	10 mm	68.82 ab	65.40 b	41.60 a
			Control	68.61 a	64.11 a	41.90 a
90	69.1	4.1	Single-layer	68.51 a	63.52 a	41.80 a
120	71.4	3.8	5 mm	67.91 b	62.77 b	42.00 a
120	61.2	2.5	10 mm	69.20 c	65.17 c	41.70 a

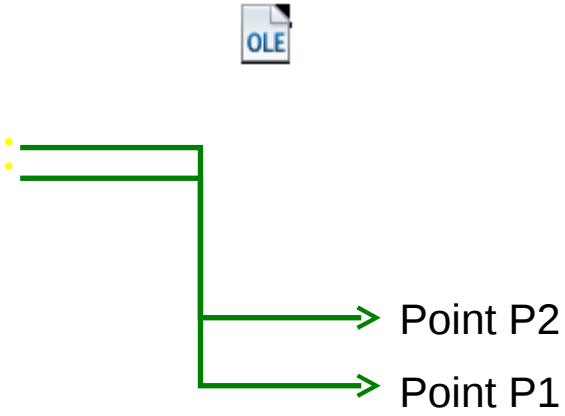
Pan et al. (2011). Transactions of the ASABE 54, 203-210.

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

Flavor Attributes	Initial MC 20%		Texture Attributes	Initial MC 20%		Initial MC 25.1%	
	Control	Treated		Control	Treated	Control	Treated
Sewer Animal	1.0 a	0.9 a	Initial Starchy Coating	2.2 a	2.2 a	2.1 a	1.9 a
Floral	0.0 a	0.0 a	Slickness	6.9 a	7.3 a	7.2 a	7.9 a
Grain/Starchy	3.4 a	3.5 a	Roughness	5.6 a	5.4 a	5.1 a	5.0 a
Hay-like Musty	0.6 a	0.5 a	Stickiness to Lips	10.2 a	9.5 b	9.0 bc	8.7 c
Popcorn	0.3 a	0.5 a	Stickiness Btwn Grains	5.6 a	5.2 a	5.8 a	5.0 a
Corn	0.8 a	1.0 a	Springiness	4.0 a	4.0 a	4.3 a	4.0 a
Alfalfa	0.0 a	0.3 a	Hardness	5.3 a	5.4 a	5.6 a	5.9 a
Dairy	0.9 a	0.5 a	Cohesiveness	5.8 a	5.7 a	5.7 a	6.0 a
Sweet Aromatic	0.4 a	0.4 a	Uniformity of Bite	6.9 a	7.5 a	7.3 a	7.2 a
Water-like Metallic	0.8 a	1.1 a	Cohesiveness of Mass	5.8 a	6.0 ac	6.8 b	6.3 c
Sweet Taste	1.3 a	1.2 a	Moisture Absorption	5.3 b	5.2 b	5.4 ab	5.2 b
Sour	0.3 a	0.3 a	Residuals	4.7 a	4.8 a	4.7 a	4.8 a
Astringent	1.0 a	1.2 a	Tooth Pack	4.1 a	4.0 a	4.0 a	4.0 a

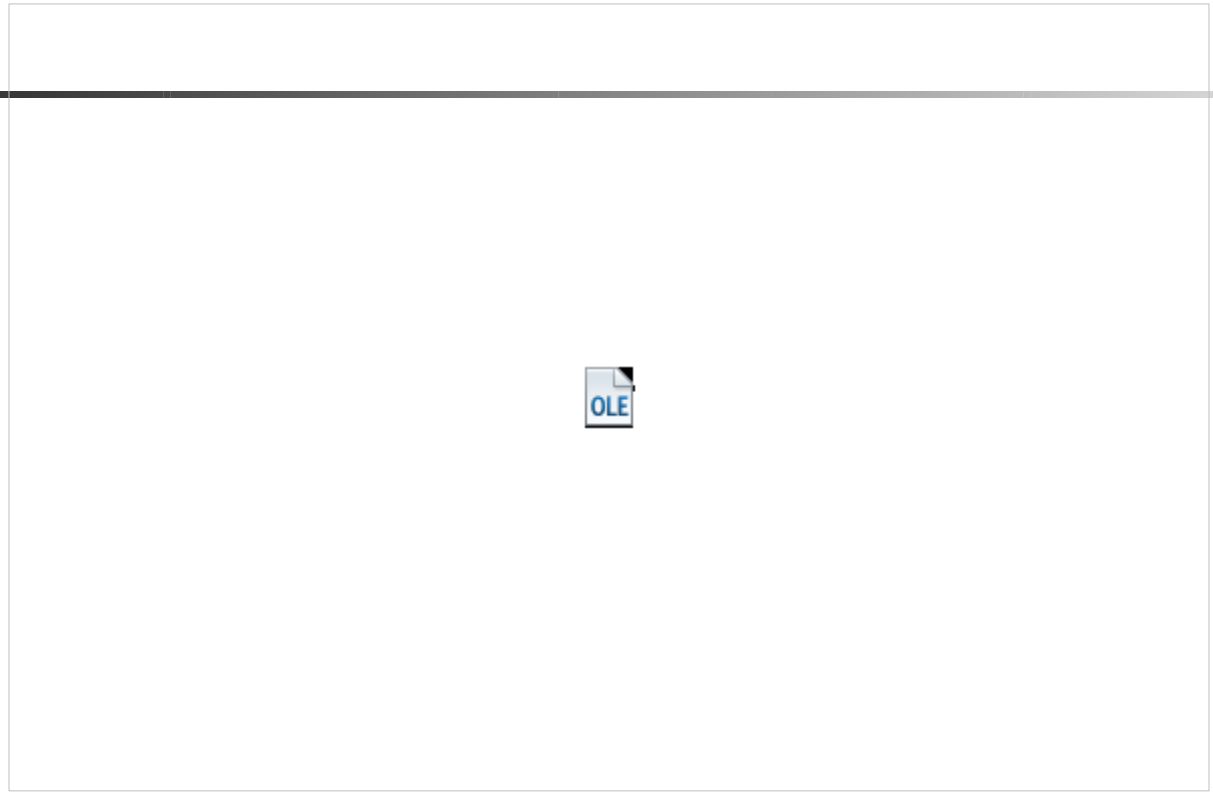
Pan et al. (2011). Transactions of the ASABE 54, 203-210.

Infrared drying: Moisture gradients



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

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)



Infested samples with adult insects

- Effectiveness of disinfestation treatment
  - Incubator was set at 28ºC and 64 % RH
  - Surviving and emerged live adults insects were visually counted during 35 days after treatment



Samples kept at relevant conditions for insect growing

Disinfestation – Results: Numbers of live moths in the rice samples

Harvest MC (%)	Heating time (s)	Rice temperature (°C)		Days of storage after treatment						
			Tempering	1[b]	5	8	15	27	32	34
20.6%	90	69.4	Yes	0	0	0	0	0	0	0
	90	69.4	No	0	0	0	0	0	0	0
	60	61.3	Yes	0	0	0	0	0	0	0
	60	61.3	No	0	0	0	0	0	0	0
	40	54.3	Yes	0	0	0	0	0	8	2.5
	40	54.3	No	0.5	0	0	0	0	0	0
	15	49.0	Yes	0	0	0	0	0.5	17.5	3.5
	15	49.0	No	0	0	0	0	0	0.5	0
25.7%	90	68.0	Yes	0	0	0	0	0	0	0
	90	68.0	No	0	0	0	0	0	0	0
	60	59.1	Yes	0	0	0	0	0	0	0
	60	59.1	No	0	0	0	0	0	0	0
	40	55.5	Yes	0.5	0.5	0	0	0	0	0
	40	55.5	No	0	0	0	0	0	0	0
	25	49.0	Yes	1	1	0	0	0	0	0
	25	49.0	No	0	0	0	0	0	0	0

Pan et al. (2008). Journal of Food Engineering 84, 469-479.

Disinfestation – Results: Numbers of live beetles in the rice samples

Harvest MC (%)	Heating time (s)	Rice temperature (°C)	Tempering	Days of storage after treatment						
				1[b]	5	8	15	27	32	34
20.6%	90	69.4	Yes	0	0	0.5	0	0.5	0	0
	90	69.4	No	0	1	0	0	0	0	0
	60	61.3	Yes	0	0	0	0	0	0	0
	60	61.3	No	0	0.5	0	0	0	0	0
	40	54.3	Yes	26	51	1	1	0	0.5	0
	40	54.3	No	0.5	0	0	0	0	0	0
	25	49.0	Yes	45.5	54.5	3.5	1.5	0.5	0	0
	25	49.0	No	50.0	44.5	2	0.5	0.5	0	0
25.7%	90	68.0	Yes	0	0	0	0	0	0	0
	90	68.0	No	0	0	0	0	0	0	0
	60	59.1	Yes	0	0	0	0	0	0	0
	60	59.1	No	2	4.5	0.5	0	0	0	0
	40	55.5	Yes	26	51	1	1.5	0	0.5	0
	40	55.5	No	0	0	0	0	0	0	0
	25	49.0	Yes	58.5	67.5	2.5	1.5	2	0	0
	25	49.0	No	29.5	48.5	0.5	1	1	0	1

Pan et al. (2008). Journal of Food Engineering 84, 469-479.

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)



IR heating

One pass

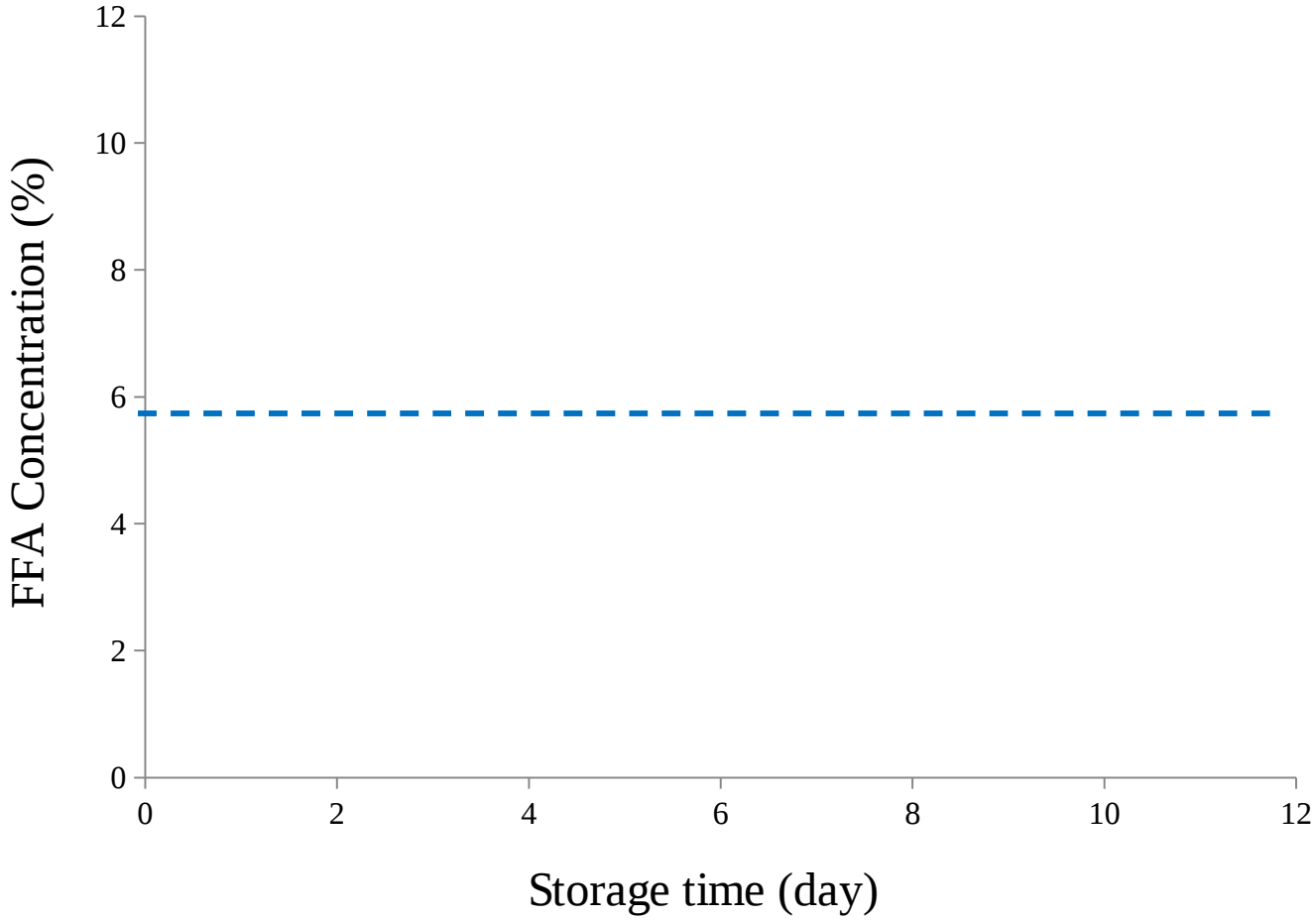
Two pass



Tempering

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)

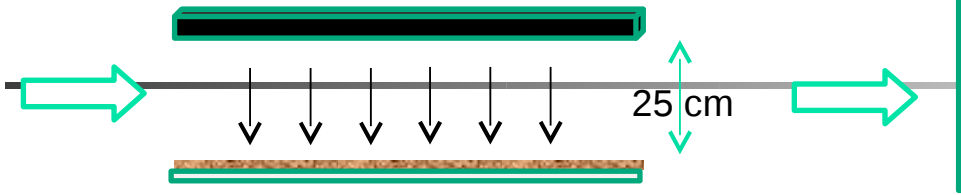
Surface rewetted storage rice: MC=15%-19% (wb)

To simulate different rice source

Disinfection - Materials and methods



25 g inoculated rice



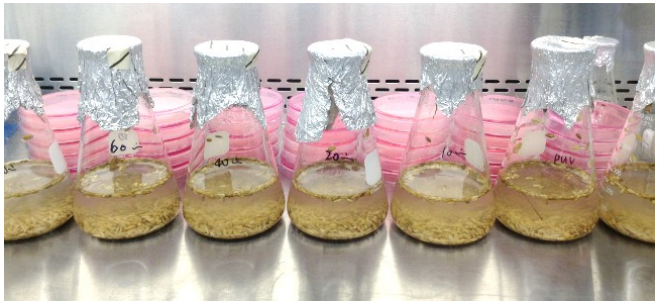
IR 35-38 s to 60°C



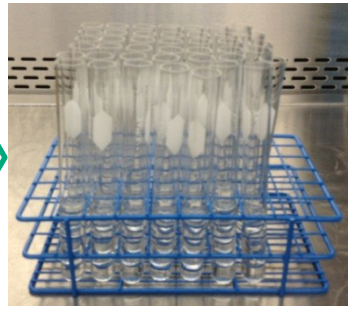
Tempering in oven at 60 °C



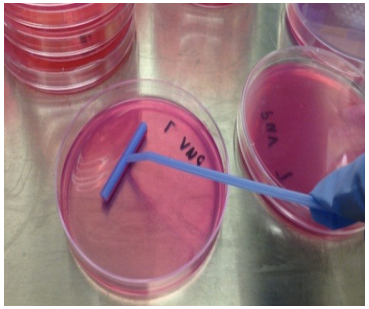
Cooling



25 g rice + 225 mL water

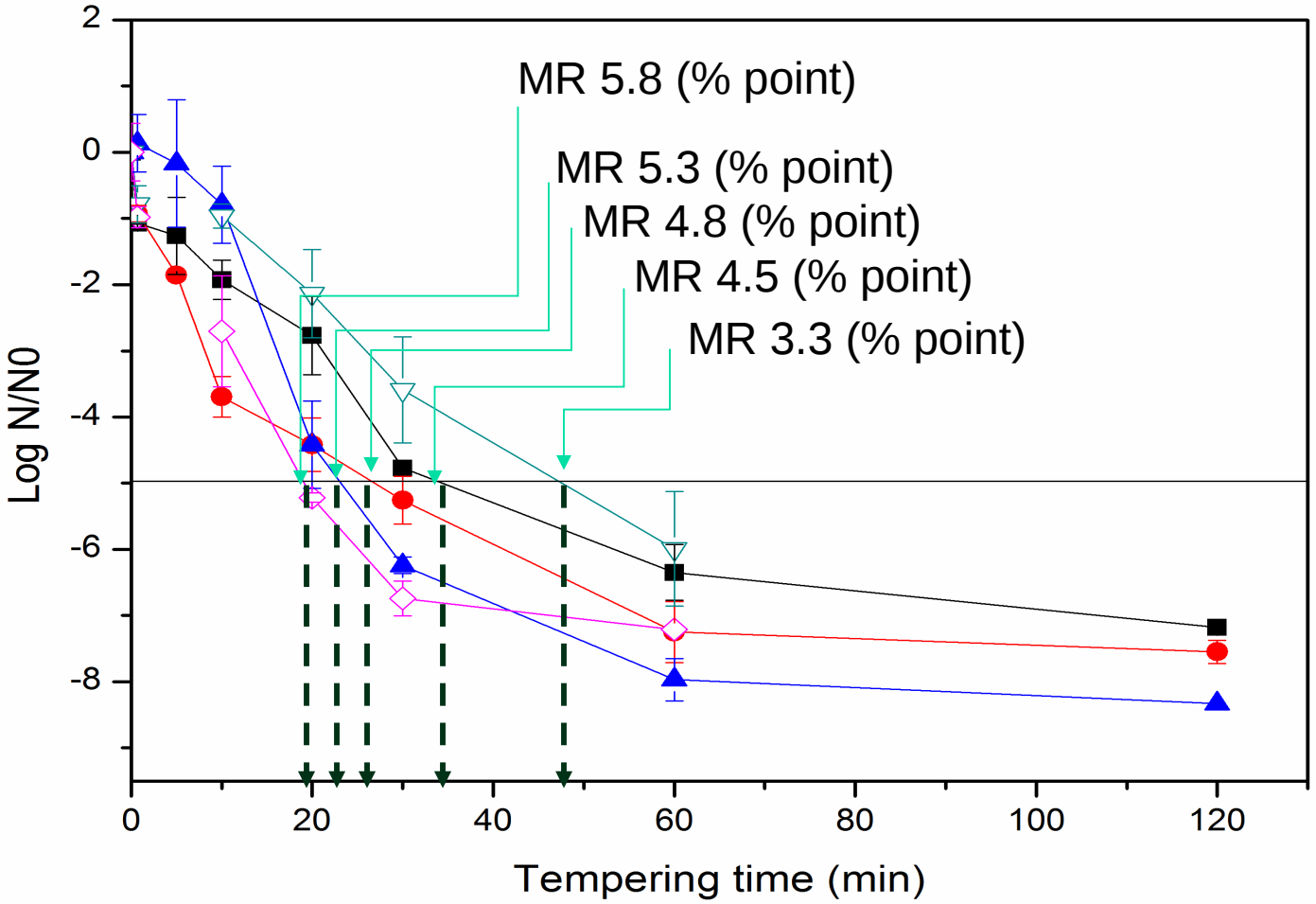


Series dilution



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



■ fresh rice MC=21.1%; ● fresh rice MC=25.0%; ▲ fresh rice MC=27.0%;
▽ surface rewetted rice MC=16.4%; ◇ surface rewetted rice MC=19.4%.
MR = Moisture removal

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



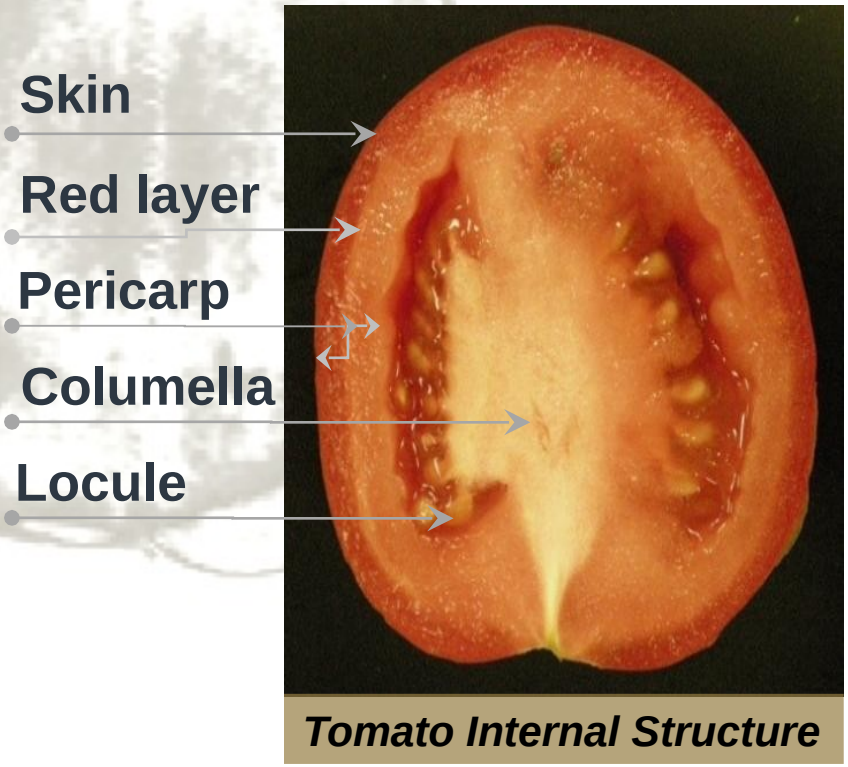
California is the largest processing tomato producer in the U.S.

Graph from *http://www.heinzketchup.com/*

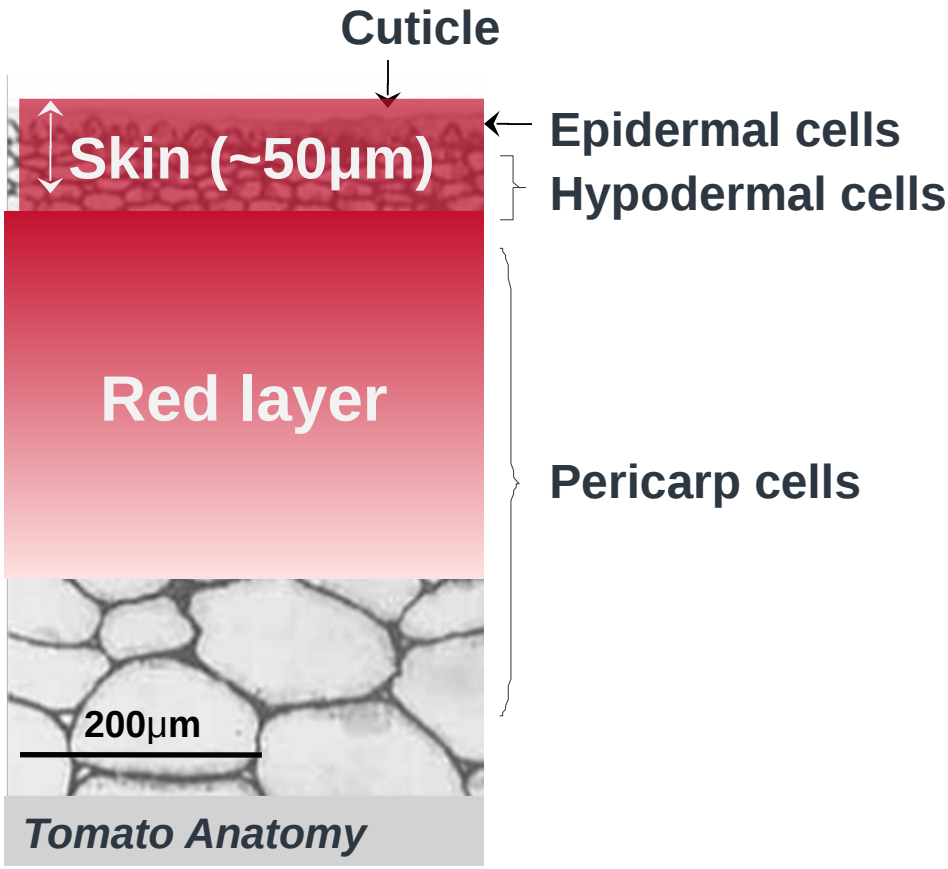




Tomato Anatomy



Tomato Internal Structure



Tomato Anatomy

Tomato Peeling Process

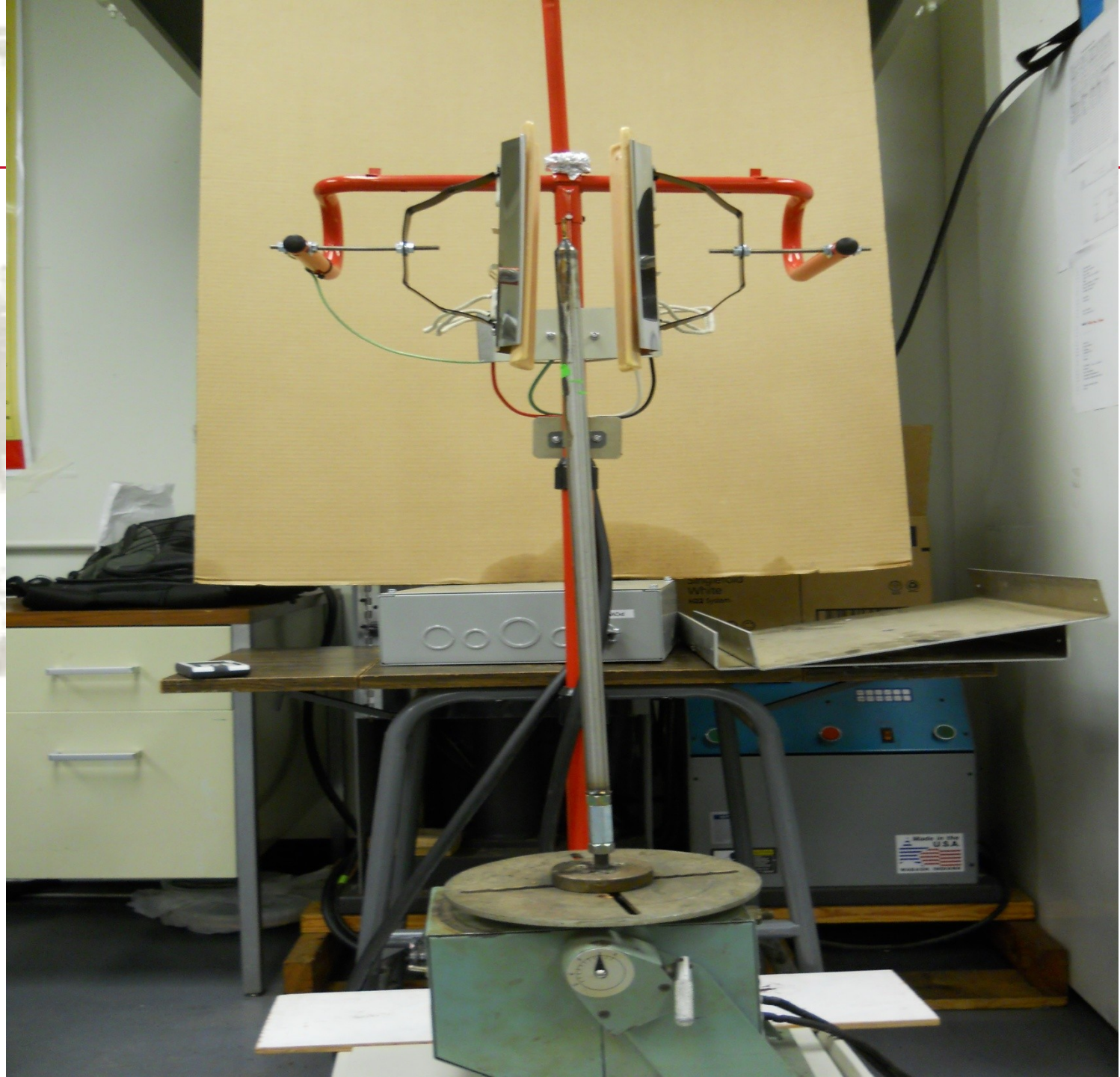
- Commercial peeling methods
  - Hot lye peeling
    - 8%~25% NaOH/KOH
    - 80°C~100°C
    - 30~75 seconds
  - Steam peeling
    - 120°C~215°C
    - 120~480 kPa

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

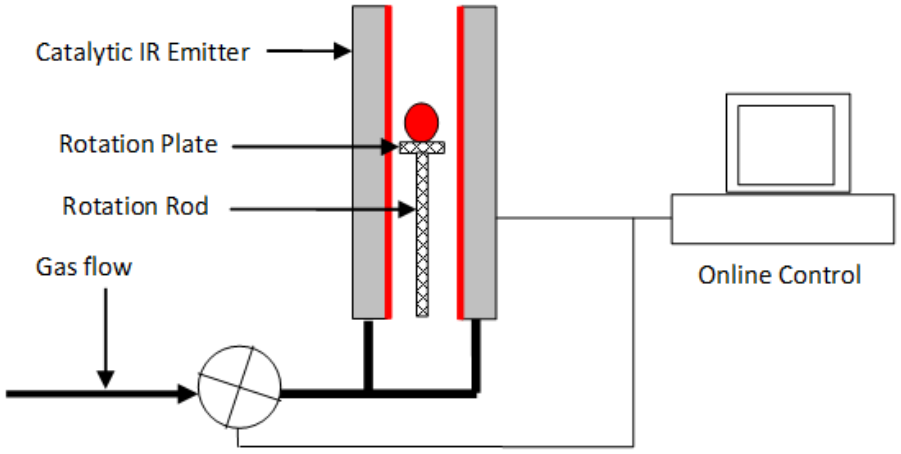




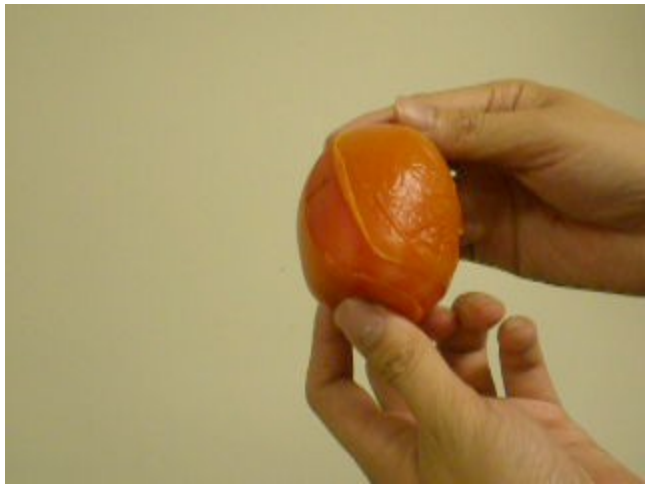
Developing Sustainable Non-Chemical Peeling Method



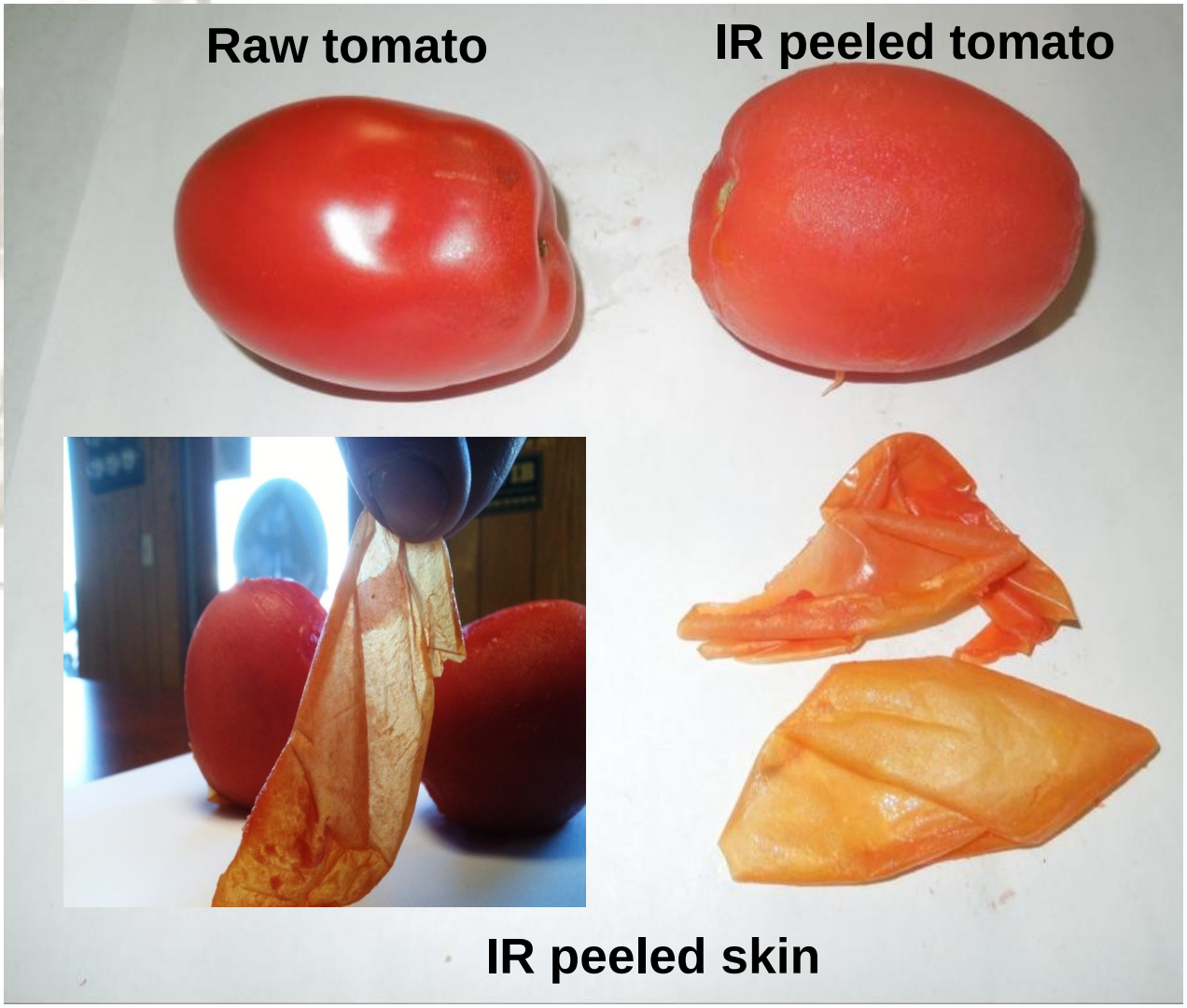
IR Experimental Setup



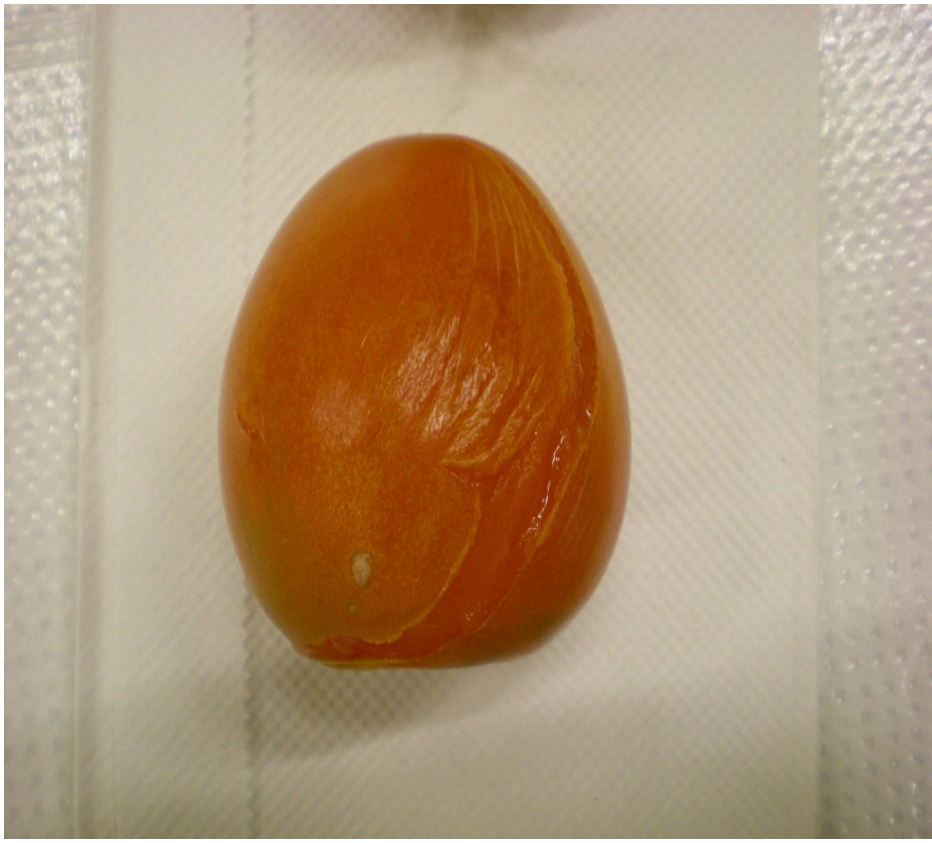




IR Peeled Tomatoes







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

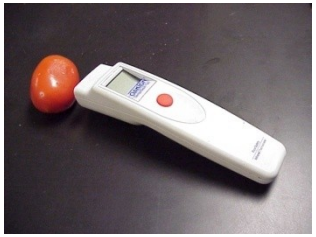
- Color
- Firmness
- Final surface temperature



Color Measurement



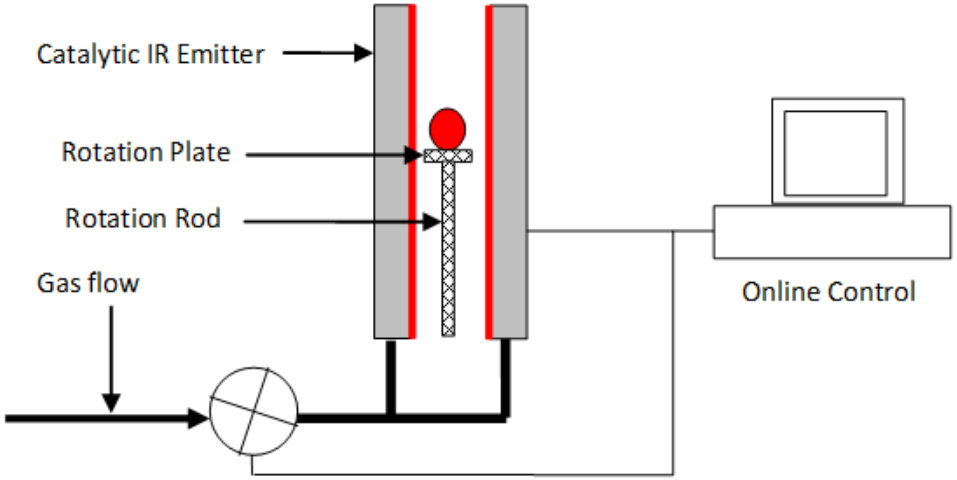
Fruit Texture Analyzer

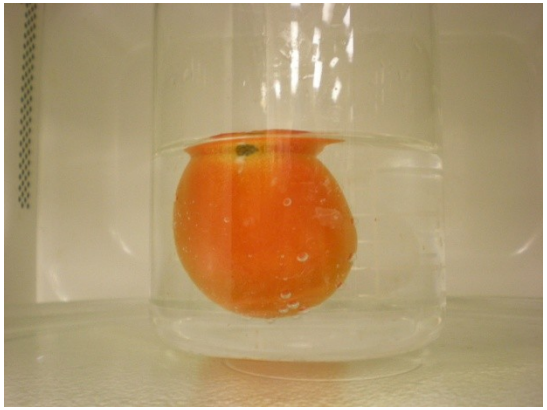


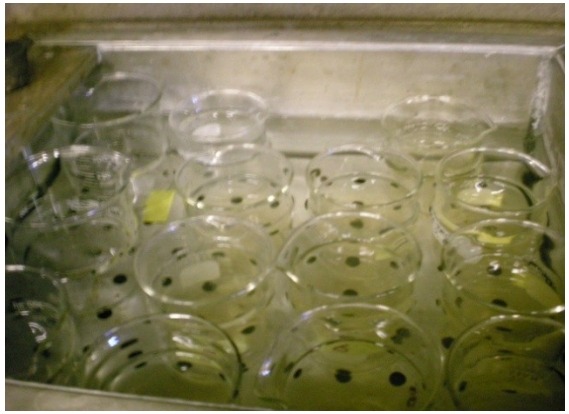
Infrared Thermometer

Peeling Methods

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



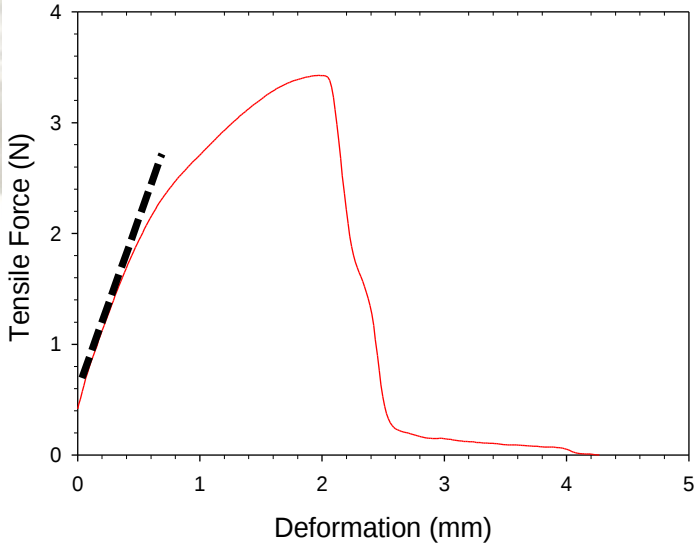




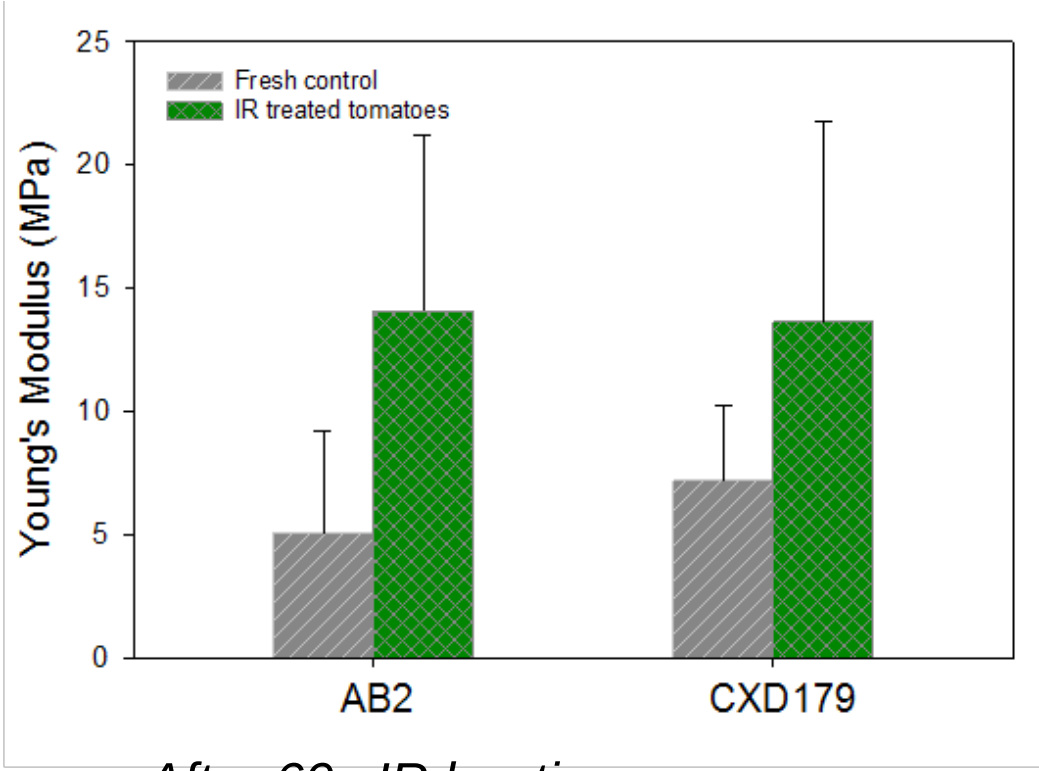
Experimental configuration for A) IR heating of tomatoes, B) Lye peeling, C)Enzymatic peeling

Mechanical Property of Tomato Peel



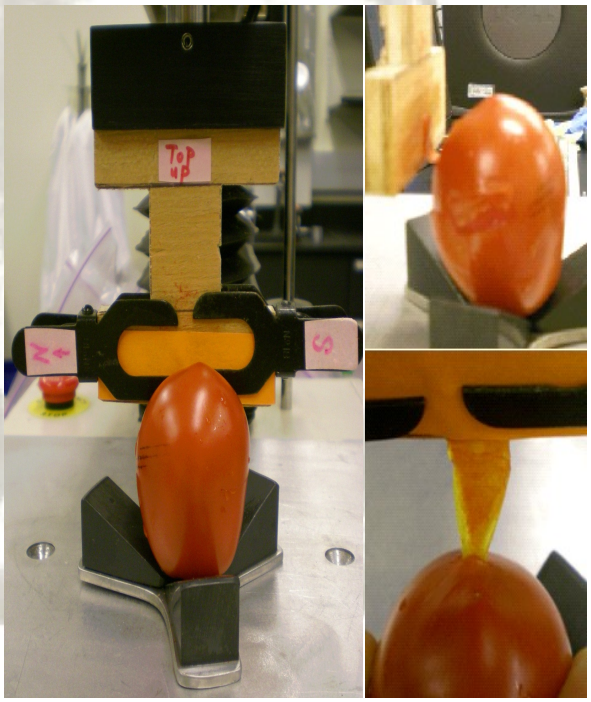


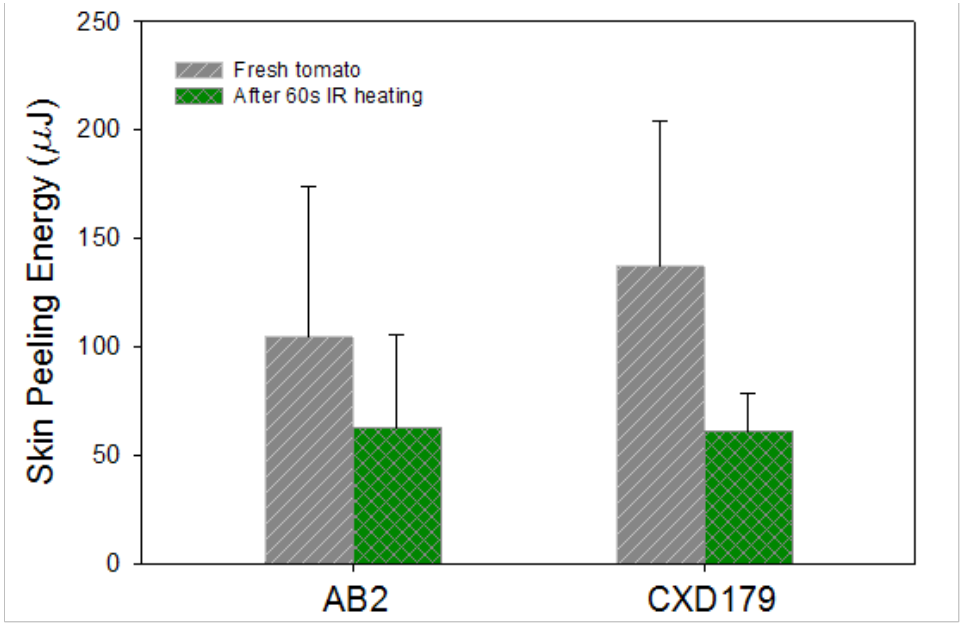
Young's Modulus of Tomato Peels

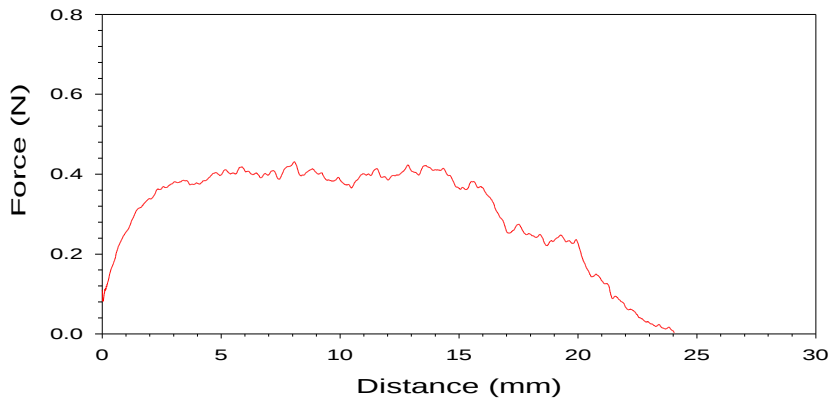


After 60s IR heating
90mm emitter gap with rotation
n=10

Adhesive Energy for Pulling Peel Off

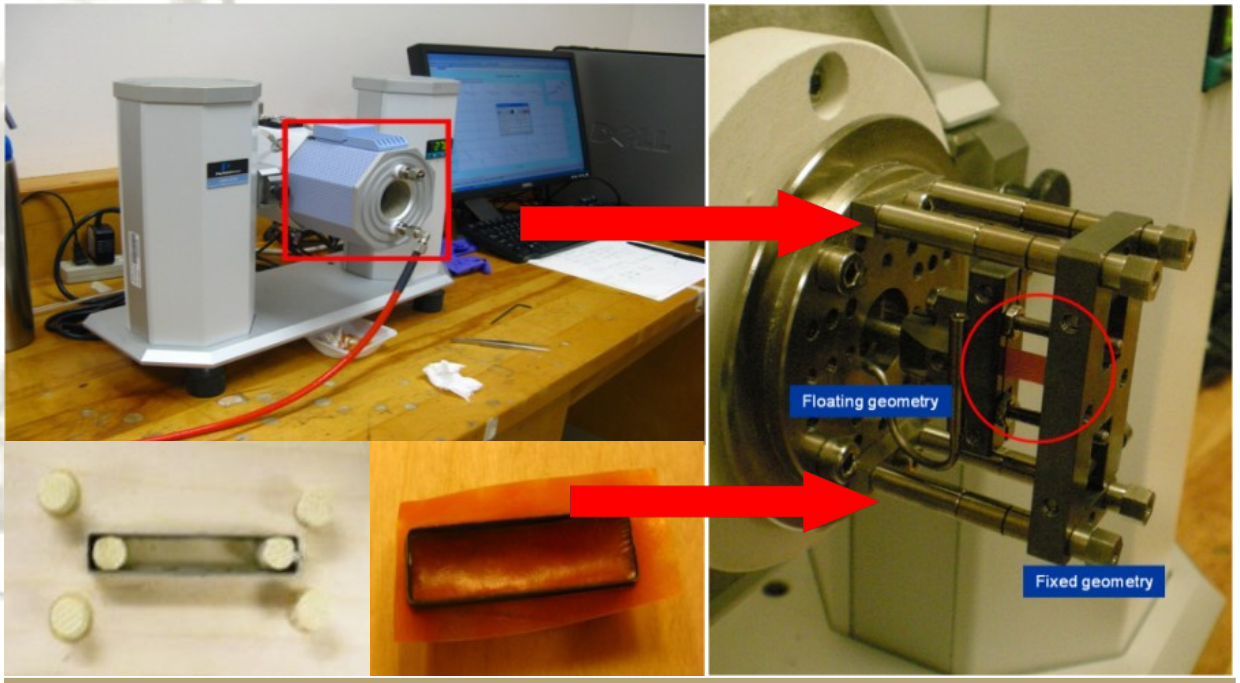






After 60s IR heating
90mm emitter gap with rotation
n=10

Dynamic Mechanical Analysis

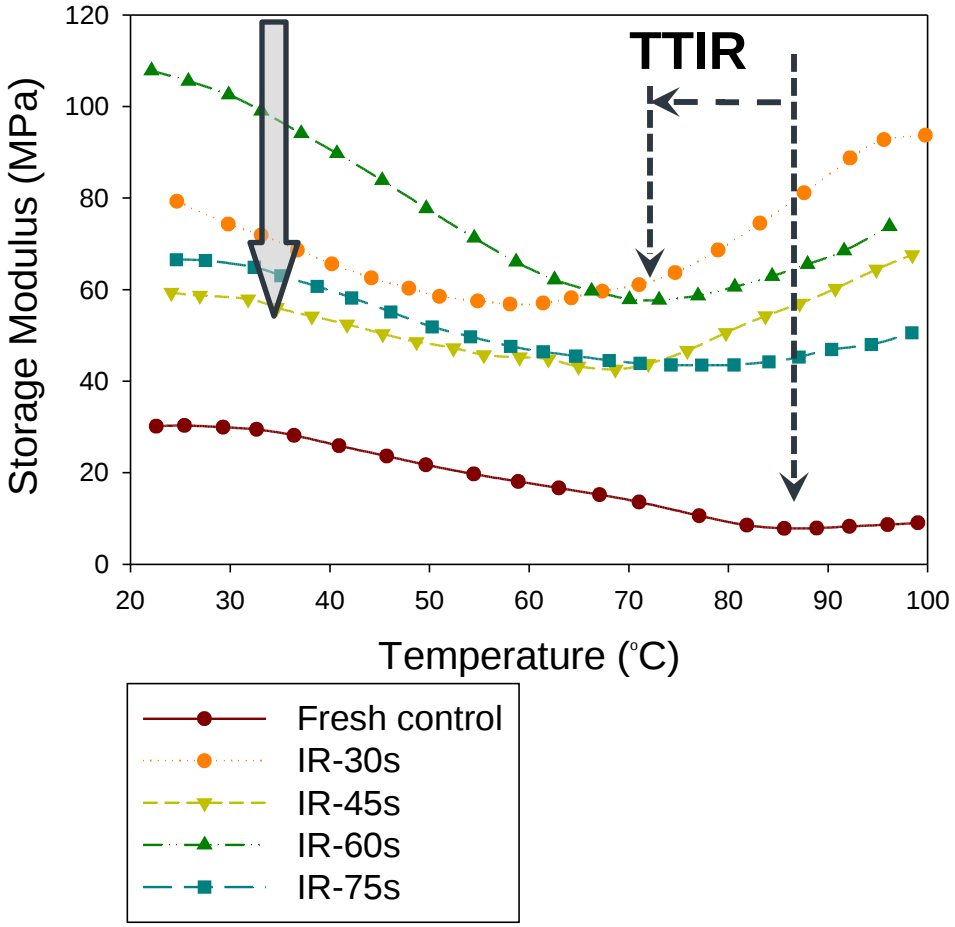


DMA 8000 (PerkinElmer) with tension clamps

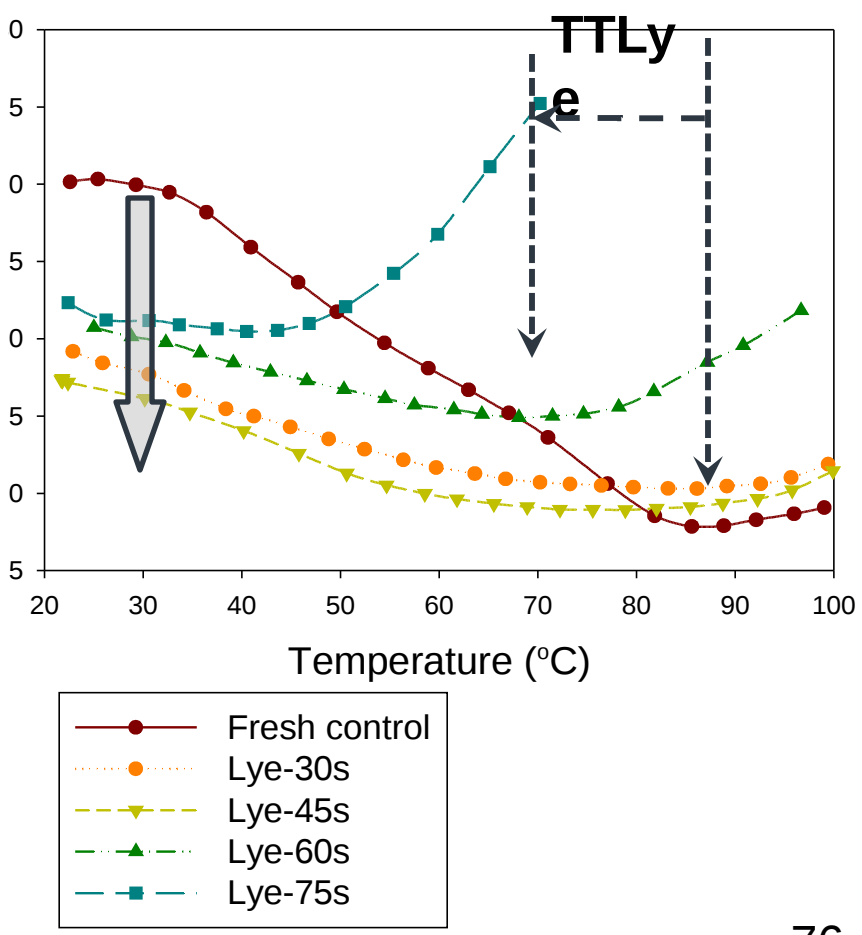
- Temperature ramp test
- Frequency sweep test

Temperature Ramp Test

IR heated peels

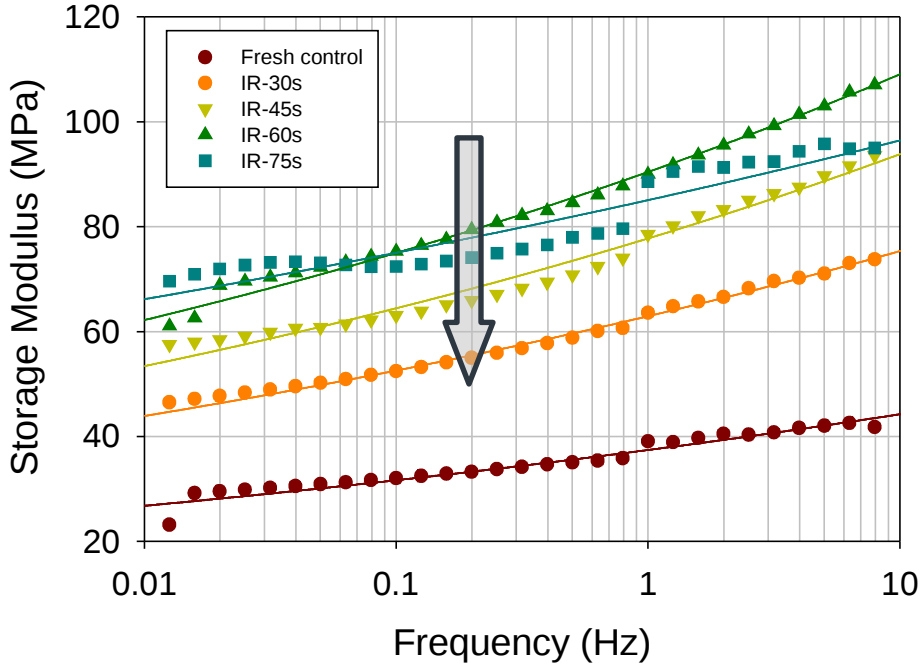


Lye heated peels

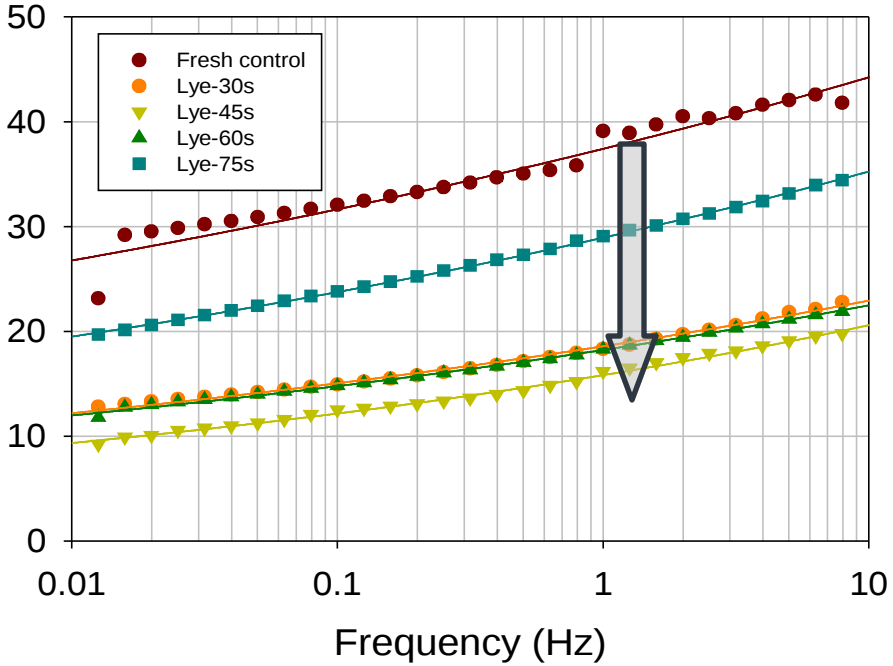


Storage Modulus of Frequency Spectra

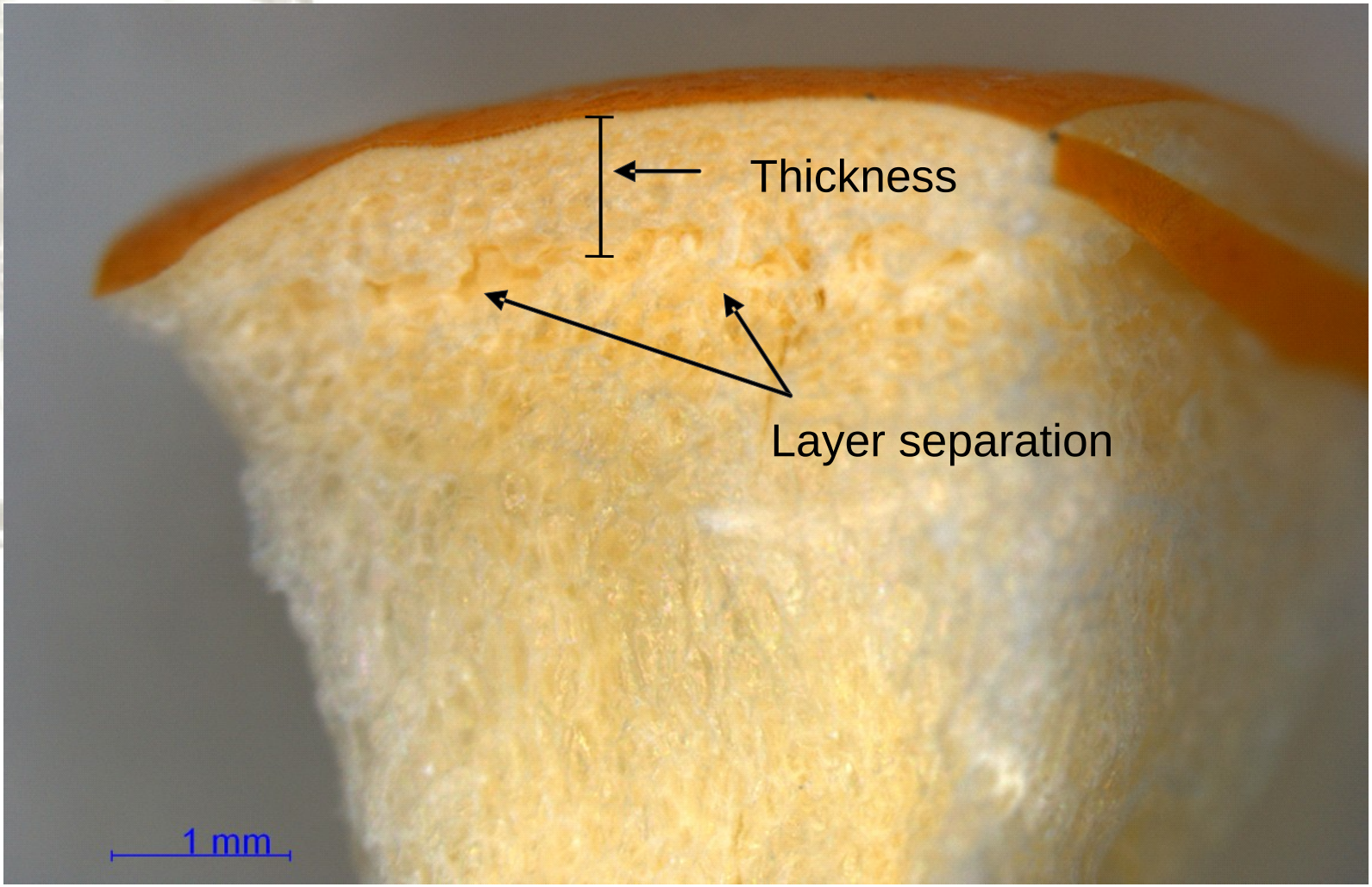
IR heated peels



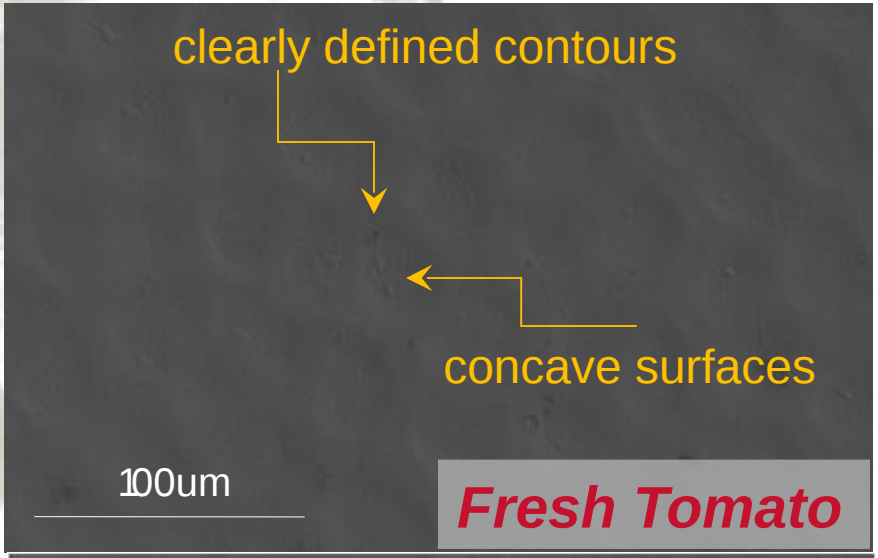
Lye heated peels

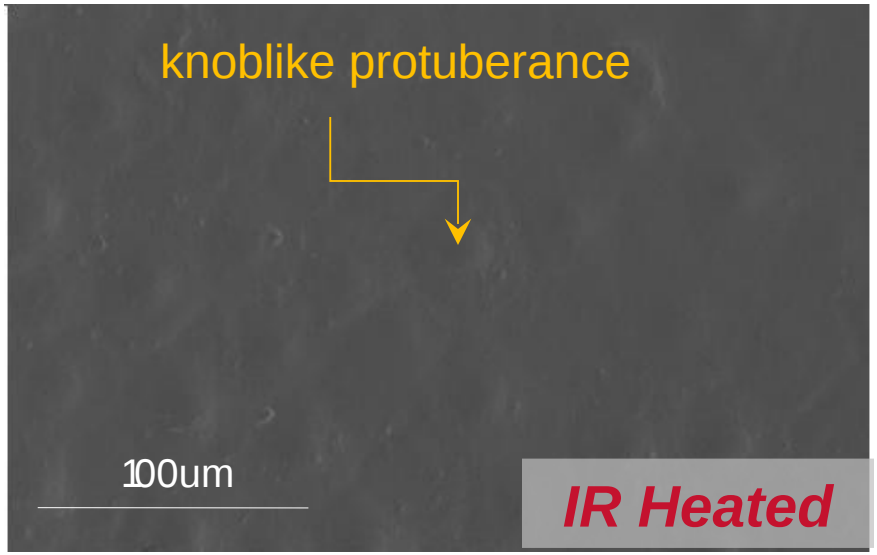


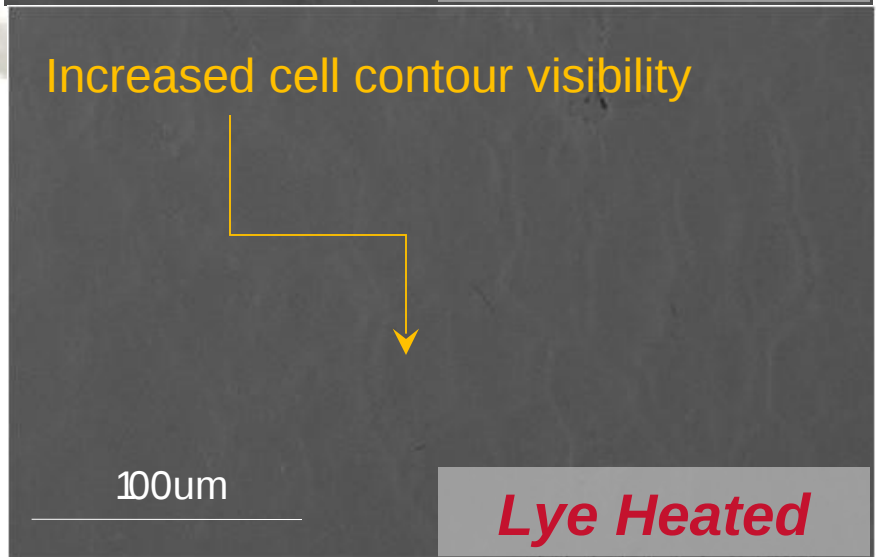
Observed Skin Separation



Microstructural Changes on Surface

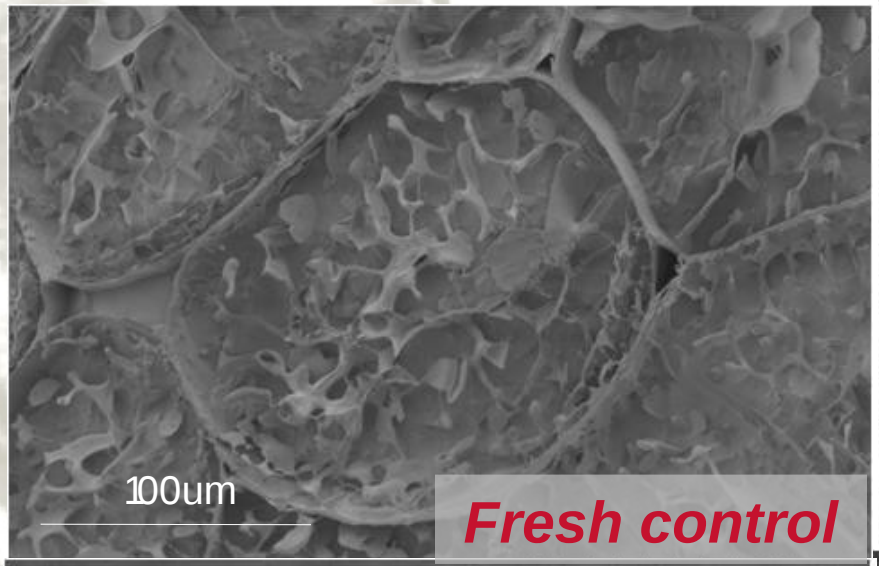


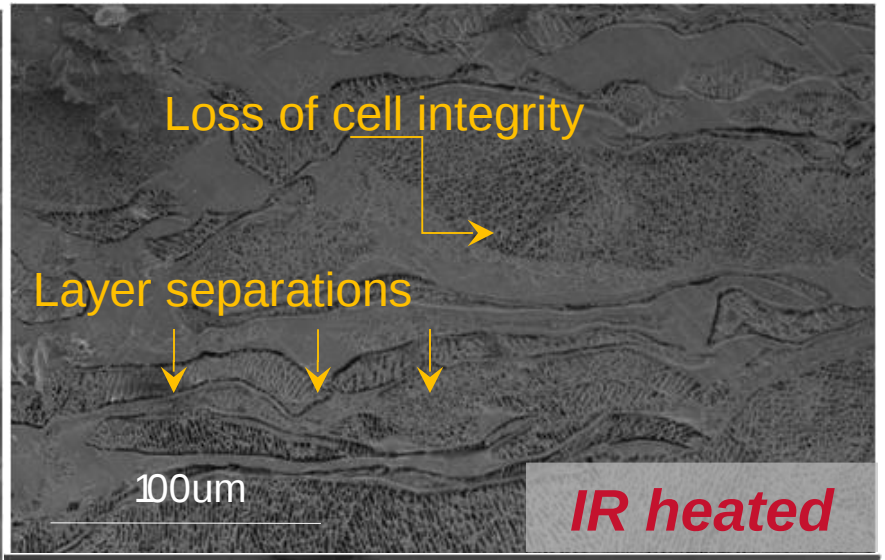


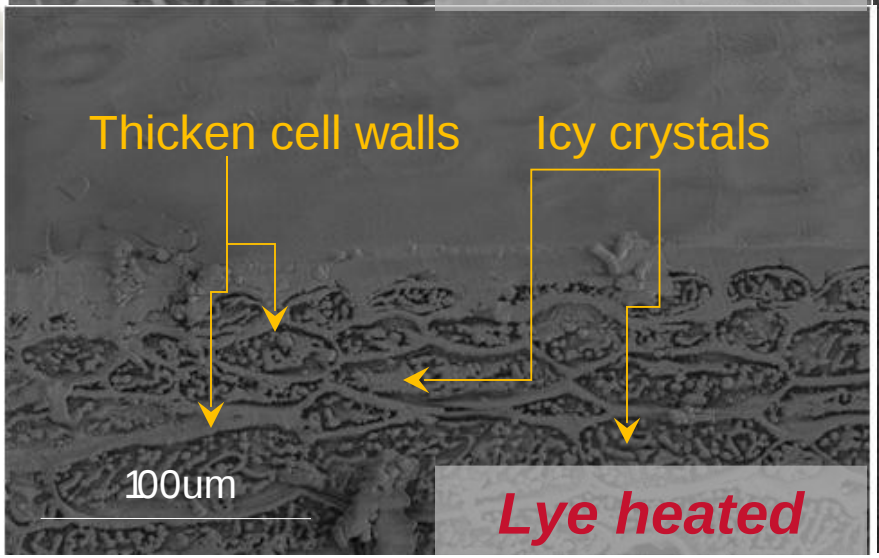


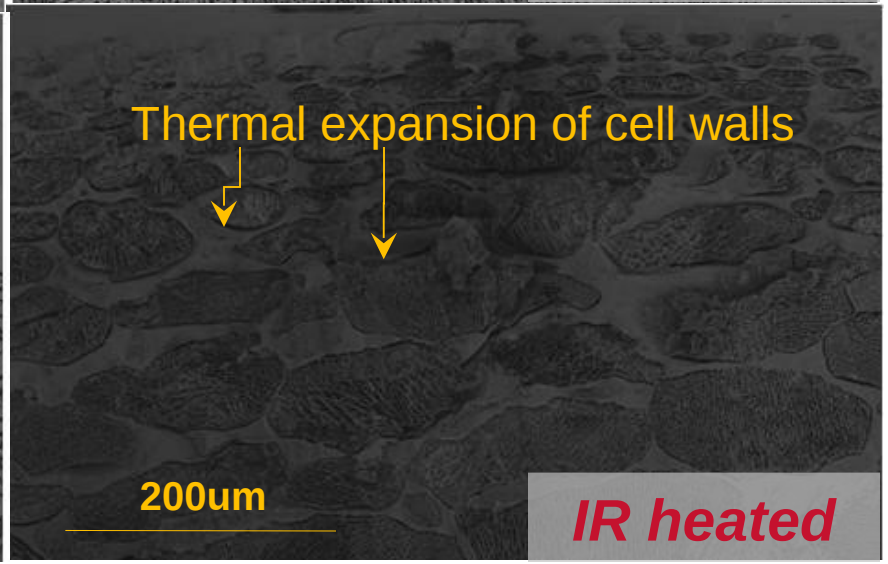
- Damaged epidermal layers
- Redistribution of cuticular wax
- Different mechanisms
  - Chemical diffusion and reaction
  - Radiation damage

Microstructural Changes in Pericarp Tissue



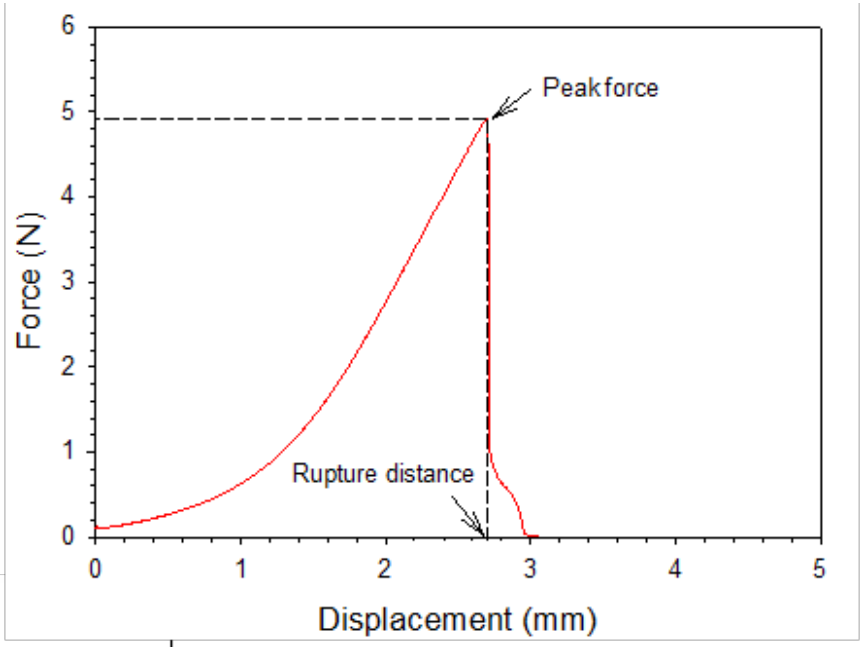


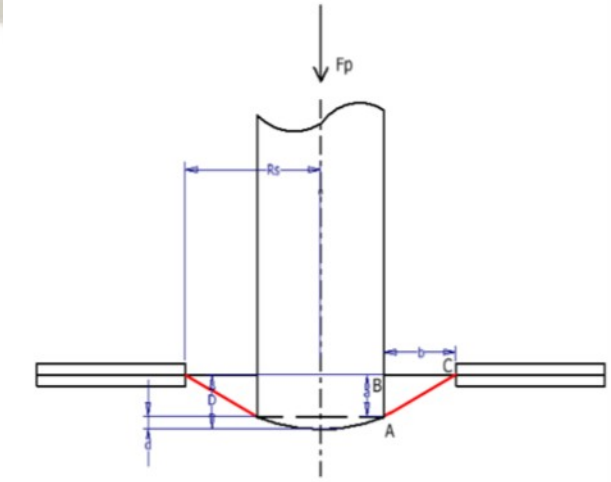


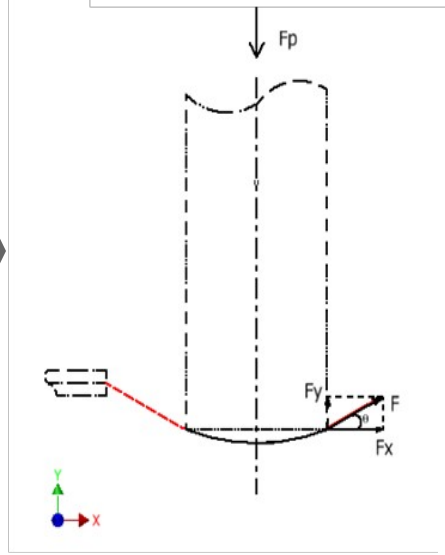


Measurements of Skin Rupture







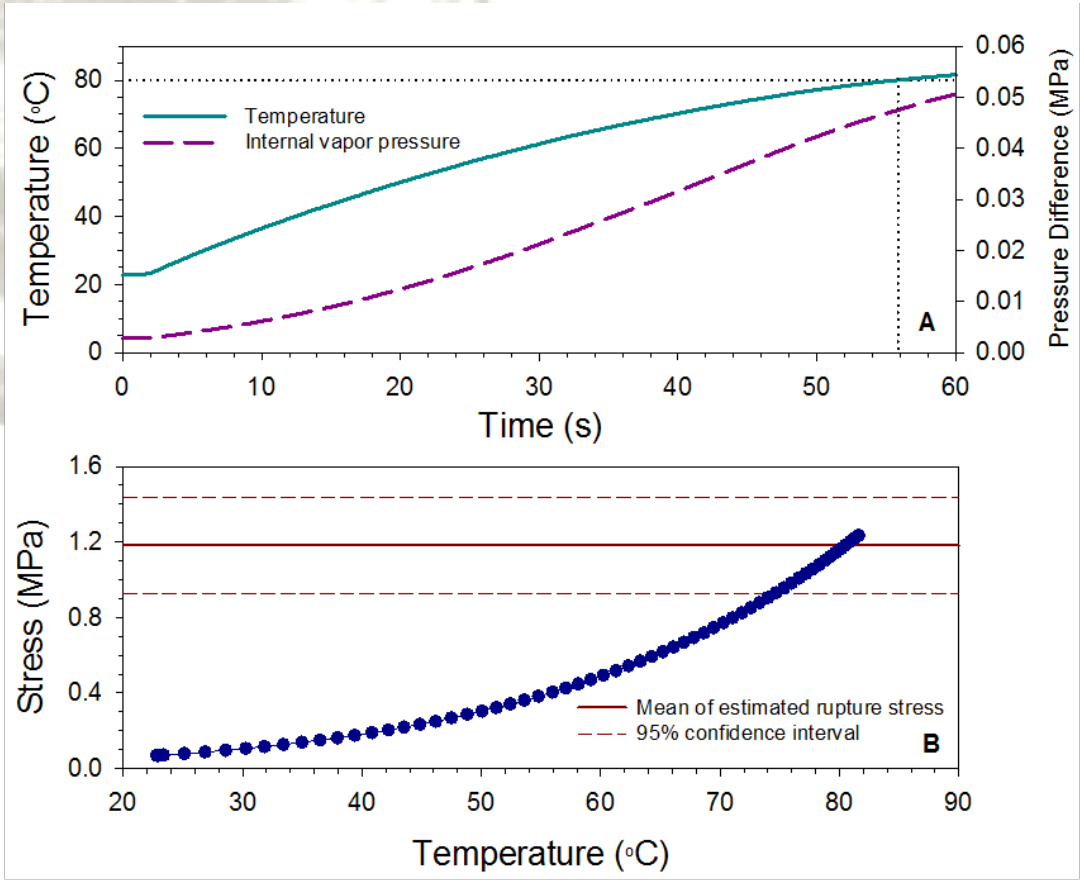


Rupture stress of IR heated skin:

$$\sigma_r = \frac{F_p}{2\pi R_p t \sin(\theta)}$$

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



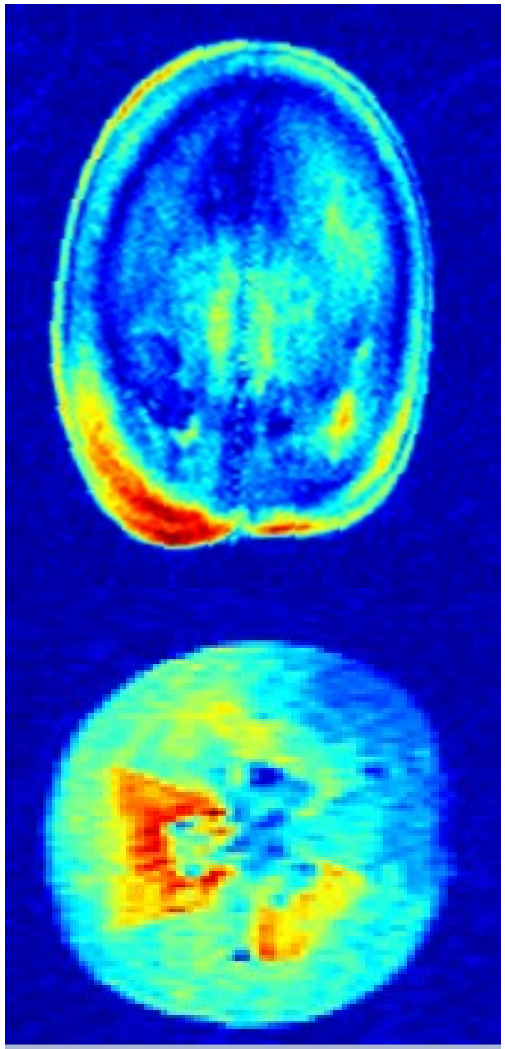
IR heating for 60s



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



MRI of Tomato Geometry

Tomato Shape Equations

$$\begin{cases} x = R(\theta)\sin(\theta)\cos(\varphi) \\ y = R(\theta)\sin(\theta)\sin(\varphi) \\ z = R(\theta)\cos(\theta) \end{cases}$$

Where

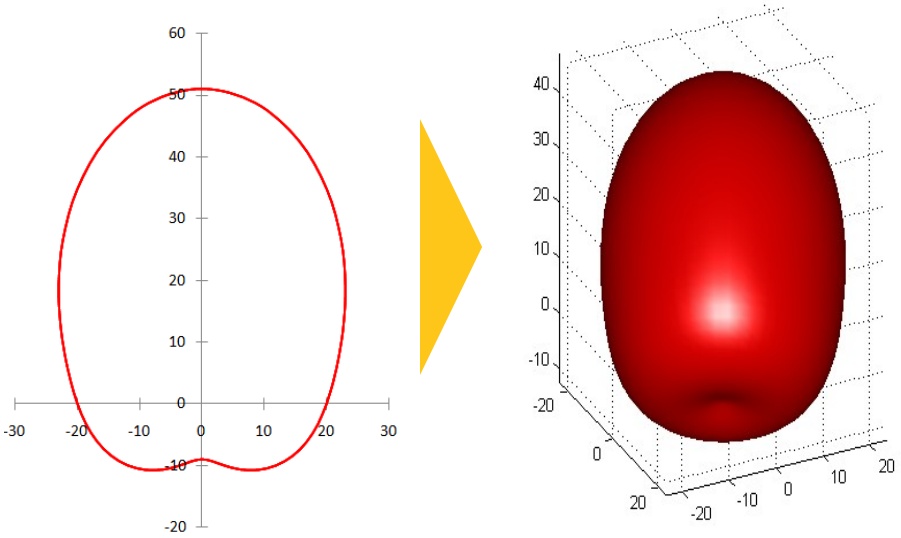
- $R(\theta)$ = radius function of distance from the origin to the boundary
- θ zenith angle, [0, π]
- φ azimuth angle, [0, 2π]

in which

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

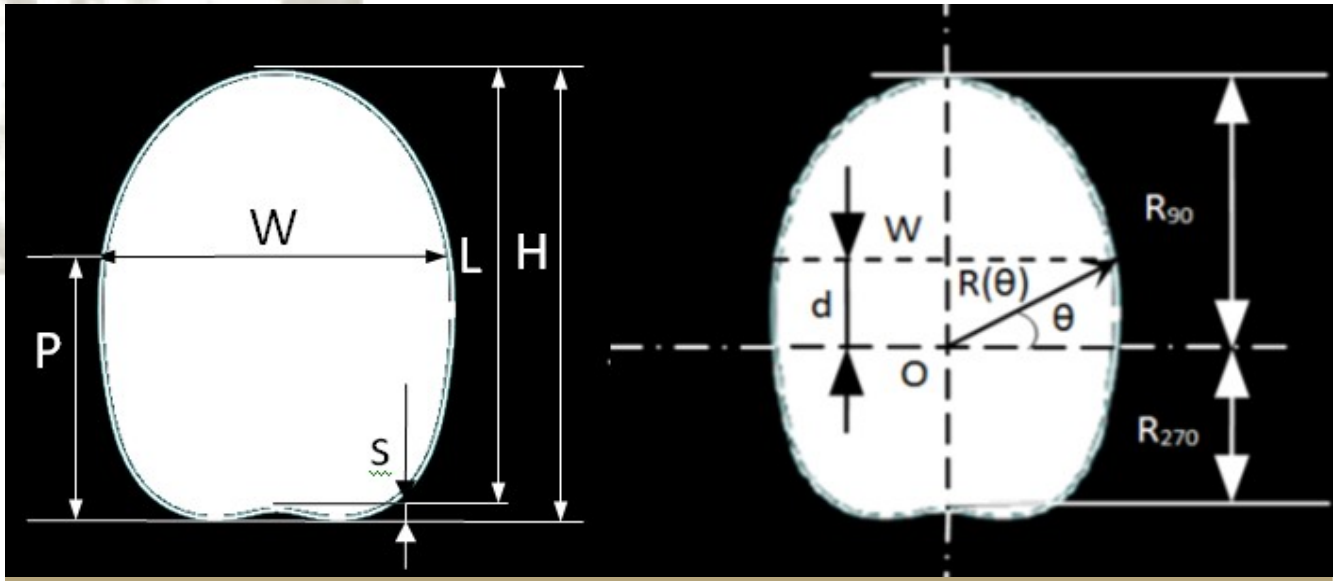
Where

- a = the semi-major axis
- b = the semi-minor axis
- c1 = shape coefficient
- c2 = shape coefficient



Experimental Measurements

- Dimensional parameters: *H, s, W, P, R90*
- Physical parameters: *mass, density, surface area*



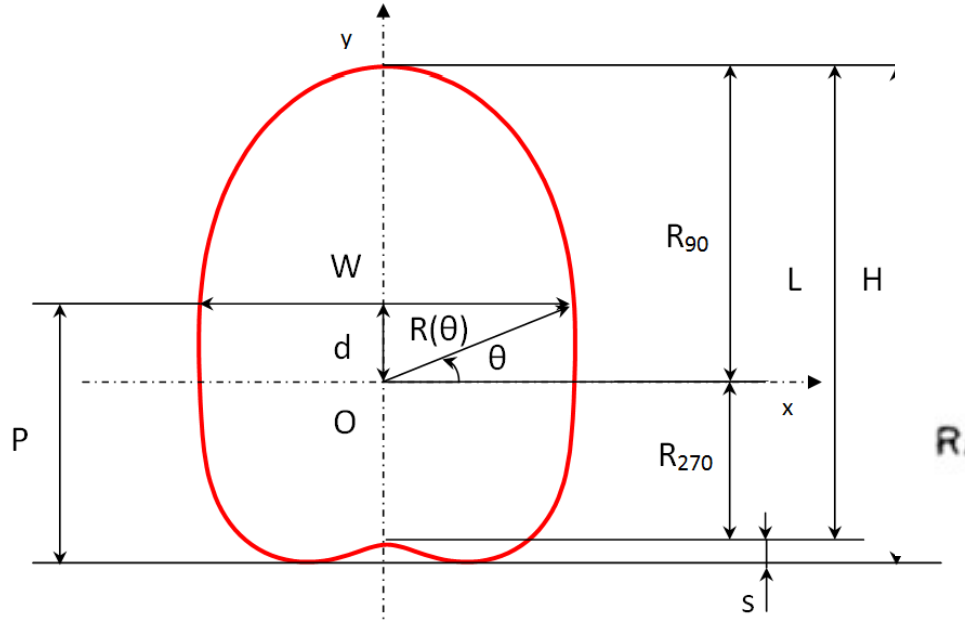
Dimensional Measurements and Geometric Relationship

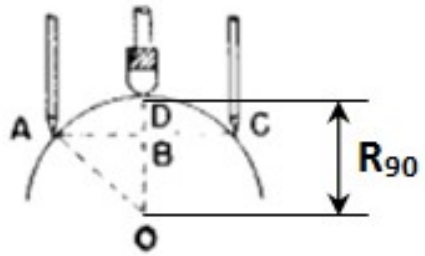
Analytical Relationship

- Mathematical relationship within tomato geometric profile

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

$$R(a, b, c_1, c_2) = g(H, s, W(\theta), P, R_{90})$$





$$\text{RADIUS} = \frac{(AC)^2}{8(BD)} + \frac{(BD)}{2}$$

ASAE S368.4 DEC2000 (R2008)

Results of Determination of Coefficients

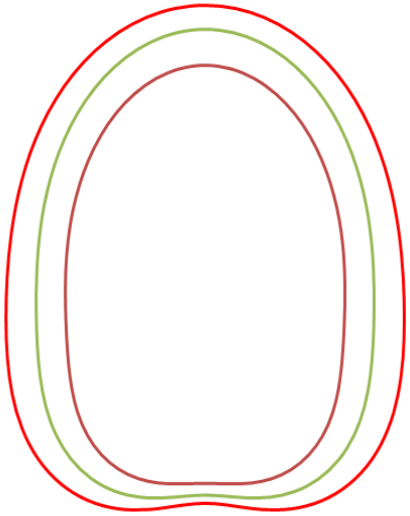
- Five necessary measurements of tomato dimensions
  - H, W, P, s and R90
- Coefficients calculated from each tomato measurements

Descriptions	Formulas	Measurements
a	$a = \frac{H - s}{2}$	H and s
b	$b = a\frac{W}{2d}\sqrt{c_1 \sin[\arctan(\frac{2d}{W})]}, where: d = \mid P + R_{90} - H \mid$	W, P, s and R90
c1	$c_1 = \frac{4(H - P - R_{90})^4 \cos^2[\arctan(\frac{2d}{W})] + (H - P - R_{90})^2 W^2 \cos^2[\arctan(\frac{2d}{W})]}{\left(\frac{H - s}{2}\right)^2 W^2 \sin^2[\arctan(\frac{2d}{W})]}$	H, W, P, s and R90
c2	$c_2 = \mid \frac{2R_{90}}{L} - c_1 - 1 \mid$	R90, H and s

Shape and Size Variations

Tomato size changes

c1= 0.24; c2=0.38;



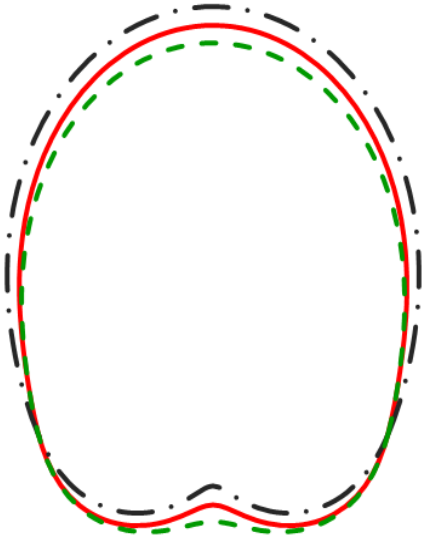
a=31, b=26

a=29,b=22

a=26,b=18

Tomato shape variations

a=26; b=18;



c1=0.25, c2=0.45

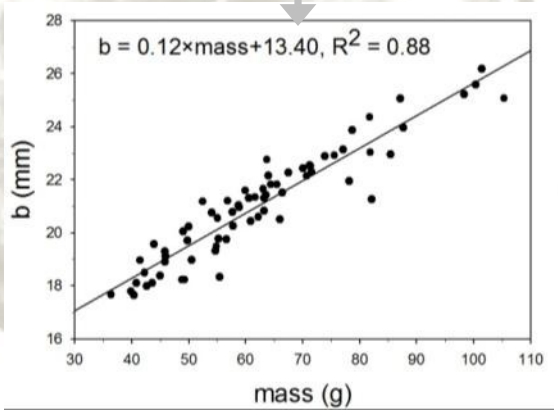
c1=0.4,c2=0.38

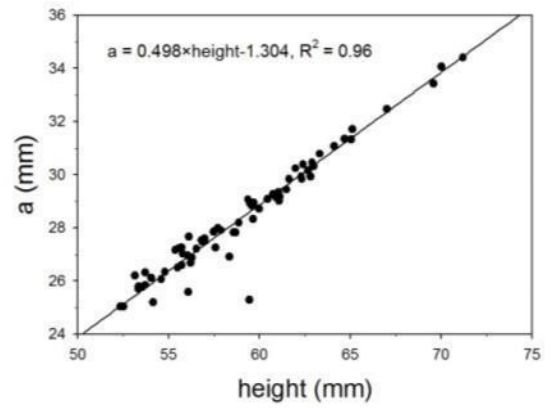
c1=0.25,c2=0.38

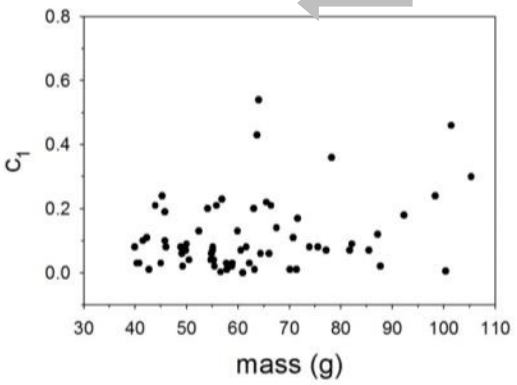
Linear Regression Analysis

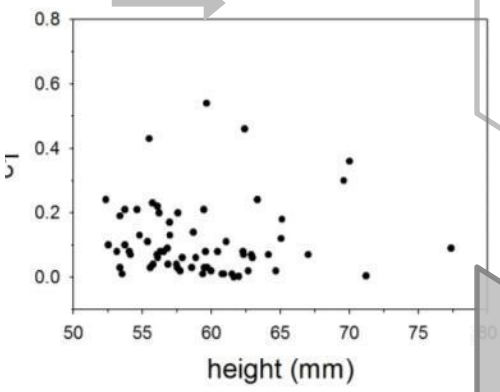
Dimensional parameters:
a vs. mass and b vs. height

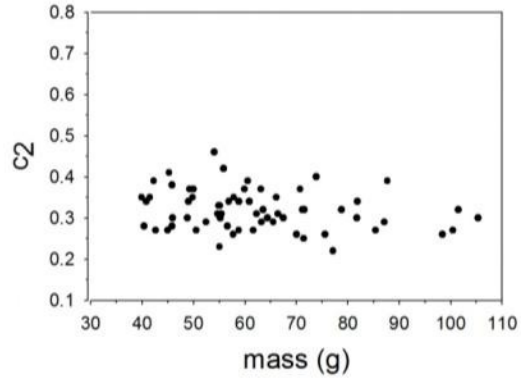
Shape coefficients:
c1 and c2 vs. mass and height

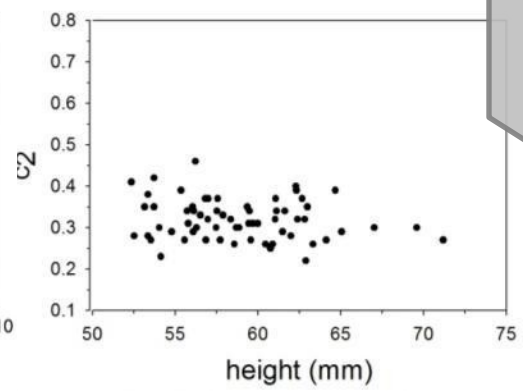












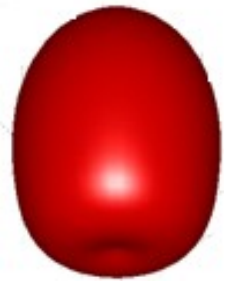
Simplified Tomato Geometric Model

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

Descriptors	Formulas
a	0.498×height-1.304
b	0.12×mass+13.40
c1	0.12 ~ 0.54
c2	0.30 ~ 0.38



Geometric Model



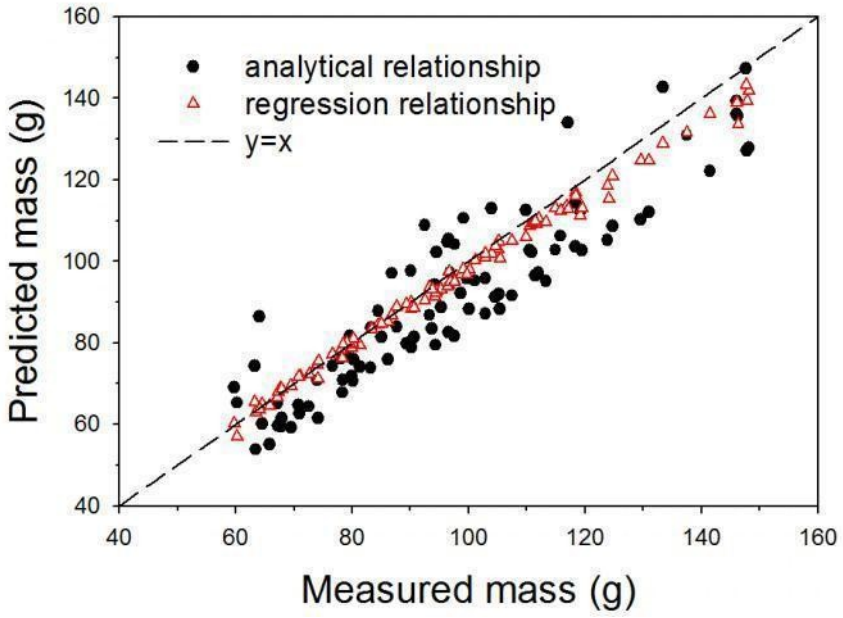
Tomato Geometric Characterization

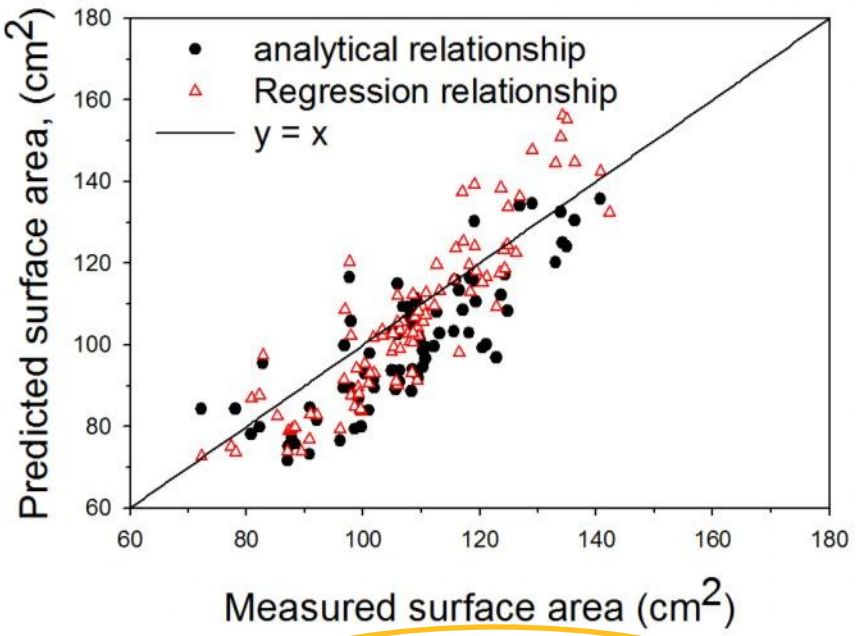
Geometry Characteristics	Derived Formulas
Mass	$m = \frac{2\pi\rho}{3}\int_{\theta_1}^{\theta_2} R^3(\theta)\cos(\theta)d\theta$
Volume	$V = \frac{2\pi}{3}\int_{\theta_1}^{\theta_2} R^3(\theta)\cos(\theta)d\theta$
Surface area	$S = 2\pi\int_{\theta_1}^{\theta_2} R(\theta)\sin(\theta)\sqrt{R(\theta)+\left(\frac{dR}{d\theta}\right)^2}d\theta$
Projected area	$A = \frac{1}{2}\int_{\theta_1}^{\theta_2} R(\theta)d\theta$
Circumference length	$C = \int_{\theta_1}^{\theta_2}\sqrt{R(\theta)+\left(\frac{dR}{d\theta}\right)^2}d\theta$

- 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





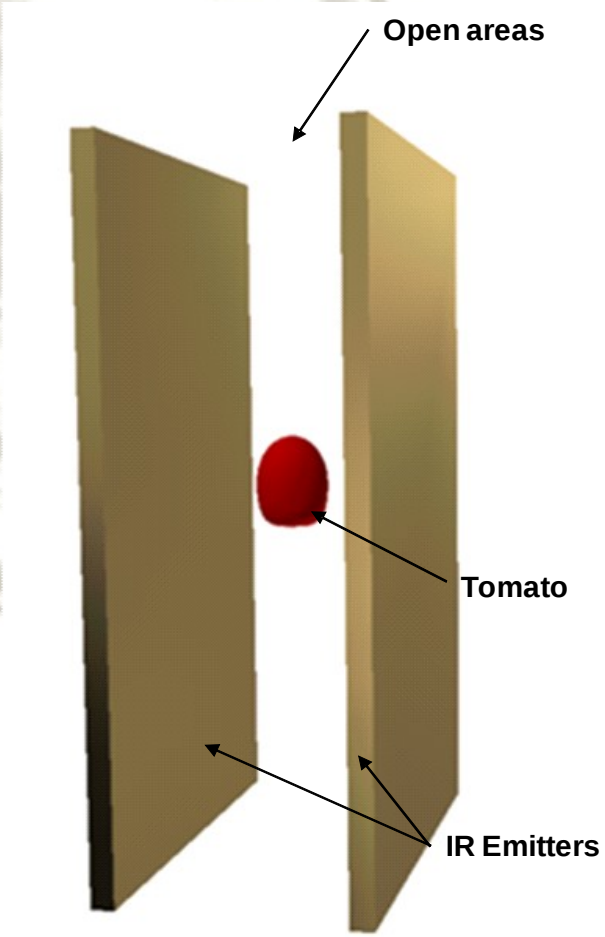
Prediction	Sample size	Predicted Values	Measured Values	R2	RMSE	Relative Error (%)
Mass	96	56.4-169.6 g	59.7-148.2 g	0.9987	1.688 g	1.2
Surface area	96	72.7-156.1 cm2	66.4-142.7 cm2	0.8745	9.776 cm2	6.7

Model Application —Design and Simulation

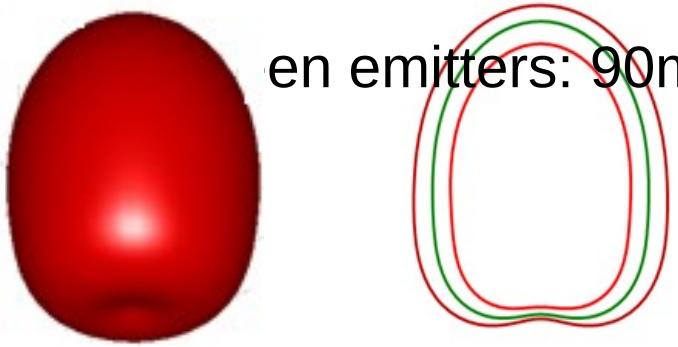
- Heating performance affected by shape and size
  - Over-heating *vs.* loss in texture and nutritional values
  - Under-heating *vs*. insufficient degree of peel loosening
- Facilitate configuration design of infrared heating system
  - Complex radiation heat transfer
  - Heating rate vs. heating uniformity
  - 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
- Dista en emitters: 90mm

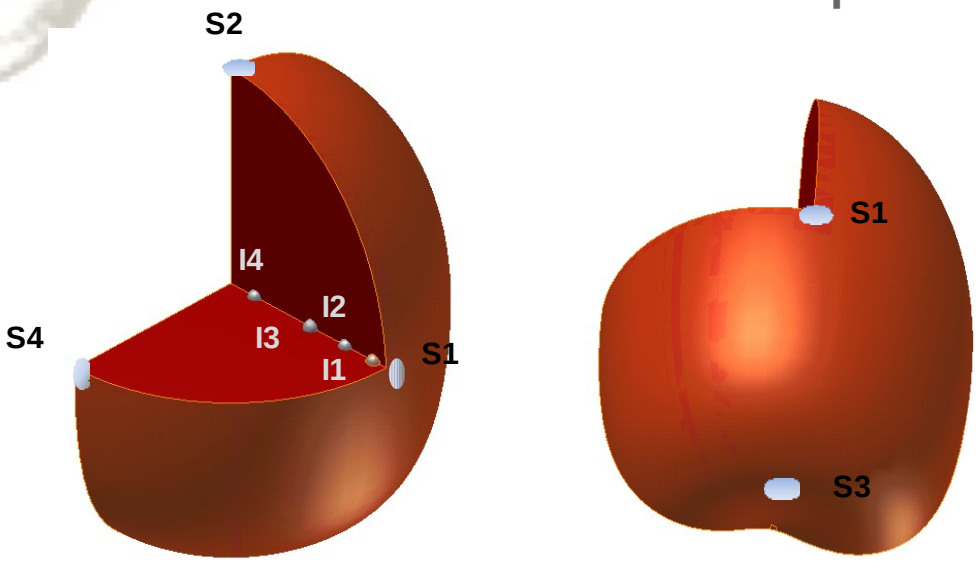


Tomato model and contours of three size levels: 42, 49, 54±1mm

Temperature Measurements

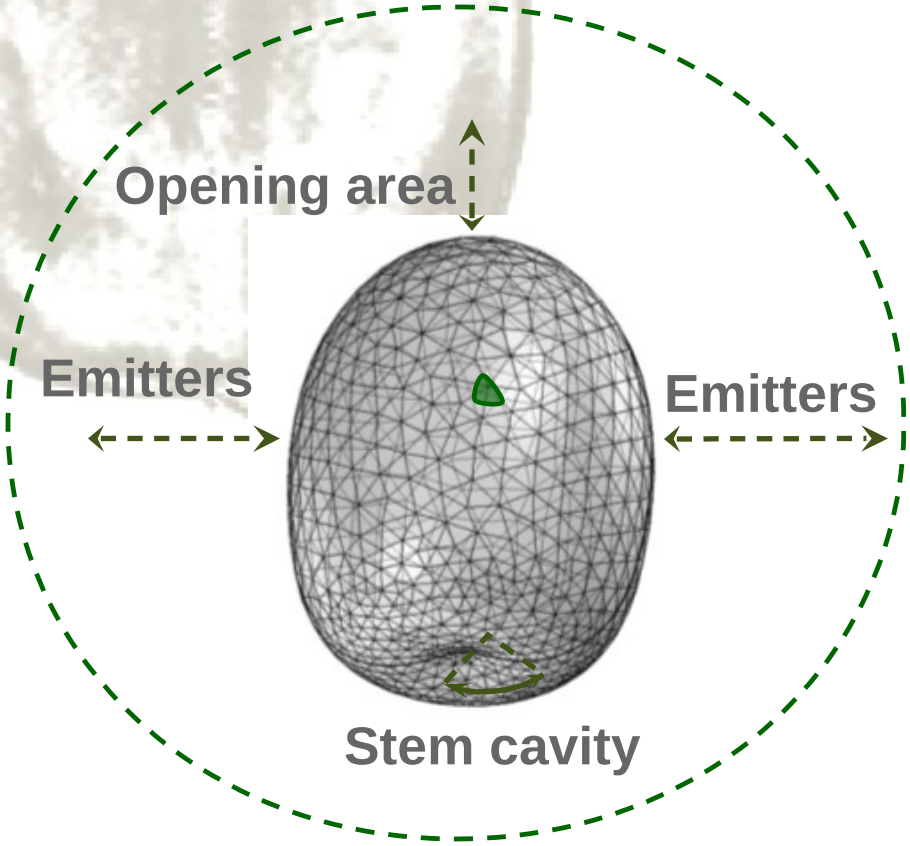
- Multiple locations in a tomato
  - Four surface locations (S1-S4): *top, bottom, side S1, side S4*
  - Four interior locations (I1-I4) : *1, 4, 8, 16mm under skin*
- Hypodermic miniature thermocouples
  - Tiny tip (0.3mm) and fast response time (60ms)
  - Five replicates at each location

Positions of thermocouples



Model Development — Radiation Heat Transfer

- Gray-diffuse radiation exchange based on enclosure theory



$$q_{rad}(x_i) = J_i(x_i) - G_i(x_i)$$

$$G_i(x_i) = \sum_{j=1}^{N} F_{dA_j - A_i}(x_j, x_i)\, J_j(x_j)\, dA_j$$

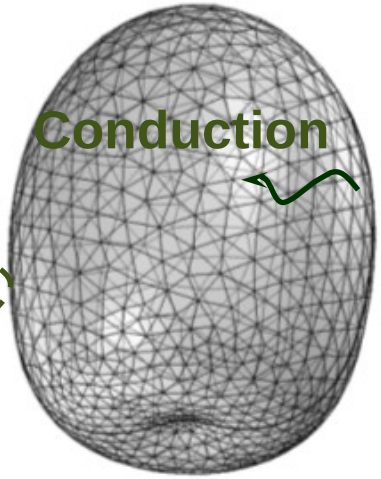
$$J_i(x_i) = \varepsilon_i \sigma T_i^4(x_i) + (1 - \varepsilon_i) G_i(x_i)$$

$$\frac{\varepsilon_i}{1-\varepsilon_i}\left[J_i(x_i) - \sigma T_i^4(x_i)\right] = \sum_{j=1}^{N} F_{dA_j - A_i}(x_j, x_i)\, J_j(x_j) - J_i(x_i)$$

$$\frac{\varepsilon_i}{1-\varepsilon_i}\left[J_i(x_i) - \sigma T_i^4(x_i)\right] = \sum_{j=1}^{N} F_{dA_j - A_i}(x_j, x_i)\, J_j(x_j) - J_i(x_i)$$

Model Development

— Combined with Conduction and Convection



Radiation qrad

Conduction

Convection

qcov

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

BC on tomato surface:

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

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

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot k \nabla T$$

BC at tomato center:

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

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

$$\rho_{ap}(T) = (1-\xi)\rho_t(T) = \frac{(1-\xi)}{\sum_{i=1}^{6} x_i \rho_i(T)}$$

Function of chemical compositions

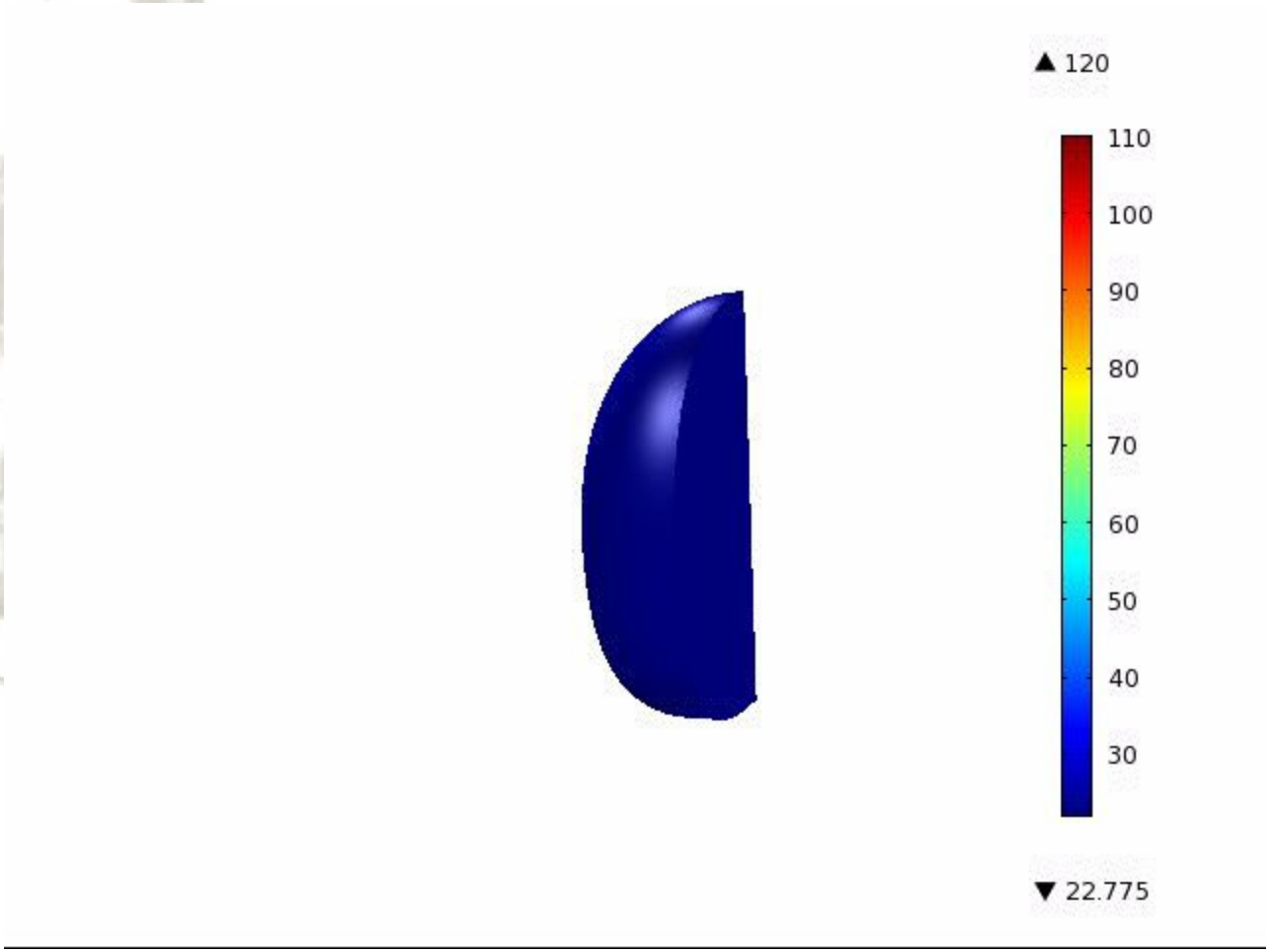
$$k_p(T) = (1-\xi)\sum y_i k_i(T) + \xi k_{air}(T)$$

Temperature depend properties

$$q_{,,}(t) = q_0(t) + \frac{(\quad)}{\xi\sqrt{2\pi}\sigma} \exp\left[\frac{(\quad) - \mu^2}{2\sigma^2}\right]$$

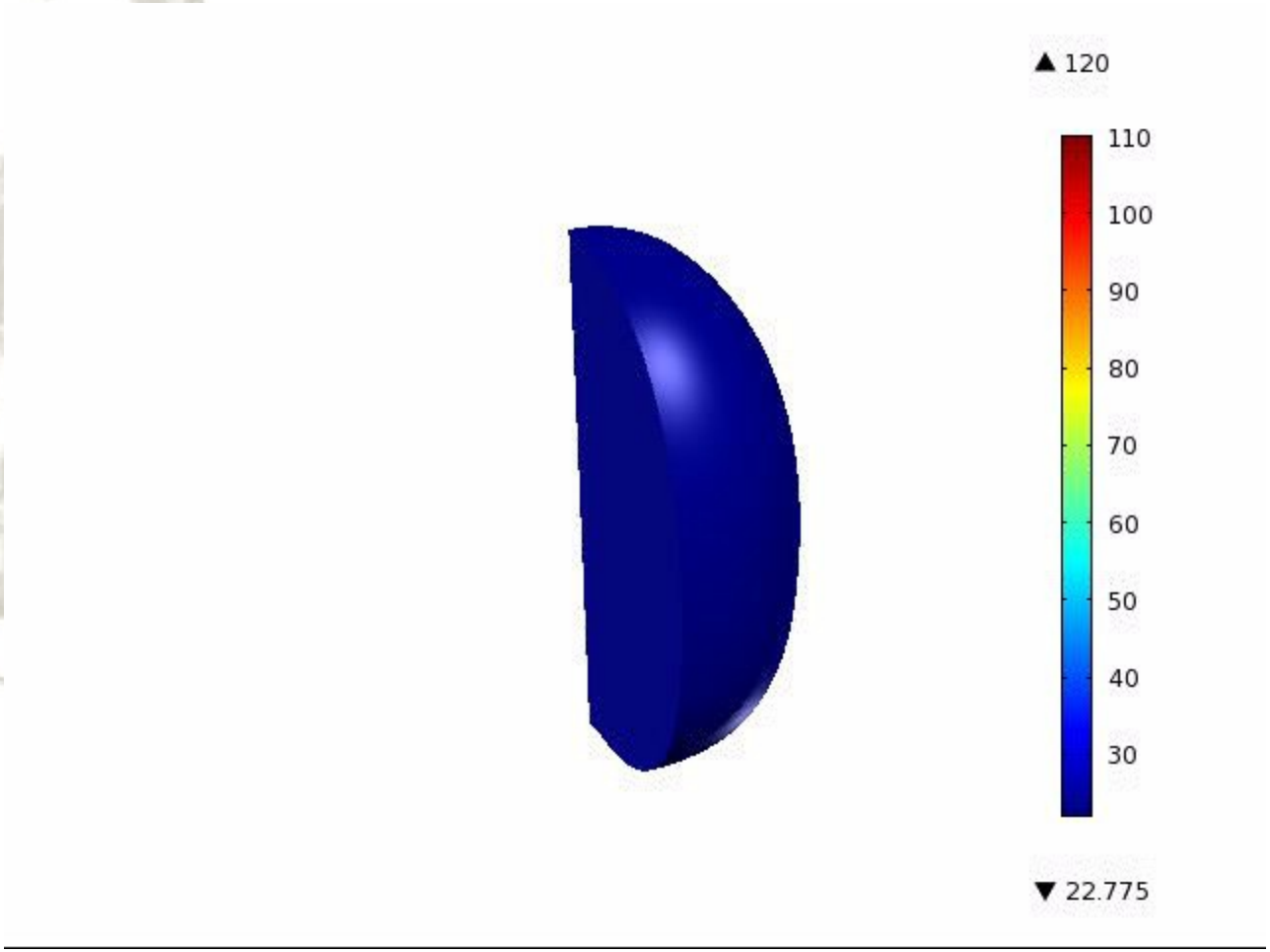
Water evaporation effect

Simulation Results — 60s IR Heating



Facing toward the emitter

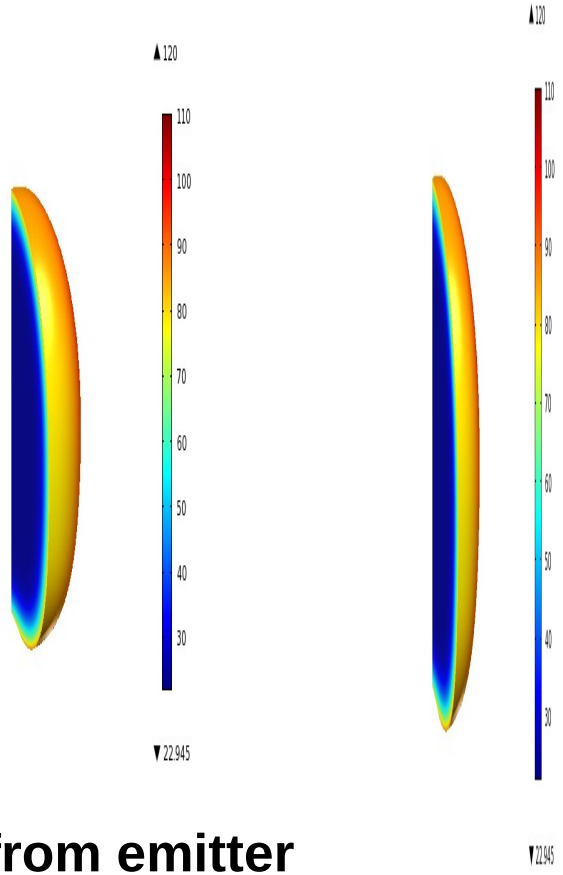
Simulation Results — 60s IR Heating



Facing away from the emitter

Simulation Results — 60s IR Heating





Facing towards emitter **Facing away from emitter**

Surface Temperature Uniformity Index (STUI)

$$STUI = \frac{1}{\bar{T}_{sur}} \sqrt{\frac{\int_S [T_{sur} - \bar{T}_{sur}]^2 dA}{A_{sur}}}$$

Model Validation

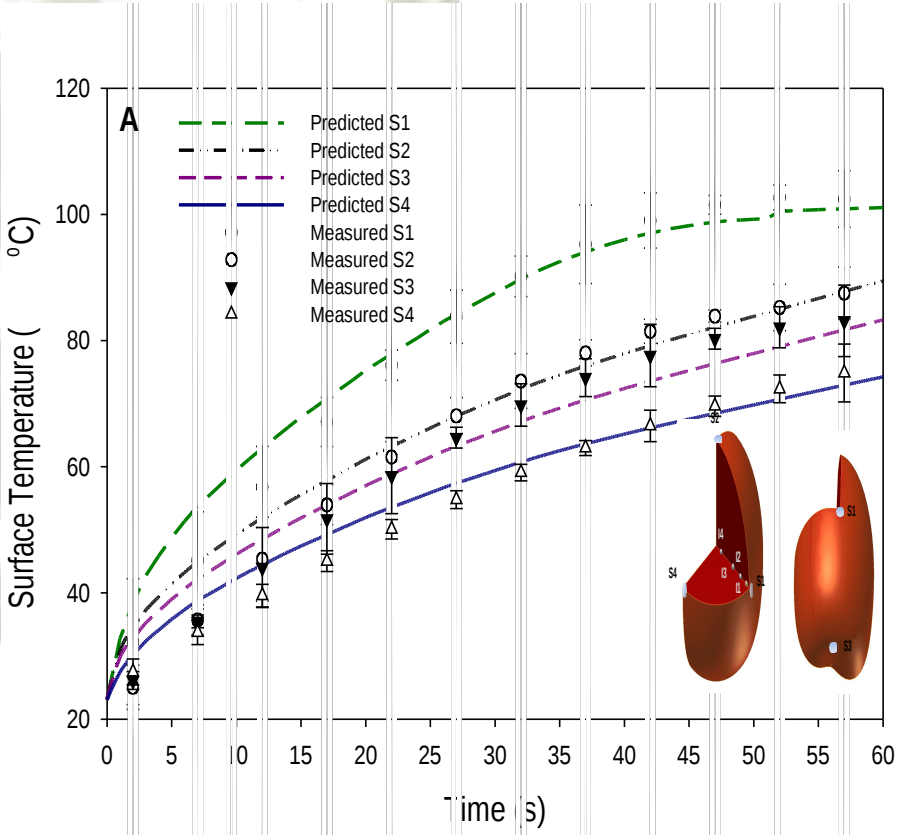
- Compare temperature at multiple locations for tomatoes of different sizes
  - Good agreement of linear correlation (R2>0.9)
  - Reasonable Standard error of estimate criteria

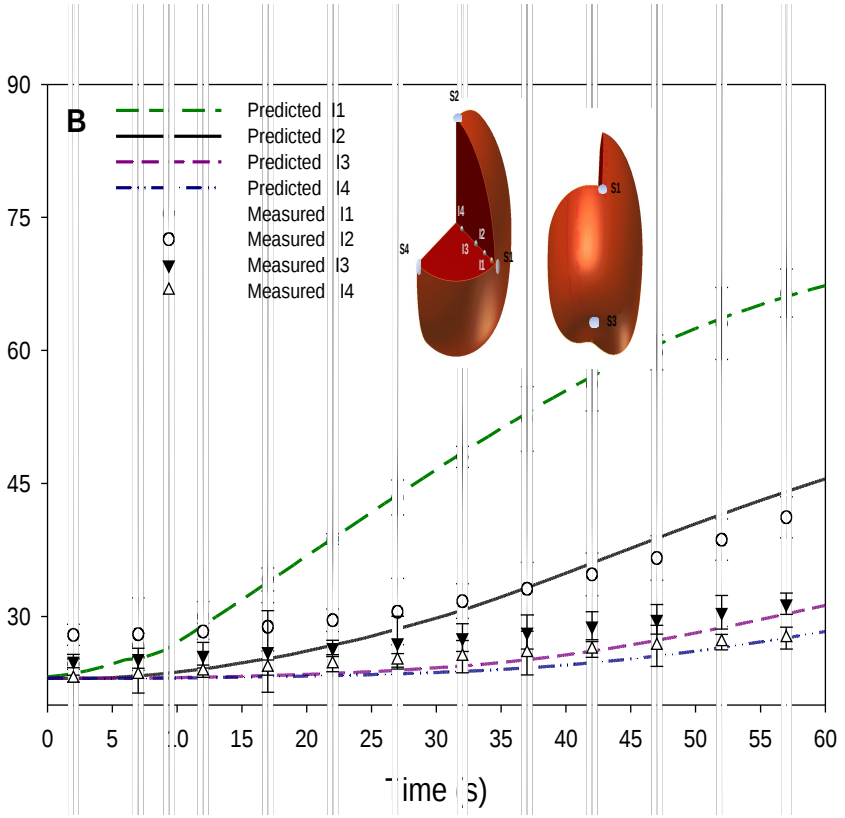
$$SEE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}[T_{pre}(i) - T_{exp}(i)]^2}$$

Smaller SEE value
Better goodness-of-fit

Tomato Size	SEE (oC)							
	S1	S2	S3	S4	I1	I2	I3	I4
Large	5.2	3.6	3.3	5.9	2.7	1.9	1.6	1.1
Medium	3.9	4.6	3.9	2.9	0.8	3.1	2.6	1.1
Small	2.3	1.9	1.5	3.1	2.1	0.7	0.8	0.7

Model Validation —Medium Size Tomatoes





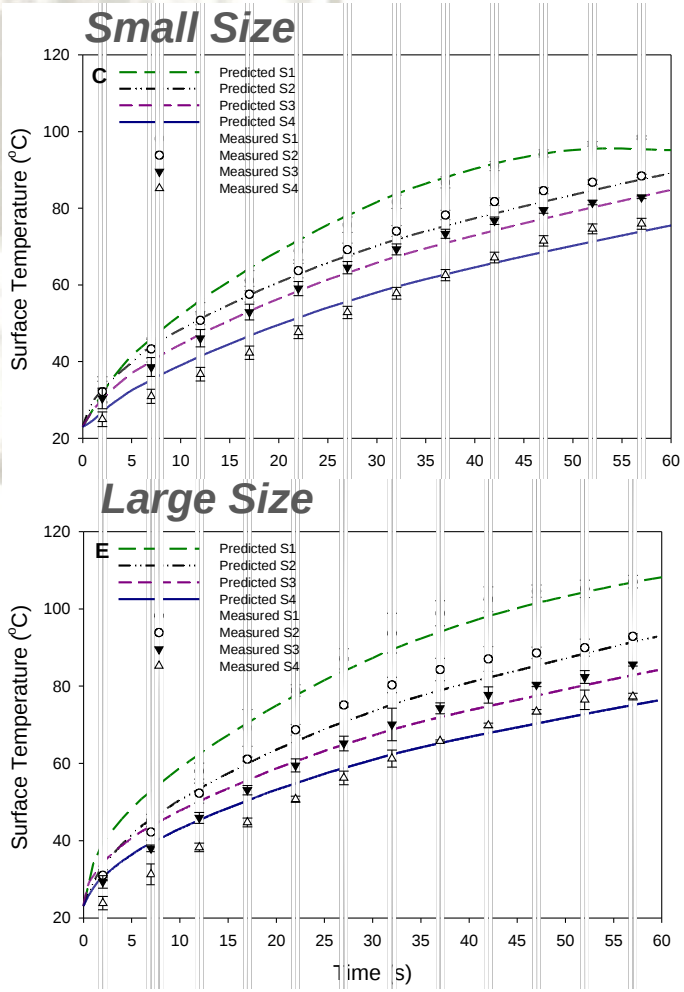
Surface temperature:
Top, bottom, two sides

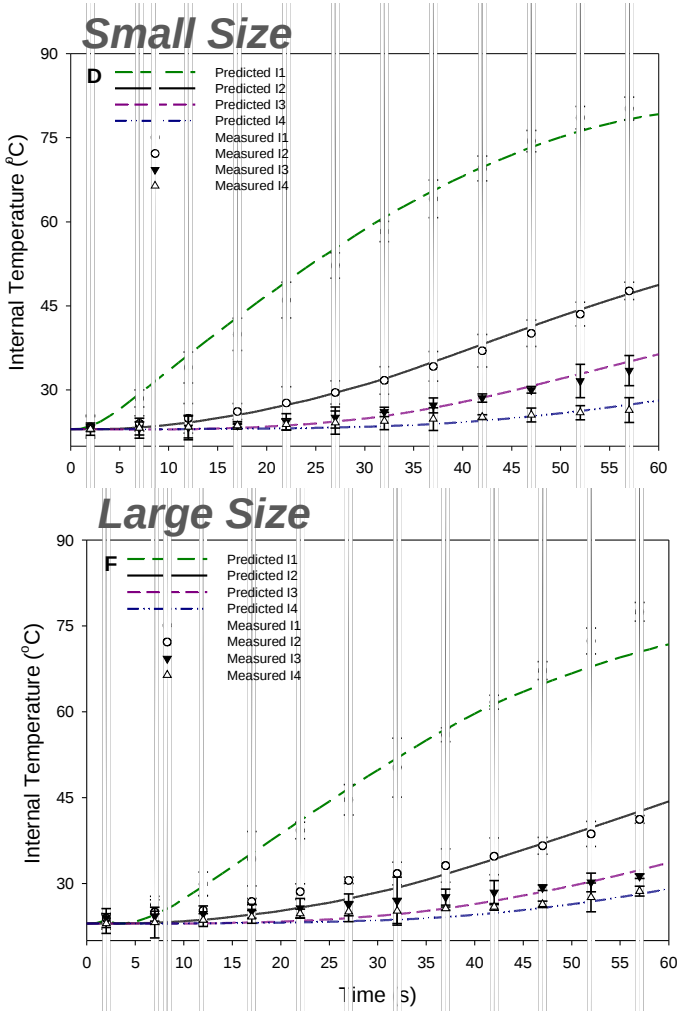
Interior temperature:
1, 4, 8, and16 mm beneath skin

Model Validation —Small and Large Size Tomatoes

Surface temperature:
Top, bottom, two sides

Interior temperature:
1, 4, 8, and16 mm beneath skin



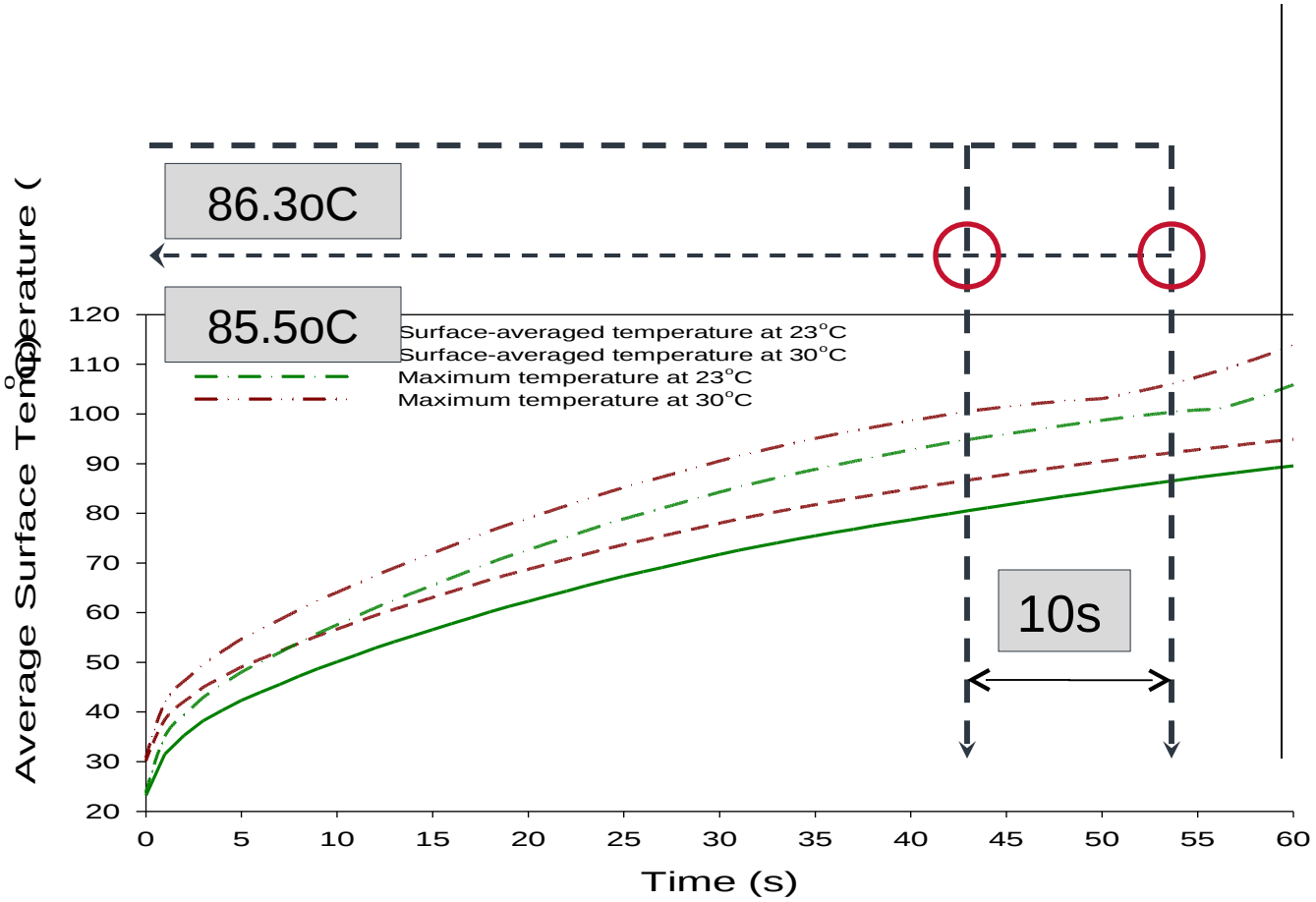


Sensitivity Analysis —Tomato Size Effects

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

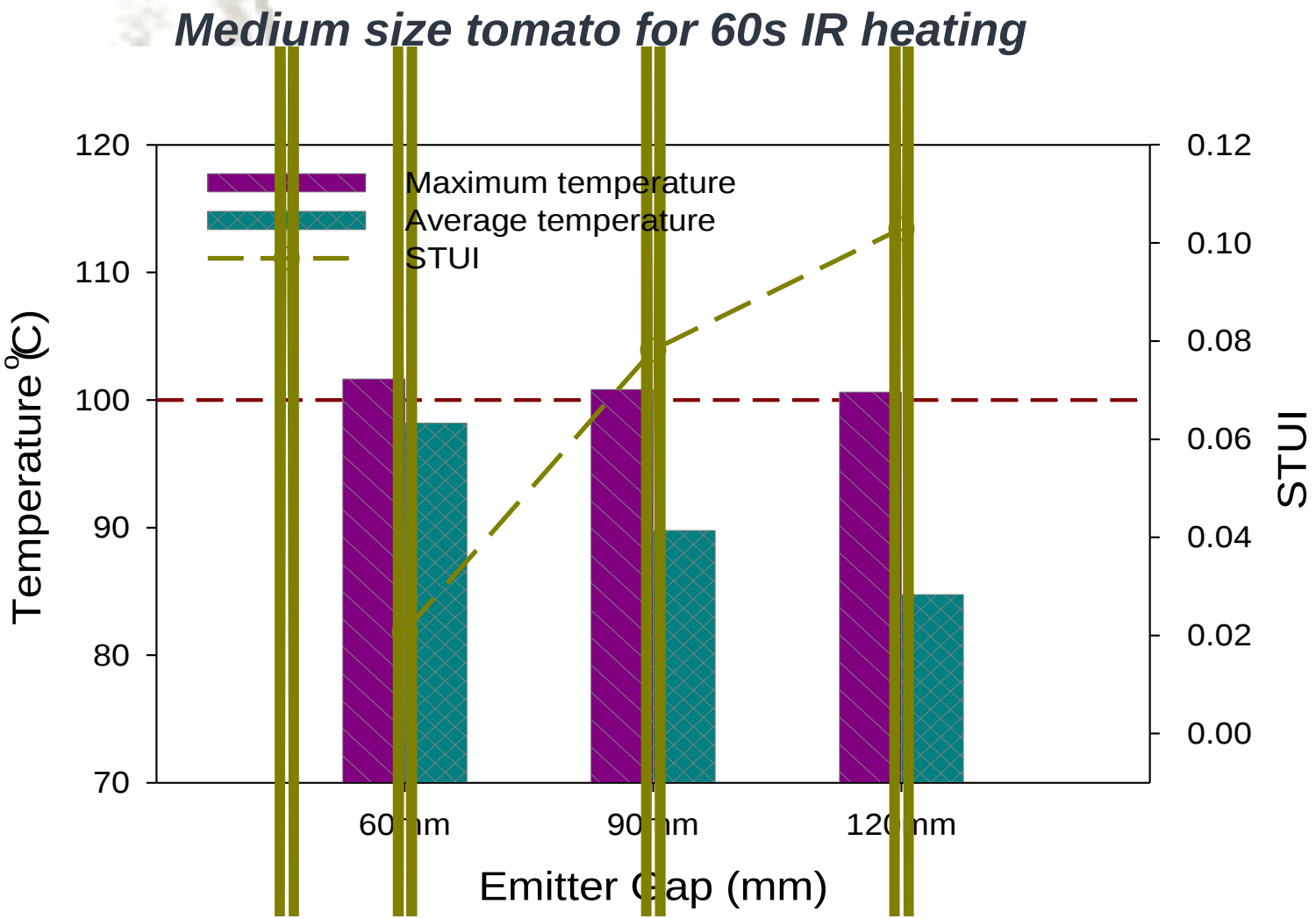
- Similar average and maximum surface temperature
- Different STUIs and overall energy absorption
- Sorting tomatoes according to their size or weight

Sensitivity Analysis —Initial Temperature of Tomatoes

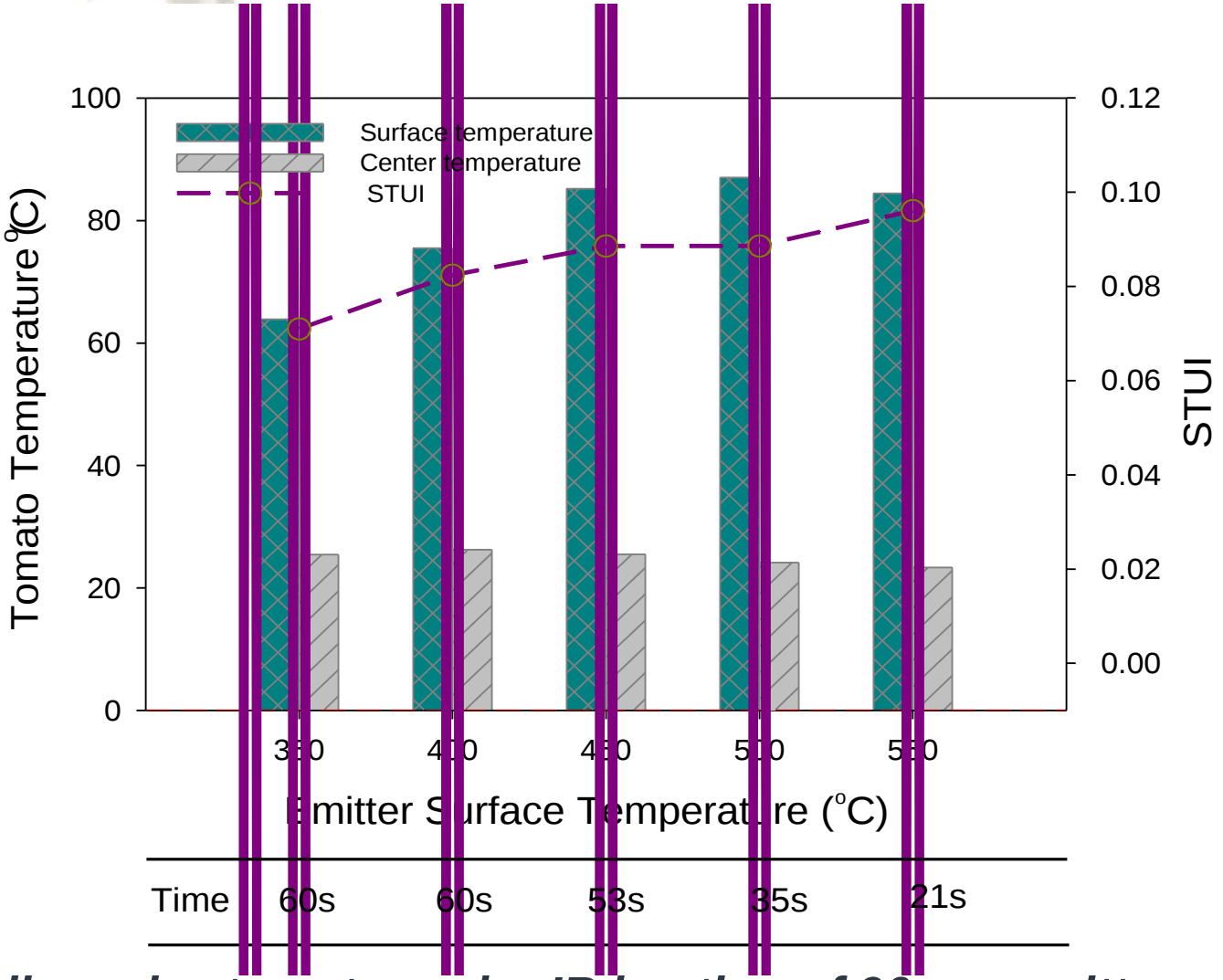


Medium size tomato for 60s IR heating of 90mm emitter gap

Sensitivity Analysis —Distance between the Emitters

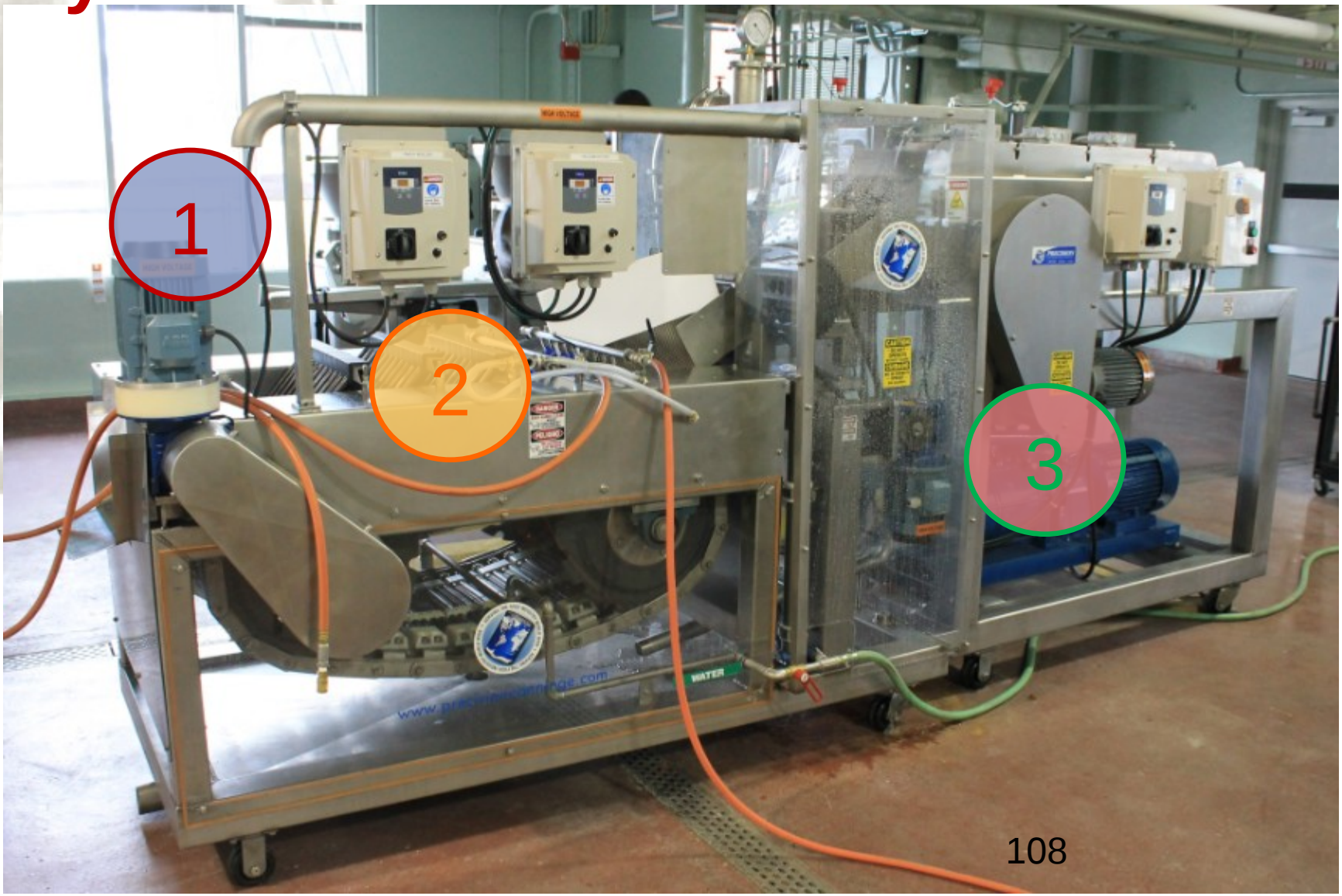


Sensitivity Analysis
— Emissive Power of the Emitters



Medium size tomato under IR heating of 90mm emitter gap

Pilot Scale Infrared Dry-Peeling System









BHAGWATI PRAKASH / UC DAVIS



Zhongli Pan, an adjunct professor in the Department of Biological and Agricultural Engineering at UC Davis, treats tomatoes with infrared heat to remove peels prior to processing.

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 lye 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



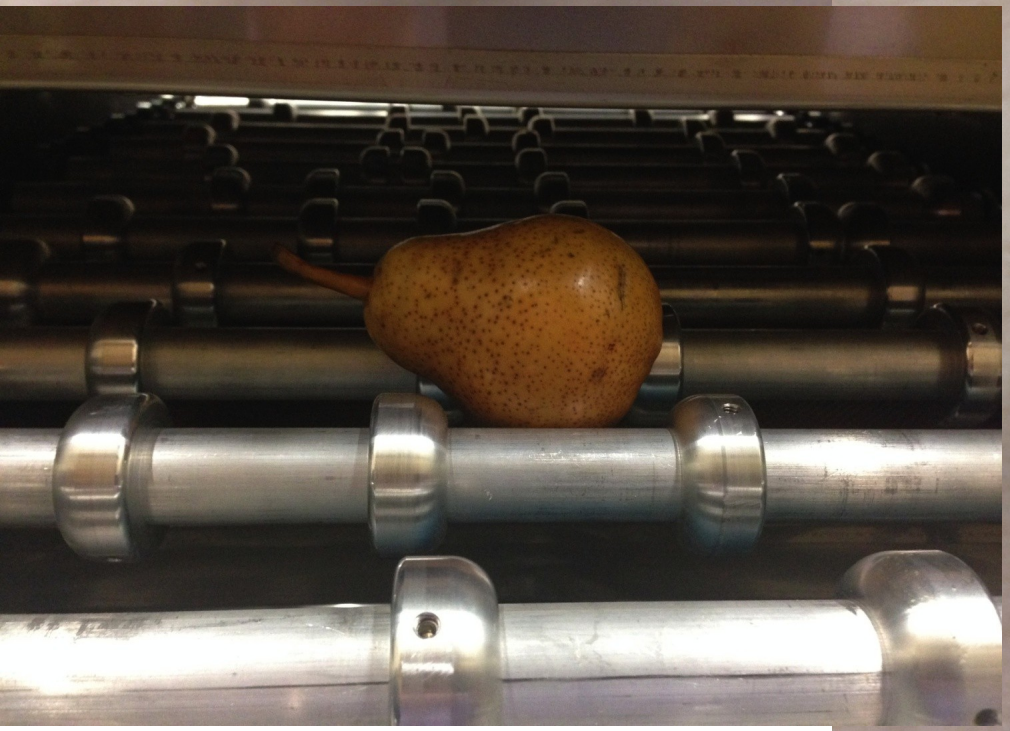


Before peeling
Small size tomatoes (42-46mm)

After peeling
Peeled under 130 s infrared heating





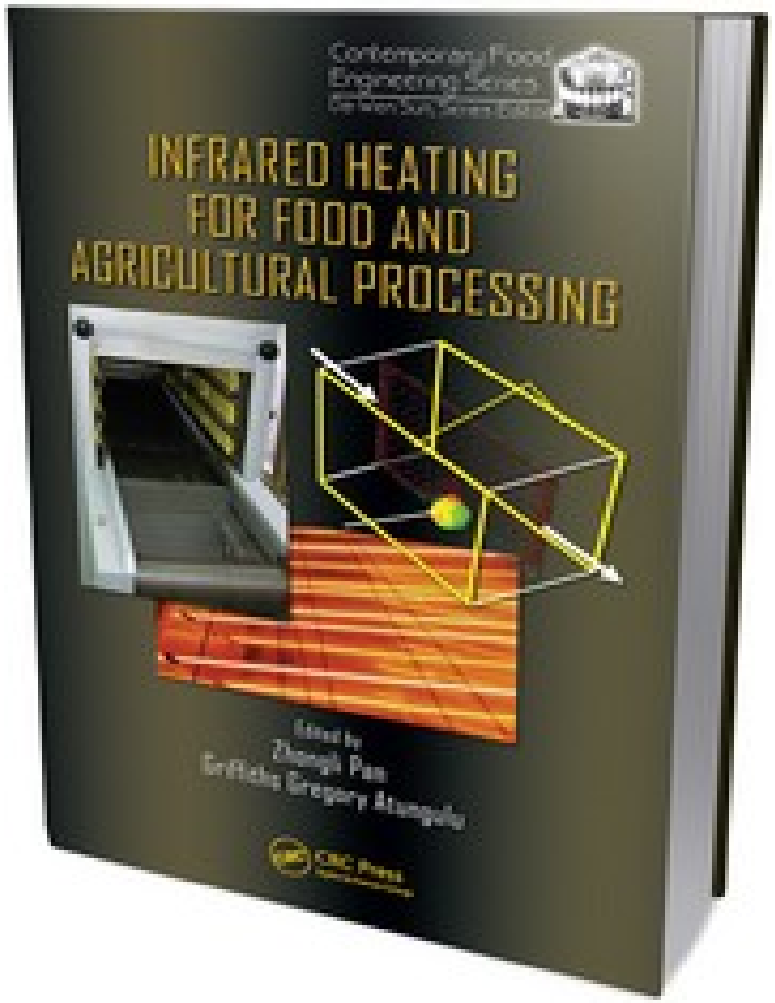




Conclusions

- 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


Contemporary Food Engineering Series
INFRARED HEATING FOR FOOD AND AGRICULTURAL PROCESSING
Zhongli Pan
Gregory Atungulu
CRC Press





United States Department Of Agriculture

Agricultural Research Service











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Farmers Rice Cooperative

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