Time-resolved NIRS and non-destructive assessment of food quality

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Non-destructive optical characterisation of internal optical properties and correlation with quality parameters

- Basic studies in apples, kiwifruits, nectarines, tomatoes, …
- Changes in optical properties during growth in Elstar apples and Tophit plums
- Texture in Jonagored apples, Braeburn apples and Pink Lady apples during storage

Non-destructive assessment of fruit maturity at harvest and correlation with quality parameters

- Basic studies in apples, kiwifruits, nectarines, peaches, mangoes, …
- Sensory attributes, aroma composition, ethylene production Ambra nectarines
- Softening prediction (based on biological age) in Spring Belle nectarines and in Tommy Atkins mangoes

Non-destructive detection of internal disorders and defects

- Browning in Granny Smith apples, Braeburn apples and Conference pears
- Watercore in Fuji apples
- Mealiness in Braeburn apples and Jonagored apples
- Chilling injuries in Jubileum plums and Morsiani 90 nectarines
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Optical characterization of foods absorption and scattering spectra

Cubeddu et al., Applied Optics 40:538-543 (2001)
Light absorption in the NIR fruit
Optical characterization of foods
effect of skin: Apple (cv. Golden Delicious)

No effect of the skin on the spectra of absorption and reduced scattering coefficients
Optical characterization of foods: effect of skin: Mango (cv. Palmer)

- Mangoes (cv Palmer) harvested in Minas Gerais (Brazil) and transported by plane to Milan (Italy)
- 20 mangoes selected
- 2 nearby regions on red (10 fruit) and green (10 fruit) side

intact areas

peeled areas
Experimental protocol

Measurements performed on both **pulp** and **skin**

- **TRS: 13 wavelengths** in the spectral range 540-900 nm
- **color measurements** with spectrophotometer (CM-2600d, Minolta):
  - spectral range: 360-740 nm;
  - color parameters: L*, a*, b* values → $C^* = [(a^*)^2 + (b^*)^2]^{-2}$
    → $H^\circ = \arctan(b^*/a^*)$.
    → absorbance
- **days 1, 4 and 11** of shelf life: temperature → 20±2°C; RH → 75±5%
TRS measurements:
Absorption and scattering spectra

green side

carotenoid accumulation
chlorophyll breakdown

red side

pulp day 1 skin day 4 day 11

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Color measurements: Absorbance

Green side:

- Pulp: day 1
- Skin: day 1, day 4, day 11

Red side:

- Carotenoid accumulation
- Chlorophyll breakdown
- Anthocyanin effect
**Correlations:**

absorption coefficients vs color parameters

**Pigment-related wavelengths:**

- 540, 580 nm → **carotenoids**
- 630, 650, 670, 690 nm → **chlorophyll**

**good correlations between pulp color and \( \mu_a \) from pulp and skin**

<table>
<thead>
<tr>
<th></th>
<th>( \mu_a^{540p} )</th>
<th>( \mu_a^{580p} )</th>
<th>( \mu_a^{630p} )</th>
<th>( \mu_a^{650p} )</th>
<th>( \mu_a^{670p} )</th>
<th>( \mu_a^{690p} )</th>
<th>( \mu_a^{540s} )</th>
<th>( \mu_a^{560s} )</th>
<th>( \mu_a^{630s} )</th>
<th>( \mu_a^{650s} )</th>
<th>( \mu_a^{670s} )</th>
<th>( \mu_a^{690s} )</th>
</tr>
</thead>
<tbody>
<tr>
<td><em><em>L^</em> pulp</em>*</td>
<td>-0.798</td>
<td>-0.597</td>
<td>0.313</td>
<td>0.438</td>
<td>0.566</td>
<td>0.431</td>
<td>-0.708</td>
<td>-0.009</td>
<td>0.560</td>
<td>0.600</td>
<td>0.452</td>
<td>0.541</td>
</tr>
<tr>
<td><em><em>a^</em> pulp</em>*</td>
<td>0.914</td>
<td>0.493</td>
<td>-0.565</td>
<td>-0.702</td>
<td>-0.725</td>
<td>-0.702</td>
<td>0.871</td>
<td>-0.041</td>
<td>-0.682</td>
<td>-0.742</td>
<td>-0.582</td>
<td>-0.717</td>
</tr>
<tr>
<td><em><em>b^</em> pulp</em>*</td>
<td>0.800</td>
<td>0.399</td>
<td>-0.563</td>
<td>-0.697</td>
<td>-0.689</td>
<td>-0.660</td>
<td>0.812</td>
<td>0.005</td>
<td>-0.573</td>
<td>-0.677</td>
<td>-0.282</td>
<td>-0.632</td>
</tr>
<tr>
<td><em><em>C^</em> pulp</em>*</td>
<td>0.816</td>
<td>0.416</td>
<td>-0.555</td>
<td>-0.689</td>
<td>-0.689</td>
<td>-0.659</td>
<td>0.825</td>
<td>0.012</td>
<td>-0.579</td>
<td>-0.682</td>
<td>-0.309</td>
<td>-0.635</td>
</tr>
<tr>
<td><strong>H° pulp</strong></td>
<td>-0.860</td>
<td>-0.417</td>
<td>0.620</td>
<td>0.763</td>
<td>0.749</td>
<td>0.724</td>
<td>-0.833</td>
<td>0.069</td>
<td>0.670</td>
<td>0.754</td>
<td>0.593</td>
<td>0.717</td>
</tr>
<tr>
<td><em><em>L^</em> skin</em>*</td>
<td>-0.378</td>
<td>-0.338</td>
<td>-0.012</td>
<td>0.036</td>
<td>-0.033</td>
<td>0.024</td>
<td>-0.354</td>
<td>-0.245</td>
<td>-0.096</td>
<td>0.036</td>
<td>0.198</td>
<td>0.075</td>
</tr>
<tr>
<td><em><em>a^</em> skin</em>*</td>
<td>0.702</td>
<td>0.556</td>
<td>-0.189</td>
<td>-0.263</td>
<td>-0.228</td>
<td>-0.248</td>
<td>0.555</td>
<td>0.128</td>
<td>-0.272</td>
<td>-0.321</td>
<td>-0.289</td>
<td>-0.354</td>
</tr>
<tr>
<td><em><em>b^</em> skin</em>*</td>
<td>-0.096</td>
<td>-0.203</td>
<td>-0.245</td>
<td>-0.221</td>
<td>-0.310</td>
<td>-0.246</td>
<td>-0.111</td>
<td>-0.320</td>
<td>-0.366</td>
<td>-0.243</td>
<td>0.006</td>
<td>-0.180</td>
</tr>
<tr>
<td><em><em>C^</em> skin</em>*</td>
<td>0.387</td>
<td>0.135</td>
<td>-0.429</td>
<td>-0.427</td>
<td>-0.510</td>
<td>-0.459</td>
<td>0.286</td>
<td>-0.339</td>
<td>-0.652</td>
<td>-0.578</td>
<td>-0.426</td>
<td>-0.509</td>
</tr>
<tr>
<td><strong>H° skin</strong></td>
<td>-0.494</td>
<td>-0.472</td>
<td>0.002</td>
<td>0.084</td>
<td>0.003</td>
<td>0.031</td>
<td>-0.492</td>
<td>-0.265</td>
<td>-0.008</td>
<td>0.087</td>
<td>0.194</td>
<td>0.108</td>
</tr>
</tbody>
</table>

\( p = \mu_a \) measured on the pulp; \( s = \mu_a \) measured through the skin

**poor correlations between skin color and \( \mu_a \)**
Conclusions

From measurements on exposed pulp and on skin, it results that:

- skin attenuates the TRS signal intensity
- skin does not affect the estimate of pulp optical properties

Absorption spectrum features:

- increase in the 540–600 nm range  
  → changes in the carotenoid content  
  → skin color measures are affected by other pigments
- decrease at 670 nm  
  → changes in the chlorophyll content

TRS non-destructive characterization of mango during ripening
Optical properties during growth
Absorption spectra

Chlorophyll breakdown in plum and apple, almost no changes in grapefruit.

Large changes during growth in the scattering properties for plum and grapefruit, minor changes for apple.

Optical properties
Effect of layered structure in grapefruit

Shorter distance: early photons travel in the albedo, late photons in the pulp
Longer distance: photon-path is mainly in the pulp
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Nondestructive assessment of maturity at harvest
Softening prediction in ‘Spring Belle’ nectarines

**Kinetic model** linking $\mu_a$ at 670 to firmness allowing softening prediction of individual fruit from $\mu_a$ measurement at harvest

$$F = \frac{F_{\text{max}} - F_{\text{min}}}{1 + e^{k_f \cdot (F_{\text{max}} - F_{\text{min}}) t + \Delta t_F^*}} + F_{\text{min}}$$

$$\Delta t_F^* = \alpha \left( \log \left( \frac{\mu_{a,\text{max}}}{\mu_a} - 1 \right) + \beta \right)$$

**Biological shift factor**

Tijskens et al., Int. J. Postharvest Technology and Innovation 1, 178-188 (2006)
Tijskens et al., Postharvest Biology and Technology 45, 204-213 (2007)

$\mu_a$ at 670 is an effective maturity index
Nondestructive assessment of maturity at harvest
Softening prediction in ‘Spring Belle’ nectarines

Distribution of biological shift factor at harvest with **Classes of usability**

Softness scores after transport and 5, 6, 13 days of shelf-life

**Classes of usability** successfully tested in an export trial from Italy to Netherlands

Eccher Zerbini et al., Biosystems Engineering 102, 360-363 (2009 in press)
Nondestructive assessment of maturity at harvest
Softening prediction in ‘Morsiani 90’ nectarines

Predicted firmness and measured firmness according to the biological shift factor model

The measured points are shifted in time according to the biological shift factor based on $\mu_a$ at harvest

Distribution of biological shift factor

Eccher Zerbini et al., Postharvest Biology and Technology 62, 275-281 (2011)
Maturity at harvest and shelf life in Tommy Atkins mangoes

**Absorption Spectra**
- **Day 0**
  - Carotenoids
  - Chlorophyll
- **Day 5**
  - 650 nm
  - 540 nm

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Maturity at harvest and shelf life in “Tommy Atkins” mangoes

Chlorophyll-a and carotenoids estimation from TRS
Open problem: extinction coefficient for carotenoids *in vivo*
Nondestructive assessment of maturity at harvest
Ethylene production in “Haden” mangoes

Ethylene production at harvest

Firmness at harvest

Nondestructive assessment of maturity at harvest
Ethylene production in “Haden” mangoes

Optical properties at harvest

- Chlorophyll: $\mu_a$ at 540 nm
- Carotenoids: $\mu_a$ at 670 nm

Nondestructive assessment of maturity at harvest
Ethylene production in “Haden” mangos

Biological shift factor model

\[ EP = \frac{EP_{\text{max}}}{1 + \exp(-\Delta t_{EP}^*)} \]

\[ F = F_{\text{min}} + \frac{F_{\text{max}} - F_{\text{min}}}{1 + \exp(\Delta t_{F}^*)} \]

\[ \Delta t_{EP}^* = \alpha_{540} \left( \log \frac{\mu_{a, \text{max}}^{540} - \mu_{a, 0}^{540}}{\mu_{a, 0}^{540} - \mu_{a, \text{min}}^{540}} \right) + \alpha_{670} \left( \log \frac{\mu_{a, \text{max}}^{670} - \mu_{a, 0}^{670}}{\mu_{a, 0}^{670} - \mu_{a, \text{min}}^{670}} \right) + \beta \]

\[ \Delta t_{F}^* = \alpha_{F,540} \left( \log \frac{\mu_{a, \text{max}}^{540} - \mu_{a, 0}^{540}}{\mu_{a, 0}^{540} - \mu_{a, \text{min}}^{540}} \right) + \alpha_{F,670} \left( \log \frac{\mu_{a, \text{max}}^{670} - \mu_{a, 0}^{670}}{\mu_{a, 0}^{670} - \mu_{a, \text{min}}^{670}} \right) + \beta_F + k_A A + k_B B \]

Ethylene production and firmness predicted by biological shift factor

Non-destructive evaluation of apple quality
Texture prediction in apples

Differently from nectarines and mangoes, apples ripening is not correlated only to chlorophyll content. Many factors are involved in the ripening process in apples.

**A more complex model is needed to describe the maturity**

An important parameter for quality in apples is **fruit texture**.

- The apple texture is linked to fruit structure at molecular, micro and macroscopic levels.
- Crispiness, juiciness and mealiness are bound to mechanical and acoustic properties of the pulp.
- Different apple texture are characterized by different pulp optical properties.

**Pulp optical properties measured by TRS**  **Fruit texture measured through mechanical-acoustic and sensory analysis**
Non-destructive evaluation of apple quality
Experimental protocol for season 2015/2016

- **Cultivar ‘Gala’:**
  - 270 apples
  - Measurements during shelf-life at harvest, after 2 and 4 months of CA storage

- **Cultivar ‘Kanzi’:**
  - 270 apples from Laimburg + 270 apples from Schudern
  - Measurements during shelf-life at harvest, after 3 and 6 months of CA storage

- **Cultivar ‘Braeburn’:**
  - 1320 apples
  - Harvested for 7 weeks (ripening on the tree) from inner and outer parts of the canopy
  - Measurements at harvest and after 2 of CA storage

**MONALISA Project:**
Monitoring key environmental parameters in the alpine environment involving science, technology and application
Non-destructive evaluation of apple quality

TRS measurements

- 3 maturity levels according to the chlorophyll content: less, medium, more
- Measurements of shelf-life at harvest
Non-destructive evaluation of apple quality
Texture Analysis

**SENSORY PROFILES** (firm, juicy, mealy, crispy)

**Relative intercellular space volume (RISV)** computed according to:
\[ \text{RISV} = 100 \times [1 - (\text{df}/\text{dj})] \]
where df=fruit density and dj=fruit juice density.

**MECHANICAL and ACOUSTIC PROPERTIES**
measured by using a TA-XT plus Texture Analyzer equipped with an acoustic emission detector (AED) which simultaneously profile a mechanical force displacement together with the corresponding acoustic response.

<table>
<thead>
<tr>
<th>MECHANICAL parameters</th>
<th>ACOUSTIC parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fmax</td>
<td>MEAN</td>
</tr>
<tr>
<td>St</td>
<td>MEAN</td>
</tr>
<tr>
<td>W</td>
<td>PK</td>
</tr>
<tr>
<td>E</td>
<td>acMAX</td>
</tr>
<tr>
<td>d</td>
<td>acFmax</td>
</tr>
<tr>
<td>F</td>
<td>dL</td>
</tr>
</tbody>
</table>
|\[ \frac{E_d}{1-\mu^2} = \frac{F}{(dL/2)^{3/2} D^{1/2}} \]

**NON destructive compression test**: each apple was compressed between two steel parallel plates to a fixed deformation of 1 mm (speed of 25 mm/min) and the modulus of deformability (Ed) was computed according to:

where: 
- F is the force at 1 mm of compression (N),
- dL is the total deformation (mm),
- D is the fruit diameter (mm);
- \(\mu\) is the Poisson’s ratio (0.3)
Non-destructive evaluation of apple quality
Main results

TRS optical properties and fruit texture

In the PCA plot:
• CHL content measured by TRS is positively related to Ed
• $\mu'$s (MUS) measured by TRS is positively related to RISV and mealiness and negatively to mechanical and acoustic parameters and to water content (H2O) measured by TRS
• sensory firmness, crispness and juiciness are positively related to mechanical and acoustic parameters

• PC1 distinguished Kanzi from Braeburn and Gala
  Kanzi had a compact, firm and crispy texture with higher H2O content and lowest MUS and RISV
• PC2 distinguished Braeburn from Gala
  Braeburn had higher CHL content, lowest acoustic parameters and a mealy texture
  Gala had higher MUS and RISV, easily deformable, moderately firm and crisp
Non-destructive evaluation of apple quality
Main results

Firmness prediction from TRS optical properties

Multiple Linear Regression model
(MUS=scattering value; CHL=chlorophyll content; H₂O=water content; \( \mu a_{670H} = \mu a_{670} \) at harvest)

**Gala**

\[
\text{firmness} = 2.35 - 1.58 \times \text{MUS} + 42.96 \times \text{CHL} + 69.82 \times \text{H}_2\text{O}
\]

\( R^2 \text{ adj} = 0.53 \)

**Kanzi after storage**

\[
\text{firmness} = 161.77 + 16.50 \times \text{CHL} - 110.6 \times \text{H}_2\text{O} - 1.30 \times \text{MUS} + 482.1 \times \mu a_{670H}
\]

\( R^2 \text{ adj} = 0.58 \)

**Braeburn**

\[
\text{firmness} = 59.82 + 1.18 \times \text{MUS} + 3.24 \times \text{CHL}
\]

\( R^2 \text{ adj} = 0.47 \)

These models are significant at \( P<0.0001 \) but explain only about 47-58% of the variability of the three cultivars
Non-destructive evaluation of apple quality
Main results

Relationships between apple texture and TRS optical properties – Gala

• CLUSTER ANALYSIS ON SENSORY ATTRIBUTES

<table>
<thead>
<tr>
<th>Cluster number and sensory profiles</th>
<th>firm</th>
<th>juicy</th>
<th>mealy</th>
<th>crispy</th>
<th>Nobs</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1 - very firm, juicy and crispy. Not mealy</td>
<td>76</td>
<td>68</td>
<td>19</td>
<td>59</td>
<td>53</td>
</tr>
<tr>
<td>W2 - firm and juicy</td>
<td>65</td>
<td>46</td>
<td>24</td>
<td>45</td>
<td>72</td>
</tr>
<tr>
<td>W3 - quite firm, juicy, crispy, mealy</td>
<td>43</td>
<td>44</td>
<td>32</td>
<td>31</td>
<td>69</td>
</tr>
<tr>
<td>W4 - mealy</td>
<td>27</td>
<td>32</td>
<td>46</td>
<td>17</td>
<td>76</td>
</tr>
</tbody>
</table>

• TRS PARAMETERS DIFFERED WITH SENSORY PROFILES

<table>
<thead>
<tr>
<th></th>
<th>CHL</th>
<th>H2O</th>
<th>µ's</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>µM-1</td>
<td>%</td>
<td>cm-1</td>
</tr>
<tr>
<td>W1</td>
<td>0.395a</td>
<td>93.9a</td>
<td>17.3a</td>
</tr>
<tr>
<td>W2</td>
<td>0.382ab</td>
<td>92.3b</td>
<td>16.8a</td>
</tr>
<tr>
<td>W3</td>
<td>0.325bc</td>
<td>92.1b</td>
<td>17.1a</td>
</tr>
<tr>
<td>W4</td>
<td>0.270c</td>
<td>92.1b</td>
<td>17.4a</td>
</tr>
</tbody>
</table>

• DISCRIMINANT ANALYSIS

Non-destructive TRS parameters (chlorophyll and water contents, scattering) were used as explanatory variables to discriminate the sensory profiles obtained by Cluster Analysis

CLASSIFICATION TABLE at harvest

<table>
<thead>
<tr>
<th>actual CLUSTER</th>
<th>Group Size</th>
<th>Predicted Cluster</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>W1</td>
</tr>
<tr>
<td>W1</td>
<td>36</td>
<td>86.1</td>
</tr>
<tr>
<td>W2</td>
<td>14</td>
<td>28.6</td>
</tr>
<tr>
<td>W3</td>
<td>24</td>
<td>25.0</td>
</tr>
<tr>
<td>W4</td>
<td>16</td>
<td>12.5</td>
</tr>
</tbody>
</table>

At harvest: only 63.3% well-classified fruit, even if very firm and juicy apples were well-classified in 86.1% of the cases

After storage: the performance of the model worsened (34.4%)

All data: the performance of the model was 41.1%
Both for Gala and Kanzi, fruit classified at harvest according to $\mu_a670$ had different firmness, crispness (acPK) deformability and RISV and developed different sensory profiles.

**Gala:** less mature apples were characterized by high % of firm and very firm texture; more mature apples had the highest % of mealy texture.

**Kanzi – Laimburg:** less mature apples had the highest % of firm and crispy texture (CL1) and the lowest of mealy; more mature apples had the highest % of mealy texture and of apples with low cispyness (CL2);

**Schlundern:** the % of very firm, juicy and crispy apples (CL1) was evenly distributed among the 3 classes; more mature apples showed the highest % of low juicy texture (CL3) and of mealy.
Non-destructive evaluation of apple quality
TRS perspectives

- **Feasibility** (now)
  - we demonstrate the possibility to perform spectral TRS measurements on apples with a portable instrumentation
  - non-destructive assessment of flesh chlorophyll content and scattering properties
  - Outcome for optical properties:
    - low correlation with firmness: ~50% (Magness Taylor)
    - better correlations with sensory profiles in some cases: contrasted results

- **Potential** (future)
  - instrumental viewpoint: there is room for smaller (more portable) instrument with reduced number of wavelengths (probably 2)

- **Gaps to be covered** (technological)
  - measurements speed: now TRS measures are too slow for inserting TRS in a sorting line. Instrument developments and feasibility test are needed

- **Alternatives**
  - possibility to non-destructively predict sensory characteristics of apples
Non-destructive evaluation of apple quality
TRS measurements in the orchards

Development of a transportable TRS set-up for measurements in the orchards

Photo of the TRS set-up

USER-PA Project:
Usability of environmentally sound and reliable techniques in precision agriculture
Non-destructive evaluation of apple quality
TRS measurements in the orchards

Experimental protocol

- Apple, cv. “Gala Brookfield”
- Orchards in Changins (Switzerland)
- 21 trees = 3 trees x 7 irrigation sectors
  (at least 4 apples from each tree)

<table>
<thead>
<tr>
<th></th>
<th>25/06/2014</th>
<th>22/07/2014</th>
<th>03/09/2014</th>
</tr>
</thead>
<tbody>
<tr>
<td># fruit</td>
<td>108</td>
<td>105</td>
<td>126</td>
</tr>
</tbody>
</table>

ETP = potential evapotranspiration
Preliminary results of field trials 2014

**Absorption coefficient**


No changes with irrigation due to excess raining in season
Conclusions

A portable TRS setup was developed to allow TRS measurements in the orchards

TRS measurements in the orchards are feasible
  - need to shield the fruit from sun light during measurement
  - June seems too early for reliable chlorophyll absorption measurements

Results are in agreement with previous measurements on harvested fruits
  - chlorophyll absorption in the fruit pulp decreases during growth
  - scattering changes may affect readings by continuous wave optical sensors
Photonics for Food @ PoliMi
Main applications

Non-destructive optical characterisation of internal optical properties and correlation with quality parameters

- Basic studies in apples, kiwifruits, nectarines, tomatoes, …
- Changes in optical properties during growth in Elstar apples and Tophit plums
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Non-destructive assessment of fruit maturity at harvest and correlation with quality parameters

- Basic studies in apples, kiwifruits, nectarines, peaches, mangoes, …
- Sensory attributes, aroma composition, ethylene production Ambra nectarines
- Softening prediction (based on biological age) in Spring Belle nectarines and in Tommy Atkins mangoes

Non-destructive detection of internal disorders and defects

- Browning in Granny Smith apples, Braeburn apples and Conference pears
- Watercore in Fuji apples
- Mealiness in Braeburn apples and Jonagored apples
- Chilling injuries in Jubileum plums and Morsiani 90 nectarines
Nondestructive detection of internal defects
Brown heart in Conference pears

Brown heart for $\mu_a @ 720$ nm > 0.04 cm$^{-1}$

Non-destructive detection of internal defects
Internal browning in “Braeburn” apples

HEALTHY

SLIGHT

MODERATE

SEVERE

BROWN CORE

BROWN PULP
Non-destructive detection of internal defects
Internal browning in “Braeburn” apples

Largest differences between healthy and browned apples at 740-780 nm

$\mu_a$ @ 740-780 nm can be selected to distinguish healthy from browned apples
## Classification table according to internal browning presence

<table>
<thead>
<tr>
<th>Year</th>
<th>TRS variables</th>
<th>Classification table</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Actual class</td>
</tr>
<tr>
<td>2009</td>
<td>$\mu_a 670, \mu_a 740-1040, \mu_s 780$</td>
<td>Healthy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Brown core</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Brown pulp</td>
</tr>
<tr>
<td></td>
<td>$\mu_a 780, \mu_s 780$</td>
<td>Healthy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Brown core</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Brown pulp</td>
</tr>
<tr>
<td>2010</td>
<td>$\mu_a 780, \mu_s 780$</td>
<td>Healthy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Brown core</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Brown pulp</td>
</tr>
</tbody>
</table>

Overall, healthy apples and apple with internal browning are classified well in about 70% of the cases.

Vanoli et al., Postharvest Biology and Technology 91:112-121 (2014)
Non-destructive detection of internal defects
Internal browning in “Braeburn” apples

Brown core – well classified

Brown core – misclassified

Brown pulp – well classified

Brown pulp – misclassified
Low temperature disorders limit the storage life of peaches and nectarines under refrigeration.

Chilling injury (CI) is classified as internal breakdown

- Wooliness
- Internal browning
- Internal bleeding (flesh reddening)
Non-destructive detection of internal defects
Chilling injury in “Morsiani 90” nectarines

Fruit stored @ 0°C and 4°C for 4 weeks

In fruit stored @ 4°C after 4 days
there were no healthy fruit

Severity index
0.3 → no fruit with defect
1.0 → all fruit with defects
Non-destructive detection of internal defects
Chilling injury in “Morsiani 90” nectarines

Absorption coefficients

At harvest, $\mu_a @ 670$ nm decreases due to fruit ripening
After storage @ 0°C, $\mu_a @ 780$ nm increases
After storage @ 4°C, $\mu_a @ 670$ nm and $\mu_a @ 780$ nm increase

Lurie et al., Postharvest Biology and Technology 59:211-218 (2011)
Non-destructive detection of internal defects
Chilling injury in “Morsiani 90” nectarines

Absorption coefficients @ 670 and 780 nm

μₐ@780 nm can distinguish healthy fruit from chilling injured ones

Lurie et al., Postharvest Biology and Technology 59:211-218 (2011)
During cold storage plums are susceptible to developing internal disorders:

- Flesh browning
- Jellying (gel-like glassy structure)

CI depends on cultivar, fruit maturity, orchard factors and storage temperature.
Fruit stored @ 1°C and 4°C for 3 weeks

The amount of jellying and internal browning was graded on a scale ranging from 0 = healthy to 10 = 100% of affected area.

Non-destructive detection of internal defects
Chilling injury in “Jubileum” plums

After storage, $\mu_a @ 670 \text{ nm}$ and $\mu_a @ 780 \text{ nm}$ increase during shelf life

This trend reflects the development of CI

Non-destructive detection of internal defects
Chilling injury in “Jubileum” plums

Correlation coefficients between internal disorders and TRS parameters after storage at 1°C and 4°C ($n = 275$).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Jellying (0-10 scale)</th>
<th>Browning area (0-10 scale)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_a@670$</td>
<td>0.68***</td>
<td>0.77***</td>
</tr>
<tr>
<td>$\mu_a@780$</td>
<td>0.70***</td>
<td>0.76***</td>
</tr>
<tr>
<td>$\mu_s@670$</td>
<td>-0.01 n.s.</td>
<td>0.03 n.s.</td>
</tr>
<tr>
<td>$\mu_s@780$</td>
<td>-0.06 n.s.</td>
<td>-0.09 n.s.</td>
</tr>
</tbody>
</table>

*** $p<0.001$; n.s.=Not significant correlation at 5% level.

- $\mu_a@670$ nm and $\mu_a@780$ nm can distinguish healthy fruit from those affected by internal disorders
- Reduced scattering coefficients not influenced by CI development

## Photonics for Food @ PoliMi

### Research activities

#### Projects
- DIFFRUIT, EU FP4, 1996-1999
- TRS APPLE, MAFF (UK), 2000
- AGROTEC, MIUR (I), 2000-2002
- CUSBO, LASERLAB, EU FP5+FP6+FP7, 2004-2014
- INSIDEFOOD, EU FP7 2009-2013
- TROPICO, Regione Lombardia (I), 2010-2012
- 3D Mosaic, EU ICT-AGRI, 2011-2013
- USER-PA EU ICT-AGRI 2013-2016
- MONALISA 2014-2016

#### Publications (2001-2013)
- >30 papers published on peer reviewed international journals
- >30 papers on international books and proceedings
- >30 talks on international conferences

#### Collaborations
- CREA-IT, Milan (I), Anna Rizzolo, Maristella Vanoli, Maurizio Grassi
- Laimburg (I), Angelo Zanella
- Agricultural Research Organization, Bet Dagan (Israel), Susan Lurie, Victor Alchanitis
- Wageningen Universiteit (NL), Pol Tijskens, Olaf Van Kooten, Rob Schouten
- Planteforsk, Lofthus (N), Eivind Vangdal
- Potsdam (D), Manuela Zude-Sasse
- Leuven (B), Bart Nicolai, Bert Verlinden, Wouter Sayes, Pieter Verboven, Maarten Hertog
- UPM, ETSI Agronomos Madrid (E), Margarita Ruiz-Altisent, Constantino Valero
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  ▪ Anna Rizzolo
  ▪ Maristella Vanoli
  ▪ Maurizio Grassi
  ▪ (Paola Eccher Zerbini)

• Research Centre for Agriculture and Forestry, Laimburg (Italy)
  ▪ Angelo Zanella