Characterizing Apple Texture During Storage Through Mechanical, Sensory And Optical Properties

M. Vanoli[1,2], A. Rizzolo[1], M. Grassi[1]
[1] CRA-IAA,
via Venezian, 26 Milano, Italy

L. Spinelli[4]
[4] Istituto Fotonica e Nanotecnologie,
CNR, Piazza L. da Vinci, 32, Milano, Italy

A.Zanella[3]
Laimburg Research Centre for Agriculture and Forestry, Laimburg 6
Vadena, Posta Ora (BZ), Italy

A. Torricelli[2]
[2]Politecnico di Milano, Dipartimento di Fisica
Piazza L. da Vinci, 32, Milano, Italy

Keywords: TRS, absorption coefficient, scattering coefficient, cluster analysis, models

Abstract

Texture is a sensory property affecting consumer acceptability and it is dependent on pulp structure. Often, changes in fruit texture are accompanied by changes in the optical properties of the flesh. The absorption (μ_a) and the scattering (μ_s') coefficients, nondestructively measured in the fruit pulp by time-resolved reflectance spectroscopy (TRS), have been found to be linked to firmness, intercellular spaces, pectic composition and additionally to be correlated with sensory attributes. This research aimed at characterizing apple texture through mechanical, sensory and optical properties during long-term storage in order to understand whether optical measurements can be used to discriminate apples with different textural properties. 'Braeburn' apples, picked with 1 week interval at beginning, mid and end of the optimal harvest window for controlled atmosphere storage, were measured at harvest by TRS at 670 nm (μ_a670), ranked by decreasing μ_a670 (increasing maturity), classified as less (LeM), medium and more (MoM) mature, randomized into 3 batches of 30 fruit/harvest for analyses at harvest and after 3 and 7 months of cold storage (1.3 °C) in controlled atmosphere (1.5% O_2, 1.3% CO_2), respectively. LeM and MoM fruit were measured by TRS in the 540-880 nm range and analyzed for mechanical (firmness, stiffness, energy-to-rupture) and sensory (firm, crispy, juicy, mealy) attributes. Cluster analysis applied on mechanical attributes produced four data sets having distinctive textural profiles. W1 apples were characterized by a very firm texture, and showed the highest scores for sensory firmness, crispness and juiciness and the highest μ_a670 values. In contrast, W3 apples having a soft texture, were judged as the most mealy and the least firm, juicy and crispy and had the lowest μ_a670 values and the highest scatterer density. TRS optical properties allowed to distinguish well enough very firm apples from mealy ones, while they did not separate apples with intermediate texture due to the fact that these fruit differed for mechanical properties but not so clearly for sensory and optical characteristics.

INTRODUCTION

Knowledge of textural properties, such as firmness, is important for apple industry in order to establish the proper harvest date, the right storage requirements (duration, temperature, atmosphere) and to meet consumer preference and acceptability.

Texture is a sensory property dependent on mechanical and structural characteristics of the fruit pulp. Textural changes due to fruit softening involve degradation and modifications of the cell wall and middle lamella structures, loss of turgor pressure, starch degradation with pectic substances playing a key role (Gwanpua et al., 2014). The changes in cohesion of the pectin matrix determines the final texture of the ripe fruit. When cell-to-cell adhesion is weaker than the individual cell walls, cell separation occurs and the intact cells are responsible for the mealy texture; on the contrary, when the individual cell walls are weaker than cell-to-cell adhesion, cell wall breakage occurs and the cellular content is released producing a juicy texture (Harker et al., 2002).

Changes in fruit texture cause variations of the optical properties of the flesh, thus extensive studies have been carried out over the past decades on the development of non destructive optical techniques. Conventional VIS/NIR spectroscopy measures an aggregate amount of light reflected back or transmitted through the samples while scattering techniques, such as time-resolved reflectance spectroscopy (TRS) and spatially resolved spectroscopy allow to separate the scattering and the absorption phenomena linked to the structure and to the chemical composition of the sample, respectively (Nicolai et al., 2014).

TRS measures the distribution of photon time-of-flight at the picoseconds or nanosecond timescale at a fixed source-detector distance through pulsed laser sources and fast detection techniques (Torricelli et al., 2008). TRS probes the fruit pulp up to 1-2 cm depth without being significantly affected by surface features allowing the simultaneous measurement of the absorption coefficient (μ_a) and of the reduced scattering coefficient (μ_s') (Cubeddu et al., 2001; Saeys et al., 2008; Torricelli et al., 2008; Seifert et al., 2014). In previous studies, TRS has been used to assess maturity, texture and cell wall structure in intact apples. The μ_a measured at 670 nm (μ_a670) can be considered a maturity index for apples as it significantly decreases during fruit growth, at delayed harvest dates and during shelf life at 20°C (Rizzolo et al., 2010; Vanoli et al., 2011 and 2013; Zanella et al., 2013; Seifert 2014). The μ_a670 also went decreasing during fruit softening and was positively correlated with pectin solubilization (Vanoli et al., 2009). Apples with high μ_a670 values (less mature) showed higher firmness and were perceived more firm, crispy and juicy but less mealy than apples with low μ_a670 values, (more mature) (Vanoli et al., 2013; Rizzolo et al., 2014). Also the scattering coefficients change according to the textural characteristics of the pulp. The μ_s' values increased with apple softening and when fruit texture changed from very firm and crispy to mealy; negative correlations of μ_s' with mechanical firmness and sensory firmness, crispness and juiciness were observed, whereas positive correlations were found between μ_s', pectin breakdown and intercellular spaces (Vanoli et al., 2009 and 2010; Rizzolo et al., 2010 and 2014).

This research aimed at characterizing apple texture through mechanical, sensory and optical properties during long-term storage in order to understand whether optical measurements can be used to discriminate apples with different textural properties.

MATERIALS AND METHODS

'Braeburn' apples were picked in 2011 at the experimental orchard in Laimburg (Bolzano, Italy) with 1 week interval at beginning, mid and end of the optimal harvest window for controlled atmosphere storage. Ninety apples/harvest were measured at harvest on two sides by TRS at 670 nm and ranked within each harvest date on the basis of decreasing μ_a670 (increasing maturity) averaged on the two fruit sides. Ranked fruit of each harvest were divided into 30 groups, corresponding to 30 μ_a670 levels; 10, less mature (LeM, batch ranks 1-10); 10, medium mature; 10, more mature (MoM, batch ranks 21-30) TRS maturity classes. The three fruit from every group were randomized into 3 batches in order to have fruit from the whole range of μ_a670 in each sample. The three batches were randomly assigned to 3 times of analysis: at harvest and after 3 and 7 months of storage at 1.3°C in controlled atmosphere (1.5% O_2, 1.3% CO_2). At each time of analysis, LeM and MoM fruit were measured by TRS in the 540-880 nm range on two opposite sides (the blush side and the opposite one) and data were averaged per fruit. The same fruit were analyzed for mechanical properties (firmness, stiffness, energy-to-rupture) and were submitted to sensory analysis (firmness, crispiness, juiciness, mealiness).

TRS measurements were performed using a set-up developed by Politecnico di Milano (Seifert et al., 2014). A model for photon diffusion in turbid media was used to analyze TRS data to assess μ_a and μ_s' of samples (Martelli et al., 2009). An approximation to the Mie theory was used to relate the μ_s' to the structural properties of the diffusive sample: $\mu_s' = A\ (\lambda/\lambda_0)^{-B}$, where λ is the wavelength, A is the scattering coefficient at wavelength λ_0=600 nm, and B is a parameter related to the size of scatterers.

Firmness was measured with an 11 mm diameter plunger mounted on an Instron Universal Testing Machine Model 4301 (Instron Ltd, High Wycombe, UK) with crosshead speed of 200 mm/min to a depth of 8 mm on two peeled areas (blush and opposite side) per fruit. The applied force was recorded. From the force–displacement curve the following variables were recorded: flesh firmness (F), stiffness (St) and energy-to-rupture (E_f) according to Mehinagic et al. (2003). Firmness, stiffness and energy-to-rupture readings were averaged for each fruit.

Sensory analyses were carried out with the aid of a panel of ten short-term-trained judges comparing apples of the LeM and MoM TRS classes coming from the three harvests. In each session, one peeled slice/fruit of LeM and MoM classes from each harvest date, coded with three digit random numbers, were presented to each panelist. In order to have the same differences in maturity (μ_a670) among fruit for all the ten assessors, fruit presented to each panelist had the same rank position in the samples. At the beginning of each session, a slice of a fruit not included in the experimental plan was tasted to eliminate the first tasting effect. Each sample was evaluated for the intensity of attributes related to fruit structure (firm, crispy, juicy and mealy) using 120 mm unstructured line scales with anchors at 12 mm from the extremes (low, high). Prior to statistical analyses, the rating scores of each attribute were standardized by panelist according to Bianchi et al. (2009) in order to remove the variability due to panelists using different parts of the scale.

According to mechanical properties, fruit were clustered into four groups, each one representing a specific textural profile, applying the Ward's clustering method and squared Euclidean distance. Data of μ_a670 and mechanical properties were submitted to ANOVA considering harvest date and storage month as factors (means compared by Tukey's test at $P \leq 0.05\%$). TRS optical properties, mechanical and sensory data were submitted to ANOVA considering as factor the four clusters (means compared by Bonferroni's test at $P \leq 0.05\%$). Classification models were developed using TRS optical properties as explanatory variables in the Linear Discriminant Analysis in order to discriminate fruit with different texture. ANOVA, Cluster Analysis and Discriminant Analysis were performed using Statgraphics ver.7 (Manugistic Inc., Rockville, MD, USA) software package.

RESULTS AND DISCUSSION

The μ_a670 significantly decreased with delaying harvest date and with storage time (Table 1). Firmness and stiffness did not change with harvest date, while E_f showed the least values in apples from third harvest (H3) (Table 1). Firmness and E_f decreased during storage, showing the highest values at harvest and the least after 7 months, whereas stiffness had the highest values at harvest, decreased after 3 months of storage without any changes up to the end of the storage period .

Cluster analysis (Fig. 1 and 2) applied on mechanical attributes produced four data sets having distinctive textural profiles according to the descriptions and centroids values reported in Table 2. W1 set grouped the apples with the highest values of firmness, stiffness and E_f mainly belonging to LeM fruit at harvest. W2 set grouped apples with high values of firmness and E_f and intermediate values of stiffness mainly belonging to fruit at harvest and stored for 3 months, without distinction between TRS maturity classes. W3 set had the least values of firmness and stiffness and intermediate values of E_f and grouped MoM stored apples. W4 set grouped apples with intermediate firmness, high stiffness and the least E_f mainly belonging to the H3 and stored for 7 months.

Sensory profiles and optical properties significantly changed according to the textural profiles obtained by cluster analysis. Considering sensory attributes (Fig. 3), W1 textural profile grouped apples judged as the most firm, crispy and juicy while W3 set grouped apples scored as the most mealy with the least values for firm, crispy and juicy. W2 textural profile showed high scores for firmness, crispness, juiciness and least values for mealiness, while W4 profile was characterized by intermediate scores for each sensory attribute.

The absorption spectra (Fig. 4, left) showed a peak at 670 nm (chlorophyll-*a*); μ_a670 had the highest values in W1 profile and the least in the W3 one. The μ_a measured in the 690-880 nm range distinguished W1, W2 and W3 sets, while W4 had intermediate values between W2 and W3. The scattering spectra (Fig. 4, right) slightly decreased as wavelength increased; apples belonging to W3 cluster showed the highest scattering values, while no difference was found among the other three clusters. The same behavior was observed for the parameter A, related to the density of the scatterers, while the parameter B, linked to the size of the scattering centers, showed similar values for the four clusters (Fig. 4, right).

The optical properties measured by TRS were used as explanatory variables in the linear discriminant analysis in order to classify apples according to the textural profiles determined by Cluster analysis. The best classification performance was obtained using the μ_a measured in the 540-880 nm range plus the scattering parameters A and B. Two discriminant functions (DF) were obtained: DF1 (78.2% of the variance, with a significant ($P < 0.0001$) canonical correlation of 0.703) had high negative coefficient for μ_a650 (–16.78), and positive for μ_a670 (8.95) and μ_a630 (6.51); DF2 (18.8% of the variance, with a significant ($P = 0.0057$) canonical correlation of 0.436) had higher and opposite coefficients for μ_a630 (9.98), and μ_a650 (–9.23). The values of the two DF for each fruit and the group (textural profile) centroids are plotted in Fig. 5. DF1 discriminated all the textural profiles, while DF2 discriminated W1 and W3 profiles from W2 and W4 ones. Textural profiles were correctly classified in 58-61% of the cases. Incorrectly classified apples belonging to W1 fall in W2 profile and only 3% of fruit were considered W3; while incorrectly W3 fruit fall in W2 and W4 profiles and no fruit was classified in W1.

CONCLUSIONS

Our results showed that different texture characteristics determined different sensory profiles together with changes in absorption and scattering properties. W1 apples characterized by a very firm texture showed the highest scores for sensory firmness, crispness and juiciness and the highest μ_a670 values. In contrast, W3 apples having a soft texture, were judged as the most mealy and the least firm, juicy and crispy and had the lowest μ_a670 values and the highest scatterer density. TRS optical properties allowed to distinguish well enough very firm apples from mealy ones, while they did not separate apples with intermediate texture due to the fact that for these fruit the differences in mechanical properties were not clearly distinguishable by sensory and optical characteristics.

ACKNOWLEDGEMENTS
Part of the presented work was carried out in the framework of the project 'Monitoring key environmental parameters in the alpine environment involving science, technology and application' (MONALISA), funded by the Autonomous Province of Bolzano (Italy).

Literature cited

Bianchi, G., Eccher Zerbini, P. and Rizzolo, A. 2009. Short-term training and assessment for performance of a sensory descriptive panel for the olfactometric analysis of aroma extracts. J. Sensory Stud. 24:149-165.

Cubeddu, R., D’Andrea, C., Pifferi, A., Taroni, P., Torricelli, A., Valentini, G., Ruiz-Altisent, M., Valero, C., Ortiz, C., Dover, C. and Johnson, D. 2001. Time-resolved reflectance spectroscopy applied to the non-destructive monitoring of the internal optical properties in apples. Appl. Spectr. 55:1368-1374.

Gwanpua, S.G., Buggenhout, S.V., Verlinden, B.E., Christiaens, S., Shpigelman, A., Vicent, V., Kermani, Z.J., Nicolai, B.M, Hendrickx, M. and Geeraerd, A.H. 2014. Pectin modifications and the role of pectin-degrading enzymes during postharvest softening of Jonagold apples. Food Chem. 158:283-291.

Harker, F.R., Maindonald, J., Murray, S.H., Gunson, F.A. and Walker, S.B. 2002. Sensory interpretation of instrumental measurements 1: texture of apple fruit. Postharvest Biol. Technol. 24:225-239.

Martelli, F., Del Bianco, S., Ismaelli, A. and Zaccanti, G. 2009. Light propagation through biological tissue and other diffusive media: theory, solutions, and software, Washington, USA, SPIE Press.

Mehinagic, E., Royer, G., Bertrand, D., Symoneaux, R., Laurens, F. and Jourjon, F. 2003. Relationship between sensory analysis, penetrometry and visible-NIR spectroscopy of apple belonging to different cultivars. Food Qual. Pref. 14:473-484.

Nicolai, B.M., Defraeye, T., De Ketelaere, B., Herremans, E., Hertog, M.L.A.T.M., Saeys, W., Torricelli, A., Vandendriessche, T. and Verboven, P. 2014. Nondestructive measurement of fruit and vegetable quality. Annu. Rev. Food Sci. Technol. 5:285-312.

Rizzolo, A., Vanoli, M., Spinelli, L. and Torricelli, A. 2010. Sensory characteristics, quality and optical properties measured by time-resolved reflectance spectroscopy in stored apples. Postharvest Biol. Technol. 58:1-12.

Rizzolo, A., Vanoli, M., Bianchi, G., Zanella, A., Grassi, M., Torricelli A. and Spinelli, L. 2014. Relationship between texture sensory profiles and optical properties measured by time-resolved reflectance spectroscopy during post storage shelf life of ‘Braeburn’ apples. J. Hort. Res. in press.

Saeys, W., Velazco-Roa, M.A., Thennadil., S.N., Ramon, H.and Nicolai, B.M. 2008. Optical properties of apple skin and flesh in the wavelength range from 350 to 2200 nm. Appl. Opt. 47:908-919.

Seifert, B., Zude, M., Spinelli, L. and Torricelli, A. 2014. Optical properties of developing pip and stone fruit reveal underlying structural changes. Biol. Plant. doi:10.1111/ppl.12232.

Torricelli, A., Spinelli, L., Vanoli, M., Rizzolo, A., and Eccher Zerbini, P. 2008. Time resolved reflectance spectroscopy for nondestructive assessment of food quality. Sens. Instrumen. Food Qual. 2:82–89.

Vanoli, M., Eccher Zerbini, P., Rizzolo, A., Spinelli, L. and Torricelli, A. 2010. Time-resolved reflectance spectroscopy for the non-destructive detection of inner attributes and defects of fruit. Acta Hort. 877:1379-1386.

Vanoli, M., Eccher Zerbini, P., Spinelli, L., Torricelli, A. and Rizzolo, A. 2009. Polyuronide content and correlation to optical properties measured by time-resolved reflectance spectroscopy in 'Jonagored' apples stored in normal and controlled atmosphere. Food Chem. 115:1450-1457.

Vanoli, M., Rizzolo, A., Grassi, M., Farina, A., Pifferi, A., Spinelli, L. and Torricelli, A. 2011. Time-resolved reflectance spectroscopy nondestructively reveals structural changes in 'Pink Lady®' apples during storage. Procedia Food Sci. 1:81-89.

Vanoli, M., Rizzolo, A., Zanella, A., Grassi, M., Spinelli, L., Cubeddu, R. and Torricelli, A. 2013. Apple texture in relation to optical, physical and sensory properties. InsideFood Symposium, 9-12 April, 2013, Leuven, Belgium. http://www.insidefood.eu/ 032P.pdf

Zanella, A., Vanoli, M., Rizzolo, A., Grassi, M., Eccher Zerbini, P., Cubeddu, R., Torricelli, A. and Spinelli, L. 2013. Correlating optical maturity indices and firmness in stored 'Braeburn' and 'Cripps Pink' apples. Acta Hort. 1012:1173-1180.

Tables

Table 1. Absorption coefficient at 670 nm (μ_a670) and mechanical properties of 'Braeburn' apples according to harvest date and storage months (mean±standard error; significance of the F-ratio: ***P<0.001;**P<0.01;*P<0.05; ns=not significant)

harvest	Storage months	μ_a670 (cm^{-1})	Firmness (N)	Stiffness (N/mm)	Energy-to-rupture (J)
1	0	0.092±0.007	83.4±2.0	33.7±0.6	0.078±0.004
	3	0.091±0.007	69.2±1.8	30.5±0.8	0.050±0.004
	7	0.077±0.006	59.3±2.0	27.3±1.2	0.038±0.003
2	0	0.076±0.006	79.9±1.8	32.4±0.6	0.075±0.003
	3	0.069±0.005	67.8±1.9	30.5±1.0	0.050±0.003
	7	0.063±0.005	59.3±2.9	29.5±1.4	0.036±0.004
3	0	0.057±0.004	76.9±2.5	32.9±0.9	0.067±0.004
	3	0.054±0.004	68.3±1.5	31.9±0.8	0.044±0.003
	7	0.047±0.003	59.6±1.8	31.6±1.2	0.027±0.003
Harvest (A)		***	ns	ns	**
Storage time (B)		*	***	***	***
AxB		ns	ns	ns	ns

Table 2. Texture profiles of the four clusters. For each cluster are reported: the description of the texture profile, the values of centroids for each mechanical property and the number of observations (N_{obs}) grouped in each cluster

Cluster number and texture profile	Firmness (N)	Stiffness (N/mm)	Energy-to-rupture (J)	N_{obs}
W1 – highest firmness, stiffness, E_f	86.31	35.10	0.080	33
W2 – high firmness and E_f, intermediate stiffness	73.70	31.55	0.062	62
W3 – least firmness, stiffness, intermediate E_f	54.55	23.86	0.040	36
W4 – intermediate firmness, high stiffness, least E_f	63.11	33.29	0.028	49

Table 3. Classification table of 'Braeburn' apples according to the textural profiles W1 to W4 obtained by Cluster Analysis (percentage of well-classified fruit in each class (bold): column: actual group, row: predicted class)

TRS variables	Classification table					
	Actual class	Group size	W1	W2	W3	W4
μ_a540-880, A and B	W1	33	**57.6**	39.4	3.0	0
	W2	62	16.1	**61.3**	3.2	19.4
	W3	36	0	16.7	**61.1**	22.2
	W4	49	0	30.6	10.2	**59.2**

Figures

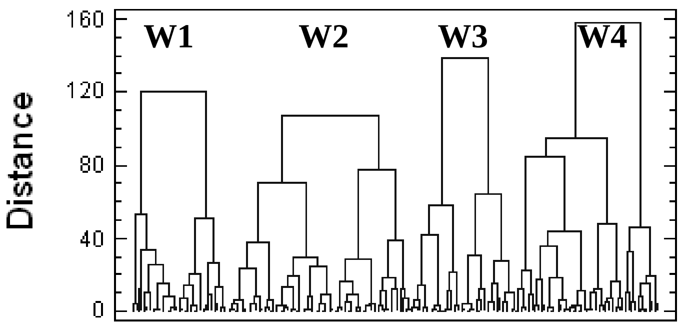

Fig. 1. Classification dendrogram (Cluster analysis on mechanical properties of 'Braeburn' apples. Codes W1 to W4 refer to profiles in table 2)

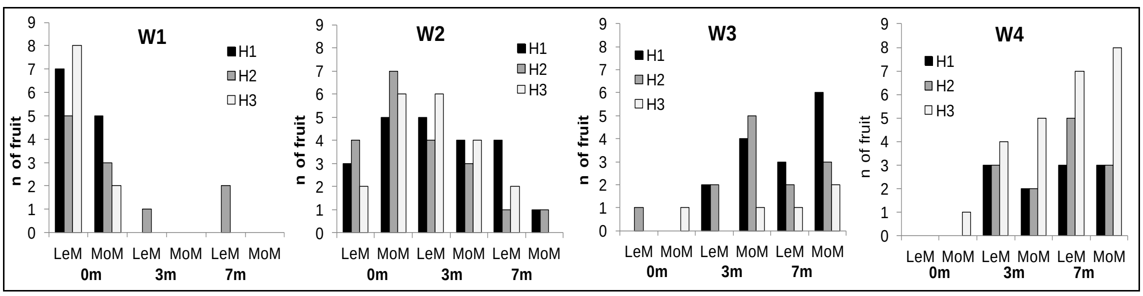

Fig. 2. Number of fruit observed for each harvest date and TRS maturity class after 0 (0m), 3 (3m) and 7 (7m) months of storage grouped in W1 to W4 texture profiles.

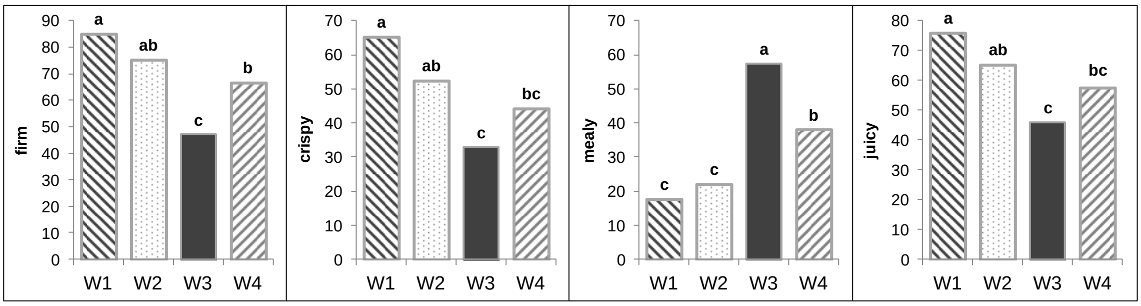

Fig. 3. Sensory attributes of 'Braeburn' apples grouped in the W1 to W4 textural profiles. For each parameter bars with different letters are statistically different (Bonferroni's test at $P\leq0.05\%$).

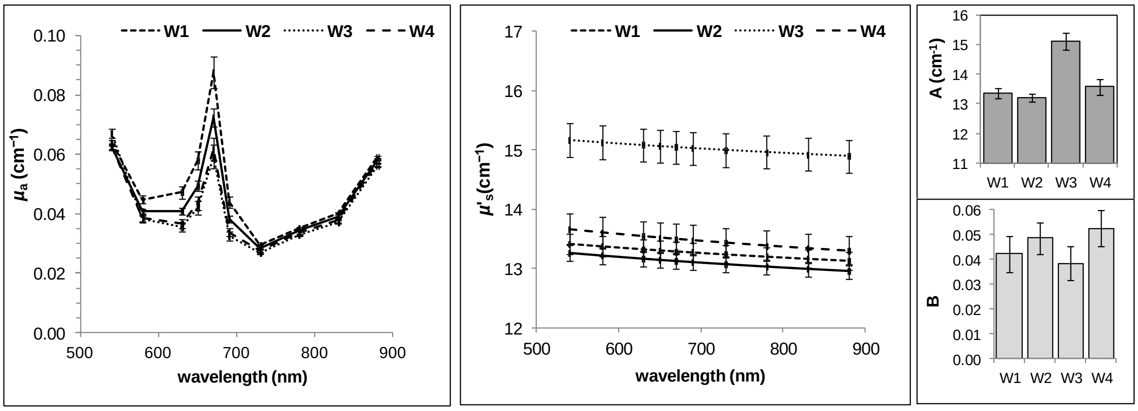

Fig. 4. Absorption spectra (left), scattering spectra (right), density and size of the scatterers (right) of 'Braeburn' apples grouped in the W1 to W4 textural profiles. Bars refer to standard error.

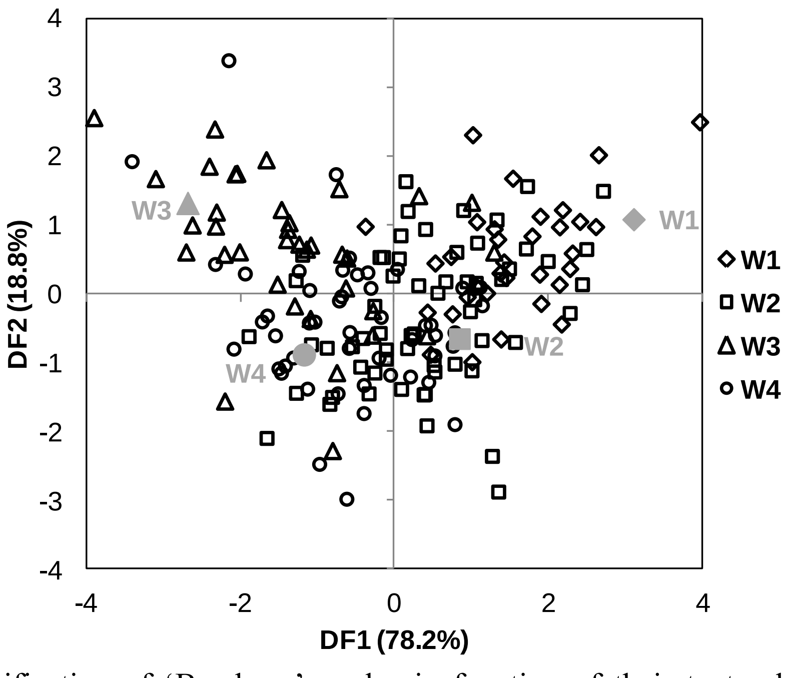

Fig. 5. Classification of 'Braeburn' apples in function of their textural profile using Linear Discriminant Analysis (grey full symbols refer to centroids)