

1 **Characterizing the tissue of apple air-dried and osmo-air-dried rings by X-ray CT and OCT and**  
2 **relationship with ring crispness and fruit maturity at harvest measured by TRS.**

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4 Anna Rizzolo<sup>a</sup>, Maristella Vanoli<sup>a,b</sup>, Giovanna Cortellino<sup>a</sup>, Lorenzo Spinelli<sup>c</sup>, Davide Contini<sup>b</sup>, Els  
5 Herremans<sup>d</sup>, Evi Bongaers<sup>e</sup>, Alexandra Nemeth<sup>f</sup>, Michael Leitner<sup>f</sup>, Pieter Verboven<sup>e</sup>, Bart M. Nicolai<sup>e</sup>,  
6 Alessandro Torricelli<sup>b</sup>

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8 <sup>a</sup> Consiglio per la Ricerca e Sperimentazione in Agricoltura, Unità di ricerca per i processi dell'industria  
9 agroalimentare (CRA-IAA), via Venezian 26, 20133 Milano, Italy

10 <sup>b</sup> Politecnico di Milano, Dipartimento di Fisica, piazza Leonardo da Vinci 32, 20133 Milano, Italy

11 <sup>c</sup> Istituto di Fotonica e Nanotecnologie, CNR, piazza Leonardo da Vinci 32, 20133 Milano, Italy

12 <sup>d</sup> BIOSYST-MeBioS, KU Leuven, Willem de Croylaan 42 - box 2428, 3001 Leuven, Belgium

13 <sup>e</sup> Skyscan Bruker Micro-CT, Kartuizersweg 3B, 2550 Kontich, Belgium

14 <sup>f</sup> RECENDT, Research Center for Non Destructive Testing GmbH, Science Park 2/2, OG, Altenberger  
15 Straße 69, A-4040 Linz, Austria

16

17 corresponding author:

18 Anna Rizzolo, Consiglio per la Ricerca e Sperimentazione in Agricoltura, Unità di ricerca per i processi  
19 dell'industria agroalimentare (CRA-IAA), via Venezian 26, 20133 Milano, Italy; Phone: +39-02-  
20 239557213, e-mail: [anna.rizzolo@entecra.it](mailto:anna.rizzolo@entecra.it)

21

22 **Abstract**

23 Air-dried apple rings were prepared from ‘Golden Delicious’ apples selected at harvest as less mature and  
24 more mature according to the absorption coefficient measured at 670 nm by TRS, stored in air for 5  
25 months, and subjected to air-drying with (OSMO) and without (noOSMO) osmodehydration pre-treatment  
26 (60% sucrose syrup). Selected rings were submitted to microstructural analysis by X-ray computed  
27 tomography (X-ray CT), to subsurface structure analysis by Optical coherence tomography (OCT) and to  
28 texture and sound emission analysis by bending-snapping test. Higher crispness index, higher number of  
29 sound events and higher average SPL characterized the OSMO rings. Total porosity was related to  
30  $SPL_{av<60}$ , tissue and pore anisotropy to  $SPL_{av>60}$ , pore fragmentation index to fracturability and specific  
31 surface area to the work required to snap the ring. A differentiation of the drying treatments, as well as of  
32 the products according to the TRS maturity class at harvest were obtained analysing by PCA  
33 microstructure parameters and texture and acoustic parameters. The differences in mechanical and acoustic  
34 characteristics between OSMO and noOSMO rings were due to the different subsurface structure as found  
35 with OCT analysis.

36

37 **Key words:** Microstructure, X-CT, OCT, raw material selection, TRS, acoustic-mechanical properties,  
38 crispness, osmodehydration pre-treatment, air-dried apple rings

39

40 **Industrial relevance**

41 There is an increasing demand of dried crispy fruit as they are considered by consumers healthy, natural  
42 and tasty foods. The textural characteristics, exerting a strong effect on crispy and crunchy sensory  
43 characteristics, have a great impact at consumption of dried crispy fruit. As their textural characteristics  
44 depend on both fruit maturity at processing and processing conditions, food industry is demanding  
45 nondestructive techniques which could be used for on-line/off-line sorting of fruit into classes each one  
46 more suited for obtaining a specific product. Furthermore, the textural properties of dried foods depend on  
47 microstructure, defined as the spatial arrangement of structural components and their interactions. Due to  
48 the microscopic complexity, unambiguous methodologies that relate quality to food microstructure do not

49 exist today, in contrast to what already existing for several engineering materials. Hence there is the need  
50 of developing methods that measure directly the microstructural properties of dried foods.

51

52 **Highlights:**

- 53 • For the first time, X-rayCT, OCT and acoustic emission coupled to texture analysis were combined  
54 to investigate the structure-property relationships of air-dried apple rings in relation to fruit  
55 maturity at harvest measured by TRS and to pre-drying osmodehydration.
- 56 • X-rayCT and OCT indicated changes in the microstructure related to crispness parameters  
57 measured by acoustic-texture analysis, which could be related to both fruit maturity at harvest and  
58 osmotic pre-treatment.
- 59 • The results show that a differentiation of the products according to the TRS maturity class at  
60 harvest was obtained.

61

## 62 1. Introduction

63 In the last few years, a new interest has arisen in the field of functional products, such as minimally  
64 processed fruits and vegetables. There is an increasing demand for innovative products that respond to  
65 changed lifestyles and working rhythms. In addition, consumers are also more and more interested in  
66 consuming healthy, natural and tasty foods. Dried crispy fruits could satisfy these requirements, as they are  
67 perceived as healthy because of their nutritional value, combined with high fiber content, but also tasty.  
68 Among these products, dried apples are part of several prepared foods including snack preparations and  
69 integral breakfast foods, as well they are used alone as snacks (Lewicki & Jakubczyk, 2004).

70 Drying is a process involving heat and mass transfer that can cause physical and chemical alteration of the  
71 material. The stress developed when water is removed from the fresh material causes shrinkage and change  
72 in shape, both of which influence the porosity of the dried material and its rehydration properties (Lewicki  
73 & Jakubczyk, 2004; Mayor, Silva & Sereno, 2005). Other consequences of the drying process involve  
74 changes in the rheological properties of the product, which are bound to changes in composition, phase  
75 transition of the material and microstructural changes due to loss of cell turgor pressure because of the loss  
76 of water from the inner parts towards the surface, possibly causing stiffness, spoilage and disruption of cell  
77 walls, or even a collapse of the cell tissue and a cell breakage (Lewicki & Lukaszuk, 2000; Maltini,  
78 Torreggiani, Venir & Bertolo, 2003). The extent of these changes depends on the species and on the  
79 maturation degree at processing, factors affecting the textural properties of the raw material.

80 The internal quality of fruit can be assessed non-destructively by using time-resolved reflectance  
81 spectroscopy (TRS), which provides a complete characterization of diffusive media with the simultaneous  
82 non-invasive measurement of the bulk optical properties. TRS is based on the measurement of the temporal  
83 delay and the broadening experienced by a short laser pulse (pulse duration in the order of 100 ps) while  
84 travelling through a turbid medium (Torricelli et al., 2008). By using an appropriate theoretical model of  
85 light penetration for the analysis of photon time distribution, it is possible to simultaneously estimate the  
86 absorption coefficient ( $\mu_a$ ) and the reduced scattering coefficient ( $\mu'_s$ ). Light penetration achieved by TRS  
87 in most fruit and vegetables can be as great as 1-2 cm, depending on the optical properties (Cubeddu et al.,  
88 2001). Hence, TRS provides information on the internal properties of the medium and is not significantly

89 affected by surface features (Saeys, Velazco-Roa, Thennadil, Ramon & Nicolai, 2008). TRS has been used  
90 to assess maturity, texture and cell wall structure as well as internal defects in intact fruit (Vanoli, Zerbini,  
91 Rizzolo, Spinelli & Torricelli, 2010), and to sort fruit at harvest according to maturity class, usually by  
92 measuring fruit at 670 nm (near the chlorophyll-*a* peak) and classifying fruit with high  $\mu_a670$  values as less  
93 mature and those having low  $\mu_a670$  values as more mature (Torricelli et al., 2008). As for air-dried apple  
94 rings, it was shown that the classification of apples at harvest based on  $\mu_a670$  was able to segregate fruit  
95 generating fresh and air-dried rings of different quality (Rizzolo, Vanoli, Cortellino, Spinelli & Torricelli,  
96 2011; Rizzolo, Vanoli, Cortellino, Spinelli & Torricelli, 2012): the differences found in the raw material  
97 affected the changes occurring in apple rings with air-drying, mainly influencing weight loss, area  
98 shrinkage and how much ring color changed due to browning phenomena. For ‘Golden Delicious’ and  
99 ‘Pink Lady®’ cultivars, by processing the more mature fruits, i.e. either after long cold storage or by using  
100 apples having lower  $\mu_a670$  at harvest, air-dried rings with low shrinkage and low color changes (i.e.  
101 showing less browning) with lower ring hardness and crispness index were obtained.  
102 However, maximal shrinkage during drying decreases as its solids increase and structure collapse was  
103 shown to decrease when fruit was impregnated with sugar prior to air drying (Torreggiani & Bertolo, 2004;  
104 Wolf, Behnilian & Speiss, 2001) by means of an osmotic process, which is carried out by immersing the  
105 fruit into aqueous solutions of high sugar concentration, so achieving a partial dehydration coupled to a  
106 solute intake (Wolf, Behnilian & Speiss, 2001). Moreover, great changes in the tissues structure could be  
107 produced by combining the osmotic dehydration with air drying (Lewicki, 1998), with texture changing  
108 from elastic-visco-plastic to rigid, becoming fragile and brittle, which are textural features linked to the  
109 crispy and crunchy sensory attributes proper of snack food (Saeleaw & Schleining, 2011). In addition, the  
110 rheological characteristics of osmo-air-dried apple rings were shown to change according to the cultivar:  
111 ‘Golden Delicious’ rings acquired rigidity but remained brittle and fragile, developing small fractures,  
112 whereas ‘Pink Lady®’ ones become rigid, but harder and stiffer, with abrupt failures of major intensity  
113 (Farris, Gobbi, Torreggiani & Piergiovanni, 2008; Gobbi, Farris, Limbo & Torreggiani, 2012). These  
114 mechanical characteristics are strictly bound to the porosity of dried apple rings, which has been  
115 characterized using different imaging 2-D techniques, such as light microscopy (Mayor, Silva & Sereno,

116 2005; Gobbi, Farris, Limbo & Torreggiani, 2012) and scanning electron microscopy (Bai, Rahaman,  
117 Perera, Smith & Melton, 2002; Acevedo, Briones, Buera & Aguilera, 2008; Askari, Eman-Djomeh &  
118 Mousavi, 2008; Witrowa-Rajchert & Rząca, 2009; Huang, Zhang, Wang, Mujumdar & Sun, 2012).  
119 Even if scanning electron microscopy is a useful tool to analyze the sample microstructure, it does not give  
120 reliable information about the total pore volume and pore size distribution in the sample. These information  
121 on the microstructure can be obtained using the X-ray microtomography, which has been applied to study  
122 the effect of far-infrared radiation assisted drying on microstructure of banana slices (Léonard, Blacher,  
123 Nimmol & Devahastin, 2007), and to quantify the pore space of apple tissue (Mendoza et al., 2007;  
124 Mendoza et al., 2010; Herremans et al., 2013).

125 Complementary information on dried ring microstructure could also be obtained using optical coherence  
126 tomography (OCT), a novel approach to assess the subsurface microstructure (Huang et al., 1991). OCT is  
127 a purely optical, non-destructive, non-invasive, and contactless high resolution imaging method, which is  
128 based on the physical phenomenon of white light interferometry. The technique employs special light  
129 sources with very short temporal coherence, which enables an excellent depth resolution in the range of  
130 only a few microns (Drexler et al., 1999). In the field of food and plant photonics so far OCT has been used  
131 to study the morphological and functional state of higher plant tissues (Sapozhnikova, Kamenskii &  
132 Kuranov, 2003; Kutis, Sapozhnikova, Kuranov & Kamenskii, 2005; Verboven et al., 2013) and to detect  
133 disease in melon seeds (Lee, Lee, Kim, Jung & Kim, 2011) and disease, defects and rots in onion  
134 (Meglinski, Buranachai & Terry, 2010; Landahl, Terry & Ford, 2012).

135 The objectives of this work were: a) to evaluate the subsurface structure and the microstructure of air-dried  
136 and osmo-air-dried apple rings by OCT and X-ray micro-tomography; and, b) to study the relationships  
137 among the microstructure features and the crispness of dried apple rings in relation to fruit maturity  
138 assessed at harvest by TRS.

139

## 140 **2. Materials and Methods**

### 141 **2.1. *Fruit and experimental plan***

142 ‘Golden Delicious’ apples (*Malus×domestica*, Borkh.) coming from Laimburg (Trentino Alto-Adige

143 region, Italy) were harvested on 8 September 2011, which corresponds to the commercial picking window  
144 for this cultivar in Trentino-Alto Adige region. Sixty fruits were selected and measured at harvest by TRS  
145 at 670 nm (close to the absorption peak of chlorophyll-*a*), ranked according to decreasing  $\mu_a670$  (increasing  
146 maturity) and randomized into three batches of 20 fruit each. The batches were stored for 5 months at +1°C  
147 in air. Each batch corresponded to a different pre-treatment: without osmodehydration pre-drying  
148 (noOSMO) and with 1 h (OSMO1) or 3 h (OSMO2) osmodehydration pre-drying. Three 5 mm thick  
149 rings/fruit were prepared. The rings from each fruit were packed together into a tulle bag and immersed for  
150 1 h (OSMO1) or 3 h (OSMO2) at 20°C in a sucrose solution ( $a_w=0.90$ , 60% w/w), which was continuously  
151 recirculated at 1.5 L/min through a peristaltic pump. The ratio fruit/solution was 1/3. Before air drying, the  
152 OSMO rings were drained, rinsed gently with tap water, and placed a few minutes over adsorbent paper to  
153 remove excess water. OSMO and noOSMO rings were air-dried at 80°C up to a constant weight using a  
154 pilot alternate upward-downward air circulated drier (Thermolab, Codogno, Italy) operating at an air speed  
155 of 1.5 m/s.

156 Due to the duration of a single analysis, for the microstructural analysis by means of X-ray micro-CT a  
157 selection of dried apple samples was made: rings obtained from the most differing pre-treatments before  
158 drying (noOSMO and OSMO2) and from the most differing apples in terms of maturity measured by  
159 means of TRS (ranks 1 and 2, less mature (LeM) fruit and ranks 19 and 20, more mature (MoM) fruit) were  
160 chosen. For the subsurface microstructure analysis by OCT, instead, within each batch, the rings obtained  
161 from the most differing apples in terms of TRS maturity (rank 1, the least mature; rank 20, the most  
162 mature) were selected. On the dried rings prepared from the selected fruit, the mechanical and acoustic  
163 properties were measured using a texture analyzer in conjunction with acoustical emission analysis  
164 (bending-snapping test).

165

## 166 2.2. *Assessment of maturity at harvest by time-resolved reflectance spectroscopy and samples* 167 *formation*

168 For TRS measurements, a compact system was used, working at 670 nm, based on a pulsed laser diode  
169 (mod. PDL800, PicoQuant GmbH, Germany), with 80 MHz repetition frequency, 100 ps duration, and 1

170 mW average power, a compact photomultiplier (mod. R5900U-L16, Hamamatsu Photonics, Japan) and an  
171 integrated PC board (mod. SPC130, Becker&Hickl GmbH, Germany). Typical acquisition time for time-  
172 correlated single photon counting is 1 s per point. A couple of 1 mm plastic fibers (Mod. ESKA GK4001,  
173 Mitsubishi, Japan) delivers light into the sample and collects the emitted photons at a distance of 1.5 cm. A  
174 band pass filter tuned at 670 nm was used to cut off the fluorescence signal due to chlorophyll. Overall, the  
175 instrumental response function duration was <160 ps. The reduced scattering coefficient ( $\mu'_s$ ) and the  
176 absorption coefficient ( $\mu_a$ ) were obtained by fitting the experimental TRS data with a standard solution of  
177 the diffusion approximation to the transport equation for a semi-infinite homogenous medium. The  
178 extrapolated boundary condition was used (Contini, Martelli, & Zaccanti, 1997) to take into account the  
179 refractive index mismatch at the surface.

180 The absorption coefficient at 670 nm was measured on two opposite sides of each fruit and the average per  
181 fruit was used for fruit ranking from less mature to more mature fruit. The 60 ranked apples were grouped  
182 by 3, with a total of 20 groups, corresponding to 20 levels of  $\mu_a$ . Each fruit from each group was randomly  
183 assigned to a different pre-drying treatment. In this way, fruit from the whole range of  $\mu_a$  were available for  
184 each pre-drying treatment.

185

## 186 **2.3. *Microstructural analysis***

### 187 *2.3.1 X-ray micro-CT*

188 For the X-ray micro-CT analysis, by using a cork borer, small cylindrical samples (3 mm diameter) were  
189 excised from the dried apple, approximately 5 mm from the peel, excluding regions in which vascular  
190 tissue could be discerned visually. The thickness of the apple slices was not altered in preparing the  
191 samples. The samples were mounted on the rotating holder and stabilized using parafilm. Because of the  
192 dry state of the samples, hardly any sample degradation was expected within the time frame of the scan (29  
193 minutes). X-ray micro-CT measurements were performed on a SkyScan 1172 system (Bruker microCT,  
194 Kontich, Belgium), operated at 55 keV source voltage and 181  $\mu$ A current and with an isotropic image  
195 pixel resolution of 2.44  $\mu$ m. The samples were rotated over 0.35° steps over a total of 180°, each time  
196 averaging 3 frames to acquire a radiographic image of 1048 by 2000 pixels. The projection images were



197 loaded into dedicated software (NRecon1.6.3.2, Bruker microCT, Kontich, Belgium) to reconstruct virtual  
198 cross-sections of the sample. This resulted in a 3D greyscale datastack, digitized to 880 slices of 2000 by  
199 2000 pixels. The images were smoothed by a Gaussian smoothing kernel, and corrected for rings and beam  
200 hardening, which are common artifacts in X-ray CT images. For image analysis a cylindrical volume of  
201 interest (diameter 2.5 mm) was cropped centrally in the imaged volume to exclude interference with the  
202 excised borders of the sample. The remaining volume for analysis measured 5.4 mm<sup>3</sup>. The images were  
203 filtered in 3D space using a median filter with filter radius of 2 pixels. Otsu's algorithm (Otsu, 1979) was  
204 applied for binarizing the image by separating two peaks in the grey scale frequency distribution: pixels  
205 with lower intensities than the Otsu threshold were assigned to the background (air) and pixels with a  
206 higher intensity than that threshold were assigned to the apple tissue material. Individual 3D objects smaller  
207 than 27 voxels were considered to be noise and were filtered out of the datastack. Morphometric  
208 parameters describing the microstructure were calculated on the 3D data using CTAn v.1.12.0.0 (Bruker  
209 microCT, Kontich, Belgium). A description of the parameters and the main concept of the calculation can  
210 be found in Herremans et al. (2013) and Skyscan (2010).

211

### 212 2.3.2 *Optical coherence tomography*

213 All measurements have been performed with a modular spectral domain OCT system (henceforth referred  
214 to as "SD-OCT"), which is composed of a light source, a probe head and a spectrometer. The  
215 supercontinuum light source (Koheras SuperK Versa, NKT Photonics, Denmark) emits light at a central  
216 wavelength of 860 nm. Its spectral bandwidth of 170 nm allows for an axial resolution of 2 μm (in air). In  
217 the probe head, the beam is split by a non-polarizing bulk beam splitter (BS) into a reference and a sample  
218 arm. In the reference arm light is reflected from a gold coated mirror (M), whereas in the sample arm it is  
219 reflected from the different layers within the sample. The light returning from both arms is recombined and  
220 sent to the spectrometer, where it is spectrally dispersed by a transmission grating and recorded by a CCD  
221 camera. The recorded spectrum is modulated by interference fringes, with the frequency of the modulation  
222 depending on the path length differences between reference and sample arm. For recording a cross-section  
223 image the beam of light is scanned over the sample surface over a range of 5 mm by means of a

224 galvanometer mirror (GM). During this process 1000 interferograms are recorded, which are used for  
225 reconstructing the images. A schematic diagram of a spectral-domain OCT system is depicted in **Fig. 1**.  
226 This particular system was equipped with a multi focal-length probe head. With such a probe head it was  
227 possible to switch between different imaging optics, and thus, to change the lateral resolution and depth of  
228 focus of the probing beam. Single depth scans were acquired at a rate of 20 kHz.

229

#### 230 **2.4. Texture and sound emission analysis**

231 A TA-XT plus Texture Analyzer (Stable Micro Systems, Godalming, UK) was used for bending-snapping  
232 test fitted with a 50N load cell and equipped with an acoustic emission detector (AED, Stable  
233 Microsystems), using the HDP/3PB Three Point Bending Rig. The lower supporting blades were separated  
234 by a distance of 45 mm, and the compressing blade was driven down between the two supports at a speed  
235 of 0.17 mm/s, bending each apple ring until it snapped. A microphone unit Type 4188-A-021 (Brüel &  
236 Kjær) was connected to an AED for sound pressure measurements and was placed at the sample level  
237 located 100 mm away from the central axis of the probe. The sound measurement system was calibrated  
238 using the Brüel & Kjær Type 4231 sound calibrator at sound pressure levels of 94 and 114 dB at 1000 Hz.  
239 The gain of AED was set at 0 dB and the sampling rate was set at 500 Hz for sound and force  
240 measurements. Acoustic signals were captured in “RAW” format used in the TA.XT plus Texture  
241 Analyzer. Data were then converted to dB. The mechanical and acoustic characteristics were extracted  
242 from the data using Texture Exponent 32 software (Stable Microsystems). All tests were performed in a  
243 laboratory with no special soundproof facilities at room temperature. Force/displacement and  
244 sound/displacement curves were simultaneously plotted. From the force curve the following parameters  
245 were extracted: number of peaks, ring hardness corresponding to the maximum force (*hardness*, N),  
246 distance at the first major point (*Travell*, mm), distance at the break (*fracturability*, mm), work required to  
247 the first major fracture point (*Area1*, N×mm), work required to snap the ring (*Total area*, N×mm), slope of  
248 the first part of the force curve (*slope*, N/mm) and gradient to the maximum force (*gradient\_max*, N/mm).  
249 From the sound curves the following data were extracted: total number of sound peaks (*N\_sounds*), number  
250 of sound peaks having SPL higher than 60 dB (*N\_sounds>60dB*), average SPL of sound peaks lower than

251 60 dB ( $SPL_{av<60}$ ), average SPL of sound peaks higher than 60 dB ( $SPL_{av>60}$ ), average SPL of total sound  
252 peaks ( $avSPL$ ). The crispness index ( $E_{mod}$ , MPa) was calculated from  $gradient\_max$  ( $E_{mod\ max}$ ) and  $slope$   
253 ( $E_{mod\ slope}$ ) according to Farris, Gobbi, Torreggiani & Piergiovanni (2008).

254

## 255 **2.5. Statistical analysis**

256 Data were submitted to Analysis of Variance and means were compared by Tukey's (mechanical and  
257 acoustic parameters) and Duncan's (morphometric parameters) tests at  $P\leq 0.05\%$  (Statgraphics v.7,  
258 Manugistic Inc., Rockville, MD, USA).

259 Principal Component analysis (PCA) was carried out in order to study the relationships between X-ray CT  
260 morphometric parameters and mechanical and acoustic properties of dried rings considering 10  
261 morphometric parameters, 6 mechanical and 5 acoustic parameters and was performed by The Unscrambler  
262 X version 10.0.1 (CAMO, Oslo, Norway) software package using the nonlinear iterative partial least-  
263 squares (NIPALS) algorithm. The principal component (PC) scores were then submitted to ANOVA, and  
264 means were compared by Duncan's test at  $P\leq 0.05\%$ .

265

## 266 **3. Results**

### 267 **3.1 Absorption coefficient at harvest**

268 The absorption coefficient at 670 nm ranged from  $0.35\text{ cm}^{-1}$  for the least mature fruit to  $0.092\text{ cm}^{-1}$  for the  
269 most mature apple; the optical properties at harvest of LeM and MoM apples selected for this study were  
270 (average  $\pm$  standard error): LeM maturity class:  $0.032 \pm 0.0083\text{ cm}^{-1}$ ; MoM maturity class:  $0.11 \pm 0.0064$   
271  $\text{cm}^{-1}$ .

### 272 **3.2. Microstructure**

273 **Fig. 2 (left)** presents an X-CT slice of an OSMO2 LeM dried apple ring. The skeleton of dried apple tissue  
274 could be accurately detected because of the high contrast with the pore space. So, a threshold was applied  
275 to segment skeleton from the pore space resulting in a binary image (**Fig. 2, right**). **Fig. 3** shows  
276 representative cross sections of noOSMO and OSMO2 MoM dried apple rings. By comparing the images,  
277 it is clear that the microstructure of dried apple ring somewhat changes with the osmodehydration pre-

278 drying. In fact, in the OSMO2 sample an higher presence of large pores than in the noOSMO ones is  
279 evident.

280 Considering the morphometric parameters computed (**Table 1**), on average (mean±standard error) the  
281 osmotic pre-treatment increased porosity (noOSMO, 77.8±1.1 %; OSMO2, 82.0±1.6 %) and tissue specific  
282 surface area (noOSMO, 144.82±8.61 mm<sup>-1</sup>; OSMO2, 159.81±2.79 mm<sup>-1</sup>) and decreased pore anisotropy  
283 (noOSMO, 0.532±0.016; OSMO2, 0.499±0.014), tissue thickness (noOSMO, 0.0233±0.0011 mm;  
284 OSMO2, 0.0205±0.00034 mm), tissue anisotropy (noOSMO, 0.564±0.012; OSMO2, 0.501±0.012) and  
285 tissue intersection surface (noOSMO, 2.67±0.23 mm<sup>2</sup>; OSMO2, 1.73±0.13 mm<sup>2</sup>). On the other hand, tissue  
286 specific surface area and tissue thickness, along with tissue fractal dimension, depended also by the TRS  
287 maturity class: in fact LeM rings on average had higher tissue specific surface area (LeM, 159.92±6.58  
288 mm<sup>-1</sup>; MoM, 144.71±6.12 mm<sup>-1</sup>) and lower tissue thickness (LeM, 0.0209±0.00083 mm; MoM,  
289 0.0228±0.00113 mm) and tissue fractal dimension (LeM, 2.490±0.012; MoM, 2.527±0.011). In addition,  
290 the comparison of the TRS maturity classes within the same pre-treatment highlighted that in noOSMO  
291 samples only porosity was influenced by TRS maturity class, with LeM rings showing higher porosity than  
292 MoM rings, while in OSMO2 samples LeM rings were characterized by lower pore fragmentation index  
293 and tissue fractal dimension, and higher tissue specific surface area, tissue fragmentation index and tissue  
294 structure model index than MoM rings. Furthermore, the osmotic pre-treatment had a diverse impact on  
295 morphometric parameters in the two TRS maturity classes. In fact, the osmotic pre-treatment induced in  
296 LeM rings a decrease in pore anisotropy, tissue anisotropy and tissue intersection surface, whereas in MoM  
297 rings an increase in tissue specific surface area and a decrease in tissue thickness and tissue fractal  
298 dimension (**Table 1**).

299 A more profound insight in the microstructure is shown by the pore space thickness and tissue structure  
300 thickness distributions. These are approximated by a 3D sphere-fitting algorithm on the skeletonized  
301 structure, hereby calculating local structure diameters for every position on the skeleton.

302 The tissue thickness distributions (**Fig. 4**) show that more than 75% of cell spaces in OSMO2 rings were  
303 smaller than 25 µm, independently from the TRS maturity class. In contrast, for noOSMO rings only  
304 60.2% (MoM) and 72.8% (LeM) of cell spaces were smaller than 25 µm. As for pore space thickness

305 distributions (**Fig. 5**), in noOSMO rings, whatever the TRS maturity class, more than 50% of pores had  
306 thickness smaller than 0.10 mm, and only about 3% of pores were larger than 0.20 mm, with a maximum  
307 value of 0.27 mm. With the osmotic pre-treatment, for both LeM and MoM rings the distribution was  
308 shifted towards larger values. In LeM rings 39.6% of pores had thickness lower than 0.10 mm, and 8.7% of  
309 pores were larger than 0.20 mm, reaching a maximum value of 0.32 mm, whereas in MoM rings only 37%  
310 of pores were smaller than 0.10 mm, and more than 17% of pores were larger than 0.20 mm, with about  
311 5.7% of pore thickness ranging from 0.40 to 0.458 mm.

312

### 313 **3.3 Subsurface structure**

314 **Fig. 6** shows representative OCT images of the subsurface of the dried rings from the least (R1) and most  
315 (R20) mature apple fruit in each batch. The shown images consist of 1000 adjacent depth scans and feature  
316 (optical) dimensions of  $5 \times 0.88 \text{ mm}^2$ . OCT clearly distinguished noOSMO and OSMO air-dried rings:  
317 noOSMO samples feature a dense structure and thus a limited penetration depth, while the OSMO ones  
318 feature a loose surface structure with large inclusions of air. The differences between the noOSMO and  
319 OSMO samples seemed to be a surface effect, since they could not be clearly reproduced at freshly  
320 prepared sites of fractures. From OCT images it was not possible to deduce the time of the  
321 osmodehydration pre-treatment or the effect of the TRS maturities.

322

### 323 **3.4 Crispness parameters of air-dried and osmo-air-dried apple rings**

324 If the mechanical and acoustic properties of dried rings from the selected fruit are considered (**Table 2**), no  
325 significant influence of TRS maturity at harvest within each pre-treatment was found for the parameters  
326 taken into consideration, with a few exceptions concerning the acoustic parameters. In noOSMO treatment  
327 LeM rings were characterized by higher value of  $SPL_{av < 60}$  than MoM ones, whereas in OSMO2 samples,  
328 LeM rings showed lower values of  $SPL_{av > 60}$  and  $avSPL$  than MoM rings.

329 In contrast, the osmotic pre-treatment strongly influenced some mechanical properties and almost all the  
330 acoustic parameters: in OSMO rings *fracturability*, *Areal* and *Travell* were lower, and *gradient\_max*,  
331 *slope*,  $E_{\text{mod.max}}$  and  $E_{\text{mod.slope}}$  were higher than in noOSMO rings, being in OSMO rings (mean  $\pm$  standard

332 error): *fracturability*,  $0.66 \pm 0.04$  mm; *AreaI*,  $1.70 \pm 0.18$  N×mm; *TravellI*,  $0.51 \pm 0.04$  mm; *gradient\_max*,  
333  $11.92 \pm 0.69$  N/mm; *slope*,  $10.72 \pm 0.38$  N/mm,  $E_{\text{mod.max}}$ ,  $279.1 \pm 26.5$  MPa; and  $E_{\text{mod.slope}}$ ,  $252.6 \pm 24.6$  MPa.  
334 No differences in mechanical properties between the times of osmotic pre-treatment were found.  
335 The  $N_{\text{sounds}}$  did not differ among the pre-treatments, even if there was a tendency to increase with the  
336 osmodehydration time, with OSMO2 rings showing a mean value almost twice the value of noOSMO  
337 samples. However, OSMO2 rings were characterized by a significantly higher  $N_{\text{sounds}} > 60\text{dB}$  ( $14.3 \pm$   
338  $3.7$ ), higher  $SPL_{\text{av} < 60}$  ( $50.37 \pm 0.45$  dB), higher  $\text{avSPL}$  ( $57.86 \pm 0.74$  dB), and lower  $SPL_{\text{av} > 60}$  ( $71.39 \pm 1.17$   
339 dB), than noOSMO rings, which showed lower  $N_{\text{sounds}} > 60\text{dB}$  ( $4.5 \pm 1.4$ ), corresponding to only about  
340 15% of  $N_{\text{sounds}}$ , lower  $\text{avSPL}$  ( $51.07 \pm 1.69$  dB) and  $SPL_{\text{av} < 60}$  ( $45.86 \pm 0.74$  dB), but higher  $SPL_{\text{av} > 60}$   
341 ( $80.00 \pm 1.74$  dB). The osmosis time significantly influenced  $SPL_{\text{av} < 60}$  and  $SPL_{\text{av} > 60}$ , being the former lower  
342 in OSMO1 rings ( $48.40 \pm 0.57$  dB), value higher than the noOSMO ones, and the latter higher in OSMO1  
343 rings ( $77.97 \pm 1.56$  dB), value not different from the noOSMO..

344

### 345 **3.5 PCA on mechanical and acoustic properties and morphometric parameters**

346 PCA based on X-CT morphometric parameters reported in Table1 and the mechanical and acoustic  
347 properties of each ring analysed by X-CT allowed the selection of four principal components (PC), which  
348 explained 89.8% of total variation (**Fig.7**). In PC1 (45.18% of total variance) *slope*, *gradient\_max* and  $E_{\text{mod}}$   
349 slope mechanical parameters were positively related to  $\text{avSPL}$ ,  $N_{\text{sounds}}$  and  $N_{\text{sounds}} > 60\text{dB}$  acoustic  
350 parameters and negatively related to  $SPL_{\text{av} > 60}$  and *AreaI* parameters. In addition, PC1 highlighted  
351 relationships between some morphometric parameters and acoustic characteristics: total porosity was  
352 related to  $SPL_{\text{av} < 60}$ , and was opposite to tissue anisotropy and pore anisotropy, which were related to  
353  $SPL_{\text{av} > 60}$ , while *AreaI* was related to tissue intersection surface. PC1 had positive scores for OSMO2 rings,  
354 with LeM OSMO2 ones having the highest value, and negative for noOSMO rings, without any difference  
355 between the TRS maturity classes (**Fig.8**). PC2 (26.55% of total variance), instead, underlined positive  
356 relationships between morphometric parameters and mechanical characteristics: pore fragmentation index  
357 was related to *fracturability* and the work required to snap the ring (*Total area*) to specific surface area.  
358 Moreover, PC2 opposed pore fragmentation index, *fracturability*, and tissue fractal dimension to tissue

359 fragmentation index, tissue structure model index, *Total area* and specific surface area, and distinguished  
360 dried apple rings according to the TRS maturity class. In fact, PC2 had negative scores for LeM rings and  
361 positive scores for the MoM ones, but this difference was statistically significant only for the OSMO2 rings  
362 (**Fig.8**). PC3 (10.67% of total variance) was mainly linked to pore anisotropy,  $SPL_{av>60}$  total porosity and  
363 tissue anisotropy, which were opposite to tissue structure model index and tissue intersection surface,  
364 whereas in PC4 (7.48% of total variance) specific surface area was inversely related to  $N_{sounds>60dB}$  and  
365  $N_{sounds}$  acoustic parameters. PC3 and PC4 distinguished the TRS maturity classes, but only for the  
366 noOSMO rings, which were characterized by positive scores for LeM rings and negative scores for the  
367 MoM ones (**Fig.8**).

368

#### 369 4. Discussion

370 The usefulness of the osmotic step as a pre-treatment prior to air-drying is related to the physico-chemical  
371 modifications occurring in the plant tissue. In fact the simultaneous counter-current mass transfer process,  
372 in which water outflows to the surrounding solution and the solute infuses into the product, causes in a  
373 short time a fully plasmolysis of the cells on the surface of the material due to osmotic dehydration, with  
374 little or no influence on the interior cells, so developing a gradient of turgor pressure, which can deform the  
375 structure. Shrinkage and stretching forces are not strong enough to break cell walls or to split middle  
376 lamella, but, when the osmotic process lasts at least 3 h, some detachments of cells occur, resulting in the  
377 deformation and creation of new and small intercellular spaces (Lewicki & Porzecka-Pawlak, 2005). It was  
378 shown that osmosis is a surface process as sugars penetrate to a depth of 2-3 mm, where a decreasing of  
379 water binding by the apple can be observed (Salvatori, Andrés, Chiralt & Fito, 1999). During subsequent  
380 air drying, sugars added during the osmotic dehydration pre-treatment helped to decrease structural  
381 collapse (del Valle, Cuadros & Aguilera, 1998; Lewicki, 1998; Lewicki & Lukaszuk, 2000), which resulted  
382 in a more porous structure. The OCT analysis, applied in this work for the first time as an alternative  
383 imaging method to study the sub-surface structure of air-dried and osmo-air-dried apple rings, confirmed  
384 the fact that the osmosis is a surface process, as the differences found by OCT imaging between noOSMO  
385 and OSMO rings could not be clearly reproduced at freshly prepared sites of fractures. The observed

386 difference in the subsurface structure, i.e. a dense structure for noOSMO rings and a loose surface structure  
387 with large inclusions of air for the OSMO ones, could be due to the fact that upon immersion in the osmotic  
388 medium the first layers of cells die, and resulting in the creation of a volume near the surface (Mavroudis,  
389 Dejmek & Sjöholm, 2004).

390 Scanning electron microscopy (SEM) studies carried out by Moreno, Simpson, Estrada, Lorenzen, Moraga  
391 & Almonacid (2011) on ‘Granny Smith’ apples showed the effects of osmodehydration in sucrose solution  
392 at microstructural levels. In fresh apples tissues are composed of numerous cells and intercellular spaces,  
393 with cells closely bound to each other by middle lamella. In these cells, a large vacuole occupies most of  
394 the protoplast, and the plasmalemma and tonoplast are close to the cellular wall. Cellular collapse as well  
395 as protoplast contraction and cell wall edge distortion were observed as a consequence of  
396 osmodehydration. On the other hand, Witrowa-Rajchert and Rząca (2009) found that air-drying at 70°C  
397 caused in apple slices (cv ‘Idared’) changes in the structure properties of the material, bound to physical  
398 alteration, such as shrinkage, increased porosity, decreased ability to imbibe water, and damage to  
399 microscopic structure. The same authors reported that in fresh tissue half of the population of the cells has a  
400 larger cross-section area than 0.034 mm<sup>2</sup>, while most of the dried cells have a cross-section area of 0.0025  
401 mm<sup>2</sup> with 50% having cross-section areas up to 0.0020 mm<sup>2</sup>. SEM images underlined that in air-dried  
402 apple rings the shrinkage stress causes numerous breaks of cell walls, with microstructure being  
403 characterized by small cavities and very high density, with larger cells only in the boundary area of the  
404 slices, suggesting that shrinkage of air-dried apple rings was anisotropic (Witrowa-Rajchert and Rząca,  
405 2009; Bai, Rahman, Perera, Smith & Melton, 2002; Lewicki & Jakubczyk, 2004). In addition, there has  
406 been reported a strong negative correlation between porosity, computed from apparent and true density  
407 values, and volume shrinkage, ranging the porosity from 69 to 74% with 73-76% volume shrinkage values  
408 (Witrowa-Rajchert and Rząca, 2009).

409 Our results showed that the pre-drying osmodehydration treatment caused an increase in the porosity and  
410 specific surface area of dried rings, which corresponded to lower volume and area shrinkage (data reported  
411 in Rizzolo, Vanoli, Cortellino, Spinelli & Torricelli, 2013), confirming the negative correlation between  
412 porosity and shrinkage found by Witrowa-Rajchert and Rząca (2009). The osmotic pre-treatment also



413 affected the degree of pore and tissue anisotropy, which are a measure of preferential alignment of the  
414 structure, and they are scaled from 0 for total isotropy to 1 for total anisotropy. Here noOSMO rings  
415 showed higher pore and tissue anisotropy values than OSMO2 rings; this difference could be ascribed to  
416 how apple rings shrank with air-drying. In fact the light microscopy images of the section of two apple  
417 rings air dried at 80°C, one after 90 min of osmosis and the other without the osmotic pre-treatment  
418 reported by Gobbi, Farris, Limbo & Torreggiani (2012) showed that an important shrinkage took place  
419 along the thickness axis in the not pretreated sample, which was characterized also by far fewer voids, with  
420 shape not as round as the pre-treated ring. The positive effect of the osmotic pre-treatment on the dried  
421 ring structure was confirmed also by the values of tissue fragmentation index, the tissue thickness  
422 distribution and pore space thickness distributions, indicating that in OSMO rings there was a more  
423 connected solid structure, with a lower local thickness of the cell spaces and an higher proportion of larger  
424 pores than in noOSMO rings. These different morphometric characteristics found for air-dried and osmo-  
425 air-dried apple rings greatly influenced the mechanical and acoustic parameters considered as indices of  
426 ring crispness. *Hardness*, gradient to the maximum force,  $E_{mod}$ , *fracturability*, work required to the first  
427 force breakdown and work to snap the ring values indicated that air-dried ring were tough (strong and  
428 highly deformable), while the osmo-air-dried one were brittle (hard and weak), as previously found by  
429 Farris, Gobbi, Torreggiani & Piergiovanni (2008) and Gobbi, Farris, Limbo & Torreggiani (2012). In  
430 addition our results showed that *slope*, *gradient\_max* and  $E_{mod}$  slope mechanical parameters, which had  
431 higher values in OSMO rings, were positively related to  $N_{sounds}$ ,  $N_{sounds}>60dB$  and  $avSPL$ , all  
432 acoustic parameters which have been associated to a high sensory crispness (Salvador, Varela, Sanz &  
433 Fiszman, 2009; Saeleaw & Schleining, 2011).

434 Also raw material characteristics (cultivar and ripeness degree) have an influence on apple air-dried ring  
435 quality. Konopacka & Plochanski (2001) found that prolonging the storage time of apple fruit (i.e.,  
436 increasing ripeness) the derived ring showed increasing density and decreasing thickness retention, and that  
437 apple rings produced by fruit after picking (less ripe) and also those produced from soft, overripe fruit after  
438 storage were harder than those produced from ripe fruit. Higher ring hardness and crispness index were  
439 also found by Rizzolo, Vanoli, Cortellino, Spinelli & Torricelli (2011, 2012) in air-dried apple rings

440 prepared either from fruit classified at harvest as less mature based on  $\mu_a$  670 or from fruit processed at  
441 harvest. Our results indicate that using less mature apples based on  $\mu_a$  670 measured at harvest by TRS, air-  
442 dried ring with higher porosity and higher  $SPL_{av<60}$  could be produced, as well as osmo-air-dried ring  
443 having a more connected solid structure, with lower tissue and pore degree of anisotropy, and defined less  
444 crispy by acoustic parameters (lower  $SPL_{av>60}$  and lower  $avSPL$ ) than osmo-air-dried rings produced by  
445 more mature fruit.

446

## 447 5. Conclusions

448 X-ray CT images were used to compute microstructural descriptors, OCT images were used to visualize the  
449 subsurface structure, and force and sound pressure level profiles were used to evaluate crispness of air-  
450 dried apple rings obtained with or without an osmodehydration pre-treatment. Higher crispness index,  
451 higher number of sound events and higher average SPL characterized the OSMO rings. Porosity was  
452 related to  $SPL_{av<60}$ , tissue and pore anisotropy to  $SPL_{av>60}$ , pore fragmentation index to *fracturability* and  
453 specific surface area to the work required to snap the ring. By using principal component analysis a  
454 differentiation of the drying treatments, as well as of the products according to the TRS maturity class at  
455 harvest were obtained. The differences in mechanical and acoustic characteristics between OSMO and  
456 noOSMO rings could be also due to the different subsurface structure as found with OCT analysis.  
457 It can be concluded that there is a clear relation between the maturity at harvest nondestructively assessed  
458 on intact fruit by TRS, the processing conditions and the microstructure features determined by X-ray CT  
459 and OCT, and texture quality (crispness) of dried apple rings. TRS therefore holds a large promise for  
460 application as a straightforward sorting tool for obtaining high quality dried apple rings.

461

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468

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580

581 **Table 1.** 3-D morphometric parameters (means  $\pm$  standard error) for noOSMO and OSMO2 dried apple  
 582 rings in function of TRS maturity class (LeM=less mature; MoM=more mature) (n=2) for tissue structure  
 583 and pore space.

584

	Means $\pm$ standard error				ANOVA <sup>‡</sup>		
	noOSMO		OSMO2		main effects		Interaction
	LeM	MoM	LeM	MoM	O	M	O×M
Porosity (%)	79.63 $\pm$ 0.82	76.04 $\pm$ 0.81	81.88 $\pm$ 0.76	82.03 $\pm$ 3.74	*	ns	ns
Pore anisotropy	0.556 $\pm$ 0.013	0.508 $\pm$ 0.016	0.470 $\pm$ 0.016	0.490 $\pm$ 0.028	*	ns	ns
Pore specific surface area (mm <sup>-1</sup> )	42.56 $\pm$ 1.65	45.15 $\pm$ 1.39	39.71 $\pm$ 1.85	37.87 $\pm$ 9.03	ns	ns	ns
Pore fragmentation index (mm <sup>-1</sup> )	-13.83 $\pm$ 17.18	-1.71 $\pm$ 9.50	-6.14 $\pm$ 1.75	0.17 $\pm$ 1.25	ns	ns	ns
Tissue specific surface area (mm <sup>-1</sup> )	155.42 $\pm$ 14.80	134.21 $\pm$ 0.79	164.42 $\pm$ 0.17	155.20 $\pm$ 2.03	*	*	ns
Tissue thickness ( $\mu$ m)	21.8 $\pm$ 1.6	24.7 $\pm$ 0.7	20.0 $\pm$ 0.1	21.0 $\pm$ 0.5	**	*	ns
Tissue anisotropy	0.582 $\pm$ 0.009	0.547 $\pm$ 0.016	0.493 $\pm$ 0.014	0.509 $\pm$ 0.024	**	ns	ns
Tissue Intersection surface (mm <sup>2</sup> )	2.36 $\pm$ 0.06	2.98 $\pm$ 0.34	1.70 $\pm$ 0.18	1.76 $\pm$ 0.27	**	ns	ns
Tissue fragmentation index (mm <sup>-1</sup> )	-2.58 $\pm$ 10.76	-12.10 $\pm$ 11.43	-13.36 $\pm$ 0.53	-20.24 $\pm$ 2.10	ns	ns	ns
Tissue structure model index	0.29 $\pm$ 0.38	0.06 $\pm$ 0.37	0.012 $\pm$ 0.027	-0.227 $\pm$ 0.035	ns	ns	ns
Tissue fractal dimension	2.496 $\pm$ 0.027	2.545 $\pm$ 0.007	2.484 $\pm$ 0.001	2.510 $\pm$ 0.008	ns	*	ns

585 <sup>‡</sup> O=osmotic pre-treatment; M=TRS maturity class; significance of P-value: \*\*, P $\leq$ 0.05%; \*, P $\leq$ 0.1%, ns, not  
 586 significant

587

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589

590 **Table 2.** Mechanical and acoustic parameters (mean±standard error) of air-dried apple rings prepared from  
 591 apple fruit selected for X-CT and/or OCT analysis in relation to pre-drying treatment (noOSMO, no pre-  
 592 treatment; OSMO1; 1h osmodehydration; OSMO2, 3 h osmodehydration). Means in the same row  
 593 followed by different letters are statistically different (Tukey’s test, P≤0.05%) (n=6).

594

	Means ±standard error						ANOVA <sup>‡</sup>		
	noOSMO		OSMO1		OSMO2		main effects interaction		
	LeM	MoM	LeM	MoM	LeM	MoM	O	M	O×M
<b>Mechanical parameters</b>									
number of peaks	2.2±0.6 <sup>a</sup>	3.2±0.84 <sup>a</sup>	4.0±1.1 <sup>a</sup>	5.0±1.1 <sup>a</sup>	3.3±0.7 <sup>a</sup>	3.8±0.5 <sup>a</sup>	ns	ns	ns
hardness (N)	5.98±0.55 <sup>a</sup>	6.83±0.61 <sup>a</sup>	6.65±0.65 <sup>a</sup>	7.13±0.37 <sup>a</sup>	7.41±0.33 <sup>a</sup>	6.82±0.54 <sup>a</sup>	ns	ns	ns
fracturability (mm)	0.95±0.06 <sup>ab</sup>	1.06±0.07 <sup>a</sup>	0.59±0.06 <sup>c</sup>	0.61±0.07 <sup>bc</sup>	0.71±0.11 <sup>bc</sup>	0.73±0.08 <sup>abc</sup>	***	ns	ns
gradient_max (N/mm)	6.98±0.81 <sup>b</sup>	6.40±0.76 <sup>b</sup>	11.49±1.06 <sup>ab</sup>	12.85±2.08 <sup>a</sup>	12.39±0.89 <sup>a</sup>	10.92±1.41 <sup>ab</sup>	***	ns	ns
Area1 (N×mm)	2.68 ±0.19 <sup>ab</sup>	3.26±0.77 <sup>a</sup>	1.25 ±0.35 <sup>b</sup>	2.08±0.45 <sup>ab</sup>	1.68±0.39 <sup>ab</sup>	1.77±0.24 <sup>ab</sup>	**	ns	ns
Total area (N×mm)	3.39±0.52 <sup>a</sup>	3.86±0.52 <sup>a</sup>	3.72±0.42 <sup>a</sup>	3.29±0.55 <sup>a</sup>	3.61±0.47 <sup>a</sup>	3.70±0.57 <sup>a</sup>	ns	ns	ns
Travell1 (mm)	0.94±0.06 <sup>a</sup>	0.96±0.15 <sup>a</sup>	0.39±0.07 <sup>b</sup>	0.57±0.10 <sup>ab</sup>	0.49±0.08 <sup>b</sup>	0.57±0.05 <sup>ab</sup>	***	ns	ns
slope (N/mm)	5.29±0.63 <sup>b</sup>	6.30±0.38 <sup>b</sup>	11.37±1.34 <sup>a</sup>	11.38±1.77 <sup>a</sup>	10.76±0.58 <sup>a</sup>	9.35±0.65 <sup>ab</sup>	***	ns	ns
<i>E</i> <sub>mod</sub> max (MPa)	132.3±20.8 <sup>bc</sup>	125.5±12.2 <sup>c</sup>	236.7±35.0 <sup>abc</sup>	343.5±80.1 <sup>a</sup>	313.8±49.1 <sup>ab</sup>	222.6±28.4 <sup>abc</sup>	**	ns	ns
<i>E</i> <sub>mod</sub> slope (MPa)	101.6±19.7 <sup>b</sup>	124.7±8.5 <sup>ab</sup>	235.9±39.8 <sup>ab</sup>	299.6±65.9 <sup>a</sup>	284.9±59.5 <sup>a</sup>	189.8±11.8 <sup>ab</sup>	**	ns	ns
<b>Acoustic parameters</b>									
<i>N</i> <sub>sounds</sub>	23.2±7.6 <sup>a</sup>	25.2±8.7 <sup>a</sup>	33.5±11.4 <sup>a</sup>	30.0±8.6 <sup>a</sup>	48.2±15.0 <sup>a</sup>	40.0±9.7 <sup>a</sup>	ns	ns	ns
<i>N</i> <sub>sounds&gt;60dB</sub>	3.5±1.8 <sup>a</sup>	5.5±2.2 <sup>a</sup>	11.5±3.7 <sup>a</sup>	11.7±2.4 <sup>a</sup>	14.5±5.8 <sup>a</sup>	14.2±5.2 <sup>a</sup>	*	ns	ns
<i>SPL</i> <sub>av&lt;60</sub> (dB)	47.84±0.46 <sup>b</sup>	43.88±0.79 <sup>c</sup>	48.07±0.88 <sup>ab</sup>	48.73±0.78 <sup>ab</sup>	50.92±0.47 <sup>a</sup>	49.81±0.72 <sup>ab</sup>	***	*	**
<i>SPL</i> <sub>av&gt;60</sub> (dB)	81.82±3.09 <sup>a</sup>	78.19±1.57 <sup>ab</sup>	76.91±2.11 <sup>ab</sup>	79.03±2.41 <sup>a</sup>	69.00±1.51 <sup>b</sup>	73.78±1.20 <sup>ab</sup>	***	ns	ns
<i>avSPL</i> (dB)	52.62±1.85 <sup>bc</sup>	49.51±2.85 <sup>c</sup>	59.35±2.02 <sup>ab</sup>	63.59±3.59 <sup>a</sup>	56.17±0.92 <sup>abc</sup>	59.54±0.68 <sup>ab</sup>	***	ns	ns

595 <sup>‡</sup>O, osmotic pre-treatment, M. TRS maturity class; significance of P-value: \*\*\* P≤0.001%; \*\* P≤0.01%; \* P≤0.05%;  
 596 ns, not significant.

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598

599 **List of Figures**

600 Figure 1 Schematic diagram of a spectral-domain OCT system. The dashed boxes represent portable and  
601 independent modules. DC – directional coupler; FC – fibre coupler; BS – beamsplitter; (G)M –  
602 (galvanometer) mirror; LX – lens; DG – diffraction grating.

603 Figure 2. Micro-CT cross-section before (left) and after (right) binarisation by Otsu thresholding for a LeM  
604 OSMO2 dried apple ring.

605 Figure 3. Reconstructed cross section of (left) noOSMO (slice 500) and (right) OSMO (slice 500) dried  
606 MoM apple rings.

607 Figure 4. Distributions of tissue space thickness ( $n=2$ ) and cumulative frequencies for OSMO 2 and  
608 noOSMO dried rings from apples of TRS less (LeM) and more (MoM) maturity classes. Bars refer to  
609 standard error.

610 Figure 5. Distributions of pore space thickness ( $n=2$ ) and cumulative frequencies for OSMO 2 and  
611 noOSMO dried rings from apples of TRS less (LeM) and more (MoM) maturity classes. Bars refer to  
612 standard error.

613 Figure 6. Examples of OCT images of the surface of noOSMO, OSMO1 and OSMO2 dried apple rings  
614 from fruit for the most differing fruit in the batch (R1, LeM; R20, MoM). Image size  $5 \times 0.88 \text{ mm}^2$ .

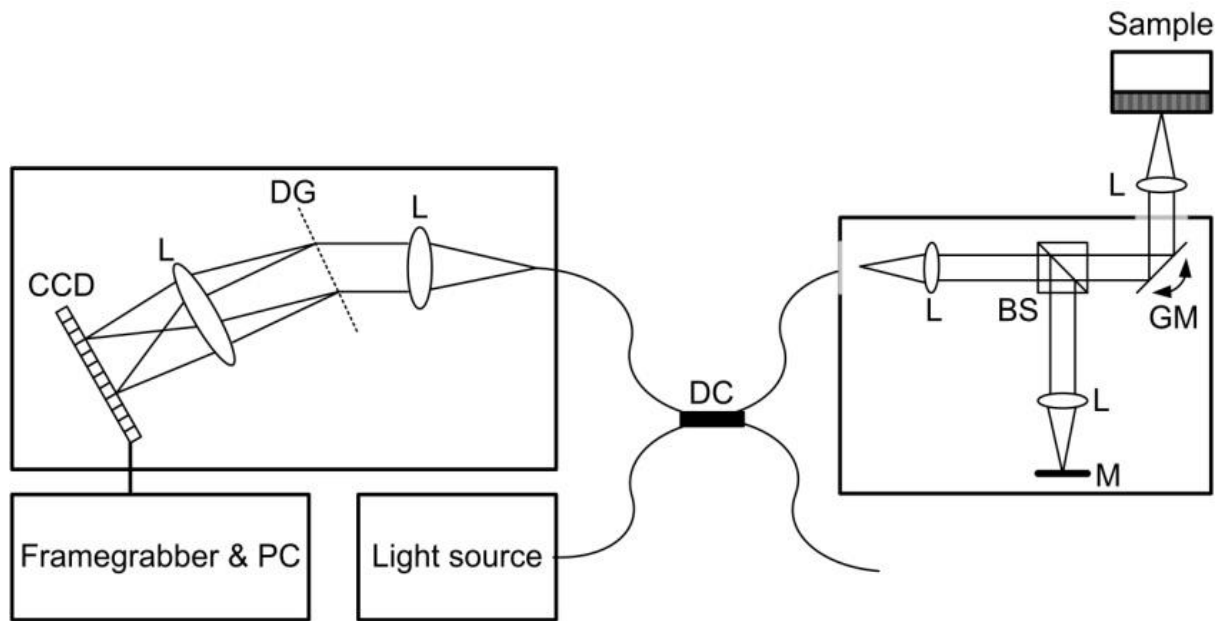
615 Figure 7. Results of PCA: biplots of PC1 vs PC2 (top) and of PC3 vs PC4 (bottom) showing the loadings of  
616 variables (cross) and the scores of OSMO (square) and noOSMO (circle) dried rings from less (filled  
617 symbols) and more (empty symbols) mature apples in the batch. Variables abbreviations: FI,  
618 fragmentation index; OSVR, tissue specific surface area.

619 Figure 8. Results of PCA: average PCs scores in function of pre-treatment and TRS maturity class (LeM,  
620 less mature; MoM, more mature). Bars refer to standard error ( $n=2$ ).

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622 Figure 1

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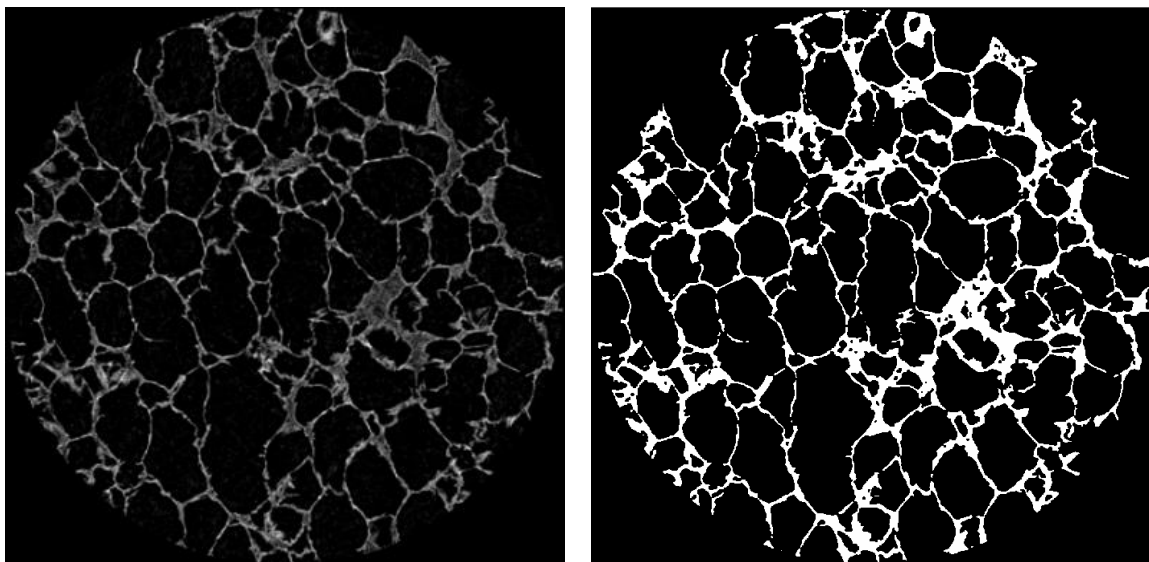
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628 Figure 2

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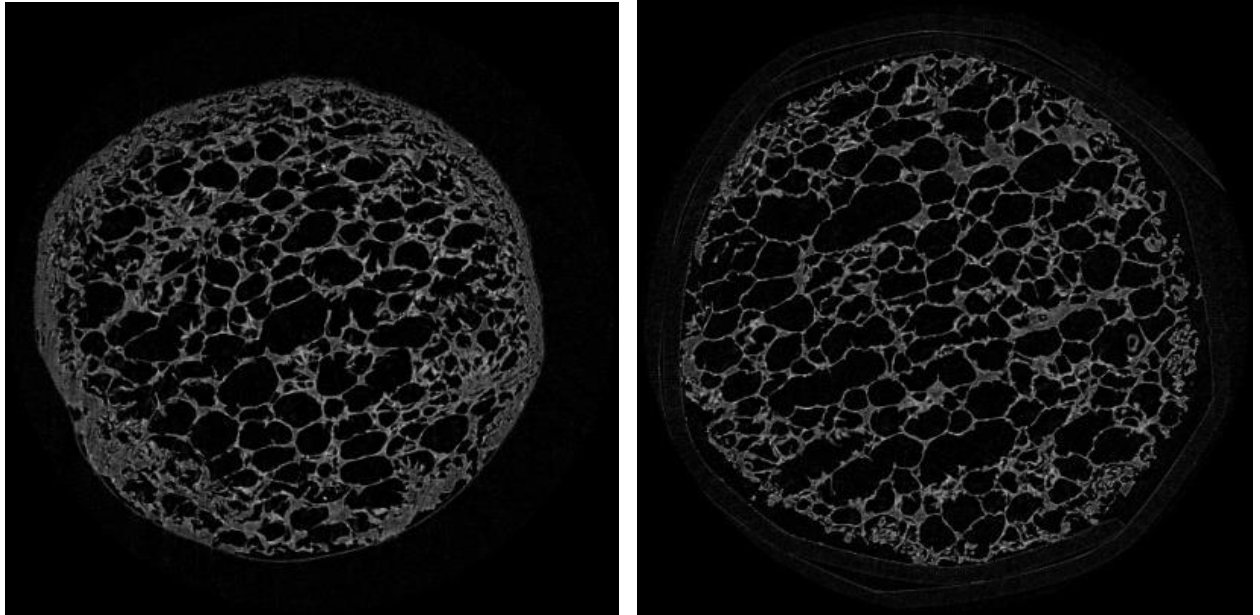
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634 Figure 3.

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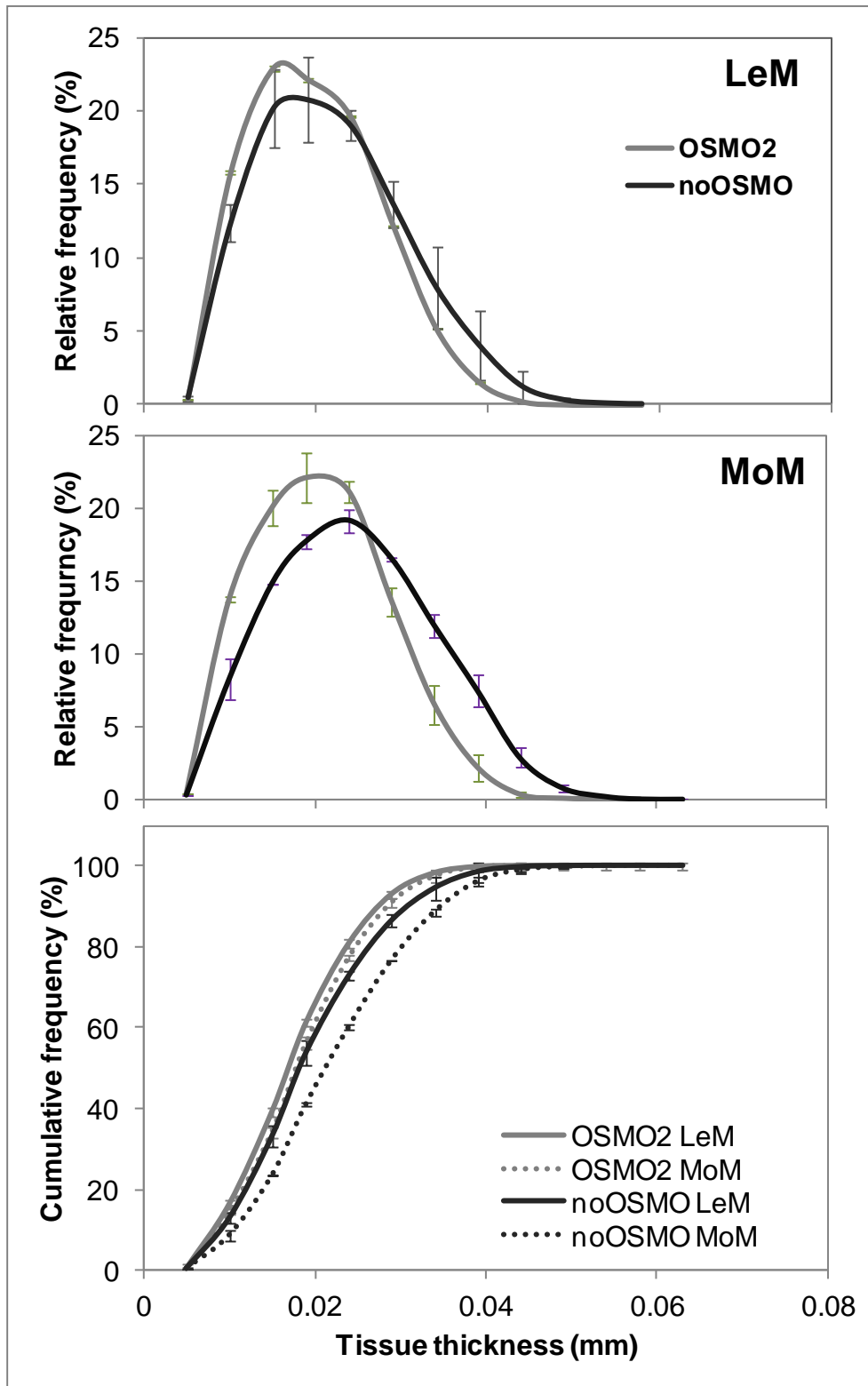
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641 Figure 4



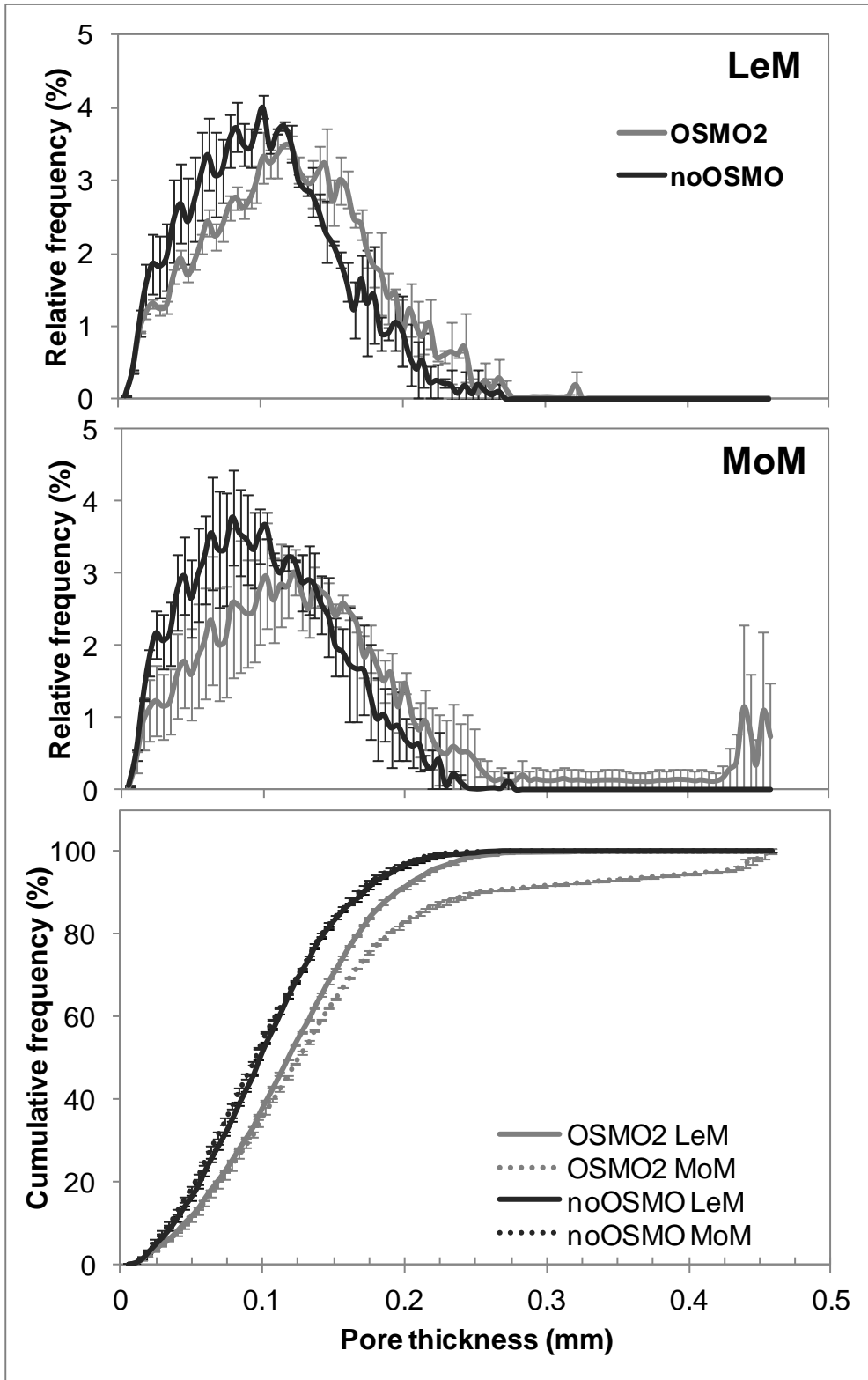
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645 Figure 5

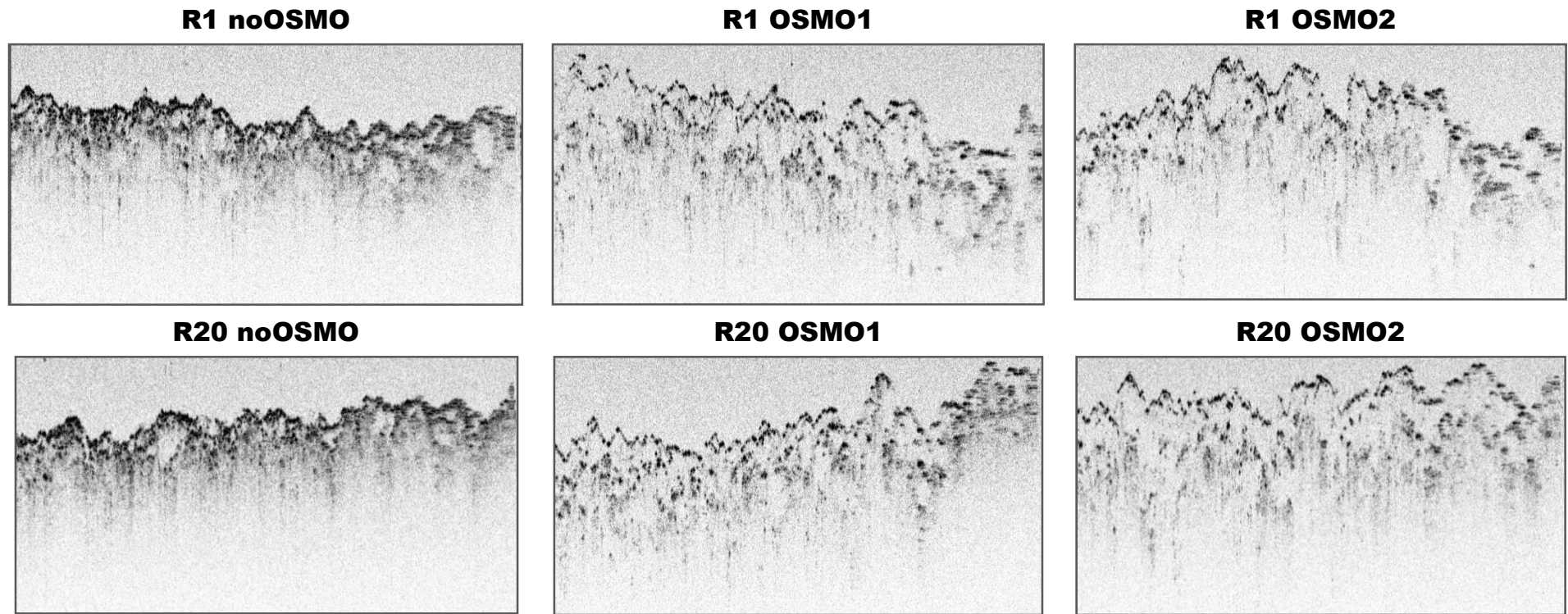
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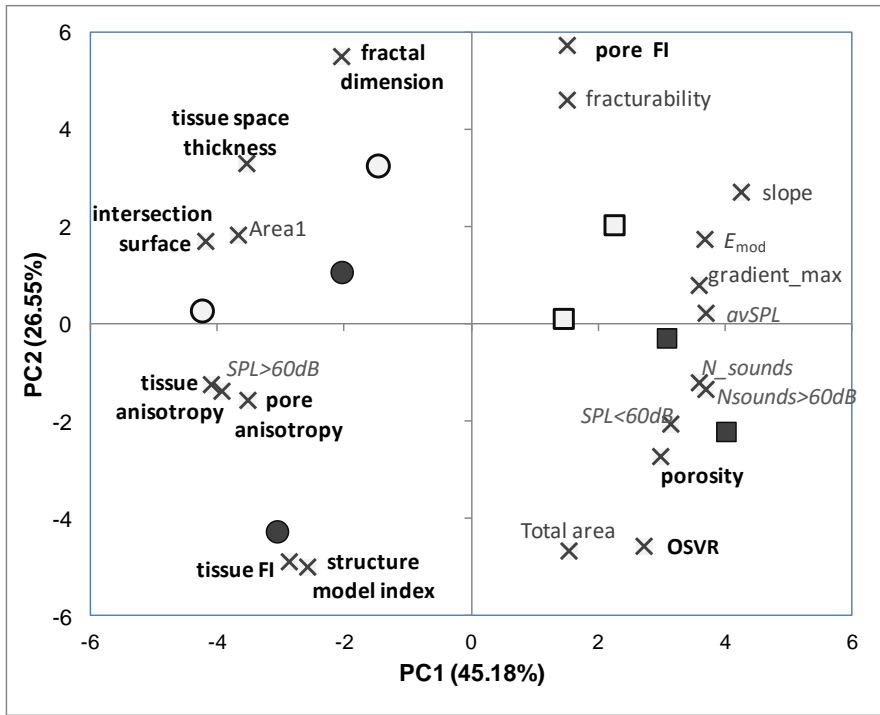
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Figure 6

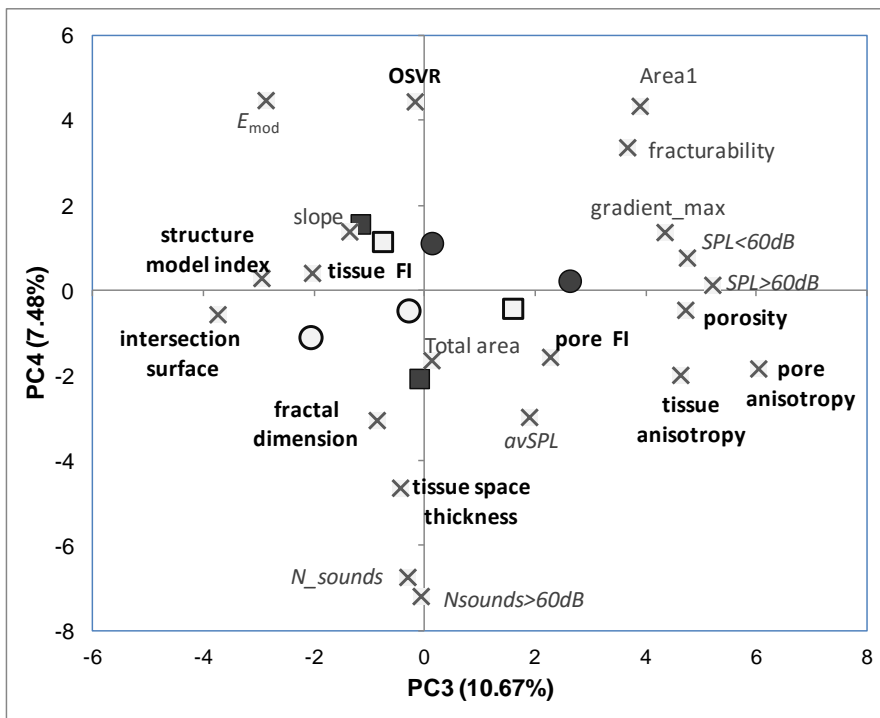




1 Figure 7



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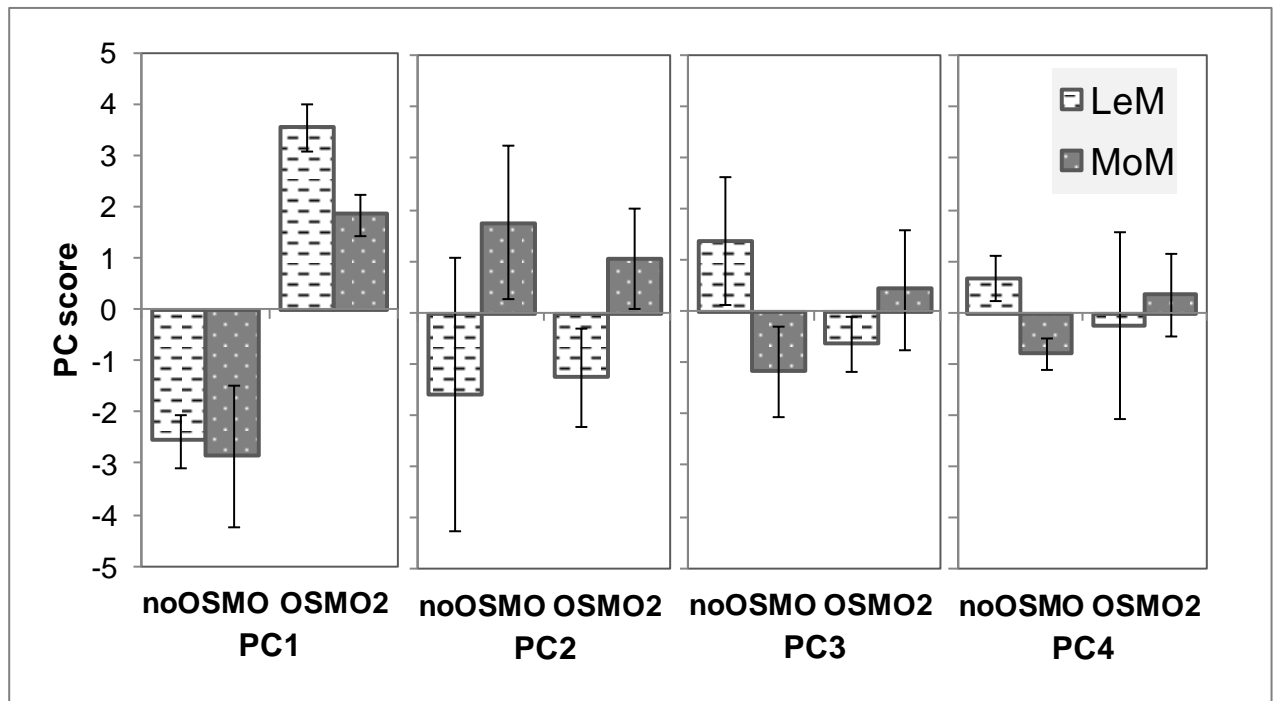
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6 Figure 8

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