

# 1 BULK OPTICAL PROPERTIES OF POTATO FLESH IN THE 500-1900 nm RANGE

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## 9 Abstract

10 In this study the optical properties of potato flesh tissue were estimated using double integrating sphere  
11 (DIS) measurements combined with an inverse adding doubling (IAD) light propagation model. Total  
12 reflectance, total transmittance and unscattered transmittance were measured for the wavelength range 500–  
13 1900 nm with 5 nm resolution. From these measurements, the bulk optical properties (absorption  
14 coefficient, scattering coefficient and anisotropy factor) of 53 potato tubers of the Hermes cultivar were  
15 estimated. The estimated absorption coefficient spectra were dominated by water and starch absorption  
16 bands, the main chemical components of potato tissue. Comparison of these values to those reported in  
17 literature for similar products showed comparable absorption profiles. The obtained scattering coefficient  
18 spectra showed a smooth decrease from 166 cm<sup>-1</sup> to 160 cm<sup>-1</sup> in the NIR spectral range with increasing  
19 wavelength, which is common for biological tissues. The anisotropy factor spectra obtained for the full  
20 wavelength range studied, ranged between 0.949 and 0.959 with a maximum variability of 0.009 among  
21 the set of samples used. The information obtained in this study is essential to understand the effects of  
22 absorption and scattering on the propagation of light through the potato tubers in order to design more  
23 efficient sensors for non-destructive quality evaluation.

24 **Keywords:** Optical properties, double integrating spheres, scattering, absorption, inverse adding doubling,  
25 potatoes.

## 26 1. INTRODUCTION

27 Potato (*Solanum tuberosum* L.) is one of the main food products globally as it is considered a staple food  
28 in many developing countries (López et al., 2013). According to the Food and Agriculture Organization of  
29 the United Nations (FAOSTAT, 2013), potato was the fifth most produced crop worldwide in 2012, after  
30 sugar cane, maize, rice and wheat.

31 The consumption of potatoes was reported to provide several benefits for health since these tubers are a  
32 good source of potassium, protein, calcium and vitamin C (Lister & Munro, 2000). **Both potato consumers**  
33 **and the retail sector prefer potatoes of high quality, which is determined by the tubers' chemical constituents**  
34 **and physical properties (microstructure).** Moreover, besides the nutritional value of potatoes, also  
35 appearance, flavour and the presence of defects caused by mechanical damage are important.

36 The traditional methods employed to determine the main constituents of potatoes involve wet chemistry  
37 methods, such as high-performance liquid chromatography (HPLC) (Mehrubeoglu & Cote, 1997).  
38 However, in today's competitive market, where the importance of quality monitoring is increasing, it is  
39 becoming necessary to develop faster, more economical, safer and more versatile non-destructive  
40 techniques to efficiently measure these properties. Near-infrared spectroscopy (NIRS) is considered one of

41 the most advanced technologies for non-destructive quality assessments of fruits and vegetables (Cubeddu  
42 et al., 2001; Nicolai et al., 2007; Cubero et al., 2011; Wang & Li, 2013).

43 NIRS technology was introduced in the industry in the 1970s, and has been used since then for moisture,  
44 protein, and fat content determination in many agricultural and food products (Davies & Grant, 1987;  
45 Gunasekaran & Irudayaraj, 2000; Nicolai et al., 2014). The detection of these chemical components relies  
46 on the wavelength-specific NIR absorbance which is linearly proportional to the concentration of the  
47 absorbing constituents. Nevertheless, next to the sample's chemical composition, the absorbance of the  
48 photons also depends on the travelled path-length. In agricultural and food products, light is typically  
49 scattered by the numerous local non-uniformities (physical microstructure): cells, cell organelles, air pores,  
50 fibrous structures, fat globules, etc. (Wang & Li, 2013). Because these light deflections increase the  
51 photon's path-length, the NIR absorbance increases to an unknown extent. In practice, the measured NIR  
52 reflectance or transmittance spectra are often dominated by these scattering effects. Accordingly, a decrease  
53 in NIR reflectance or transmittance caused by a change in scattering might be misinterpreted as an increase  
54 of the sample's actual absorption coefficient, while the latter should be normalized for the photon's path-  
55 length to follow a linear relation with the sample composition.

56 Simulation of the light propagation through the tissues of interest could provide insight in the specific  
57 relations between scattering, absorption and measured spectroscopic signals, promoting a more efficient  
58 NIR sensor design, data processing and data interpretation (Zamora-Rojas et al., 2014; Steponavičius &  
59 Thennadil, 2009, 2011, 2013). Light propagation in homogeneous turbid media such as potatoes can be  
60 described with the radiative transport equation (RTE) which uses the bulk optical properties of the tissue:  
61 the bulk absorption coefficient ( $\mu_a$ ), bulk scattering coefficient ( $\mu_s$ ) and anisotropy factor ( $g$ ) as input  
62 parameters. The  $g$  and  $\mu_s$  can be combined to obtain a parameter called reduced scattering coefficient ( $\mu_s'$ )  
63 (Aernouts et al., 2013; Arimoto et al., 2005; Bashkatov et al., 2005a; Lino et al., 2003; Zamora-Rojas et al.,  
64 2013a). The bulk absorption coefficient relates linearly to the sample's composition, while the bulk  
65 scattering coefficient and scattering anisotropy factor define the level and the angular distribution of the  
66 light deflections (Xia et al., 2007). An anisotropy factor of 0 implies isotropic scattering, while a value of  
67 1 denotes exclusive forward scattering. Knowledge of the potential range of the sample's bulk optical  
68 properties is essential to perform detailed light propagation studies (Arimoto et al., 2005; Lino et al., 2003;  
69 Zamora-Rojas et al., 2013a).

70 Double integrating sphere (DIS) measurements, either alone or in combination with unscattered  
71 transmittance measurements, are the "golden standard" method to obtain accurate estimates of the optical  
72 properties for thin slices of biological tissue (Pickering et al., 1993). A DIS setup allows to measure the  
73 total reflectance and total transmittance simultaneously, providing more robust and accurate estimates of  
74 the bulk optical properties compared to single integrating sphere measurements (Bashkatov et al., 2011;  
75 Pickering et al., 1993; Prahl, 2011). The theory and practicability of integrating spheres for measuring the  
76 reflectance of a sample have been widely studied (Pickering et al., 1993). However, the bulk optical  
77 properties cannot be estimated directly from DIS and unscattered transmittance measurements, but have to  
78 be estimated by performing an iterative inversion of a light propagation model (Zamora-Rojas et al., 2013a).  
79 The RTE describes photon propagation in scattering and absorbing media for single scattering events, based  
80 on the optical properties of the sample (Martelli, 2012). With the objective of solving the RTE for multiple  
81 scattering samples, the adding doubling (AD) method allows to calculate the total reflectance and  
82 transmittance very accurately, while maintaining a high degree of flexibility and time efficiency. Moreover,

83 this method uses the RTE to obtain the reflectance and transmittance for a single ‘infinitesimally’ thin  
84 sample layer. Accordingly, this layer is ‘doubled’ and the reflectance and transmittance of this doubled  
85 layer are calculated by combining the values from two single layers. Finally, this process is repeated until  
86 the desired thickness of the homogeneous sample is reached (Saeys et al., 2008; Zamora-Rojas et al.,  
87 2013a). As the AD method calculates the total reflectance and transmittance for a tissue layer with known  
88 bulk optical properties, it has to be inverted to allow extraction of the bulk optical properties ( $\mu_a$  and  $\mu_s$ )  
89 from DIS measurements. The inverse AD (IAD) algorithm, developed by Prahl et al. (1993), estimates the  
90 optical properties by iteratively changing their values in the AD simulations until the simulated reflectance  
91 and transmittance values match with the measured ones (Prahl, 2011; Saeys et al., 2008; Zamora-Rojas et  
92 al., 2013b). Moreover, by an accurate measurement of the unscattered transmittance, the bulk extinction  
93 coefficient ( $\mu_t$ ) is obtained and all bulk optical properties ( $\mu_a$ ,  $\mu_s$  and  $g$ ) can be derived (Prahl, 2011). The  
94 unscattered transmittance should be measured in a configuration especially optimized to minimize the  
95 collection of scattered photons (Aernouts et al., 2013; De Vries et al., 1999; Prahl, 2011). Otherwise, the  
96 unscattered transmittance could be overestimated, leading to an underestimation of  $\mu_t$  (Prahl, 2011,  
97 Aernouts et al., 2013).

98 Since 2000, the bulk optical properties of many food products have been characterized in the visible (Vis)  
99 and near infrared (NIR) spectral ranges. Cubeddu et al. (2001), measured the internal optical properties of  
100 apples by Time-resolved reflectance spectroscopy, while Fraser et al. (2003) studied the light distribution  
101 inside mandarins using a custom-made probe connected to a spectrometer. Wang & Li (2013) and Saeys et  
102 al. (2008) used integrating sphere techniques to determine the bulk optical properties of respectively onions  
103 and apples. Regarding potatoes, Karagiannes et al., (1989) studied the bulk absorption and reduced  
104 scattering coefficients of Idaho potatoes in the 340-1360 nm spectral range, assuming a wavelength-  
105 independent value for  $g$ . Nevertheless, both the bulk scattering coefficient and the anisotropy factor are  
106 essential inputs for simulation studies to develop and evaluate novel optical quality sensors for the non-  
107 destructive analysis of tubers. Additionally, the NIR range above 1400 nm include important absorption  
108 bands related to potato constituents (e.g. water, starch, ...). Therefore, the aim of this study was to measure  
109 all three bulk optical properties ( $\mu_a$ ,  $\mu_s$  and  $g$ ) of potato flesh in the 500 - 1900 nm wavelength range.

## 110 2. MATERIALS AND METHODS

### 111 2.1- Sample set

112 Potato (*Solanum tuberosum* L.) samples were provided by The Basque Institute for Agricultural Research  
113 and Development (Neiker Tecnalia) in Spain, and were sent to KU Leuven Department of Biosystems,  
114 MeBioS, Leuven, Belgium, for the measurements. A total of 53 different tubers belonging to the Hermes  
115 cultivar were used in this study and 2-3 replicates of each tuber were analysed accounting for a total of 143  
116 samples of flesh. Potato tubers were kept in a refrigerator at 4 °C before analysis. Then, tubers were washed,  
117 weighted and peeled. Potato flesh samples were sliced into 550  $\mu\text{m}$  thickness portions of 30 mm diameter  
118 using a meat slicer (Junior sup 19 mod 30-595A, CAD, ITALY). The thin portions were sandwiched  
119 between two optical borosilicate glass plates after adding distilled water to remove air and consequently  
120 reduce the refractive index (RI) mismatch at the glass-sample boundary. **The thickness of the sample slides**  
121 **was measured with a calliper with an accuracy of 5  $\mu\text{m}$ . The thickness of the cuvette, together with the**  
122 **thickness of the sample slab and glass plates (1100  $\mu\text{m}$ ) was used to calculate the thickness of the present**  
123 **water layer.**

124 2.2- DIS and unscattered transmittance measurements

125 To acquire total reflectance ( $M_R$ ), total transmittance ( $M_T$ ) and unscattered transmittance ( $M_U$ ), a  
126 wavelength-tuneable DIS and unscattered transmittance measuring system was used. Detailed information  
127 about the used system can be found in Aernouts et al. (2013). The measurements were taken in the  
128 wavelength range 500 – 1900 nm with an interval step of 5 nm.

129 In this setup, illumination of the samples is provided by a high power (4 W) supercontinuum laser source  
130 with a 460–2400 nm range (SC450-4, Fianium Ltd., Southampton, UK) coupled into a high precision  
131 monochromator (Oriel Cornerstone™ 260×, Newport, Irvine, US) covering the 450-2800 nm wavelength  
132 range in order to obtain a high signal to noise ratio (SNR) for DIS measurements on biological tissues. A  
133 flip mirror, located behind the monochromator, reflected or passed the collimated light towards either the  
134 DIS or the unscattered transmittance measurement path.

135 The thin potato tissue samples were placed between two optical borosilicate glass slides (1.1 mm wall  
136 thickness), separated by a spacer of 550  $\mu\text{m}$  (path-length). For DIS measurements, the sample (tissue +  
137 glass plates) was positioned between the two Infragold® coated integrating spheres (RT-060-IG,  
138 Labsphere, Inc., North Sutton, US. 700–20,000 nm wavelength range; 6 inch inner diameter). The sample  
139 port has a diameter of 1 inch, while all detector ports were 0.5 inch in diameter (Aernouts et al., 2013;  
140 Zamora-Rojas et al., 2013a). Two detectors are located on the wall of each sphere: a large-area Silica (Si)  
141 detector (PDA 100A, Thorlabs Inc., New Jersey, USA) for the 500-1050 nm range and a one-stage Peltier-  
142 cooled extended-InGaAs detector (PDA10DT-EC, Thorlabs Inc., New Jersey, USA) for measurements in  
143 the 1050-2250 nm range. To avoid detection of reflected or transmitted light coming directly from the  
144 sample, baffles are located on the inner sphere wall between the sample and the detectors (Aernouts et al.,  
145 2013).

146 For the unscattered transmittance measurements, 3 round slits are optically aligned: one immediately before  
147 and after the sample and a third one at a 1.5 m distance behind the sample. This design ensures a maximum  
148 collection angle of 5 mrad in order to minimize the number of scattered photons captured. The sample is  
149 placed in a sample holder, perpendicular to the incident collimated light beam. An automated flip mirror,  
150 located behind the third slit, reflects or passes the light respectively towards a Si or an extended-InGaAs  
151 detector with the specifications mentioned above. Instrumental calibration and sample analysis were  
152 performed following the methodology described by Prahl (2011). To prevent detector saturation during  
153 calibration of the unscattered transmittance setup, a neutral density filter (NDF, Qioptiq Limited,  
154 Luxembourg) of optical density 3.0 was located in the sample holder (Zamora-Rojas et al., 2013a). The  
155 system (laser, monochromator, flip mirror and detectors) and data collection were automated and controlled  
156 with LabView 8.5 software (National Instruments Corporation, Austin, TX) (Aernouts et al., 2013).

157 2.3- Optical properties estimation

158  $M_R$ ,  $M_T$  and  $M_U$  were calculated from the DIS and unscattered transmittance measurements in Matlab (ver  
159 7.10, The Mathworks Inc., Massachusetts, USA), as described by Aernouts et al. (2013). From these values,  
160 the absorption coefficient ( $\mu_a$ ), reduced scattering coefficient ( $\mu_s'$ ) and anisotropy factor ( $g$ ) were calculated  
161 using the IAD software provided by Prahl (2011) and implemented in Matlab. To correct for reflections at  
162 the glass-sample boundaries, the refractive index (RI) of potato tissue samples has to be supplied to the  
163 algorithm in order to solve the inverse problem. The wavelength-dependent RI values were estimated by  
164 adding the difference between the RI of potato and water at 589.29 nm to the wavelength-dependent RI

165 values for water reported by Hale and Querry (1973) and Segelstein (1981). According to Birth (1978), the  
166 RI value for potato at 589.29 nm is 1.4, while the RI of water is 1.33 (Hale & Querry, 1973; Segelstein,  
167 1981). The scattering coefficient ( $\mu_s$ ) was calculated from  $\mu_s'$  and  $g$  using the similarity relation (Tuchin,  
168 2007):

$$169 \quad \mu_s = \frac{\mu_s'}{(1-g)} \quad (1)$$

170 Additionally, through the unscattered transmittance measurement of 1 mm water, the  $\mu_a$  spectrum of pure  
171 water was derived. Taking into account this water spectrum, as well as the thickness of the water layer and  
172 the sample slab in the cuvette, the  $\mu_a$  spectrum of the sample slab alone was obtained. Furthermore, the  $\mu_s$   
173 and  $\mu_s'$  spectra were rescaled with the thickness of the sample slab relative to the total thickness (sample  
174 slab + water layer).

### 175 3. RESULTS AND DISCUSSION

176 In Fig. 1 the mean and standard deviation (vertical lines) of the total reflectance ( $M_R$ ), total transmittance  
177 ( $M_T$ ) and unscattered transmittance spectra ( $M_U$ ) acquired for 143 potato tissue samples in the 500-1900 nm  
178 wavelength range are illustrated.

179 All the measured spectra ( $M_R$ ,  $M_T$  and  $M_U$ ) show clear valleys around 970, 1210, 1440-1490 and at 1900  
180 nm, all associated with water absorption bands related to the second and first overtones of OH stretching  
181 and OH combination bands. As raw tubers usually have a water content of approximately 80% (Büning-  
182 Pfaue, 2003), it is not surprising that the acquired spectra are dominated by the absorption signature of  
183 water. At 1765 nm another valley can be observed which can be related to the first overtone of the CH  
184 stretching. This can be attributed to starch which represents approximately 60-80% of the dry matter of raw  
185 potato tubers and contains both CH and CH<sub>2</sub> groups. Due to the high water absorption, the measurement  
186 values were close to zero in the 1900-2250 nm wavelength range (data not shown). As a result, the system  
187 failed to estimate the bulk optical properties at these wavelengths. In the 500-1900 nm range  $M_U$  values  
188 varied between 0% and 0.04%  $\pm$  0.01%. These low values indicate that only a very small fraction of the  
189 photons passes through the tissue without being scattered. This limits the SNR of the obtained  $M_U$  (Zamora-  
190 Rojas et al., 2013a).

191 In Fig. 2 the mean and standard deviation of the bulk optical properties ( $\mu_a$ ,  $\mu_s$  and  $g$ ) calculated with the  
192 IAD method are illustrated. As mentioned above, no reliable values could be obtained in the 1900-2250 nm  
193 wavelength range (not shown) as the signal-to-noise ratios of the DIS and unscattered transmittance  
194 measurements were too low. As can be seen in the plot, the absorption coefficient ( $\mu_a$ ) spectrum shows  
195 absorption peaks at 970, 1210 nm and 1440-1490 nm due to the high water content in raw potatoes. A small  
196 peak around 1765-1800 nm is observed which can be related to the starch content. Additionally, an increase  
197 in the absorption of visible light can be noticed towards 500 nm. This is more clearly presented in the detail  
198 plot in Fig. 3. The absorption at these wavelengths corresponds to the yellow colour of potato flesh and is  
199 probably related to the presence of beta-carotene (Penner, 2010; Du et al., 1998). The bulk scattering  
200 coefficient ( $\mu_s$ ) spectrum changes only gently with increasing wavelength, decreasing from 166 to 160 cm<sup>-1</sup>  
201  $\pm$  7.35 cm<sup>-1</sup> for wavelengths below 1900 nm. This decreasing tendency with increasing NIR wavelength  
202 is typical for the scattering characteristics of biological tissues (Bashkatov et al., 2005b). The estimated  
203 anisotropy factor values were quite stable ranging from 0.959 to 0.949. It should be noted that the accuracy  
204 of the estimated anisotropy factor values was negatively influenced by the strong water absorption at 1440-  
205 1490 nm, as can be seen from the larger standard deviations.

206 In Fig. 3 and 4, the bulk optical properties of potato flesh of this study are plotted together with the values  
207 reported by Karagiannes et al. (1989) for Idaho potato tubers. In the latter study, potato tuber samples of  
208 3.5 mm were measured in air in the 340-1360 nm spectral range with a two-channel integrating sphere  
209 spectrophotometer. The optical properties were estimated from these data with two formulations of the 1D  
210 diffusion approximation differing in the utilized phase function, assuming a refractive index for potato  
211 equal to 1.36 (Karagiannes & Grossweiner, 1988) and a fixed anisotropy factor  $g$  of 0.

212 In Fig. 3, the average absorption coefficient spectrum obtained in this study and the one reported by  
213 Karagiannes et al. (1989) are plotted together with the absorption coefficient spectrum of water from 500  
214 to 1900 nm (Segelstein et al., 1981). Although the same absorption bands for water appear in both potato  
215 spectra, the values at the absorption peaks are on a different level. The estimated values at 970 and 1200 nm  
216 reported by Karagiannes et al. (1989) considerably exceed the absorption coefficient values of pure water.  
217 These values are highly questionable as water is the most important NIR absorbing component in potatoes.  
218 Therefore, it is hypothesized here that these values are overestimated due to an inferior separation between  
219 scattering and absorption. This can additionally be noticed at 800 nm, where a baseline is clearly present in  
220 the  $\mu_a$  reported by Karagiannes et al. (1989), while nearly no absorption is expected as potato constituents  
221 do not absorb significant amounts of light at this wavelength. In the 600-1400 nm range, the  $\mu_a$  spectrum  
222 obtained in this study is very close to the absorption coefficient spectrum of water (Fig. 3), suggesting that  
223 the sample consists mainly of water. As explained before, some water was added to the samples to reduce  
224 the RI mismatch at the boundaries, probably causing an increase in water content of the samples. In the  
225 1500-1790 nm range, the average  $\mu_a$  spectrum of the samples is higher compared to the water spectrum.  
226 This can be attributed to the first overtone absorption bands of the CH and CH<sub>2</sub> bands in the starch  
227 molecules. The  $\mu_a$  values in the 1400-1500 nm range are probably slightly overestimated due to imperfect  
228 separation of the scattering and absorption coefficient values in this region, induced by the low signal levels  
229 (Fig. 1). Although the results in this study are not perfect, they are much closer to reality than those reported  
230 by Karagiannes et al. (1989).

231 In Fig. 4, the scattering coefficient  $\mu_s'$  values in the 500-1900 nm spectral range estimated in both studies  
232 are shown. It can be observed that the  $\mu_s'$  spectrum obtained in this study is relatively steady along the  
233 entire spectral range with values between 7.5 and 8.3 cm<sup>-1</sup> except at the 1440-1490 nm range where it is  
234 influenced by water and values decrease down to 6.6 cm<sup>-1</sup>. The reduced scattering coefficient values  
235 obtained by Karagiannes et al. (1989) are smaller, which may be attributed to a difference in the  
236 microstructure properties of the cultivars and samples considered in both studies. However, as no  
237 microstructure information on the samples is available, this hypothesis cannot be verified. On the other  
238 hand, as their absorption coefficient values were most likely overestimated, it is likely that they  
239 underestimated the reduced scattering coefficient  $\mu_s'$  values due to imperfect separation of the absorption  
240 and scattering properties (Zamora-Rojas et al., 2013a).

241 Recently, Wang & Li (2013) measured the bulk absorption coefficients, reduced scattering coefficients and  
242 scattering anisotropy of skin and flesh of four different onion cultivars at 633 nm. They obtained absorption  
243 coefficient values between 0.32-1.2 cm<sup>-1</sup> for the flesh of the different cultivars and bulk scattering  
244 coefficients in the 5.8-6.6 cm<sup>-1</sup> range for white and yellow onions. These values are similar to those obtained  
245 in this study for potato flesh. The estimated anisotropy values at 633 nm for onion flesh tissues varied from  
246 0.35-0.73, which is considerably smaller than those obtained for potato tissue in our study.

247 Saeys et al. (2008) studied the optical properties of both skin and flesh for three different apple cultivars at  
248 1450 nm by using a single integrating sphere measurements in combination with IAD. The reduced  
249 scattering coefficient values for apple flesh obtained in their study ranged from 10 to 15 cm<sup>-1</sup> in the 350-  
250 1900 nm range, while those for apple skin ranged from 30 to 60 cm<sup>-1</sup> in the same wavelength range. This  
251 suggests that both apple flesh and skin tissue are more optically dense than potato flesh tissue.

252 The fact that the bulk optical properties estimated in this study are more reliable than those obtained by  
253 Karagiannes et al. (1989) can most likely be attributed to the use of a DIS system in combination with a  
254 high power supercontinuum laser, rather than the use of a single integrating sphere in combination with a  
255 halogen light source. The DIS system allows for simultaneous and robust measurement of  $M_T$  and  $M_R$   
256 without replacing the sample or the sphere. The use of a supercontinuum laser light source makes it possible  
257 to focus a high power beam on a very small spot on the sample, reducing the lateral light losses. Another  
258 possible explanation for the difference between the bulk optical properties obtained in both studies may be  
259 related to the use of different light propagation models, the instrument calibration and the heterogeneity of  
260 the samples (Tuchin, 2007).

#### 261 **4. CONCLUSIONS**

262 In this study, the bulk optical properties of potato flesh were measured in the 500-1900 nm wavelength  
263 range by means of double integrating spheres and unscattered transmittance measurements. This resulted  
264 for the first time in a wavelength-dependent estimate of the anisotropy factor for potato flesh over that  
265 wavelength range. The obtained results show that the bulk absorption coefficient spectra are mainly  
266 dominated by water, especially in the NIR region, while the starch absorption bands are less pronounced,  
267 but still clearly visible. The bulk scattering coefficient spectra slightly decreases with increasing  
268 wavelength. The estimated values for the anisotropy factor were high (>0.94) over the considered spectral  
269 range, which indicates that potato tissue is highly forward scattering. Compared to the results obtained by  
270 other authors, the absorption and reduced scattering coefficient spectra for potato tissue retrieved in this  
271 study were likely more reliable. Moreover, the optical properties were obtained in the visible and extended  
272 NIR range from 500 to 1900 nm, compared to 340-1360 nm. The added value of the extended range is  
273 significant as the relevant absorption peaks for water and starch are located in the NIR region of the  
274 spectrum. Additionally, the obtained optical properties were comparable to the values obtained for other  
275 products (apple and onion flesh and skin) reported in literature.

276 The optical characterization of potato flesh elaborated in this study provides information about the  
277 absorption, scattering and the angular scattering distribution of light propagating through the tissue. This  
278 information is essential to understand the effects of absorption and scattering on the reflectance and  
279 transmittance spectra measured with Vis-NIR spectroscopy.

#### 280 **Acknowledgements**

281 This study was accomplished at the University of Leuven (KU Leuven) while Ainara López-Maestresalas  
282 was a visiting PhD student. The funding of this work has been covered by the Universidad Pública de  
283 Navarra through the concession of both a predoctoral research grant and a mobility grant, by the National  
284 Institute for Agricultural and Food Research and Technology (INIA) project: “Genetic improvement of  
285 Potato. Characterization of the material by NIRS technology” RTA 2011-00018-C03-03, and by the  
286 Agency for Innovation by Science and Technology in Flanders (IWT) through the Chameleon (SB-100021)  
287 project. The authors would also like to thank the Basque Institute for Agricultural Research and

288 Development (Neiker Tecnalia) for supplying the potato samples. Robbe Van Beers is a PhD student funded  
289 by the Institute for the Promotion of Innovation through Science and Technology in Flanders (IWT-  
290 Flanders, grant 131777). Ben Aernouts has been funded through a PhD fellowship of the Research  
291 Foundation-Flanders (FWO-Flanders, grant 11A4813N).



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