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Optical absorption and scattering properties of normal and defective pickling cucumbers for 700–1000 nm

Renfu Lu · Diwan P. Ariana · Haiyan Cen

Abstract An effective optical inspection system for detecting defective pickling cucumbers is needed to help the pickle industry deliver consistent pickled products to the consumer. This research was intended to measure the optical absorption and scattering properties of normal and internally defective pickling cucumbers, using hyperspectral imaging-based spatially-resolved technique. Spatially-resolved hyperspectral scattering images were acquired from 50 freshly harvested 'Journey' pickling cucumbers in the summer of 2008 before they were subjected to rolling under mechanical load to induce internal damage. The damaged cucumbers were imaged 1 h and 1 day after the mechanical stress treatment. Spectra of the absorption and reduced scattering coefficients for pickling cucumbers were extracted from the spatially-resolved scattering profiles, using an inverse algorithm for a diffusion theory model, for the spectral range of 700–1000 nm. It was found that within 1 h after mechanical damage, changes in the absorption and reduced scattering coefficients for the cucumbers were minimal. One day after mechanical damage, the absorption coefficient for the cucumbers increased significantly (at 5–10% level) for the wavelengths of 700–920 nm, whereas the reduced scattering coefficient decreased significantly for the wavelengths of 700–1000 nm (at 10% level). Overall mechanical damage caused greater changes in absolute value to the scattering properties than to the absorption properties. This research suggests that effective defect detection can be achieved by enhancing scattering characteristics measurement in the optical evaluation of pickling cucumbers.

Keywords Pickling cucumbers · Defect · Optical properties · Absorption · Scattering · Hyperspectral imaging · Spatially-resolved spectroscopy

Introduction

Currently, pickling cucumbers in the U.S. are mechanically harvested once over. Since individual fruit on cucumber plants do not grow and mature at the same rate, this once-over harvest practice means that not all cucumbers are harvested at their optimal maturation stage. Fruit that are harvested too late or too large in size tend to have more internal quality problems during brining [1]. In addition, these cucumbers would be more susceptible to mechanical damage during harvest, transport, and postharvest handling. Internal defects, either physiological or mechanical, in pickling cucumbers are normally displayed in the form of soft or watery carpel tissue, loose seeds, and split or hollow center.

With current production/processing practices, harvested cucumbers are trucked to the pickle processing facilities, at which they are washed and sorted or graded for size, misshape, and surface defects. The graded cucumbers are then sent to brining facilities for brining or fermentation, a crucial step in making them into pickles. While machine vision now is commonly used for sorting and grading for size and misshapen fruit, many pickle processors still rely on humans for surface defect sorting [2]. Since internal

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defects are hidden inside the cucumber fruit and are diffi-
cult to detect by machine vision systems or human
inspectors, processors have no control over internal quality
of the cucumbers that go into the brining tanks. Hence, it is
desirable to have an automatic inspection system that can
remove defective pickling cucumbers in order to reduce the
incidence of bloater damage, thus improving the quality of
final pickled products and reducing labor cost.

Optical technology is promising for grading and sorting
both internal and external quality of pickling cucumbers.
Among different techniques, hyperspectral imaging has
recently emerged as a powerful technique for quality and
safety inspection of food and agricultural products [3, 4].
Ariana and Lu [5, 6] developed a laboratory hyperspectral
imaging prototype, which was operated in simultaneous
reflectance (400–740 nm) and transmittance (740–1000
nm) modes for detection of surface and internal defects of
cucumbers. While this new technique is potentially useful for
online sorting and grading of pickling cucumbers and whole
pickles, improvements in both hardware and software are
needed for more effective and rapid detection and segrega-
tion of defective cucumbers or pickles. This would require
better understanding of the optical properties of cucumbers/
pickles, so that an effective lighting/sensing configuration
can be designed for accurate detection of internal defect in
pickling cucumbers. The objective of the research was
therefore to measure the spectral absorption and scattering
properties of normal and defective pickling cucumbers over
the wavelengths of 700–1000 nm, and to quantify the effect
of mechanical damage and post-damage time on the
absorption and scattering properties of cucumber tissue.

Materials and methods

Diffusion theory model

Light transfer in biological materials takes place in the form
of absorption and scattering. Scattering is dominant in tur-
bid plant materials, which suggests that light transfer in the
plant tissue may be simplified as a diffusion process. Thus
diffusion approximation theory can be applied to describe
light transfer in turbid plant materials [7]. Analytical solu-
tions to the diffusion theory equation can be obtained under
specific boundary conditions. Based on the work of Farrell
et al. [8], Kienle et al. [9] derived an improved analytical
solution to describe diffuse reflectance distributions at the
surface of a semi-infinite homogeneous medium, which is
illuminated vertically by an infinitely small continuous-
wave (or steady-state) light beam. The reflectance, R(r), at a
given distance r from the light incident point at the medium
surface may be expressed as a function of the absorption
(μ_a) and reduced scattering (μ_s') coefficients as follows:

$$R(r) = \frac{C_1}{D}\left[\frac{\exp(-\mu_{eff}r_1)}{r_1} - \frac{\exp(-\mu_{eff}r_2)}{r_2}\right]$$
$$+ C_2\left[\frac{1}{\mu_t'}\left(\mu_{eff} + \frac{1}{r_1}\right)\frac{\exp(-\mu_{eff}r_1)}{r_1^2}\right.$$
$$\left.+ \left(\frac{1}{\mu_t'} + 2z_b\right)\left(\mu_{eff} + \frac{1}{r_2}\right)\frac{\exp(-\mu_{eff}r_2)}{r_2^2}\right] \quad (1)$$

where the first term represents the isotropic fluence rate and
the second term is the flux, $C_1 = 0.0101$, $C_2 = 0.0260$,
$D = [3(\mu_a + \mu_s')]^{-1}$ is the diffusion coefficient, $\mu_{eff} = [3(\mu_a + \mu_s')]^{1/2}$ is the effective attenuation coefficient,
$\mu_t' = \mu_a + \mu_s'$ is the total attenuation coefficient, $r_1 = (z_0^2 + r^2)^{1/2}$ and $r_2 = [(z_0 + 2z_b)^2 + r^2]^{1/2}$ are the dis-
tances from the observation point at the interface to the
isotropic and image sources, $z_0 = (\mu_a + \mu_s')^{-1}$ and $z_b = 2D(1 + R_{eff})/(1 - R_{eff})$ for the extrapolated boundary
condition, and R_{eff} is the effective reflection coefficient,
which is equal to 0.4498 for the refractive index $n = 1.35$
for many biological materials [10]. Thus if R_{eff} is deter-
mined, the shape of the reflectance profile is uniquely
determined by μ_a and μ_s' through Eq. 1. Conversely, if the
reflectance profile over the surface of the investigated
material is known, μ_a and μ_s' could be determined through
Eq. 1 using an inverse algorithm.

In this research, cucumbers were assumed to be homo-
geneous and semi-infinite. The optical properties of
cucumber peel and mesocarp tissues are quite different.
Moreover, the properties of endocarp or carpel (i.e., the
central part of the fruit that containing seeds) are also
different from that of the mesocarp tissue. Thus cucumber
fruit should be considered multi-layer media in order to
more accurately describe their structural characteristics.
This would make the problem extremely complex and
difficult to solve. Hence as a first step, it seems reasonable
to impose the homogeneity assumption for determining the
optical properties of cucumbers. Cucumber fruit have a
large dimension (typically > 80 mm in length for com-
mercial size three) along the stem-blossom axis, whose
cross sections are approximately circular with the diameter
being 37–55 mm for commercial size three. Since light
attenuates in most plant materials rapidly and an effective
scattering distance needed for the optical property mea-
surement is often within 10 mm from the incident point.
Thus the semi-infinite medium assumption would be
approximately valid.

Optical property measuring system

A hyperspectral imaging-based spatially-resolved system
in push-broom or line scanning mode, developed in the

Fig. 1 Hyperspectral imaging-based spatially-resolved method in line scanning mode for measuring the optical properties of turbid biological materials: **a** principle and **b** schematic of the system
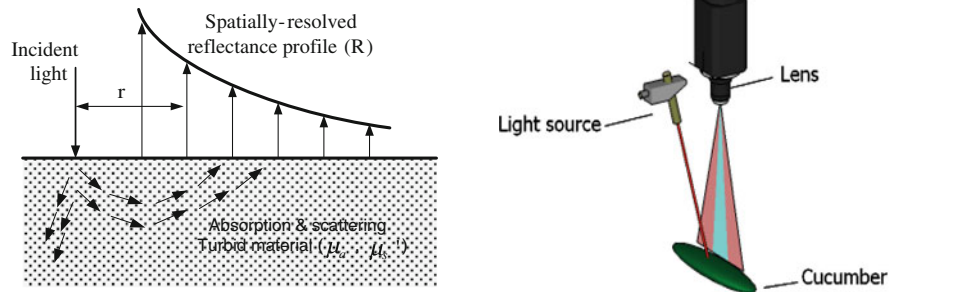
U.S. Department of Agriculture Agricultural Research Service postharvest engineering laboratory at Michigan State University in East Lansing, MI, was used to measure the optical properties of cucumbers and pickles. The optical property measuring system was operated based on the steady-state spatially-resolved measurement principle using the diffusion theory model (Eq. 1), as described in "Diffusion theory model" section, and it also is schematically shown in Fig. 1.

The system consisted of a high performance back-illuminated CCD camera coupled with an imaging spectrograph, a specially designed light source, and the sample handling unit (not shown in Fig. 1b). A detailed description of the system can be found in [11] and [12]. Each cucumber sample was placed on the sample holder which was controlled by two precision motorized stages—one moved vertically and the other horizontally. The cucumber was such positioned that its stem-blossom axis would be approximately parallel with the scanning line (Fig. 1b). Upon reaching the specified height, the cucumber started moving horizontally in the direction perpendicular to the scanning line. The hyperspectral imaging system scanned the surface of the cucumbers to obtain spatially-resolved spectral scattering profiles for the wavelengths of 400–1000 nm. The hyperspectral imaging system had a nominal spectral resolution of 5 nm and a spatial resolution of 0.2 mm per pixel after 4×4 binning.

Experimental procedure

'Journey' pickling cucumbers were hand harvested from an experimental field in Oceana County, MI in August 2008. The samples were cleaned in water and visually inspected to ensure that no surface defect existed. Several cucumbers were cut open for examination of their internal condition prior to the experiment, and no internal defect (i.e., bruise, soft or watery carpel tissue, loose seeds, and split or hollow

center) was observed in these cucumbers. A total of 50 pickling cucumbers were used in the experiment; their size (or diameter), measured at the middle section of the cucumbers, ranged between 37 and 55 mm.

Each fresh cucumber was first scanned by the hyperspectral imaging system, following the procedure described in "Optical property measuring system" section (Fig. 1b), to produce spatially-resolved hyperspectral scattering images. Ten hyperspectral scattering images were collected from each sample with 10 mm horizontal movement and these images were then averaged to obtain one final image for further extraction of the absorption and scattering coefficients. After imaging, each cucumber was subjected to rolling under a 10-kg load for 30 s to induce mechanical injury [5]. Within 1 h after the mechanical treatment, the cucumbers were imaged again by the hyperspectral imaging system. Twenty-four hours after the mechanical treatment, the same cucumbers were imaged for the third time. The purpose of measuring the cucumber samples at three different times was to determine the effect of mechanical treatment and post-treatment time on the optical properties of individual cucumbers.

Determination of optical properties

Figure 2 shows a hyperspectral scattering image for a pickling cucumber covering the wavelengths of approximately 600–1000 nm and a total spatial distance of 20 mm. Regions beyond the wavelengths of 600–1000 nm were removed because of low signal to noise ratios. The spectral scattering image shown in Fig. 2a is represented by a spatial dimension for the horizontal axis and a spectral dimension for the vertical axis. Each row of pixels taken from the image (Fig. 2a) represents one scattering profile for a specific wavelength with a 5-nm interval (Fig. 2b). Hence there are a total of 61 spectral scattering profiles covering the wavelengths of 700–1000 nm, a spectral region that was

Fig. 2 Hyperspectral scattering image for a pickling cucumber (**a**) and scattering profiles taken for three selected wavelengths (**b**)
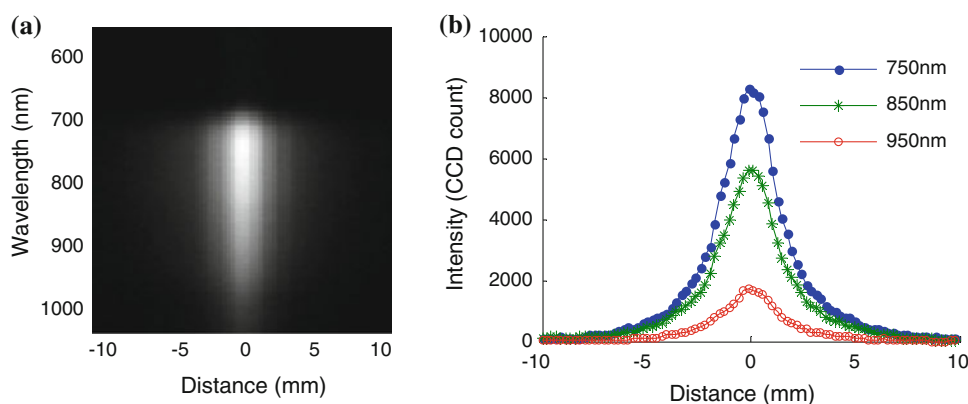
used for extracting the optical parameters. Each scattering profile contains information about the absorption and scattering properties for a given wavelength.

The hyperspectral scattering images for individual cucumbers or pickles were processed and analyzed to obtain the absorption and reduced scattering coefficients for the wavelengths of 700–1000 nm. The procedures of determining the optical properties are as follows:

1. Extract spatial scattering profiles from each hyperspectral image for each wavelength;
2. Convert the two-sided symmetric scattering profiles into one-sided scattering profiles with respect to the point of light incidence (or the zero position on Fig. 2b) and the converted profiles were normalized with respect to their peak values;
3. Determine the absorption and reduced scattering coefficients for 700–1000 nm by fitting the diffusion theory model (Eq. 1) using a trust-region least squares inverse algorithm to the logarithm of the converted scattering profiles in three steps: (a) an initial curve fitting was performed by treating both μ_a and μ'_s as unknown parameters; (b) after the initial values of μ_a and μ'_s were determined for the spectral region of 700–1000 nm, the function $\mu'_s = a\lambda^{-b}$, in which a and b are parameters and λ is the wavelength in nm, was used to fit the spectrum of the reduced scattering coefficient. This procedure removed the noises introduced during the initial curve-fitting process; and (c) the new values of μ_a were obtained by treating it as the only unknown parameter and μ'_s as a known parameter (using the values obtained in step b). This three-step approach reduced the overall noise in determining μ_a and μ'_s [11].

A more detailed description of the procedures for extracting the optical parameters can be found in [11] and [12].

Results and discussion

Figure 3 shows the mean spectra and standard deviations of absorption and reduced scattering coefficients for the 50 normal cucumbers and the 50 defective cucumbers 1 day after the mechanical stress treatment. The spectra of absorption and reduced scattering coefficients for the normal and defective classes of cucumbers were similar in pattern but different in magnitude. Overall the absorption coefficient varied greatly in relative magnitude for the spectral region of 700–1000 nm. The absorption coefficient decreased rapidly from 700 to 730 nm, and it then started to increase gradually at around 730 nm and rapidly beyond 910 nm. Absorption reached a peak at 960 nm, corresponding to a major water absorption waveband, and thereafter it started to decrease again. Considerable variations in the absorption coefficient among the test cucumbers were observed, as shown in Fig. 3a1 and b1. The coefficient of variation, i.e., the ratio of standard deviation to mean, for the absorption coefficient for normal cucumbers was between 40 and 90% for the spectral region of 700–1000 nm. One day after mechanical damage, the variations in absorption among the cucumber samples (Fig. 3a1 vs. b1) were somewhat greater (i.e., values of the coefficient of variation were between 70 and 90%).

The reduced scattering coefficient, on the other hand, exhibited a very different pattern from that for the absorption coefficient (Fig. 3a2, b2); it decreased steadily with the increasing wavelength throughout the spectral region of 700–1000 nm. The relative variations for μ'_s, measured by the coefficient of variation, for normal and defective cucumbers were in the range of 26–40% except for the lower end wavelengths close to 700 nm due to high noise in the image data, which are smaller than those for μ_a. The overall patterns of the absorption and reduced scattering coefficient spectra for the cucumbers are similar to those for normal and bruised apple fruit [12].

Fig. 3 Mean spectra and two standard deviations of the absorption and reduced scattering coefficients for **a** 50 normal cucumbers, and **b** 50 defective cucumbers 1 day after the mechanical stress treatment
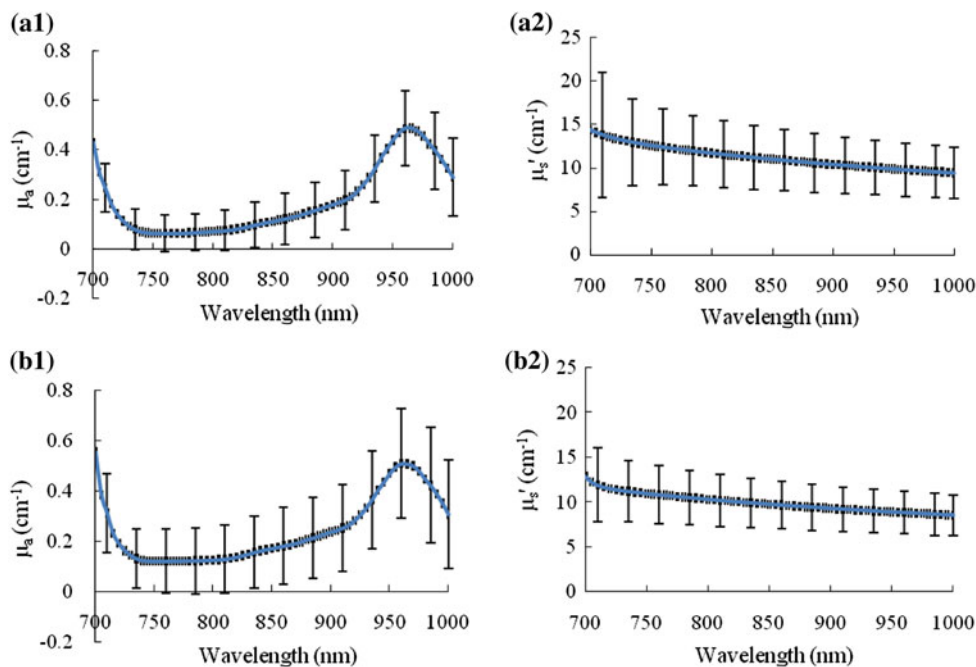
Fig. 4 Mean spectra of **a** absorption and **b** reduced scattering coefficients of 50 normal and defective cucumbers measured at different times after rolling mechanical treatment (1 h and 1 day)
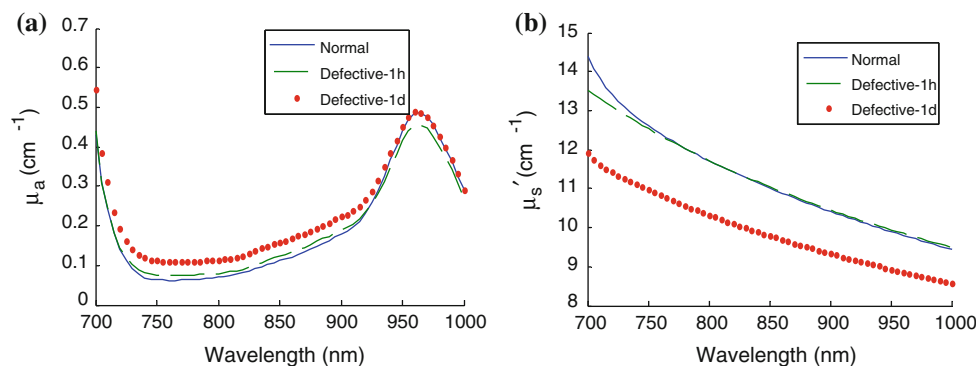

Figure 4 shows the effect of mechanical treatment and post-treatment time on the absorption and scattering spectra for normal cucumbers and stress-induced cucumbers for 1 h and 1 day after the mechanical treatment. Within 1 h after the treatment, changes in the optical properties of the cucumbers were minimal. Small increases in the absorption coefficient were observed for the wavelengths of 720–920 nm, although they were not statistically significant. Beyond 920 nm, normal cucumbers had higher absorption than the same cucumbers that were mechanically treated and tested 1 h later. One day after the mechanical treatment, the cucumbers had noticeable increases in the absorption coefficient for the wavelengths of 700–920 nm. Significant differences (at the level of 5 or 10%) in the absorption coefficient between the normal and 1 day defective cucumber samples were observed for the wavelength of lower than 920 nm, but no significant differences in the absorption coefficient for the normal and 1 h damaged cucumbers were found. Beyond 920 nm, the

differences in absorption coefficient were not statistically significant among the three groups of samples.

The pattern of changes for the reduced scattering coefficient was opposite to that for the absorption coefficient (Fig. 4b). Within 1 h after the mechanical treatment, the reduced scattering coefficient decreased in value for the wavelengths of 700–750 nm, but it remained the same beyond 750 nm. For cucumbers that were tested 1 day after the mechanical treatment, large drops in absolute magnitude for the reduced scattering coefficient were observed. The changes in the reduced scattering coefficient between normal and 1 day samples were significant at 10% level. The trend of changes in the reduced scattering coefficient for cucumbers after the mechanical treatment has some similarities and differences compared with bruised apple tissue. Lu et al. [12] reported large decreases in the reduced scattering coefficient right after the apple tissue was bruised; thereafter, the reduced scattering coefficient steadily decreased with the increasing time. Slight decreases or

no changes in the reduced scattering coefficient for the 1 h damaged cucumbers suggested that initial damage had been primarily confined to the endocarp tissue (the center part of the fruit) which was structurally weaker and more susceptible to rolling damage, while the mesocarp tissue was little affected within an initial hour after the rolling treatment. One day later, mechanical damage might have propagated from the endocarp tissue to the mesocarp tissue (perhaps also in the form of water redistribution or change in the mesocarp tissue), thus resulting in a large drop in the reduced scattering coefficient.

In summary, this research showed that mechanical injury had different effects on the absorption and reduced scattering coefficient for cucumbers. Values of the absorption coefficient generally increased after mechanical injury, while an opposite pattern of changes in the reduced scattering coefficient was observed. In terms of absolute magnitude, mechanical injury had greater impact on the scattering properties than on the absorption properties. In other words, mechanical damage tended to enhance the absorption capabilities of cucumbers, while reducing their scattering capabilities. It should be mentioned that due to the shape of pickling cucumbers (i.e., relatively small diameter compared to longitudinal dimension) and the roughness of cucumber surface (i.e., the presence of warts on the surface of cucumbers), greater errors in experimental measurement of the optical properties could have been expected. This may also, in part, explain large variations in both absorption and scattering properties for the tested samples.

This study, for the first time, provided spectral absorption and scattering data for pickling cucumber. This information is useful in at least two areas. First, the measured optical property data can be used for quantitative understanding of light propagation in cucumber fruit through computer simulation based on radiation transport theory, which would enable us to gain insight about the interaction of light with the cucumber tissue. Second, the optical absorption and scattering data also offer a useful guide in development of effective optical inspection techniques for detection of internal quality/defect of cucumbers. Relatively large changes in the optical absorption and scattering properties in the spectral range of 700–920 nm between normal and defective cucumbers suggest that this region would be good for internal quality inspection of pickling cucumber. Further, greater changes in the absolute value of the reduced scattering coefficient also indicate that it would be beneficial to design an optical inspection system that would take into consideration the scattering characteristics of cucumber tissue. Based on this finding,

Arian and Lu [13] has demonstrated that laser scattering image technique, which captures transmission scattering images from pickling cucumbers generated by a laser diode at 808 nm and then quantifies them using a set of scattering image features, was effective for detecting normal and defective pickling cucumbers.

Conclusions

This research provided new knowledge on the spectral absorption and scattering properties of pickling cucumbers before and after mechanical stress treatment, for the spectral region of 700–1000 nm. Mechanical damage caused different patterns of changes to the absorption and reduced scattering coefficients. Changes in the optical properties for pickling cucumbers were minimal within 1 h after the mechanical treatment and became noticeable 1 day later. One day after the mechanical treatment, the absorption coefficient for cucumbers increased significantly at 700–920 nm, whereas an opposite trend was observed for the reduced scattering coefficient, which had greater decreases in absolute magnitude for the spectral region of 700–1,000 nm. To effectively detect internal defects, it is desirable to enhance scattering characteristics measurement in the spectral region of 700–920 nm.

References

1. H.P. Fleming, R.L. Thompson, R.J. Monroe, J. Food Sci. **43**, 892 (1978)
2. D.P. Ariana, R. Lu, Sens. Instrumen. Food Qual. **2**, 144 (2008)
3. R. Lu, Trans. ASAE **46**, 523 (2003)
4. K. Chao, C.C. Yang, Y.R. Chen, M.S. Kim, D.E. Chan, Poultry Sci. **86**, 2450 (2007)
5. D.P. Ariana, R. Lu, Sens. Instrumen. Food Qual. **2**, 152 (2008)
6. D.P. Ariana, R. Lu, J. Food Eng. **96**, 583 (2010)
7. J. Mobley, T. Vo-Dinh, in *Biomedical Photonics Handbook*, chapter 2, ed. by T. Vo-Dinh (CRC Press LLC, Boca Raton, 2003), pp. 1–75
8. T.J. Farrell, M.S. Patterson, B.C. Wilson, Med. Phys. **19**, 879 (1992)
9. A. Kienle, M.S. Patterson, J. Opt. Soc. Am. A Opt. Image Sci. Vis. **14**, 246 (1997)
10. R.C. Haskell, L.O. Svaasand, T.T. Tsay, F.C. Feng, M.S. McAdams, J. Opt. Soc. Am. A Opt. Image Sci. Vis. **11**, 2727 (1994)
11. J. Qin, R. Lu, Postharvest Biol. Technol. **49**, 355 (2008)
12. R. Lu, H. Cen, M. Huang, D.P. Ariana, Trans. ASABE **53**, 263 (2010)
13. D.P. Ariana, R. Lu, in *Proceedings of the 17th World Congress of CIGR (International Commission of Agricultural Engineering)*, Quebec City, Canada, June 13–17, 2010, Paper # 100653