Feasibility of Using Terahertz Spectroscopy To Detect Seven Different Pesticides in Wheat Flour

INHIE MAENG,1,2 SEUNG HYUN BAEK,1 HWA YEON KIM,1 GYEONG-SIK OK,2 SUNG-WOOK CHOI,2 and HYANG SOOK CHUN*1

1Department of Chemistry and School of Food Science and Technology, Chung-Ang University, Ansung, Gyoonggi 456-756, Republic of Korea; and 2Food Safety Research Center, Korea Food Research Institute, Sungnam 465-746, Republic of Korea

ABSTRACT

This study investigated the feasibility of detecting pesticides using terahertz (THz) spectroscopy in high-density polyethylene and/or wheat flour mixtures. The absorption spectra of seven pesticides (dicofol, chlorpyrifos, chlorpyrifos-methyl, daminozide, imidacloprid, diethylthiocarbamate, and dimethyldithiocarbamate) were measured in the frequency range 0.1 to 3 THz at room temperature. Five of the seven pesticides exhibited specific absorption peaks in the low-energy THz range. The two remaining pesticides had no specific absorption peaks in this frequency range, but they exhibited different frequency-dependent refractive indices. The absorption coefficients of imidacloprid increased with its increasing weight ratio in high-density polyethylene, and the fitted power absorptions and refractive indices using a Maxwell-Garnett effective medium model were comparable to the measured data. Imidacloprid was also identified from its characteristic absorption peaks in wheat flour mixtures, and a linear relationship between the absorption coefficient and the weight ratio was observed. Our results show the potential of detection of selected pesticides in foods, such as wheat flour, using THz spectroscopy.

The presence of pesticide residues in finished and raw food products is a growing concern among consumers. To date, pesticide detection depends largely on the use of chromatographic methods, such as gas chromatography and high-performance liquid chromatography (HPLC) coupled with different detectors (3, 8). Although these chromatography-based methods have a high detection precision, they are labor intensive and time consuming (8). Spectroscopic methods, including UV spectroscopy and near-infrared (IR) spectroscopy, are used as alternative methods because their procedures are faster and easier to use (1, 27). UV spectroscopy and near-IR spectroscopy are suitable for qualitative analysis with the complex spectra obtained from intramolecular overtones and the combination bands of compounds, but quantitative analysis requires a lot of information (2, 11).

Terahertz (THz) spectroscopy, which uses the frequency range between the far-IR and the millimeter or microwave regions, enables us to analyze samples both qualitatively and quantitatively (7, 13, 29). The THz region (0.1 to 30 THz, 3.3 to 1,000 cm–1) has a unique property: many materials are transparent or semitransparent to THz radiation, whereas many crystalline materials exhibit characteristic spectral features in the THz region (13, 20, 24). The absorption features within the mid-IR region are dominated by intramolecular vibrations of the sample molecules. In contrast, the absorption features in the THz region are dominated by the intermolecular vibrations corresponding to motion associated with coherent, delocalized movements of large numbers of atoms and molecules (6, 9). Because these properties are unique to a particular molecule, it is possible to obtain a “THz fingerprint,” enabling the identification of a compound (14, 17, 19, 23, 25, 28, 30). Consequently, THz spectroscopy could potentially be used to characterize the properties of pesticides.

THz spectroscopy is a low-energy technique that allows nondestructive analysis of materials, because the energy of a THz pulse is less than that of the typical background radiation present in the environment. THz frequencies can also penetrate a wide range of dielectric materials, such as clothing, paper, cardboard, wood, plastic, and ceramics. This makes it possible to directly monitor packaging materials for quality control using THz spectroscopy or imaging (10, 16, 26). With the development of THz instrumentation, the applications of THz spectroscopy have expanded to include the food industry.

Recently, THz time-domain spectroscopy (THz-TDS) has been used as a noninvasive tool to detect pesticides in sticky rice, sweet potato, and lotus roots. It was shown that four pesticides (imidacloprid, carbendazim, tricyclazole, and buprofezin) had specific absorbance peaks in the THz range (0.5 to 1.6 THz) (12). It has also been reported that THz-TDS can potentially detect antibiotic residues in feedstock. Standard mixtures of antibiotics and powdered polyethylene
were prepared in a pelletized form, and transmission THz-TDS spectra were obtained in the frequency range from 0.1 to 2 THz (21). Eight of the 11 antibiotics tested had specific signatures in the THz region, whereas two of them (doxycycline and sulfapyridine) were examined when mixed with different food matrices (e.g., animal feed, milk, and egg powder). However, substantial variation was reported in absorption spectra recorded using a common compound; therefore, a wide range of food compounds and physical conditions must be measured (10). In addition, there have been relatively few feasibility studies for applications of THz-TDS in the food sector.

With this background, we analyzed seven different pesticides (two organophosphates, one organochlorine, two dithiocarbamates, one aminoazide, and one chloronicotinoid) to investigate the feasibility of detecting pesticides using THz spectroscopy qualitatively and quantitatively in high-density polyethylene (HDPE) and wheat flour. We first sought to identify different pesticides based on their specific absorption fingerprint in the frequency range 0.1 to 3 THz. For our quantitative analysis, we analyzed imidacloprid with different weight ratios in HDPE and calculated the expected spectra using a Maxwell-Garnett (MG) effective medium model. Then, the partial least squares (PLS) method was applied to assess our quantitative analysis of imidacloprid in a matrix of wheat flour.

MATERIALS AND METHODS

Chemicals and samples. The seven pesticides were selected from different chemical classes of organic compound: dicofol (2,2,2-trichloro-1,1-bis[4-chlorophenyl]ethanol, an organochlorine insecticide), chlorpyrifos (O,O-dimethyl O-3,5,6-trichloropyridin-2-yl phosphorothioate, an organophosphate insecticide), chlorpyrifos-methyl (O,O-dimethyl O-3,5,6-trichloropyridin-2-yl phosphorothioate, an organophosphate insecticide), daninozide (N-[dimethylamino]succinamic acid, an herbicide), imadacloprid ([E]-1-[6-chloro-3-pyridylmethyl]N-nitromiazodolizin-2-ylideneamine, a chloronicotinoid insecticide), diethylthiodicarbamate sodium salt trihydrate (sodium N,N-diethylcarbamodithioate trihydrate, a diethiocarbamate herbicide), and dimethylthiodicarbamate sodium salt hydrate (N,N-dimethylthiodicarbamate sodium salt hydrate, a diethiocarbamate herbicide). Chlorpyrifos (CAS no. 2921-88-2), chlorpyrifos-methyl (CAS no. 5598-13-0), daninozide (CAS no. 1596-84-5), dicofol (CAS no. 115-32-2), N,N-diethyldithiocarbamate sodium salt trihydrate (CAS no. 20624-25-3), and N,N-dimethylthiodicarbamate sodium salt hydrate (CAS no. 207233-95-2) (Dr. Ehrenstorfer, Augsburg, Germany) had purities of 98, 97.5, 97, 98.5, 99.5, and 99%, respectively. Imadacloprid (CAS no. 138261-41-3, Sigma Chemicals, St. Louis, MO) had a purity of 99.9%.

HDPE powder (particle size, <10 μm) was purchased from TeraView Ltd (Cambridge, UK). The wheat flour matrix used was purchased at local stores and characterized using HPLC analysis to be free of imidacloprid residues (18). Sample tablets for qualitative detection were prepared using both pure pesticide powders and those mixed with HDPE powder. The pellets were loaded in a hydraulic press (Specac Ltd, Orpington, UK) at different pressures depending on pellet diameter. The pure pesticide pellets contained 36 mg of pesticide powder using 2 tons of compressive loads. The resulting sample tablets (5-mm diameter, ~1.4-mm thickness) were easily broken, and chlorpyrifos-methyl powder did not form any pellets. HDPE, which has a low refractive index and low absorption in the THz region, was used as a binder for the pellets. The pesticide compound was mixed in an HDPE matrix in a loading ratio of 10 wt%. Circular tablets (total weight, 360 mg; diameter, 13 mm; thickness, 2.8 to 3.1 mm) were formed using a compressive load of 5 tons. In the next step, imidacloprid, which showed strong absorption features, was mixed with various weight fractions of HDPE and wheat flour. To prepare food mixture samples, known amounts of pure imidacloprid were added to the wheat flour used as a food matrix. All the samples were prepared and measured in triplicate.

Measurements. THz-TDS is a powerful technique; the pump-probe configuration allows direct measurement of the transient electromagnetic field of the THz pulse. The THz spectrum is then obtained from the time domain data by Fourier transform. Because the absorption coefficient and the refractive index of the material studied are directly related to the amplitude and the phase of the transmitted electromagnetic field, respectively, complex optical properties can be obtained with high accuracy. In contrast, Fourier transform far-IR spectroscopy measures only the field intensity and, therefore, measures only the absorption coefficient. Although the refractive index can be calculated from Fourier transform far-IR spectroscopy data using Kramers-Kröning relations, this calculation is not straightforward and has many potential sources of error. As a further consequence of its coherent pump-probe detection scheme, TDS has a very high signal-to-noise ratio, typically >10^6 for the powder, compared with a signal-to-noise ratio of approximately 300 for far-IR Fourier transform spectroscopy (19).

A TPS spectra 3000 spectrometer (TeraView Ltd, Cambridge, UK; http://www.teraview.com) (22), with a spectral resolution of 0.036 THz over the range 0.1 to 3 THz, was used for the THz pulsed spectroscopy measurements. The samples were measured in the very stable fast-scan mode, which allowed 30 measurements to be performed per second. We obtained 1,800 signals and averaged them to analyze the spectrum. The sample chamber was filled with dry air to prevent any water absorption occurring. The signals, transmitted through pinholes with diameters of 3 and 10 mm depending on the size of the samples, were used as reference signals.

Data analysis. A TPS spectra 3000 spectrometer acquired the time-domain data using the time delay between generation and detection. The time-domain data were transformed into the frequency domain using a Fourier transformation (TeraView). The Black-Harris three-term apodization method was applied to the Fourier transformation (TeraView). The power absorption coefficient, α(v), is given by α = 4πk1/λ, where k is the imaginary refractive index and λ is the wavelength. The refractive index, n(v), of the sample was calculated as a function of the applied THz frequency, ν, using the following equations:

\[ α(ν) = -\ln[(T(ν)E_{sample}(ν))/(E_{reference}(ν))]/d \]  
\[ n(ν) = 1 + c(Φ_{sample}(ν) - Φ_{reference}(ν))/2πvd \]  
\[ T(ν) = 1 - [n(ν) - 1]^2/[n(ν) + 1]^2 \]

where E and Φ denote the THz amplitude and the phase, respectively. The term c is the velocity of light, d is the sample thickness, and T(ν) is the amplitude transmission coefficient given by the Fresnel equation. The complex dielectric constants \( \varepsilon(ν) = \varepsilon_1(ν) + i\varepsilon_2(ν) \) are related to the refractive index, \( \bar{n}(ν) = n(ν) + ik(ν) \), and to each other through \( \varepsilon(ν)^2 = \varepsilon(ν) \). In the case of a mixed sample, they are characterized by the macroscopic
properties of a medium based on each of the constituent properties and the relative fractions of each of its components. The MG effective medium model, which is widely used to determine the optical properties of heterogeneous materials, is described by equation 4 (15):

\[
\frac{\varepsilon_{\text{eff}}}{\varepsilon_{\text{eff}} + 2\varepsilon_h} = f_i \frac{\varepsilon_i - \varepsilon_h}{\varepsilon_i + 2\varepsilon_h}
\]

where \(\varepsilon_{\text{eff}}\) is the complex dielectric constant of the effective medium, \(\varepsilon_h\) is the complex dielectric constant of the host HDPE, \(\varepsilon_i\) is the complex dielectric constant of pesticide, and \(f_i\) is the volume-filling factor of the pesticide. The dielectric constant of HDPE, \(\varepsilon_h\), was measured and the filling factor, \(f_i\), was calculated using the density of the fabricated samples. We estimated the frequency-dependent absorption coefficients and the refractive indices of the pesticides from our experimental data using the MG effective medium model.

A PLS regression analysis was performed using the Unscrambler v.10.2 (Camo Software, Oslo, Norway) to analyze the imidacloprid mixtures quantitatively (5). The PLS technique first extracts the orthogonal features from the original spectra within a selected frequency range and then correlates these features to the target variable. Calibration models were developed using a test set validation by splitting the samples randomly into two groups: one group (six samples) was used for calibration purposes, and the other group (six samples) was used for validation purposes. The developed models were then tested using an independent set of imidacloprid mixtures (seven samples). The correlation coefficient and the root mean square error (RMSE) of the calibration set (RMSEC) were used to calculate the model precision to evaluate the model performance, and \(f_i\) and \(R\), the root mean square error of the prediction set (RMSEP) and the relative error of the prediction set (\(E_i\)), were applied to test the precision of the model prediction.

RESULTS AND DISCUSSION

THz spectra of the seven pesticides. Figure 1 shows the time-domain THz signals measured passing through the pesticide samples that had not been premixed, imidacloprid, \(N,N\)-diethylcarbamodithioate trihydrate, daminozide, and \(N,N\)-dimethylthiocarbamate sodium salt hydrate and also the empty sample holder as a reference. The signals from the samples showed a different time delay that had a decrease in amplitude compared with the reference signal. The pesticide samples that had not been premixed had only their THz spectral properties measured below 2 THz because the transmitted THz signals were undetectable over 2 THz. The amplitude of transmitted THz signals depended on the optical properties and the thickness of the sample. The pure pesticide samples had a physical limit on their thickness, which is why we opted to use HDPE as a binder. The THz spectral properties of the mixed samples containing HDPE were also extracted, and the THz spectral properties of the pure pesticides were calculated using the MG effective medium model. We assumed that the sample contained 3 to 5% air.

The power absorption spectra and refractive indices of seven pesticide samples are shown in Figure 2a and 2b. The dotted lines represent the properties of the pure pesticide samples, and the various lines represent the premixed samples. As shown in Figure 2, the properties of the pure samples and those calculated using the MG effective medium model were in reasonable agreement and show many absorption peaks. The absorption peaks of the seven pesticides are summarized in Table 1. The imidacloprid, \(N,N\)-diethylthiocarbamate sodium salt trihydrate, daminozide, and \(N,N\)-dimethylthiocarbamate sodium salt hydrate samples clearly showed more than three absorption peaks in this region. The molecular structures of the two DTC-based pesticides, \(N,N\)-diethylthiocarbamate sodium salt trihydrate and \(N,N\)-dimethylthiocarbamate sodium salt hydrate, are similar, but the THz spectra of the two compounds were different. Dicofol showed much broader and weaker peaks than four other pesticides (imidacloprid, \(N,N\)-diethylthiocarbamate sodium salt trihydrate, daminozide, and \(N,N\)-dimethylthiocarbamate sodium salt hydrate). However, no specific THz absorption peaks were observed for the two organophosphate insecticides, chlorpyrifos and chlorpyrifos-methyl.

The specific absorption peaks of each pesticide component (Table 1) allow them to easily be distinguished from each other: for imidacloprid, peak positions occurred at 1.36, 1.76, and 2.15 THz; for \(N,N\)-diethylthiocarbamate sodium salt trihydrate, 0.63, 1.11, 1.41, 1.74, and 2.40 THz; for daminozide, 1.32, 2.40, and 2.79 THz; for \(N,N\)-dimethylthiocarbamate sodium salt hydrate, 0.99, 1.41, and 1.50 THz; and for dicofol, 2.34 THz.

Figure 2b shows the refractive index of the seven pesticides in the range 0.1 to 3 THz, derived from the transmission amplitude of the THz field passing through samples. The average refractive indices for chlorpyrifos, chlorpyrifos-methyl, daminozide, dicofol, \(N,N\)-diethylthiocarbamate sodium salt trihydrate, \(N,N\)-dimethylthiocarbamate sodium salt hydrate, and imidacloprid in the range 0.1 to 2.5 THz were 1.67, 1.58, 1.68, 1.70, 1.99, 2.08, and 1.87, respectively. Although there were no peaks in the THz spectra of chlorpyrifos and chlorpyrifos-methyl, it is obvious that the refractive indices of chlorpyrifos and chlorpyrifos-methyl were different in this range.

Hua and Zhang (12) reported that four pesticides (imidacloprid, carbendazim, tricyclazole, and buprofezin)
had specific absorbance peaks in the region from 0.5 to 1.6 THz. In their study, imidacloprid exhibited absorption
peaks at 0.89, 1.13, 1.24, 1.46, and 1.57 THz (12).

We compared the absorption peaks of imidacloprid, a pesticide common to both Hua and Zhang’s study and our study, in the range from 0.1 to 1.6 THz. In contrast to Hua and Zhang, we did not observe absorption peaks at 0.89, 1.13, or 1.24 THz, and we found a deviation in the reported peak positions at 1.46 (1.37) and 1.57 (1.76) THz. This large deviation (peak occurring at 1.57 THz) may result from the

use of a different sample handling system. Moreover, because of the wider frequency range used in our study, we observed an additional fingerprint peak for imidacloprid at 2.15 THz.

In this study, no distinct peaks were seen in the THz spectra of the two structurally similar organophosphates, chlorpyrifos and chlorpyrifos-methyl; however, because their refractive indices were different in this range, they could be easily distinguished from each other. Overall, these results provide a bibliographic record of the spectral features and refractive indices of these pesticides in the THz range.

Spectra from imidacloprid samples with different weight percentages. We fabricated imidacloprid-HDPE mixtures samples with seven different mixture ratios from 0.5 to 10 wt% for quantitative detection measurements. The absorption coefficient and refractive indices of each imidacloprid sample were extracted using the MG effective medium model (see Fig. 3). The amplitude of the refractive index and the power absorption increased linearly with increasing imidacloprid content.

The calculated power absorption and refractive indices are indicated with dotted lines in Figure 3a and 3b. The inset of Figure 3a shows the amplitude of the power absorption for each absorption peak along with the fit from the MG effective medium model. The fitted power absorptions and refractive indices were comparable to the measured data. However, the sample with 5 wt% imidacloprid had lower amplitude than expected. This discrepancy is considered to be an error derived from the fabrication process (mostly the density of the sample). The amplitude of power absorption for samples with <1 wt% content appeared to be similar, and the spectra were difficult to distinguish from each other. However, the amplitude increased linearly (see inset, Fig. 3a) with increasing content. Samples with <0.5 wt% insecticide content could not be distinguished from each other.

Spectra of the imidacloprid and wheat flour mixtures. The main absorption features of imidacloprid were still identifiable when it was mixed with wheat flour as a food matrix. Figure 4 shows the spectra of mixtures of imidacloprid with wheat flour at different weight fractions (0, 11, 20, 33, 50, and 100%), which circumvent the effect of HDPE using the MG effective medium model. The absorption spectrum of wheat flour increased almost linearly with increasing frequency because of its strong absorption, whereas the absorption spectrum of imidacloprid with 0% wheat flour did not increase. Nonetheless, as the weight ratio of imidacloprid to wheat flour increased from 0 to 100%, the amplitude of the absorption increased linearly. Peaks occurring at 1.36, 1.76, and 2.15 THz were clearly identified in most of the spectra. The power absorption spectrum of wheat flour increased almost linearly with increasing frequency because of its strong absorption, whereas the absorption spectrum of imidacloprid with 0% wheat flour did not increase. Nonetheless, as the weight ratio of imidacloprid to wheat flour increased from 0 to 100%, the amplitude of the absorption increased linearly. Peaks occurring at 1.36, 1.76, and 2.15 THz were clearly identified in most of the spectra. The power absorption spectrum of the mixture of wheat flour with 11 wt% imidacloprid was not distinguishable from that of wheat flour alone, but the refractive indices showed clear differences. The low sensitivity observed may result from physical variations in the sample (e.g., particle size) causing scattering and a low system signal. Scattering may adversely
affect measurements of the THz absorption of some materials. When the grain size of a solid is comparable to the THz wavelength, then extinction spectra are markedly influenced by scattering losses. Bandyopadhyay et al. investigated the effect of scattering on THz-TDS spectra in the range 0.2 to 1.2 THz for granular solids (ammonium nitrate, flour, and salt) as a function of grain size (4).

We used PLS to explore the potential of performing quantitative analysis of imidacloprid in wheat flour mixtures. The PLS algorithm was applied to six synthetic samples (listed in Table 2); the RMSEP and RSEP values were acceptable. The lowest detectable weight ratio of imidacloprid in wheat flour was estimated to be about 11%. Considering that foods and agricultural products are contaminated with pesticides in trace amounts, further research will be required to improve the sensitivity and increase the resolution.

In conclusion, we have shown the potential of using THz-TDS for qualitative and quantitative analysis of pesticide components. We confirm that THz-TDS has the

**TABLE 1. List of the pesticides used, along with their molecular formula and the positions of the power absorption peaks**

<table>
<thead>
<tr>
<th>Substance</th>
<th>Formula</th>
<th>Power absorption peak (THz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imidacloprid</td>
<td>C_{9}H_{10}ClN_{5}O_{2}</td>
<td>1.36, 1.76, 2.15</td>
</tr>
<tr>
<td>N,N-Diethylthiocarbamate sodium trihydrate</td>
<td>C_{10}H_{12}NNaS_{2} × 3H_{2}O</td>
<td>0.63, 1.11, 1.41, 1.74, 2.40</td>
</tr>
<tr>
<td>Daminozide</td>
<td>C_{6}H_{12}N_{2}O_{3}</td>
<td>1.32, 2.40, 2.79</td>
</tr>
<tr>
<td>N,N-Dimethyldithiocarbamate sodium hydrate</td>
<td>C_{12}H_{22}NNaS_{2} × H_{2}O</td>
<td>0.99, 1.41, 1.50</td>
</tr>
<tr>
<td>Dicofol</td>
<td>C_{14}H_{9}Cl_{5}O</td>
<td>2.34</td>
</tr>
<tr>
<td>Chlorpyrifos-methyl</td>
<td>C_{8}H_{11}ClNO_{3}PS</td>
<td>—</td>
</tr>
<tr>
<td>Chlorpyrifos</td>
<td>C_{8}H_{11}ClNO_{3}PS</td>
<td>—</td>
</tr>
</tbody>
</table>

**FIGURE 3.** Absorption spectra (a) and refractive indices (b) of imidacloprid-HDPE composites as a function of the weight fraction, with fitted lines using the Maxwell-Garnett effective medium model. The absorption peak of the amplitude and its fitted line are shown in the inset.
FIGURE 4. Absorption spectra (a) and refractive indices (b) of imidacloprid–wheat flour composites as a function of the weight fraction, with fitted lines using the Maxwell-Garnett model. The absorption peak of the amplitude and its fitted line are shown in the inset. Absorption features occurring around 1.36, 1.76, and 2.15 THz were observed.

**TABLE 2.** Predicted values for imidacloprid and statistical results using the PLS method

<table>
<thead>
<tr>
<th>Added (mg)</th>
<th>Spectral range (THz)</th>
<th>0.1–3.0</th>
<th>0.8–2.2</th>
<th>1.3–2.2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Determined (PLS)(^a)</td>
<td>Recovery (%)</td>
<td>Determined (PLS)(^b)</td>
<td>Recovery (%)</td>
</tr>
<tr>
<td>4.5</td>
<td>4.2</td>
<td>93.3</td>
<td>3.8</td>
<td>84.4</td>
</tr>
<tr>
<td>9.0</td>
<td>8.6</td>
<td>95.6</td>
<td>8.1</td>
<td>90.0</td>
</tr>
<tr>
<td>18.0</td>
<td>17.2</td>
<td>95.6</td>
<td>16.9</td>
<td>93.9</td>
</tr>
<tr>
<td>36.0</td>
<td>36.3</td>
<td>100.8</td>
<td>36.4</td>
<td>101.1</td>
</tr>
<tr>
<td>7.2</td>
<td>7.8</td>
<td>108.3</td>
<td>8.2</td>
<td>113.9</td>
</tr>
<tr>
<td>14.4</td>
<td>13.8</td>
<td>95.8</td>
<td>13.1</td>
<td>91.0</td>
</tr>
<tr>
<td>21.6</td>
<td>21.9</td>
<td>101.4</td>
<td>22.5</td>
<td>104.2</td>
</tr>
</tbody>
</table>

\(^a\) The root mean square error of prediction (RMSEP) and regression coefficient of the calibration model (\(R^2\)) were 0.54 and 0.997, respectively.

\(^b\) The RMSEP and regression coefficient of the calibration model (\(R^2\)) were 1.07 and 0.990, respectively.

\(^c\) The RMSEP and regression coefficient of the calibration model (\(R^2\)) were 1.11 and 0.989, respectively.
potential to be developed as an identification and quantification technique in the food industry. Despite their low sensitivity, the ability of THz waves to pass through a wide variety of packaging materials and to characterize the molecular structure of many substances makes this technique an attractive detection tool for enhanced monitoring of food. For the practical application of THz spectroscopy, much more work is required, including the development of a cost-effective THz spectrometer with high sensitivity, THz spectral library databases for a wide group of food chemicals, and dedicated software for the chemometric treatment of spectral information.

ACKNOWLEDGMENTS

This work was financially supported by Public Welfare & Safety, a research program through the National Research Foundation of Korea (NRF), by the Ministry of Education, Science and Technology grant 2011-0020819, South Korea.

REFERENCES