I2MTC 2009 - International Instrumentation and Measurement Technology Conference
Singapore, 5-7 May 2009

Quantitative Determination of Cyfluthrin in N-hexane by Terahertz Time-domain Spectroscopy With Chemometrics Methods

Yuefang Hua, Hongjian Zhang *, Hongliang Zhou
State Key Laboratory of Industrial Control Technology, Department of Control Science and Engineering
Zhejiang University, Hangzhou 310027, P. R. China
Tel: +86 571 87952253

***Abstract*—Terahertz time-domain spectroscopy (THz-TDS) was used for the detection of cyfluthrin content in n-hexane solvent with the concentration range of 0.5-10μg/mL. The absorbance of the solution form cyfluthrin was obtained in the frequency range between 0.5-1.5THz. Two kinds of multivariate linear regression models were then built between the absorbance and the concentration of 15 samples, using partial least squares (PLS) and principle component regression (PCR) methods. The number of factors leading to the least root-mean-square error of cross validation (RMSECV) was 2 for PCR and 9 for PLS respectively. Compared to the PCR model, the PLS model proves to be more effective, with the RMSECV as low as 0.565μg/mL. Results show that the THz-TDS plus PLS method is very promising for the further pesticide residue detection in food safety control, with the characteristics of being nondestructive and laborsaving compared to other analytical tools.**

Keywords—Terahertz time-domain spectroscopy (THz-TDS); Cyfluthrin; Partial least squares (PLS); Principle component regression (PCR); Quantitative

I. INTRODUCTION

Due to the mass use of pesticides in agriculture and household protection, pesticide detection has gained more and more attention in the modern world. Conventional ways to detect pesticides are to use gas and high pressure liquid chromatography (GC and HPLC), and mass spectrometry (MS)-coupled GC and liquid chromatography (LC) [1-3]. Although these techniques are highly sensitive and accurate, they are complex, and require skilled personnel, large amounts of samples, and time-consuming sample pretreatment. As a result, they are unsuitable for fast pesticide detection.

More direct ways for pesticide analysis are to use spectral analysis techniques, such as near and mid infrared, Raman, and ultraviolet-visible (UV-Vis) spectroscopy [4-6]. Though these methods are not as sensitive as the aforementioned chromatographic and MS spectroscopic methods, they are faster and easier to use, and can be handled without tedious sample preparation. Furthermore, the sample and reagent consumption are greatly eliminated, and the waste generation is thus reduced.

A recently arisen spectroscopic method is terahertz time-domain spectroscopy (THz-TDS), which bridges the gap between infrared and microwave and is highly sensitive in both time and frequency domains [7,8]. Moreover, it can penetrate through nonpolar materials such as paper, clothes, ceramic, nonpolar organic solvents, and so on, while exhibiting strong spectral fingerprints for proteins, explosives, pesticides, etc. More interesting is that the photon energy of terahertz (THz) wave is in the level of several microvolts. So it is quite safe for exposure of human beings, live organisms, active ingredients in food and medicine. No wonder is that this method has found significant applications in biochemistry, safety defense, medicine quality control, food safety control et al [9-14].

Cyfluthrin is a synthetic cyano-containing pyrethroid pesticide that is contact and stomach poisoning [15]. It is mainly used to protect crops such as cotton, turf, ornamentals, hops, cereal, corn, deciduous fruit, peanuts, potatoes, and other vegetables. The use of cyfluthrin in household pest control is also increasing due to its high efficiency for chewing and sucking insects and safety for non-target organism.

Previous reports of THz-TDS for pesticide detection have been mostly limited to the detection of pesticides in powder form for the simple reason that there is generally a shortage of fingerprints for solution form pesticides. However, experiments show that there is link between the cyfluthrin solution properties and the associated terahertz (THz) spectra. In this paper, we investigated 15 cyfluthin n-hexane solutions with the concentration range between 0.5-10μg/mL and found concentration correlated changes in the THz spectra in both time and frequency domains. Linear regression models were then built between the concentration and the absorbance of the samples using partial least squares (PLS) and principle component regression (PCR) methods. Further, we made comparison between the two models, and found that the PLS model presented better performance than the PCR model. The combination of both THz-TDS and chemometrics methods proved to be a potential analytical tool for further pesticide residue analysis.

*Corresponding author: hjzhang@iipc.zju.edu.cn
This work is financially supported by the National Natural Science Foundation of China (grant no. 60774054) and the Research Fund for the Doctoral Program of Higher Education (grant no. 20070335123)

978-1-4244-3353-7/09/$25.00 ©2009 IEEE

II. EXPERIMENTAL METHODS

A. Experimental Setup

The experimental setup, shown in Fig.1, is comprised of a THz-TDS system from Zomega Terahertz Corporation and a femtosecond Ti-sapphire laser (Coherent Vitesse-800-5). The input laser beam is split into a pump beam and a detection beam. After transmitting through the delay line, the pump beam elicits a terahertz (THz) beam at the emitter which is composed of a photo-conductive antenna. Then the THz beam is focused onto the sample by two parabolic mirrors. Again with two parabolic mirrors, the sample-characteristic-carried terahertz beam meets the detection beam at the ZnTe crystal and is detected through the electro-optic effect. To avoid moisture absorption in the air, the setup is covered in a nitrogen purged plastic box. The effective frequency range for this experiment is 0.5-1.5THz.

B. Sample Preparation

The standard cyfluthrin n-hexane solution was purchased from Environmental Protection Research and Monitoring Institute, Ministry of Agriculture, China, with the concentration of 100μg/mL and the uncertainty of ±0.17μg/mL. A series of samples were prepared with the concentration range between 0.5-4.5μg/mL (the interval of 0.5μg/mL) and 5-10μg/mL (the interval of 1μg/mL).

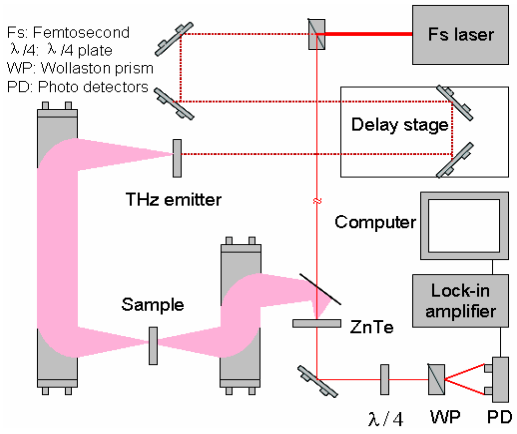

Figure 1. Schematic of the experimental setup

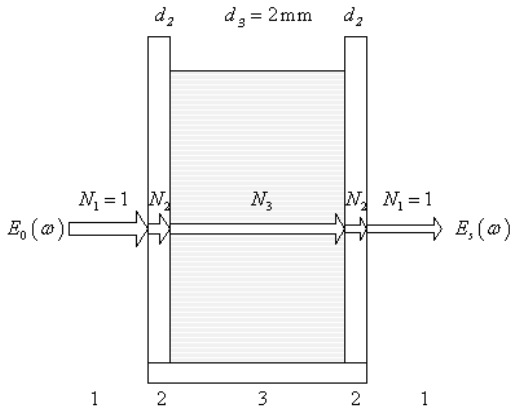

Figure 2. Schematic of the sample mounted in a quartz cell

C. Data Acquisition

The cyfluthrin solution is mounted in a 2mm quartz cell, shown in Fig.2, where 1, 2, 3 stand for nitrogen, the quartz cell and the solution, with the complex refractive index as N_1, N_2 and N_3 respectively; the thicknesses of the quartz cell and the solution are denoted as d_2 and d_3; $E_0(\omega)$ and $E_s(\omega)$ are the fast Fourier transforms of terahertz pulses before and after the quartz cell holding the solution (referred to as the sample pulse in the later discussion). The reference pulse is obtained by scanning the quartz cell holding the n-hexane solvent, the fast Fourier transform of which is denoted as $E_{re}(\omega)$. Then, we can calculate the absorbance of cyfluthrin in solution form using the following equation [16]:

$$absorbance(\omega) = -lg\left(\left|\frac{E_s(\omega)}{E_{re}(\omega)}\right|^2\right) . \quad (1)$$

D. Modeling Theories and Methods

Provided that there is no light reflection, scattering or fluorescence but absorption effect in the transmission of THz pulses, which are the assumptions in Lambert-Beer's law, and that the incidence angle of the terahertz beam is 90° , the transfer function of the sample in the quartz cell can be simplified as [17]:

$$\frac{E_s(\omega)}{E_0(\omega)} \approx \exp\left[\frac{i\omega(2N_2d_2 + N_3d_3 - 2N_1d_2 - N_1d_3)}{c}\right] . \quad (2)$$

Also, the transfer function of the solvent in the quartz cell can be written as:

$$\frac{E_{re}(\omega)}{E_0(\omega)} \approx \exp\left[\frac{i\omega(2N_2d_2 + N_4d_3 - 2N_1d_2 - N_1d_3)}{c}\right] , \quad (3)$$

where N_4 is the complex refractive index of the solvent. By taking into the function:

$$N_i = n_i + \frac{i\alpha_i c}{2\omega}(i=1, 2, 3, 4), \quad (4)$$

where n_i , α_i stand for the refractive index and absorption coefficient, with the subscript number $i=1, 2, 3, 4$ denotes nitrogen, the quartz cell, the sample and the solvent respectively; c is the vacuum light velocity; and ω is the spectrum frequency, the real part of the ratio of the sample and reference spectra can be given as:

$$\left|\frac{E_s(\omega)}{E_{re}(\omega)}\right| \approx \exp\left[-\frac{(\alpha_3 - \alpha_4)d_3}{2}\right] . \quad (5)$$

Using (1) and (5), the absorbance of cyfluthrin can be transformed into:

$$absorbance(\omega) \approx -(\alpha_3 - \alpha_4)d_3 . \quad (6)$$

As is in Lambert-Beer's law, the sample absorption coefficient is proportionally related to the concentration:

$$\alpha_3 \propto c_x , \quad (7)$$

where c_x is the cyfluthrin concentration of the sample. It is not difficult to get:

$$absorbance(\omega) \propto c_x . \quad (8)$$

Once we have obtained the absorbance and the relative concentration of a series of samples, a linear regression model can be built. The concentration of unknown samples can thus be calculated using this model. The simplest way to build this model is to use the simple Beer's law, which is, however, based on only one frequency and is therefore, more fragile to environmental and instrumental noises.

To build a more robust and precise linear model, two multivariate linear chemometrics methods, PCR and PLS, are adopted respectively. Both of these methods are factor analysis based, with the decomposition of correlated spectrum variables into fewer uncorrelated information-intensive variables (referred to factors in the later discussion). The main difference between these two methods is that factors drawn with the PCR method account for only the spectral information, while those with the PLS method are related to both spectral and concentration information. Detailed information of the PCR and PLS methods can be referred to in [18-21].

III. Results And Discussion

A. Sample Spectra

The sample and reference pulses were obtained by scanning the quartz cell holding the cyfluthrin solution and the n-hexane solvent respectively. The reference pulses were obtained before every three sample pulses to compensate for the background change. To reduce the variations caused by instrumental and environmental noises, each case was scanned for more than three times, and the mean pulse was calculated for each case. For clarity, we present only 10 mean sample pulses (in the range of 1-10μg/mL, the interval of 1μg/mL) and one reference pulse in Fig.3, among the obtained 15 mean sample pulses and 5 mean reference pulses.

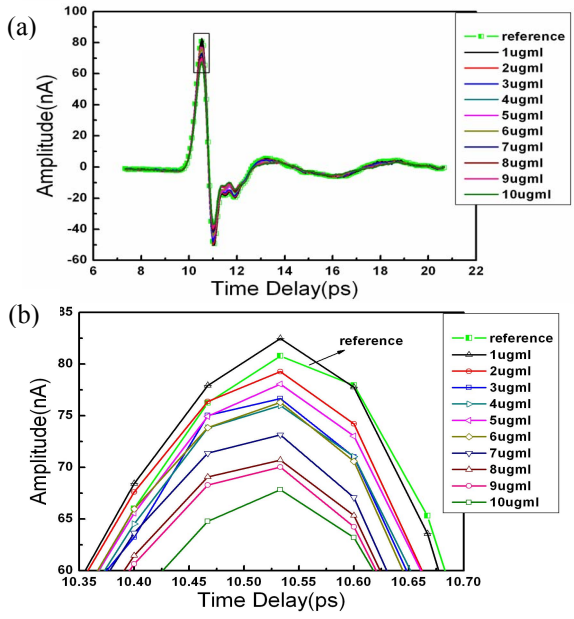

Figure 3. Selected mean THz pulses of the samples and the reference: (a) overall view of the THz pulses, (b) enhanced view. The concentration range of the samples presented is 1-10μg/mL (the interval of 1μg/mL).

As can be seen in Fig.3a, the waveforms of all the sample pulses are quite similar, showing the stability of the system performance. Moreover, the pulse amplitude decreases with the increase of concentration (the general trend, shown in Fig.3b), especially for samples with the concentration higher than 5μg/mL, indicating the probability of the determination of cyfluthrin content based on the absorption effect of the samples. Exceptions for this trend may be caused by random noises or errors in operation, which can be improved with chemometrics modeling methods.

After the application of fast Fourier transforms on both the sample and reference pulses, the absorbance spectra of all the samples can be calculated according to (1), of which 10 spectra (corresponding to the samples shown in Fig.3) are presented in Fig.4. The general increasing trend with concentration is more obvious than what is implied in the time-domain pulses. Again, this trend is especially true for samples with the concentration higher than 5μg/mL, as is also indicated by Fig.3b. However, the relative position of the 3μg/mL and 4μg/mL sample spectra in Fig.4 does not match that in Fig.3b, which can be explained by the use of reference pulses obtained at different time.

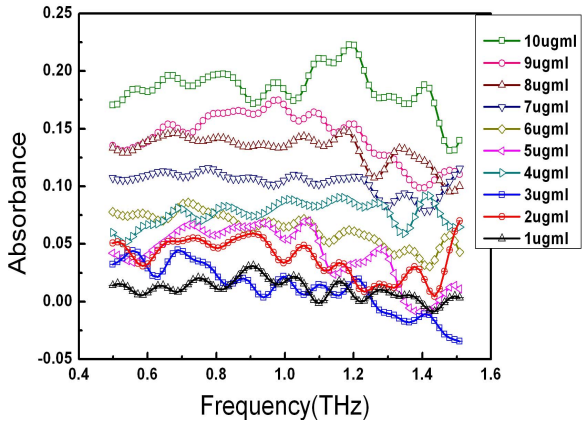

Figure 4. Selected absorbance spectra of the samples. The concentration range of the samples is 1-10μg/mL (the interval of 1μg/mL), which corresponds to that in Fig.3.

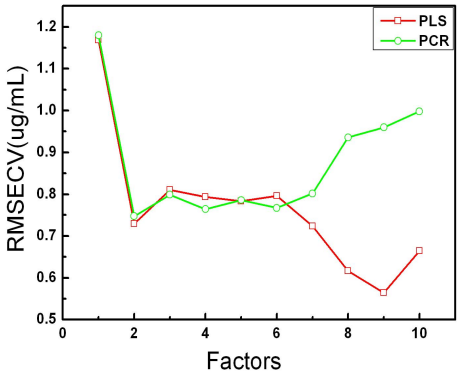

Figure 5. Correlation between root-mean- squre error of cross-validation (RMSECV) and factors for PLS and PCR methods.

B. Results with PLS and PCR Models

We apply a commercial software, TQ Analyst v6, for the building of the PLS and PCR models between the absorbance and concentration of the 15 samples, all of which are used as the calibration set. As there are no obvious spectral peaks in the absorbance spectra, the whole frequency range 0.5-1.5THz is selected for modeling. The selection of factor number is based on Fig.5, which shows the correlation between the number of factors and the root-mean-square error of cross-validation (RMSECV) for both PCR and PLS models. We choose 2 factors for PCR and 9 factors for PLS according to the least RMSECV. For comparison, a 9-factor PCR model is also built. It should be noted that the selection of more factors will lead to greater model precision within the calibration set but may result in worse prediction ability due to the introduction of noise with these increased factors. Calibration results of the 9-factor PCR, 2-factor PCR and 9-factor PLS models are shown in Fig.6 and Table 1.

Fig.6 shows us the scattered plot of the predicted concentration against the reference values, with the reference line representing zero residuals between the predicted and reference values. The predicted concentration in Fig.6a is calculated from the above three models with the input of the absorbance spectra from the calibration set, while that in Fig.6b is obtained through the leave-one-out cross-validation, during which one sample is removed from the 15-sample calibration set and its concentration is predicted from the model built with the left 14 samples. It is easy to tell that the closer the scattered points are to the reference line, the better the performance will be. Moreover, the result in Fig.6a is related to the model precision within the calibration set, whereas that in Fig. 6b reflects the prediction precision of the models to some extent.

As can be seen in Fig.6a，almost all the points from the 9-factor PLS model sit on the reference line, while the points from the 9-factor PCR model are more scattered, and those from the 2-factor PCR model the most. From this, we can tell that the 9-factor PLS model has the best model precision and that the increase of factors results in better model precision within the PCR model.

Fig.6b manifests that the points from the 9-factor PLS model keep the closest to the reference line, while those from the 2-factor PCR model the second and those from the 9-factor PCR model the third. Thus the 9-factor PLS model exhibits the best prediction ability. The increase of factors leads to worse prediction ability for the PCR models here due to the introduction of extra noise. Furthermore, it is clear that the points for the higher concentration are relatively closer to the reference line than those for the lower concentration, indicating that all of the three models predict the samples with higher concentration better than those with lower concentration. Thus the PLS method proves to be better than the PCR method in this experiment.

The calibration parameters of the three models are listed in Table 1, with the correlation coefficient (R), the root-mean-square error of calibration (RMSEC) obtained from the data in Fig.6a and RMSECV from the data in Fig.6b [22]. The closer R is to 1 and RMSEC is to 0, the higher the model precision is, whereas the closer RMSECV is to 0, the higher the model prediction precision is. Apparently, the 9-factor PLS model ranks the first in model performance among the three, with the largest R, the least RMSEC and RMSECV. Compared to the 9-factor PCR model, the 2-factor PCR model has better prediction precision but worse model precision, with smaller RMSECV and R but larger RMSEC. The results in Table 1 accord well with those from Fig.6.

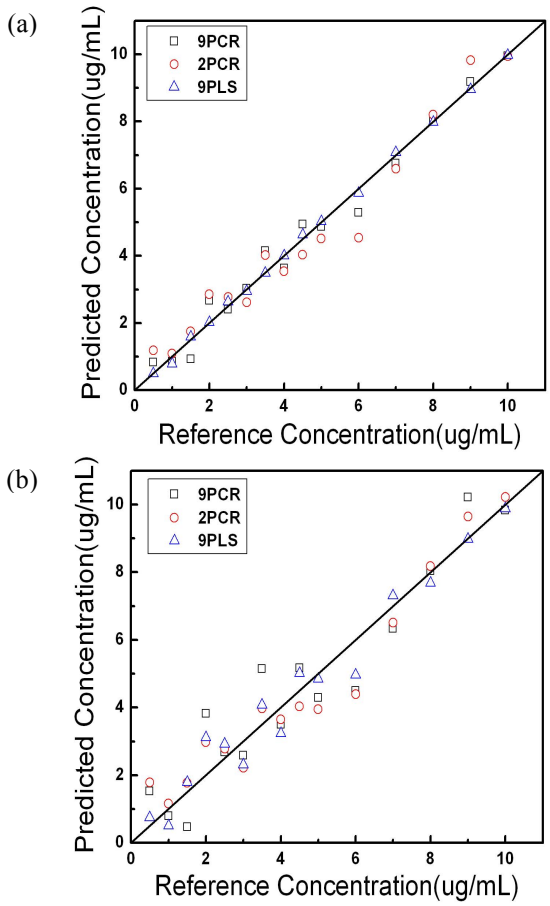

Figure 6. Plots of the predicted concentration vs. the reference concentration from (a) the calibration set, (b) leave-one-out cross-validation, with the 9-factor PCR, 2-factor PCR and 9-factor PLS models. The reference line in both (a) and (b) indicates the zero residual line between the predicted and reference concentration.

TABLE I. CALIBRATION RESULTS OF R, RMSEC AND RMSECV FROM THE 9-FACOR PCR, 2-FACTOR PCR AND 9-FACTOR PLS MODELS

Method	Factors	Calibration Precision		Prediction Precision
		R	RMSEC (μg/mL)	RMSECV(μg/mL)
PCR	9	0.991	0.390	0.960
	2	0.977	0.605	0.747
PLS	9	0.999	0.087	0.565

IV. CONCLUSION

This paper proved the feasibility of the combination of THz-TDS and chemometrics methods for the detection of cyfluthrin n-hexane solutions. Both PLS and PCR methods were used for the modeling between the calculated absorbance and concentration of the samples. As there were no spectral fingerprints in the absorbance spectra, the whole frequency range was selected. The number of factors was chosen as 2 for PCR and 9 for PLS, which corresponded to the least RMSECV. Compared to the PCR model, the PLS model gave better performance. Results with the two built PCR models also showed that the increase of factors for modeling would lead to higher model precision but might result in lower prediction precision due to the introduction of noise with these increased factors.

Moreover, it is not difficult to notice that the model performance is influenced by three parts: the modeling part, the absorbance calculation part, and the concentration obtaining part. The first part is affected by the linearity between the absorbance and the concentration, the selection of the modeling methods and frequency range; the second is related to the calculation process of the absorbance and the noise introduced by the originally obtained time-domain pulses; and the third is more fragile to errors produced in the sample preparation process. On the above analyses, further research can be carried out by introducing proper pretreatment and careful frequency range selection of the absorbance spectra. Reflection and scattering effects in THz transmission will be taken into account, which results in nonlinearity between the absorbance and the concentration. And a more accurate model should be developed, giving better explanation of this relationship. Errors in the sample preparation process can also be reduced by using more precise gauges.

REFERENCES

[1] G. A. Bonwick, C. Sunb, P. Abdul-Latifb, P. J. Baughb, C. J. Smith, R. Armitaged, and D. H. Davies, "Determination of permethrin and cyfluthrin in water and sediment by gas chromatography-mass spectrometry operated in the negative chemical ionization mode," Journal of Chromatography A, vol. 707, pp. 293-302, 1995.

[2] L. M. Ravelo-Perez, J. Hernandez-Borges, and M. A. Rodriguez-Delgado, "Pesticides analysis by liquid chromatography and capillary electrophoresis," Journal of Separation Science, vol. 20, no. 17, pp. 2557-2577, 2006.

[3] B. A. Khan, A. Farid, M. R. Asi, H. Shah, and A. K. Badshah, "Determination of residues of trichlorfon and dimethoate on guava using HPLC," Food Chemistry, vol. 14, no. 1, pp. 286-288, 2009.

[4] M. Khanmohammadi, S. Armenta, and M. de la Guardia, "Mid- and near-infrared determination of metribuzin in agrochemicals,"Vibrational Spectroscopy, vol. 46, no. 2, pp. 82-88, 2008.

[5] S. Armenta, S. Garrigues, and M. de la Guardia, "Determination of iprodione in agrochemicals by infrared and Raman spectrometry," Analytical and Bioanalytical Chemistry, vol. 387, no. 8, pp. 2887-2894, 2007.

[6] L. Zelayaran Melgar and S. A. S. Machado,"Determination of fenitrothion in commercial formulations by square wave voltammetry and UV-Vis spectroscopy," Journal of the Brazilian Chemical Society, vol. 16, no. 4, pp. 743-748, 2005.

[7] D. Dragoman and M. Dragoman, "Terahertz fields and applications", Progress in Quantum Electronics, vol. 28, no. 1, pp. 1-66, 2004.

[8] P. Y. Han, M. Tani, M. Usami, S. Kono, R. Kersting, and X. C. Zhang, "A direct comparison between terahertz time-domain spectroscopy and far-infrared Fourier transform spectroscopy" , Journal of Applied Physics, vol. 89, no. 4, pp. 2357-2359, 2001.

[9] P. H. Siegel, "Terahertz Technology in Biology and Medicine," IEEE Transactions on Microwave Theory and Techniques, vol. 52, no. 10, pp. 2438-2447, 2004.

[10] Z. Y. Zhang, X. H. Yu, H. W. Zhao, T. Q. Xiao, Z. J. Xi, and H. J. Xu, "Component analysis to isomer mixture with THz-TDS," Optics Communications, vol. 277, no. 2, pp. 273-276, 2007.

[11] Y. Ueno, R. Rungsawang, I. Tomita, and K. Ajito, "Quantitative measurements of amino acids by terahertz time-domain transmission spectroscopy," Analytical Chemistry, vol. 78, no. 15, pp. 5424-5428, 2006.

[12] Y. Hu, P. Huang, L. T. Guo, X. H. Wang, and C. L. Zhang, "Terahertz spectroscopic investigations of explosives," Physics Letters A, vol. 359, no. 6, pp. 728-732, 2006.

[13] Y. Zhang, X. H. Peng, Y. Chen, J. Chen, A. Curioni, W. Andreoni, S. K. Nayak, and X. C. Zhang, "A first principle study of terahertz(THz) spectra of acephate," Chemical Physics Letters, vol. 452, no. 1-3, pp. 59-66, 2008.

[14] C. J. Strachan, P. F. Taday, D. A. Newnham, C. J. Strachan, P. F. Taday, D. A. Newnham, K. C. Gordon, J. A. Zeitler, M. Pepper, and T. Rades, "Using terahertz pulsed spectroscopy to quantify pharmaceutical polymorphism and crystallinity," Journal of Pharmaceutical Sciences, vol. 94, no. 4, pp. 837-846, 2005.

[15] E. D. Calisir and S. Erkoc, "Structural, electronic and QSAR properties of the cyfluthrin molecule: A theoretical ami and PM3 treatment," International Journal of Modern Physics C, vol. 17, no. 10, pp. 1391-1402, 2006.

[16] H. B. Liu, "Terahertz spectroscopy for chemical and biological sensing applications," Ph.D. dissertation, Dept. Phys., Rensselaer Polytechnic Inst., Troy, NY, 2006.

[17] S. Gorenflo, "A comprehensive study of macromolecules in composites using broadband terahertz spectroscopy," Ph.D. dissertation, Dept. Math and Phys., Albert Ludwigs Univ., Freiburg, Germany, 2006.

[18] G. A. Hadad, A. El-Gindy, and W. M. M. Mahmoud, "HPLC and chemometrics-assisted UV-spectroscopy methods for the simultaneous determination of ambroxol and doxycycline in capsule," vol. 70, no. 3, pp. 655-663, 2008.

[19] R. Palermo, R. P. Cogdill, S. M. Short, J. K. Drennen, and P. F. Taday, "Density mapping and chemical component calibration development of four-component compacts via terahertz pulsed imaging," Journal of Pharmaceutical and Biomedical Analysis, vol. 46, no. 1, pp. 36-44, 2008.

[20] N. Qu, M. C. Zhu, H. Mi, Y. Dou, and Y. L. Ren, "Nondestructive determination of compound amoxicillin powder by NIR spectroscopy with the aid of chemometrics," Spectrochimica Acta, Part A (Molecular and Biomolecular Spectroscopy), vol. 70, no. 5, pp. 1146-1151, 2008.

[21] L. Y. Yu and B. R. Xiang, "Quantitative determination of acyclovir in plasma by near infrared spectroscopy," Microchemical Journal, vol. 90, no. 1, pp. 63-66, 2008.

[22] P. F. Taday, "Applications of terahertz spectroscopy to pharmaceutical sciences," Philosophical Transactions of Royal Society of London Series A-Mathematical Physical and Engineering Sciences, vol. 362, no. 1815, pp. 351-363, 2004.