The Canadian Society for Bioengineering
The Canadian society for engineering in agricultural, food, environmental, and biological systems.

CSBE | SCGAB

La Société Canadienne de Génie Agroalimentaire et de Bioingénierie
La société canadienne de génie agroalimentaire, de la bioingénierie et de l'environnement

Paper No. CSBE18-237

Terahertz Technologies for Food Safety

Shravani Prasad[1], Camille A. Leclerc[1], Ashutosh Singh[2], and Christopher M. Collier[1]

[1]Applied Optics and Microsystems Laboratory, School of Engineering, University of Guelph, Guelph, ON, Canada, N1G2W1

[2]Food Engineering Laboratory, School of Engineering, University of Guelph, Guelph, ON, Canada, N1G2W1

Written for presentation at the
CSBE/SCGAB 2018 Annual Conference
University of Guelph, Guelph, ON
22-25 July 2018

ABSTRACT

Terahertz radiation, over wavelengths of 30 to 3,000 microns, has emerged as a novel technology for material testing. This terahertz radiation can be used to detect unique chemical signatures and can pass through materials that are opaque to other wavelengths. As such, terahertz radiation is ideal for food safety applications. This work describes the emission and detection of terahertz radiation in the context of food safety applications.

.

Keywords: Food safety, photonics, terahertz spectroscopy.

INTRODUCTION Foreign object, microbe, and allergen contamination of food products cause one in eight Canadians (four million) to fall ill annually, and 240 of these Canadians succumb to the illness (CFIA, 2017). The death toll due to these food contaminations is believed to be even greater due to suspected unreported deaths (Wilcock et al., 2004). Such food contaminations provide a source for public mistrust and costly product recalls. This hinders the yield that Canadian businesses can attain (Wilcock et al., 2004). Numerous microbial food contamination has occurred within the last

---

decade such as the North American peanut industry's Salmonella outbreak in 2009 (Cohen, 2009), Ontario Maple Leaf Foods' Listeriosis outbreak in 2008 (Lerners lawyers, 2012), and President's Choice's Clostridium botulinum outbreak in in 2017 (CFIA, 2017). Food allergen exposure is a common cause of asphyxiation. In 2017, cases of foreign object contamination involved the recall of Zabiha Halal and Maple Lodge Farms chicken frankfurters that contained sharp bone fragments (CFIA, 2017). Improvements of food safety technologies are necessary to protect the wellbeing and health of Canadians and to avoid economic losses in Canada due to common food product contamination via microbes, allergens, and foreign objects.

Presently, the food product industry uses a two-step process for the detection of food product contamination: 1) Initial contamination of food products are lessened or avoided entirely via the Hazard Analysis and Critical Control Points (HACCP) protocols; and 2) the detection of contamination that were not avoided through HACCP protocols is facilitated with chemical food safety technologies. These chemical food safety technologies are based on microanalytical and microbiological techniques and can be insufficient and unable to detect contaminations. The issues that are relevant with the present food safety technologies include the following: long sample preparation times, long analysis times, and insensitivity to the presence of microbes and allergens. Additionally, the applications for the chemical food safety technologies are limited to off-line analyses (i.e., testing small samples of total food products) instead of on-line analyses (i.e., testing the entirety of food products sold and distributed). Thus, innovative and original food safety technologies are needed to solve the existing issues.

To address the substantial need, spectroscopy techniques using the electromagnetic (EM) spectrum have been investigated by researchers for solutions (Rodriguez-Saona, 2011). Research has been performed on EM food safety technologies that utilise wavelengths in ultraviolet/visible (Nowrocka and Lamorska, 2013), infrared (Fu and Ying, 2016), and terahertz (THz) spectra (Wang and Duncan, 2017). This trend of increasing wavelength for EM food safety has provided evidence that the THz spectrum provides an increased spectral sensitivity to the presence and properties of contaminants (Gowen et al., 2012). The THz spectrum has been shown to be able to pass through most packaging materials, with a potential use in post-packaging foreign object detection (Gowen et al., 2012). This spectrum has also been used identify allergens (Zhang et al., 2018) and microbes (Park et al., 2014) in minute quantities. Additionally, due to the low photon energies involved, the process is non-ionizing (Qin et al., 2013). For these reasons, THz spectral imaging holds much promise for the future of food safety technologies.

This paper discusses instrumentation for THz technologies, being THz emission and THz detection. This paper also reviews progress in THz spectroscopy in food safety, being the THz detection of microbes, allergens, and foreign objects in food products.

TERAHERTZ TRANSMITTERS AND RECEIVERS

Terahertz Spectroscopy The development of femtosecond pulsed lasers has allowed many scientific measurements, including ultrafast material characterisations (Jin et al., 2012, Collier et al., 2013b, Born et al., 2016) and THz spectroscopy (Collier et al., 2015). Shown in Figure 1, a THz spectroscopy system includes a femtosecond pulsed laser with light being focused through an objective onto a THz transmitter, with parabolic mirrors for THz collimation and focusing, a dichroic beam splitter to overlap a light beam and THz beam, and a THz receiver (Collier et al., 2014). The (optical) input to the system is a femtosecond pulsed laser beam, which is split with a beamsplitter into a pump beam for emission and a probe beam for detection of THz pulses. The pump beam passes through a delay stage, to a photoconductive (PC) or electro-optic (EO) transmitter that produces a THz pulse from the optical input. This THz pulse passes along with the probe pulse (with temporal separation controlled by the delay stage), and the two pulses interact in and are measured by a PC or EO detector (Collier et al., 2015). Figure 1 shows a THz spectroscopy schematic that utilises a PC transmitter and an EO receiver, which can be replaced with an EO transmitter and/or a PC receiver as needed.

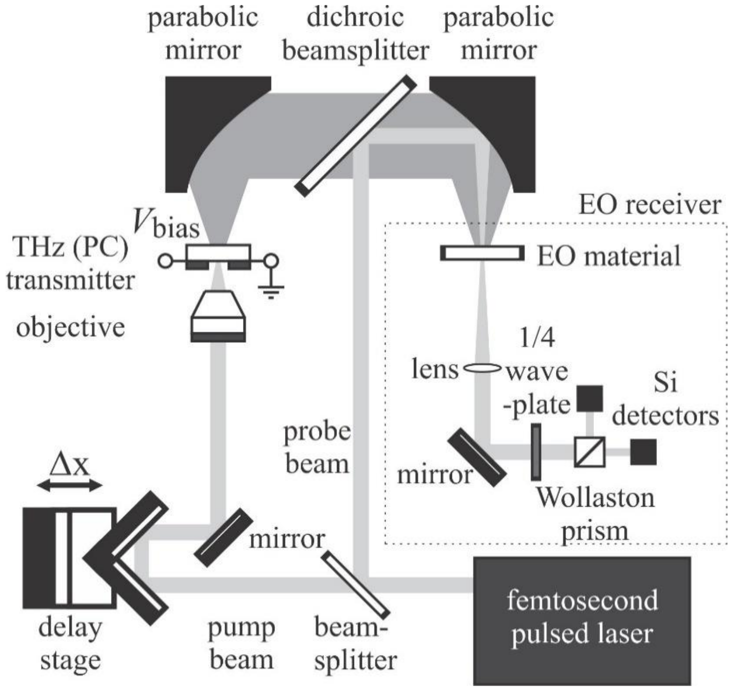

Figure 1. THz setup with a PC transmitter and an EO receiver.

A THz spectroscopy system is used in THz spectroscopy. Here, THz spectroscopy is achieved by measuring the range of THz frequencies that a sample (located between the left parabolic mirror and the dichroic beamsplitter) absorbs and refracts in a single pulse. (The THz spectroscopy requires comparison to a measured THz pulse without the sample present.) This THz spectroscopy is done by determining the refractive index $n(\nu)$ and absorption coefficient $\alpha(\nu)$ of a sample given the Fourier transform of a reference pulse $E_{ref}(\upsilon)$ (with the pulse propagating through the THz spectrometer without a sample present), the Fourier transform of a sample pulse $E_{sam}(\upsilon)$, and the sample thickness d (Al-Hujazy and Collier, 2018, Jepsen and Fischer, 2005). Specifically, the amplitude ratio $A(\upsilon) = |E_{sam}(\upsilon)|/|E_{ref}(\upsilon)|$ and phase $\varphi(v)$ can be calculated and used to determine $n(\nu)$ and $\alpha(\nu)$ of the sample to be

$$n(\nu) = 1 + \frac{c}{2\pi\nu d}\varphi(\nu), \tag{1}$$

and

$$\alpha(\nu) = -\frac{2}{d}\ln\left\{A(v)\frac{[n(v)+1]^2}{4n(v)}\right\}. \tag{2}$$

Terahertz Transmitters Photoconductive transmitters (Takazato et al., 2007), shown in Figure 2(a), utilise a PC material (e.g., GaAs) that has high mobility and high (dark) resistivity. A PC transmitter consists of the PC material connected to two metal electrodes that are separated by a gap. The electrodes are connected to a voltage V_{bias}. The biased PC gap is optically excited with an optical pulse from the ultrafast pulsed laser, which causes the material to quickly transition (timescale less than one picosecond) from insulating to conducting. The photo-excited carriers (electrons and holes) within the material accelerate and produce a current that resembles a mathematical step function. Proportional to the derivative of this mathematical step function, a THz pulse with broadband frequencies is produced. The advantages of PC transmission include compactness and scalability with V_{bias}. The efficiency of PC transmitters can be improved by changing the temporal properties of the mobility, being using a PC material with transient mobility (Collier et al., 2013a), or by changing the temporal properties of the conductivity, by using a PC material with short charge-carrier lifetime (Collier et al., 2012, Collier et al., 2014, Collier et al., 2016).

Electro-optic transmitters (Nagai and Tanaka, 2004), shown in Figure 2(b), utilise an EO material, (e.g., <110> ZnTe) that displays birefringence properties. This is a nonlinear optical rectification process that occurs due to the first-order polarization (i.e., Pockels effect) in the EO crystal, as the squared electric field is emitted. For a sinusoidal EM field, this squared electric field produces a second harmonic term E_{SH} and a rectified component E_{THz} (being the THz pulse). The second harmonic term can be filtered out to leave only the THz pulse, which has a pulse duration approximately equal to that of the pulsed laser. For a short optical pulse as an input, a broad spectrum is produced as an output which is a rectified THz pulse.

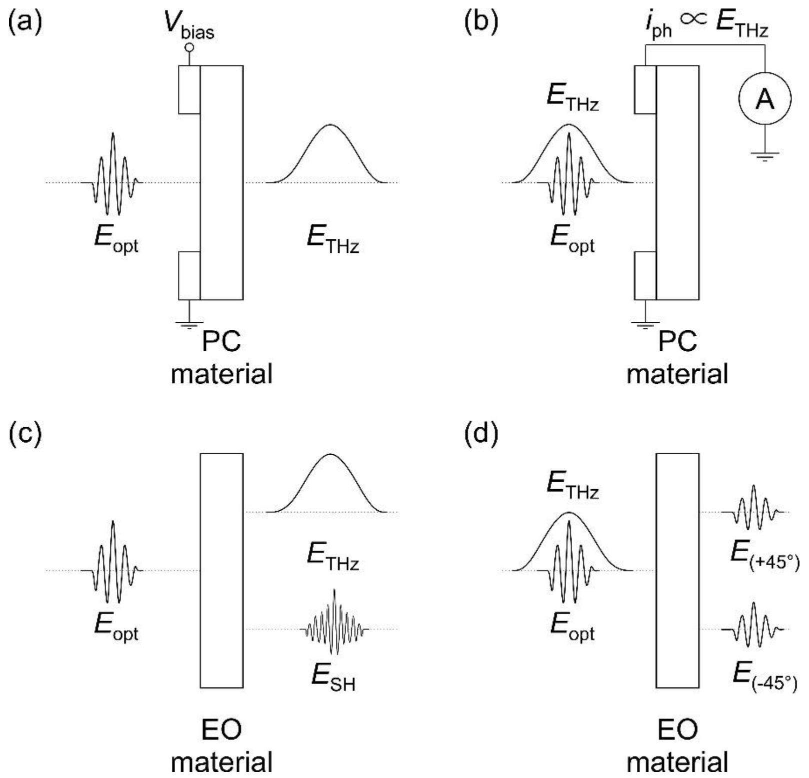

Figure 2. Transmitters and detectors used in THz spectroscopy, being (a) PC transmitter, (b) PC receiver, (c) EO transmitter, and (d) EO receiver.

Terahertz Receivers Photoconductive receivers (Takazato et al., 2007), shown in Figure 2(c), ultise a PC material (e.g., low temperature grown GaAs) and operate in the reverse process of PC transceivers. For PC receivers, the THz pulse biases the PC material as the optical pulse short circuits the PC gap, producing a photocurrent i_{ph}. This photocurrent is proportional to the electric field of the THz pulse and can be measured with an ammeter.

Electro-optic receivers (Nagai and Tanaka, 2004), shown in Figure 2(d), utilise an EO material (e.g., <110> ZnTe). Here, the electric field of the THz pulse changes the birefringence of the EO crystal, causing a difference in the refractive index for polarizations along different axes of the EO material. This difference of refractive index changes the polarization of probe beam. This process can be explained by further elaborating on the EO receiver setup on Figure 1. As the THz pulse and optical probe pulse pass through the EO material, the horizontal component of the optical probe pulse is delayed relative to the vertical component of the optical probe pulse. A ¼ wave-plate then transitions the optical probe pulse to either circular polarization (with no THz pulse present) or to elliptical polarization (with a THz pulse present). The degree of ellipticity is measured by differencing the electrical signal for two Si photodiodes after a Wollaston prism divides the horizontal and vertical components of the optical probe pulse. This differencing cancels common noise present on each Si photodiode.

TERAHERTZ SPECTROSCOPY IN FOOD SAFETY Given the above developments, researchers are now able to use THz spectroscopy for food safety applications (Gowen et al. 2012; Qin et al., 2013). Biologicals molecules and substances have distinct THz absorption signatures (He et al.,

2006) which can be used in their identification through THz spectroscopy. The THz pulse interacts weakly with non-polar molecules such as plastics and ceramics and are nondestructive for both polar and non-polar molecules, with the ability to penetrate through most packaging and detect embedded foreign objects post-packaging (Gowen et al., 2012; Qin et al., 2013). Water is an extremely absorptive molecule of the THz spectrum, making it an efficient method of analyzing the moisture content in food and agriculture (Qin et al., 2013). The next sections summarise the results of numerous researchers that use THz spectroscopy to detect microbe, allergen, and foreign object food contaminations within food products.

Terahertz Detection of Microbes Research on the detection of microbes using THz EM radiation has been explored by various researchers. Park et al. (2014) used a combination of THz spectroscopy and metamaterials sensors to detect the frequency shifts of penicillia (mold) as a function of dielectric constants of the metamaterial and density of the penicillia sample. Besides penicillia detection, it was shown that Escherichia coli in an aqueous solution could be detected with a THz frequency shift under the presence of the metamaterial (Park et al., 2014). Through the use of a THz photo-mixing spectrometer, it was possible to detect distinct THz absorption signature of the endospores of a common soil bacteria, Bacillus thuringiensis (Zhang et al., 2014). The data collected by Zhang et al. (2014) provide evidence that there is a correlation between the hydration level of the endospores and the respective THz absorption signatures of the endospore sample. Terahertz spectroscopy was further utilised by Wang et al. (2010) to determine the absorption signatures of Bacillus subtilis, which resides in the soil or gastrointestinal tract of humans. The applicability of THz spectroscopy for the detection Acinetobacter baumanii, Pseudomonas aeruginosa, and Staphylococcus aureus (all commonly found bacteria in infectious diseases) frequency absorption signatures (Yang et al., 2016). The Frequency absorption signatures were also found to vary depending on if the bacteria were living, dead, or bacterial powder (Yang et al., 2016).

Terahertz Detection of Allergens (and Toxins) Research on the detection of allergens and toxins using THz spectroscopy has also been investigated by numerous researchers. Zhang et al. (2018) found that there is a distinct frequency absorption signature for Gallic acid and its monohydrate within the range of 0.5 to 4.5 THz. Gallic acid is a chemical compound found in sumac, tea leaves and other plants (NCBI, 2018) is also an allergen for various individuals. Another allergen such as wheat, for which 141,000 Canadians are allergic (AllerGen, 2017), was found to have a THz frequency absorption signature between 0.2 to 2.0 THz (Ge et al., 2015). This THz range was also used by Ge et al. (2015) to identify eight different varieties of wheat, which is a common ingredient in a great number of food products (Fletton, 2017). Toxins such as pesticides, which can cause numerous health problems when consumed (WHO, 2016; Tripathi et al., 2015), can be found in wheat products. The detection of five different kind of pesticides out of a sample of seven within wheat flour was achieved in a frequency range of 0.1 to 3 THz by Maeng et al. (2014). Identification of the frequency absorption signatures of other toxins such as antibiotics (sulfapyridine, sulfathiazole, and tetracycline) and two acaricides (coumaphos and amitraz) was achieved using the frequency range of 0.5 to 6.0 THz (Massaouti et al., 2013).

Terahertz Detection of Foreign Objects Terahertz spectroscopy has been used to detect objects through cloth and other materials and this has been used extensively in security applications to detect concealed weapons (Cooper et al., 2011, Kowalski and Kastek, 2016). This is because THz radiation can pass through materials that are opaque to other wavelengths (e.g., visible or infrared).

This concept can be applied to food safety for the detection of foreign objects. Specifically, foreign objects such as granite, aluminum, crickets, and maggots have been detected at a continuous THz frequency of 2 THz (Lee et al., 2011).

CONCLUSION Food contaminant outbreaks continue to be a common problem for Canada. These circumstances entail that an elaborate, effective, and universal detection method is needed to prevent future outbreaks. Such an improved detection method could very well be THz spectroscopy as many researchers have shown its promise for detecting the food contaminants.

Acknowledgements. This work was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC).

REFERENCES

Al-Hujazy, R. and C. M. Collier. 2018. Design considerations for integration of terahertz time-domain spectroscopy in microfluidic platforms. *Photonics*. 5(1): 5.

Allergen. 2017. Estimated food allergy prevalence among canadian children and. Available at: adultshttp://allergen-nce.ca/wp-content/uploads/Canadian-food-allergy-prevalence-Jul-2017.pdf Accessed 22 June 2018.

Baek, S. H., H. B. Lim, and H. S. Chun. 2014. Detection of melamine in foods using Terahertz time-domain spectroscopy. *Journal of Agricultural Food Chemistry.* 62(24): 5403-5407.

Born, B., S. Geoffroy-Gagnon, J. D. A. Krupa, I. R. Hristovski, C. M. Collier, and J. F. Holzman. 2016. Ultrafast all-optical switching via subdiffractional photonic nanojets and select semiconductor nanoparticles. *ACS Photonics*. 3(6): 1095-1101.

CFIA. 2017. Causes of food poisoning. Available at http://www.inspection.gc.ca/food/information-for-consumers/fact-sheets-and-infographics/food-poisoning/eng/1331151916451/1331152055552 Accessed 19 June 2018.

CFIA. 2017. Food recall warning- Maple Lodge Farms brand chicken frankfurters and Zabiha Halal chicken frankfurters may be unsafe due to potential presence of bone fragments. Available at http://www.inspection.gc.ca/about-the-cfia/newsroom/food-recall-warnings/complete-listing/2017-08-11/eng/1502492949623/1502492953267 Accessed 19 June 2018.

CFIA. 2017. Updated food recall warning – PC organics brand baby food pouches recalled due to potential presence of dangerous bacteria. Available at http://www.inspection.gc.ca/about-the-cfia/newsroom/food-recall-warnings/complete-listing/2017-02-08/eng/1486618317290/1486618321366 Accessed 19 June 2018

Collier, C. M., B. Born, and J. F. Holzman. 2012. Ultrafast response of SiC and Si nanocomposite material systems. *Electronics Letters*, 48(25): 1618-1619.

Collier, C. M., B. Born, M. Bethune-Waddell, X. Jin, and J. F. Holzman. 2013a. Ultrafast photoexcitation and transient mobility of GaP for photoconductive terahertz emission. *IEEE Journal of Quantum Electronics*, 49(8): 691-696.

Collier, C. M., B. Born, X. Jin, and J. F. Holzman. 2013b. Ultrafast charge-carrier and phonon dynamics in GaP, *Applied Physics Letters*, 103(7): 072106.

Collier, C. M. and J. F. Holzman. 2014. Ultrafast photoconductivity of crystalline, polycrystalline and nanocomposite ZnSe material systems for terahertz applications, *Applied Physics Letters*, 104(4): 042101.

Collier, C. M., M. H. Bergen, T. J. Stirling, M. A. DeWachter, and J. F. Holzman. 2015. Optimization processes for pulsed terahertz systems. *Applied Optics.* 54(3): 535-545.

Collier, C. M., T. J. Stirling, I. R. Hristovski, J. D. A. Krupa, and J. F. Holzman. 2016. Photoconductive terahertz generation from textured semiconductor materials, *Scientific Reports*. 6: 23185.

Cooper, K. B., R. J. Dengler, N. Llombart, B. Thomas, G. Chattopadhyay, and P. H. Siegel. 2011. THz imaging radar for standoff personnel screening. *IEEE Transactions on Terahertz Science and Technology*. 1(1): 169-182.

Fletton, H. 2017. Wheat free Glossary. Available at: https://www.wheat-free.org/all.html Accessed June 21 2018.

Fu, X., Y. Ying. 2016. Food safety evaluation based on near infrared spectroscopy and imaging: a review. *Critical Reviews in Food Science and Nutrition*. 56(11): 1913-1924

Ge, H., Y. Jiang, F. Lian, Y. Zhang, and S. Xia. 2015. Characterization of wheat varieties using terahertz time-domain spectroscopy. *Sensors (Basel, Switzerland).* 15: 12560-12572.

Gowen, A. A., C. O'Sullivan, C. P. O'Donnell. 2012. Terahertz time domain spectroscopy and imaging: emerging techniques for food process monitoring and quality control. *Trends in Food Science & Technology*. 25(1): 40-46.

He, M., Azad, A. K., Ye, S., & Zhang, W. 2006. Far-infrared signature of animal tissues characterized by terahertz time-domain spectroscopy. *Optics Communications*. 259(1): 389-392.

Jepsen, P. U., and B. M. Fischer. Dynamic range in terahertz time-domain transmission and reflection spectroscopy. 2005. *Optics Letters.* 30(1): 29-31.

Jin, X., C. M. Collier, J. J. A. Garbowski, B. Born, and J. F. Holzman. 2013. Ultrafast transient responses of optical wireless communication detectors. *Applied Optics*. 52(20): 5042-5049, 2013.

Kowalski, M. and M. Kastek. 2016. Comparative studies of passive imaging in terahertz and mid-wavelength infrared ranges for object detection. *IEEE Transactions on Information Forensics and Security*. 11(9): 2028-2035.

Lee, Y-K., S-W. Choi, S-T. Han, D. H. Woo, and H. S. Chun. 2012. Detection of foreign bodies in foods using continuous wave terahertz imaging. *Journal of Food Protection.* 75(1): 179-183.

Lerners Lawyers. 2017. 1688782 Ontario v. Maple Leaf Foods. Available at http://www.lerners.ca/cases/1688782-ontario-ltd-v-maple-leaf-foods-inc-et-al/ Accessed 19 June 2018.

Maeng, I., S. H. Baek, H. Y. Kim, G-S. Ok, S-W. Choi, and H. S. Chun. 2014. Feasibility of using terahertz spectroscopy to detect seven different pesticides in wheat flour. *Journal of Food Protection.* 77(12): 2081-2087.

Massaouti, M., C. Daskalaki, A. Gorodetsky, A. D. Koulouklidis, and S. Tzortzakis. 2013. Detection of harmful residues in honey using terahertz time domain spectroscopy. *Applied Spectroscopy.* 67(11): 1264-1269.

Nagai, M., and K. Tanaka. 2004. Generation and detection of terahertz radiation by electro-optical process in GaAs using 1.56μm fiber laser pulses. *Applied Physics Letters.* 85(18): 3974-3976.

NCBI. 2018. PubChem Compound Database; Gallic Acid, Available at: https://pubchem.ncbi.nlm.nih.gov/compound/370 Accessed 21 June 2018.

Nowrocka, A., J. Lamorska. 2013. Determination of food quality by using spectroscopic methods. In S. Grundas (Ed.), *Advances in Agrophysical Research* (347-367). Rijeka, Croatia: InTech.

Park, S. J., J. T. Hong, S. J. Choi, H. S. Kim, W. K. Park, S. T. Han, J. Y. Park, S. Lee, D. S. Kim, and Y. H. Ahn. 2014. Detection of microorganisms using terahertz metamaterials. *Scientific Reports*. 4(4988): 1-7.

Rodriguez-Saona, L. E., and M.E. Allendorf. 2011. Annu. Use of FTIR for rapid authentication and detection of adulteration of food. *Annual Review of Food science and technology.* 2: 427-483.

Takazato, A., M. Kamakura, T. Matsui, J. Kitagawa, and Y. Kadoya. 2007. Terahertz wave emission and detection using photoconductive antennas made on low-temperature-grown InGaAs with 1.56μm pulse excitation. *Applied Physics Letters*. 91(1): 011102.

Tripathi, A. K., R. Ghosh, N. Singh, M. Siddarth, D. Chawla, B. D. Banerjee, O. P. Karla. 2015. Association of blood level of organochlorine pesticide with chronic kidney disease of unknown etiology. *Toxicology Letters.* 238(2): 133-134

Wang, C., J. Gong, Q. Xing, Y. Li, F. Liu, X. Zhao, L. Chai, C. Wang, and A. M. Zheltikov. 2010. Application of terahertz time-domain spectroscopy in intracellular metabolite detection. *Journal of Biophotonics*. 3(10-11): 641-645.

Wang, Y., and T. V. Duncan. 2017. Nanoscale sensors for assuring the safety of food products. *Trends in Food Science & Technology*. 44: 74-86.

WHO. 2016. Pesticide residues in food? Available at: http://www.who.int/features/qa/87/en/ Accessed 21 July 2018.

Wilcock, A., M. Pun, J. Khanona, and M. Aung. 2004. Consumer attitudes, knowledge and behavior: a review of food safety issues. *Trends in Food Science & Technology.* 15: 56-66.

Yang, X., D. Wei, S. Yan, Y. Liu, S. Yu, M. Zhang, Z. Yang, X. Zhu, Q. Huang, H-L. Cui, and W. Fu. 2016. Rapid label-free detection and assessment of bacteria by terahertz time-domain spectroscopy. *Journal of Biophotonics*. 9(10): 1050-1058.

Zhang, B., S. Li, C. Wang, T. Zou, T. Pan, J. Zhang, Z. Xu, G. Ren, and H. Zhao. 2018. Terahertz spectroscopic investigation of gallic acid and its monohydrate. *Spectrochimica acta. Part A, Molecular and Biomolecular Spectroscopy*. 190: 40-46.

Zhang, W., E. R. Brown, L. Viveros, K. P. Burris, and C. N. Stewart, Jr. 2014. Narrow terahertz attenuation signatures in Bacillus thuringiensis. *Journal of Biophotonics*. 7(10): 818-824.