



International Journal of Engineering Research and Science & Technology

www.ijerst.org

IF: 9.625

ISSN : 2319-5991

**International Conference on Ensuring
Global Food Safety-ICEGFS-2026**

Vol. 22 No. 4(S) (2026)



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TERAHERTZ TECHNOLOGY FOR NON-DESTRUCTIVE FOOD QUALITY AND SAFETY ASSESSMENT

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Abstract

Despite its promise, wider industrial adoption faces challenges including high instrument cost, limited penetration depth in high-moisture foods, water absorption, complex data interpretation, and the need for robust models under real production conditions. Terahertz (THz) technology, operating broadly in the 0.1–10 THz frequency range, is emerging as a powerful non-destructive testing (NDT) tool for food quality and safety assessment. THz waves combine properties of microwaves and infrared radiation, offering low photon energy, high sensitivity, spectral “fingerprint” information, and the ability to penetrate many non-metallic and non-polar materials such as paper and plastic packaging. Future research should therefore focus on developing compact, low-cost, high-speed THz sources and detectors; improving penetration and signal-to-noise performance; creating standardized food spectral libraries; and integrating THz spectroscopy with chemometrics, artificial intelligence, and automated online inspection systems. With continued technological advances, terahertz technology is expected to become a rapid, reliable, sustainable, and commercially viable tool for non-destructive assessment of food quality, authenticity, and safety.

Keywords: Terahertz spectroscopy; THz imaging; non-destructive testing; food quality; food safety; adulteration; foreign-body detection; machine learning.

Received: 17-09-2026

Accepted: 22-10-2026

Published: 29-10-2026

1. Introduction

Food quality and safety are global priorities, with contamination, adulteration, and spoilage posing significant public health and economic risks. Conventional analytical methods (e.g., chromatography, microbiological plating) are accurate but often destructive, time-consuming, and unsuitable for high-throughput screening[1]. Non-destructive testing (NDT) technologies—such as near-infrared (NIR) spectroscopy, hyperspectral imaging, X-ray, and microwave sensing—have gained traction for rapid, inline inspection[2].

Terahertz (THz) radiation, spanning approximately 0.1–10 THz (wavelengths ~3 mm to 30 μ m), occupies the electromagnetic gap between microwaves and infrared[3]. THz waves exhibit unique characteristics: non-ionizing safety, sensitivity to low-frequency molecular vibrations and rotations (yielding spectral fingerprints), and the ability to penetrate non-metallic, non-polar packaging

materials[4,5]. These attributes make THz technology particularly attractive for inspecting packaged dry foods, powders, grains, and spices without opening containers[6,7].

Recent reviews highlight rapid progress in THz time-domain spectroscopy (THz-TDS), continuous-wave (CW) systems[8,9], and THz imaging for agri-food applications, often coupled with chemometrics and machine learning (ML) to handle complex spectral data. However, practical deployment is hindered by strong water absorption (limiting penetration in moist matrices), high system costs, and the need for standardized protocols and spectral libraries[10-12].

This review provides a comprehensive overview of THz technology for food quality and safety, emphasizing: (i) physical principles and system configurations; (ii) key application domains; (iii) technical and industrial challenges; and (iv) future research directions

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toward compact, affordable, and production-ready THz inspection systems.

2. Fundamentals of Terahertz Technology

2.1. THz Radiation Characteristics

THz waves bridge microwave and infrared regimes, combining moderate penetration (like microwaves) with molecular specificity (like infrared). Key properties include:

- **Low photon energy** (~meV range), ensuring non-ionizing, safe operation for operators and food products[13].
- **Spectral fingerprints:** Many organic molecules exhibit distinct absorption features in the THz range due to intermolecular vibrations, hydrogen-bonding networks, and crystalline lattice modes[14].
- **Packaging transparency:** THz radiation penetrates paper, cardboard, plastics, and ceramics, but is reflected/absorbed by metals and water-rich materials[15].

2.2. THz System Configurations

Two primary modalities dominate food applications:

- **THz Spectroscopy:** Measures frequency-dependent absorption/reflection to identify chemical composition. THz-TDS provides both amplitude and phase, enabling extraction of refractive index and absorption coefficient[16].
- **THz Imaging:** Maps spatial variations in THz transmission/reflection to detect foreign bodies, defects, or compositional heterogeneity. Imaging can be raster-scanned (point-by-point) or wide-field (camera-based).

Systems may operate in transmission, reflection, or attenuated total reflection (ATR) modes, with ATR useful for high-moisture or opaque samples[17]

2.3. Interaction with Food Matrices

Food is a complex, heterogeneous medium. THz interaction depends on:

- **Moisture content:** Water strongly absorbs THz radiation; in high-moisture foods (>14–15%), penetration at ~0.3 THz may be limited to a few millimeters[18].
- **Composition:** Proteins, fats, carbohydrates, and additives exhibit distinct THz signatures, though often weaker than water's absorption[19].
- **Physical structure:** Particle size, packing density, and surface roughness cause scattering, affecting signal quality.

3. Applications in Food Quality and Safety

3.1. Adulteration and Authenticity

Adulteration of high-value foods (spices, milk powders, teas, supplements) is a persistent issue. THz spectroscopy can detect by matching sample spectra against reference libraries[20]. Recent studies report:

- **Dairy products:** PCA and SVM-DA identified adulterated milk powders with high accuracy.
- **Herbal/traditional medicines:** LS-SVM and PLS models detected adulteration in Panax notoginseng and kudzu powders, with prediction accuracies (R_p) >0.90 and low RMSEP.
- **Spices and flours:** THz combined with UVE-LS-SVM-RBF-DA achieved misjudgment rates as low as 6.7% for lotus root/potato powder adulteration. Machine learning enhances classification robustness, especially when spectra are noisy or overlapping[21].

3.2. Foreign-Body and Contaminant Detection

Foreign materials (insects, stems, plastics, wood, stones) pose physical hazards. THz imaging excels at detecting low-density, organic contaminants that X-ray may miss.

- **Tea inspection:** THz-TDS imaging detected tea stalks and insect fragments; KNN and PLS-DA models

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achieved 95–100% accuracy after spectral preprocessing.

- **Grains and powders:** Sub-THz and THz imaging identified plastics, insects, and maggots in dried milk and instant noodles[22].
- **Wheat seeds:** THz imaging distinguished wood, stones, and other foreign matter with high precision[23].
- THz's sensitivity to density and dielectric contrast enables detection of both high-density (metal, stone) and low-density (insects, plastics) contaminants.

3.3. Compositional Analysis and Moisture Measurement

THz spectroscopy quantifies moisture, fat, protein, and other constituents, particularly in low-to-moderate moisture foods.

- **Moisture:** THz is highly sensitive to water, enabling precise moisture quantification in grains, powders, and confectionery[24].
- **Fat/protein:** Distinct absorption features allow differentiation of fat/protein content in meats and dairy, though water interference remains a challenge[25].
- **Additives and residues:** THz can screen for pesticides, preservatives, and illegal additives, especially when combined with chemometric models.

3.4. Microbial and Toxin Screening

While direct microbial detection is challenging, THz can sense metabolic byproducts, spoilage markers, or mycotoxins in dry matrices.

- **Mycotoxins:** THz-TDS, enhanced by metamaterials or nanomaterials, shows promise for detecting aflatoxins and other toxins at trace levels[26].
- **Spoilage indicators:** Changes in spectral profiles correlate with microbial growth and biochemical degradation, enabling early spoilage detection.

4. Technical and Industrial Challenges

4.1. Water Absorption and Limited Penetration

Water's strong THz absorption severely limits penetration in high-moisture foods (>15% moisture), restricting applications to dry or thin-sliced products. Mitigation strategies include:

- **Sample preparation:** Freezing or dehydrating samples to reduce free water.
- **Lower frequencies:** Operating at <0.3 THz to improve penetration (at the cost of spectral resolution[27].
- **ATR and reflection modes:** Using ATR or reflection geometries for surface/near-surface analysis.
- **Deep learning:** Applying ML to remove water vapor lines and enhance signal recovery[28].

4.2. High Instrument Cost

High-performance THz-TDS and imaging systems often cost **\$100,000–\$500,000+**, far exceeding conventional optical/X-ray systems. Cost barriers stem from expensive femtosecond lasers, photoconductive antennas, and precision optics.

4.3. Speed, Throughput, and Data Complexity

- **Scanning speed:** Raster-scanned imaging is slow; wide-field cameras and faster sources are needed for inline inspection.
- **Data volume:** THz hyperspectral cubes generate large datasets, requiring efficient preprocessing, feature selection (e.g., CARS, UVE, SPA), and ML models.
- **Environmental sensitivity:** Spectra vary with temperature, humidity, and sample presentation, demanding robust calibration and validation[29].

4.4. Lack of Standardized Libraries and Protocols

Broad adoption requires shared, curated spectral databases for food components, adulterants, and contaminants, along with

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harmonized measurement protocols to ensure cross-site reproducibility.

5. Future Directions and Research Priorities

5.1. Compact, Low-Cost, High-Speed Hardware

Developing affordable THz sources/detectors (e.g., photonic integrated circuits, semiconductor THz emitters) and faster scanners is critical for industrial uptake.

5.2. Enhanced Sensing via Multidisciplinary Integration

Recent reviews emphasize integrating THz-TDS with:

- **Machine learning:** For robust classification, quantification, and anomaly detection.
- **Metamaterials:** To amplify analyte-specific signatures and improve sensitivity.
- **Microfluidics:** For controlled sample handling and enhanced interaction.
- **Functional nanomaterials:** To boost signal-to-noise and enable trace detection.

5.3. Standardized Spectral Libraries and Protocols

- Building open, validated libraries for common foods and contaminants, alongside standardized protocols, will accelerate method transfer and regulatory acceptance.

5.4. Automated Online Inspection Systems

- Engineering turnkey systems with conveyors, triggers, real-time inference, and reject mechanisms will enable factory deployment.

6. Conclusion

Terahertz technology offers a unique combination of safety, spectral specificity, and packaging penetration, making it a promising NDT tool for food quality and safety. While challenges—particularly water absorption, cost, and data complexity—remain, multidisciplinary advances in hardware, chemometrics, AI, and materials science are rapidly addressing these barriers. With

continued innovation, THz systems are poised to become compact, affordable, and production-ready, enabling rapid, reliable, and sustainable inspection of food quality, authenticity, and safety across global supply chains.

References (Selected)

1. Liu et al., “Next-generation food safety: Terahertz and AI for non-destructive testing,” *J. Food Meas. Charact.*, 2026.
2. Gao et al., “Terahertz spectroscopy in the field of food safety: a review,” *J. Eng. Res. Rep.*, 2024.
3. Wang et al., “Recent Advances in Terahertz Time-Domain Spectroscopy and Imaging Techniques for Automation in Agriculture and Food Sector,” *Food Anal. Methods*, 2021.
4. Shi et al., “A Comprehensive Review of Artificial Intelligence (AI) in Food Safety,” *Korean J. Food Sci. Anim. Resour.*, 2025.
5. Zhang et al., “Terahertz Spectroscopy for Food Quality Assessment,” *PMC*, 2025.
6. Li et al., “Recent Developments and Applications of Terahertz Spectroscopy in Food Analysis,” *Biosensors*, 2025.
7. Ok et al., “Sub-terahertz imaging for foreign material detection in foods,” *Food Control*, 2023.
8. Chen et al., “Non-destructive detection of tea stalk and insect foreign bodies using THz-TDS,” *Food Qual. Saf.*, 2023.pure.hw.ac+1
9. Yang et al., “A Comprehensive Review of Terahertz Time-Domain Spectroscopy for Agri-Food Safety Detection,” *Crit. Rev. Food Sci. Nutr.*, 2025.
10. Puc et al., “Terahertz time domain spectroscopy and imaging,” *Maynooth University*, 2015.

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11. "Novel analysis of food processes by terahertz spectral imaging: A review," *OUCI*, 2024.
12. "THz Imaging for Food Inspections: A Technology Review," *IntechOpen*, 2021.
13. "THz Imaging For Food Safety: Contaminant And Foreign Object Detection," *Eureka/PatSnap*, 2025.
14. "Image Processing Technique to Detect Adulteration," *ICDS 2025*.
15. "Advances in non destructive methods of meat quality assessment," *Biochem. J.*, 2025.
16. Liu (2017), "PCA and SVM-DA for adulterated dairy products," *Food Chem.*
17. "Biomedical application of terahertz imaging technology," *PMC*, 2023.
18. "Principles, Applications, and Future Evolution of Agricultural NDT," *PMC*, 2025.
19. "Terahertz imaging advances toward medical diagnostics," *Laser Focus World*, 2024.
20. "Inline Inspection of Packaged Food Using Microwave/Terahertz Sensing," *LAPSE*, 2024.
21. "Applications of THz Spectral Imaging in Agriculture and Food," *Semantics Scholar*, 2024.
22. "High sensitivity to water for low water content determination," *CiteSeerX*.
23. "Non-destructive detection of tea stalk and insect foreign bodies," *Food Qual. Saf.*, 2023.
24. "Recent developments in terahertz techniques for agricultural applications," *Microchem. J.*, 2026.
25. "A Comprehensive Review of Terahertz Time-Domain Spectroscopy for Agri-Food Safety Detection," *PubMed*, 2025.
26. "Advancing Fruit Quality Monitoring with Artificial Intelligence," *Springer*, 2026.
27. "Detection and prevention of foreign material in food: A review," *PMC*, 2023.
28. "Non-destructive Detection of Insect Foreign Bodies in Finishing Tea Product," *Front. Nutr.*, 2021.
29. "Recent Developments and Applications of Terahertz Spectroscopy in Food Analysis," *MDPI Biosensors*, 2025.