A Comprehensive Review on Different Food Adulteration with the Application of ATR-FTIR.

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Abstract

The practice of food adulteration creates major health threats together with economic issues around the world. Researchers have examined how ATR-FTIR spectroscopy detects adulterants within five routine food products which include milk together with coffee along with honey and also ghee and oils. The presented review evaluates ATR-FTIR by examining recent publications about its functioning approaches together with its restrictions and forensic uses in food authentication fields. This study shows ATR-FTIR enables fast and non-destructive and highly sensitive assessment of adulterants throughout different food samples requiring minimal sample handling. The article investigates detection thresholds and shows the specific spectral elements that signify different adulterated substances while exploring traditional analytical techniques. The discussion ends by showcasing how ATR-FTIR shows promise for food safety and authentication regulation adoption which requires future research for specific knowledge acquisition.

Keywords: - ATR-FTIR spectroscopy; food adulteration; forensic analysis; milk authenticity; honey detection; edible oils; rapid testing

1. Introduction

The deliberate practice of food adulteration through intentional product contaminations exists as a worldwide problem with severe impacts on public well-being and monetary stability and consumer confidence (Sharma & Bansal, 2014). The detection of complex adulterants through traditional analysis methods such as chemical testing with sensory evaluation takes too much time before revealing results in addition to requiring extensive laboratory preparation work (Jindal et al., 2016). The contemporary food industry demands immediate access to dependable non-destructive methods that prevent advanced adulteration practices from damaging food quality.

ATR-FTIR spectroscopy featuring Attenuated Total Reflection and Fourier Transform Infrared functions has proven to be an effective analytical instrument which detects food adulteration and confirms authenticity(Saini et al., 2015). ATR-FTIR operates with advantages such as requiring small sample preparation while offering non-destructive analysis and fast results and allowing simultaneous detection of multiple adulterants(Yang et al., 2021). ATR-FTIR finds its core forensic use in food safety regulation and food quality control as well as food fraud cases in legal settings(Malik et al., 2019).

This review examines ATR-FTIR technology for detecting adulterants that occur in the five popular food items including milk, coffee, honey, ghee along with edible oils. This paper evaluates both established techniques and detection capabilities as well as fundamental spectral patterns of common adulterants followed by a comparative analysis versus conventional detection methods. The scope includes an examination of ATR-FTIR technology used for food authentication testing as well as its readiness for regulatory frameworks.

2. ATR-FTIR: Principles and Methodology

2.1 Basic Principles

The ATR-FTIR spectroscopy method uses attenuated total reflection to analyze the results from a high refractive index crystal probably composed of diamond or zinc selenide and germanium (Saini et al., 2015). When exposed to the evanescent wave stemming from internal infrared beam reflection a sample interacts by absorbing wavelengths that match the molecular vibrations of sample elements(El-Din et al., 2020). The spectrum generated from FT-IR has a distinctive pattern that reveals the chemical composition of the sample for identifying adulterants and contaminants (Saini et al., 2015).

2.2 Methodological Approaches

The method used for food adulteration detection via ATR-FTIR follows these main steps:

1. Preparation of samples requires minimal work that includes either homogenization of the material or direct placement of samples on the ATR crystal(Saini et al., 2015).

2. Spectral acquisition: Recording of infrared spectra, generally in the mid-infrared region (4000-400 cm^{-1})(Wang et al., 2019).

3. Data preprocessing includes techniques for baseline correction along with normalization and smoothing to improve the spectral quality of the obtained spectra(Katz, L., & Fisher, K. 2019).

4. The identification of diagnostic adulterant fingerprints depends on matching spectra to reference information and multivariate statistical methods (Saini et al., 2015).

5. The measurement of contaminant amounts takes place through realized calibration models together with chemometric strategies (Rodriguez-Saona, L. E., & Allendorf, M. E. 2011).

ATR-FTIR benefits substantially from chemometrics usage to detect food adulteration through advanced analytic tools. The analysis of authentic and adulterated samples together with adulterant measurement becomes possible through advanced statistical techniques that include Principal Component Analysis (PCA) and Partial Least Squares Regression (PLSR) and Soft Independent Modeling of Class Analogy (SIMCA)(Grassi et al., 2014).

3. Application of ATR-FTIR in Detecting Adulteration in Selected Food Products

3.1 Milk and Dairy Products

The problem of milk adulteration affects public health strongly in developing nations (Pallavi, V., & Prakash, M. 2018). The additives used for adulteration most commonly include water as well as detergents and synthetic milk and melamine along with urea and multiple chemical preservatives(Malik, A., & Arora, G. 2019). Through the analysis of spectral markers ATR-FTIR has successfully detected adulterants according to Table 1.

Table 1: Common Milk Adulterants and Their Characteristic ATR-FTIR Spectral Markers

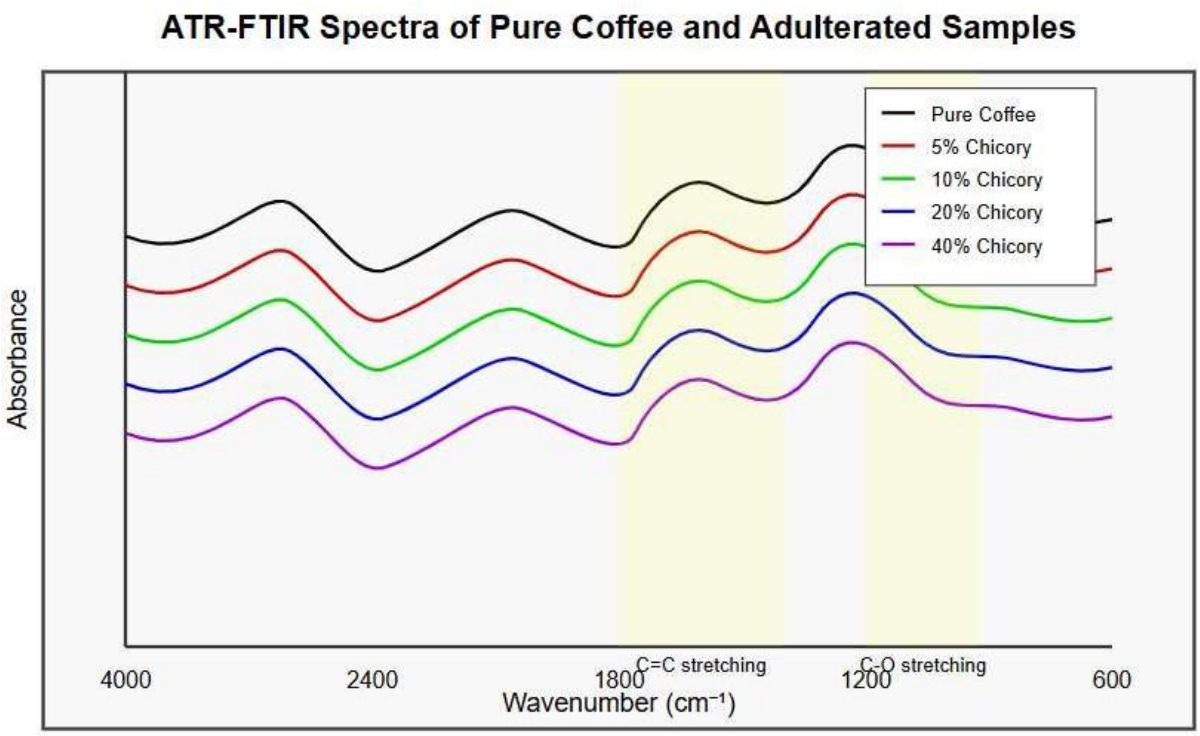
Adulterant	Characteristic Spectral Markers (cm^{-1})	Detection Limit
Water	Decreased intensity at 1640-1650 (O-H bending)	5-10% v/v
Detergents	1550-1570 (COO^- stretching), 1080-1100 (S-O stretching)	0.5-1% w/v
Melamine	1650-1660 (C=N stretching), 1000-1010 (C-N stretching)	0.1% w/v
Urea	1680-1700 (C=O stretching), 1450-1470 (N-H bending)	0.2% w/v
Synthetic milk	Multiple markers: 1740-1760, 1200-1210, 970-980	10-15% v/v

Pallavi and Prakash(Pallavi, V., & Prakash, M. 2018) demonstrated ATR-FTIR's capability in detecting water adulteration in milk samples. Their study revealed that water adulteration led to notable changes in the infrared spectra, particularly in the regions associated with protein and lactose content. Even at low concentrations, these spectral changes enabled accurate detection of adulteration.Similarly, (Malik, A., & Arora, G. 2019) investigated the application of ATR-FTIR in detecting detergent adulteration in milk. Their research demonstrated that ATR-FTIR could identify even trace amounts of detergent through characteristic spectral features, providing a rapid and non-destructive method for quality control in the dairy industry.

(El-Din et al.,2020) examined ATR-FTIR's effectiveness in detecting chemical contaminants in dairy products, including pesticides and antibiotics. Their findings highlighted ATR-FTIR's sensitivity in identifying these contaminants at concentrations relevant to regulatory limits, underscoring its potential application in food safety monitoring.

3.2 Coffee

The global market values coffee as one of its most valuable agricultural commodities but it battles extensive adulteration issues(Jha et al., 2015). Several compounds like cereals and chicory and corn and barley together with various fillers which lower production expenses also degrade product quality while possibly creating health risks(Craig et al., 2012). The spectral characteristics of different adulterants enable ATR-FTIR to precisely recognize them (Figure 1).

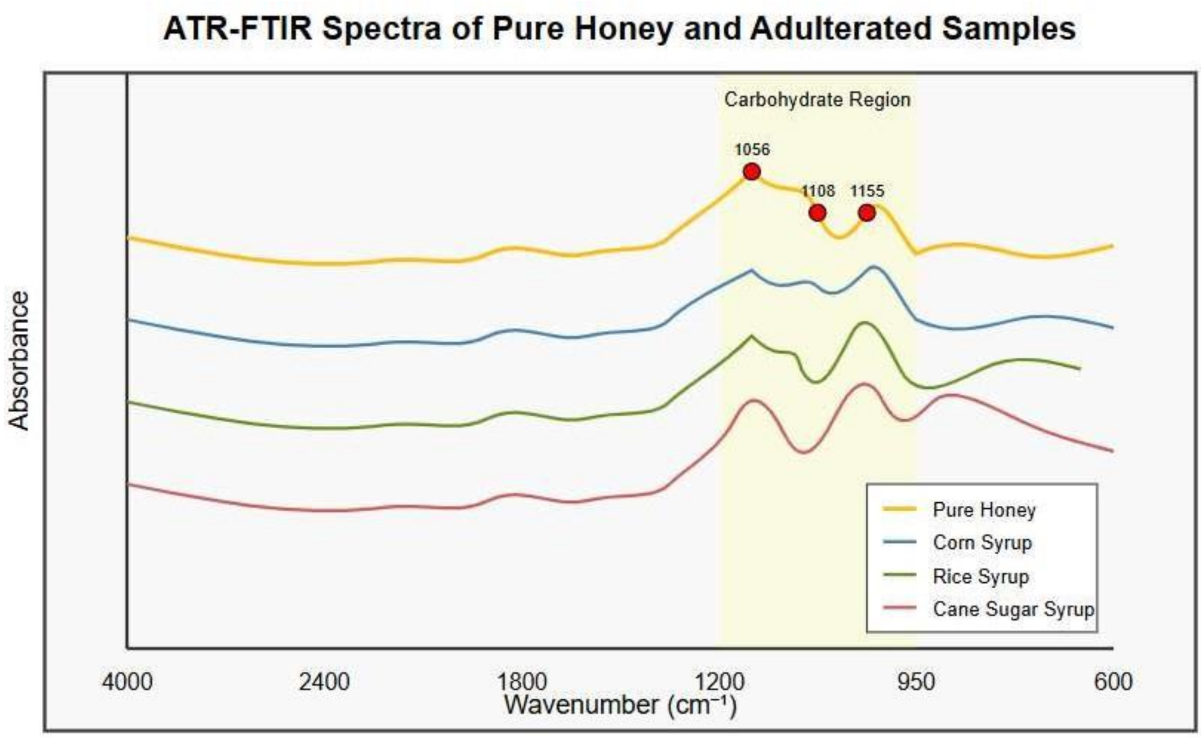


ATR-FTIR spectroscopy operated with chemometric analysis allowed (Rodriguez et al.,2018) to determine chicory adulteration in coffee testing samples. Researchers identified two distinct spectral bands (1050-1150 cm^{-1} and 1590-1630 cm^{-1}) which distinctly distinguished adulterated and pure coffee samples. The analytical method produced minimum detection capability of 5% for determining chicory mixtures in coffee samples.

ATR-FTIR analysis was used by (Craig et al.,2018) to identify cereal-based contaminants in ground coffee products. According to their research this method upheld its competence to separate pure coffee from contaminated samples using distinct spectral markers which appeared within the fingerprint region (1200-900 cm^{-1}).

3.3 Honey

The addition of sugar syrups from corn and rice and sugar cane to honey products has become a major manufacturing problem throughout the international food industry(Yang et al., 2021). ATR-FTIR operates as a reliable assessment method that reveals spectral markers to identify authentic honey from adulterated specimens (Figure 2).



Through their research (Yang et al., 2021) proved that ATR-FTIR can detect adulteration of honey using various sugar syrups. ANOES researchers maintained spectroscopic identification differences between unadulterated honey and contaminated products in the region that contains carbohydrate signature (950-1200 cm^{-1}). This detection method showed capability to detect sugar syrup adulteration down to 7% levels.

ATR-FTIR technology linked with multivariate analysis methods allowed researchers from (Torkashvand et al.,2020) to detect adulterated honey samples in their study. According to their findings ATR-FTIR produced spectral signatures which distinguished pure honey from samples containing different types of sugar syrup additives for authenticating honey quickly and dependably.

3.4 Ghee

Ghee (clarified butter) exists as a premium dairy product which experiences frequent dilution with less expensive animal fats as well as vegetable oils(Koca et al., 2010). The detection of adulterated ghee with cheapest vegetable oils and animal fats becomes feasible through ATR-FTIR because the instrument can identify specific spectral signatures (Table 2).

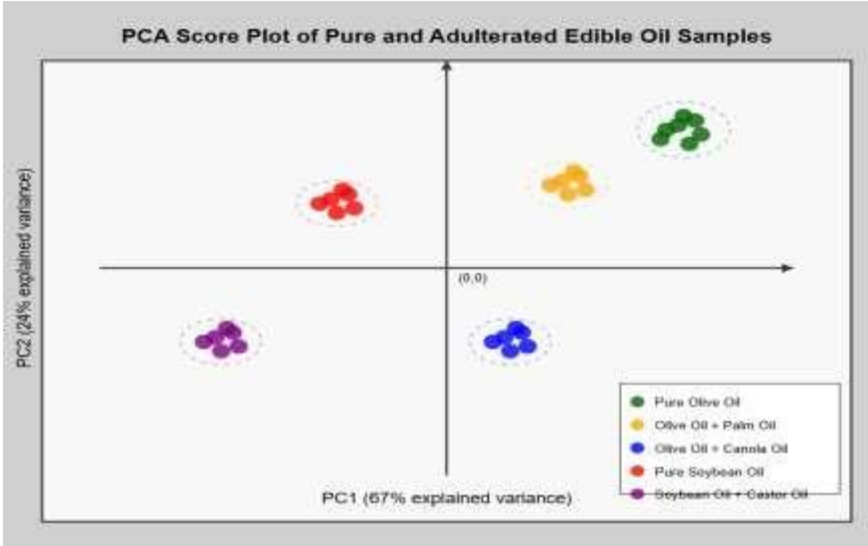
Table 2: Common Ghee Adulterants and Their Characteristic ATR-FTIR Spectral Markers

Adulterant	Characteristic Spectral Markers (cm^{-1})	Detection Limit
Vegetable oils	3008-3010 (=C-H stretching), 1650-1655 (C=C stretching)	5-10% w/w
Animal fats	1740-1745 (C=O stretching), 1160-1170 (C-O stretching)	7-12% w/w
Hydrogenated fats	965-975 (trans C=C bending)	3-8% w/w
Mineral oils	720-725 (CH_2 rocking), 1375-1380 (CH_3 bending)	1-3% w/w
Palm oil	1120-1140 (C-O stretching), 3006-3008 (=C-H stretching)	8-15% w/w

(Sharma et al., 2016) employed ATR-FTIR for identifying vegetable oil adulteration in ghee samples. The research team found distinct spectral domains through which they could distinguish pure ghee from adulterated products especially within fatty acid regions that lack unsaturation. This method detected vegetable oil adulteration down to a level of 5%.

(Nurrulhidayah et al.,2014) used ATR-FTIR with chemometric analysis for detecting hydrogenated fat adulteration in ghee products. The research confirmed how the method could identify pure ghee from adulterated samples by measuring different spectral markers present in regions containing trans-fatty acid details.

3.5 Edible Oils The practice of adulterating edible oil stands as a leading economic and health-related concern across the global sphere(Wang et al., 2019). Two major types of adulterants found in edible oils include cheaper oils and processed fats and non-edible oils(Wang et al.,2019). ATR-FTIR has established itself as an important method for edible oil authentication because it reveals specific spectral patterns that identify authentic from adulterated samples (Figure 3).



(Wang et al.,2019) studied how ATR-FTIR technology could determine castor oil contamination in soybean oil. The study showed that small amounts of castor oil detection becomes possible through ATR-FTIR by identifying distinct spectral characteristics in the fingerprint region between 1500-900 cm^{-1}. The analytical method succeeded in detecting 2% of castor oil when hidden within other oil samples.

The team of (Jiménez-Carvelo et al.,2019) used ATR-FTIR together with multivariate analysis to detect when olive oil got mixed with various vegetable oils. ATR-FTIR analysis showed clear spectral patterns between pure olive oil and adulterated tests that mainly appeared in areas representing unsaturated fatty acids (3008-3010 cm^{-1}) together with triglyceride composition (1750-1740 cm^{-1}).

4. Comparative Analysis of ATR-FTIR with Traditional Detection Methods

ATR-FTIR's ability to detect food adulteration obtains evaluation by comparing to conventional methods across multiple aspects which include sensitivity and specificity together with time duration and price points and expertise needs and destructiveness of the analysis (Table 3).

Table 3: Comparative Analysis of ATR-FTIR with Traditional Detection Methods for Food Adulteration

Parameter	ATR-FTIR	Chemical Testing	Chromatography	Sensory Analysis	PCR-Based Methods
Sensitivity	Moderate to High	Moderate	Very High	Low	Very High
Specificity	High	Moderate	Very High	Low	Very High
Time Required	Minutes	Hours	Hours to Days	Minutes	Hours to Days
Sample Preparation	Minimal	Extensive	Extensive	None	Extensive
Destructive Nature	Non-destructive	Destructive	Destructive	Non-destructive	Destructive
Expertise Required	Moderate	High	Very High	High	Very High
Cost per Analysis	Low	Moderate	High	Low	Very High
Portability	High	Low	Very Low	High	Very Low
Multiple Adulterant Detection	Yes	Limited	Yes	Limited	Limited

Quantification Capability	Moderate	High	Very High	Low	Moderate

The existing chemical testing combined with chromatographic methods yields enhanced sensitivity and specificity although they need large amounts of preliminary preparation together with expert personnel and prolonged analysis periods(Jindal et al., 2016). The rapid ATR-FTIR analysis offers minimal preparation needs and non-destructive testing which detects most adulterants reliably and gives result promptly(Saini et al., 2015).

When ATR-FTIR operates with chemometric approaches the detection capabilities increase dramatically because it now brings improved ability to distinguish authentic from adulterated items and to measure concentrations of adulterants precisely(Borras e al., 2015). The combined method fills the gap between standard testing procedures and quick screening methods to provide suitable solutions for food adulteration detection.

5. Forensic Applications of ATR-FTIR in Food Authentication

ATR-FTIR offers food authentication capabilities which advance beyond regular quality control into various regulatory matters and legal disputes and food fraud criminal proceedings (Ellis et al., 2013). The following forensic relevant features stand out:

5.1 Evidentiary Value

The information gathered through ATR-FTIR acts as legitimate scientific data which stands firm against legal examination(Karoui, R., & De Baerdemaeker, J.2007). The analytical data operates as a specific chemical signature of the food substance to detect alimentary adulterants and contaminants accurately. The data collected by ATR-FTIR serves as essential proof which stands up perfectly well in legal cases dealing with food fraud and consumer protection.

5.2 Chain of Custody and Sample Integrity

ATR-FTIR operates non-destructively thus maintaining sample integrity so further analytical methods can be used when needed according to (Malik, A., & Arora, G. 2019). This capability enables reliable forensic work since forensic investigation needs to prioritize both evidence preservation and chain of custody protection.

5.3 Database Development and Reference Standards

The advancement of spectra databases consisting of authentic food items and popular adulterant samples strengthens ATR-FTIR's role in food investigations (McGrath et al., 2018). The databases function as reference tools for assessing suspect samples which facilitates prompt detection of adulterated products.

5.4 Integration with Regulatory Frameworks

ATR-FTIR holds great potential to enhance regulatory frameworks for food safety and authentication that fight against food fraud (Malik, A., & Arora, G. 2019). The technique works at high speeds with non-destructive features to become suitable for standard food examination programs and special enforcement tasks performed by regulatory organizations.

6. Challenges and Future Perspectives

Despite its numerous advantages, ATR-FTIR faces several challenges in food adulteration detection that merit consideration (Table 4):

Table 4: Challenges in ATR-FTIR Application for Food Adulteration Detection and Potential Solutions

Challenge	Description	Potential Solutions
Detection limits	May not detect trace amounts of certain adulterants	Coupling with preconcentration techniques; Advanced chemometrics
Complex matrices	Food matrices with multiple components can complicate analysis	Development of specialized algorithms; Sample pre-processing
Spectral overlap	Similar chemical groups in adulterants and authentic products	Multivariate statistical approaches; Derivative spectroscopy
Quantification accuracy	Challenges in precise quantification of adulterants	Improved calibration models; Machine learning approaches
Standardization	Lack of standardized protocols across laboratories	Development of international standards; Collaborative studies

Research on ATR-FTIR application for food adulteration detection should move in these directions:

1. Scientists must develop compact ATR-FTIR systems that users can operate in the field for carrying out on-site analyses and preliminary screenings of food throughout the distribution chain (Katz, L., & Fisher, K. 2019).

2. ATR-FTIR receives enhanced sensitivity and quantitative capabilities through advanced chemometrics technology that couples natural intelligence algorithms to reach improved specificity measures(Borras et al., 2015).

3. Spectral libraries with authentic products and contaminants need establishment as comprehensive standardized datasets to support fast food identity and authenticity verification (McGrath et al.,2018).

4. ATR-FTIR systems benefit from multi-technique analysis methods which integrate additional analytical methods for better detection and limitation avoidance(Callao, M. P., & Ruisánchez, I. (2018)..

5. Companies can establish immutable food authentication records through blockchain integration which combines tests using ATR-FTIR with supply chain tracking(Galvez et al., 2018).

7. Conclusion

ATR-FTIR spectroscopy serves as an effective technology for revealing food adulteration in milk alongside coffee products and honey along with ghee and edible oils. This analytical method provides maximum benefit to food quality control and forensic investigations through its non-destructive operation and simple requirements for sample preparation as well as fast detection speed and simultaneous ability to identify multiple contaminants.

FTIR spectroscopy produces accurate results for multiple food product contaminant assessments which include the detection of water together with detergents in milk and sugar syrups in honey and vegetable oils in ghee and cheaper oils in premium edible oils. Chemometric methods boost its operational effectiveness by providing superior means to distinguish original vs unauthorized products.

The forensic application of ATR-FTIR provides multiple benefits including automatic evidence generation while protecting sample wholesomeness and regulatory framework compatibility. Its capabilities aid both standard quality control work and legal examinations linked to food fraud and consumer protection.

The detection limits and complex sample compositions along with standardization issues continue to present difficulties but technological progress continues to expand ATR-FTIR system capabilities. The fight against food fraud will gain strength through future portable technology developments and advancements in chemometric capabilities and spectral database accuracy plus multi-method analysis techniques.

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