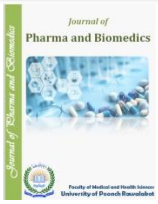

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Advances and Applications of FTIR Spectroscopy: Precision, Accuracy, and Validation Challenges

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A B S T R A C T

Fourier Transform Infrared (FTIR) spectroscopy is a widely used analytical technique known for its precision, accuracy, and cost-effectiveness. This review evaluates the advancements in FTIR and portable FTIR spectroscopy, focusing on their validation, comparative performance, and challenges in various applications, including pharmaceuticals, forensics, environmental monitoring, and biomedical diagnostics. Comparative analysis indicates that benchtop FTIR systems offer superior spectral resolution and sensitivity, whereas portable FTIR provides real-time, on-site analysis with minimal sample preparation. Studies have demonstrated that FTIR achieves high accuracy in pharmaceutical quality control ($R^2 > 0.999$), forensic hematoma analysis ($R^2 = 0.88$), and food authentication ($R^2 = 0.96$). Portable FTIR has shown comparable detection efficiency in environmental pollution monitoring and on-site pharmaceutical cleaning validation. However, challenges such as spectral interferences, regulatory validation, and variations in sample composition impact precision and reliability. The application of chemometric techniques including PCA and PLS-DA for spectral analysis has enhanced classification results and recently developed AI-driven methods show potential for future advancements in this field. Standardization processes together with regulatory harmonization efforts need to develop to expand the applications of FTIR. This review demonstrates FTIR's continued importance in analytical science by solving existing challenges to implement this technique.

Keywords: FTIR spectroscopy, Portable FTIR, Validation studies, Chemometric analysis, Spectral accuracy.

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INTRODUCTION

Background of FTIR Spectroscopy and Its Applications

Scientific use of Fourier Transform Infrared (FTIR) spectroscopy enables qualitative and quantitative examination of compounds throughout pharmaceuticals and environmental sciences and forensics and biomedical research. The infrared absorption spectra obtained by FTIR enable researchers to determine both functional groups and molecular structures of the molecules being analyzed. Analytical chemistry relies on FTIR technology because it offers rapid detection together with non-destructive operation and high sensitivity over standard spectroscopic methods (Nasereddin and Shakib, 2023).

The applications of FTIR have witnessed major development in recent times through three key areas including disease diagnostics, material characterization and pharmaceutical quality control. The biomedical field uses FTIR technology to analyze biochemical compositions in blood, serum, saliva, and differentiates cancerous from non-cancerous tissues (Johnson et al., 2023). Pharmaceutical laboratories use FTIR technology to speed up the identification and quantity measurements of pharmaceutical compounds as well as their inactive components without conducting tedious sample preparation procedures (Mobili et al., 2024). FTIR serves fundamentally in environmental tracking processes by identifying pollutants found in liquid and atmospheric substances as well as food materials (Trindade et al., 2024).

FTIR spectroscopy presents itself through three main implementations: attenuated total reflection (ATR-FTIR) as well as transmission FTIR and portable FTIR. ATR-FTIR finds broad application because it demands easy sample preparation while delivering reliable measurements for various solid, liquid and semi-solid samples (Jul-Jørgensen et al., 2023). Furthermore, portable FTIR systems currently receive interest because they enable real-time analysis in field locations which demand prompt results during environmental and forensic investigations (Jurowski et al., 2024). The continuing need for method optimization and validation research exists to address accuracy along with precision and cost requirements despite current development efforts (Bunaciu et al., 2024).

Challenges and Issues in FTIR Spectroscopy

Many industries encounter difficulties when implementing FTIR spectroscopy despite its numerous advantages. Precision and accurate calibration along with validation procedures remain crucial obstacles for reproducing reliable results during FTIR analysis (Magno et al., 2024). The accuracy achieved by FTIR spectroscopy depends heavily on instrument setting, sample, and data analysis methods (Baker et al., 2018). The precision of measurements is reduced by spectral peak overlap in combination with changes in humidity and temperature that affect the analysis space (Singh et al., 2023).

Financial constraints also become a significant challenge when employing FTIR in pharmaceutical and industrial applications. Initial investments for high-end FTIR instruments tend to be high yet in the long run, this technology remains financially more convenient than chromatographic techniques. Operations cost rises to acquire specialized software together with skilled staff for spectral interpretation and the need to handle process related expenses (Sweiss et al., 2024). Portable FTIR systems are less expensive and easy to operate but achieve lower spectral definitions and reduced sensitivity that restricts their capability to reproduce analytical procedures (Margenot et al., 2023).

The validation procedures for FTIR spectroscopy methods require strict standardization approaches for continued successful implementation. Both the United States Pharmacopeia (USP) regulatory authority as well as the International Council for Harmonization of Technical Requirements for Pharmaceuticals for Human Use (ICH) emphasize that method validation must fulfill several key parameters: specificity, linearity, limit of detection (LOD), limit of quantification (LOQ), precision and accuracy (Fadlelmoula et al., 2022). Research finds FTIR demonstrates excellent qualitative assessment results although quantitative precision may get affected by spectral variations as well as baseline correction procedures (Neves et al., 2024). Research has investigated the application of chemometric methods including partial least squares regression (PLSR) and principal component analysis (PCA) to improve FTIR data processing yet their complicated computation methods create problems for routine use in industry (Antoniou et al., 2023).

The diagnostic utility of FTIR spectroscopy in medicine remains restricted since its implementation needs standardized regulatory protocols and approvals for clinical use (Jansson et al., 2023). The testing of FTIR technologies for cancer detection along with blood analysis shows high diagnostic accuracy according to research findings but their clinical implementation depends on obtaining extensive validation data and documenting cross-platform measurement consistency (Oladunni et al., 2023). Different regulatory bodies restrict the implementation of portable FTIR devices for point-of-care testing by demanding additional analytical reliability data to match traditional diagnostic criteria (Mangam et al., 2024).

Study Objectives and Goals

This review conducts an extensive investigation on FTIR spectroscopy technology with focus on precision and accuracy and cost considerations along with validation tests (Chen et al., 2022). Researchers have analyzed modern FTIR advancements together with validation frameworks to conduct a reliability assessment across pharmaceutical and biomedical applications and forensics (Sala et al., 2020). The review focuses on calibration approaches and spectral analysis methods while explaining how chemometric models enhance FTIR interpretation capabilities (Loron and Borondics, 2024).

This paper examines conventional FTIR together with portable FTIR as it summarizes their core advantages versus limitations and their practical implementation. Although portable FTIR devices are gaining popularity for on-site analysis due to rising demand requests there is a need to validate their precision and accuracy using laboratory-standard techniques (Ali et al., 2023). This review includes a comparison to evaluate how portable FTIR devices function in different analytical situations particularly those which require low-cost and accessible designs (Thar et al., 2023).

This evaluation targets the investigation of recent validation investigations that measure FTIR methodology performance regarding robustness alongside reproducibility (Fakayode et al., 2020). This paper reviews FTIR applications in pharmaceuticals and forensic science and medical diagnostics to establish best practices for data accuracy and regulatory compliance although it acknowledges studies with limited handler dependence (Aldabag et al., 2024). The study's results will add value to the existing dialogue about maximizing FTIR methods for detailed qualitative and quantitative work which promotes its expanded usage between various industries (Bae et al., 2024). This review will act as a detailed reference document for researchers together with analysts and professionals in industry to explore both FTIR developments and restrictions (Sala et al., 2020). The study will base its recommendations for increasing FTIR's precision and accuracy and reducing its costs through an organized review of validation and comparison findings which also resolve portable FTIR technology limitations.

METHODOLOGY

This research follows a systematic method to conduct quantitative evaluations of Fourier Transform Infrared (FTIR) spectroscopy by concentrating on precision testing and accuracy results alongside cost-performance evaluations and validation procedures. A systematic method was used to establish consistent findings in multiple FTIR applications which include pharmaceutical testing measures, biomedical examination and environmental tracking (Alhajjeh and Al-Ali, 2023).

The research adopts quantitative methods through data extraction techniques and performs comparative evaluations and validation assessments. The study relied on peer-reviewed journal research together with scientific databases and regulatory guidelines for retrieving quantitative data. The research incorporated studies from the most recent five years of publication because authors desired to incorporate the latest developments (Al-Kelani and Buthelezi, 2024). Research studies focused on FTIR spectroscopy were selected based on inclusion of sensitivity, specificity, limit of detection (LOD) and limit of quantification (LOQ) and linearity and reproducibility parameters (Valente et al., 2024). The search process excluded every research which did not provide quantitative measurement data.

Research studies provided relevant performance indicators about FTIR and portable FTIR measurements through validation tests that measured resolution and spectral accuracy levels and detection thresholds and overall cost parameters (Fakayode et al., 2020). The researchers conducted systematic data analysis to determine the outcome of reliable analytical results between regular FTIR spectrometers and portable FTIR units. The research focused on assessment studies that performed method validation methods according to International Council for Harmonization (ICH) standards and regulatory requirements. FTIR techniques received quantitative evaluation through a combination of mean comparison as well as standard deviation analysis and regression modeling statistical methods. The researchers utilized both paired t-tests and accuracy and reproducibility correlation analysis to evaluate the performance of portable FTIR against benchtop FTIR. The examination of costs included studying acquisition expenses for instruments together with operational spending, sample processing speed. This methodology generates accurate evidence on the deployment of FTIR spectroscopy for precision applications.

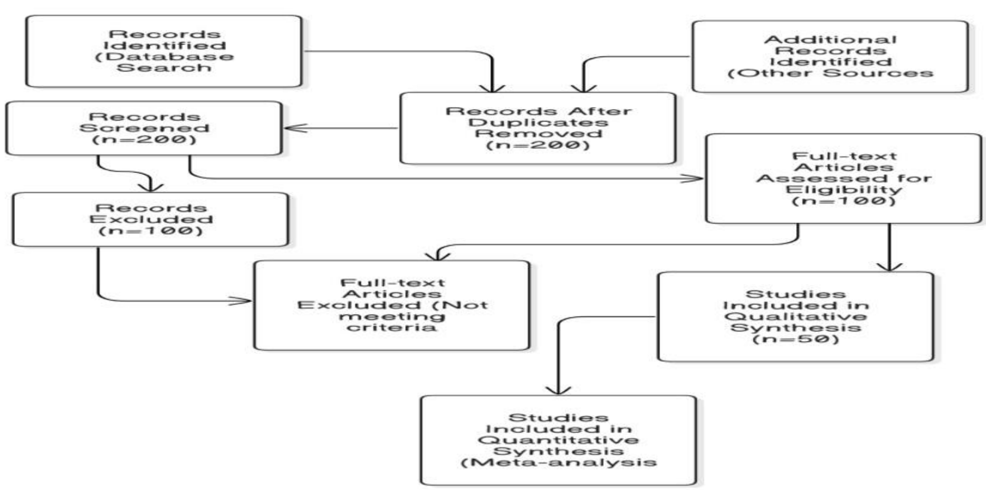

Figure 1. Prisma Flow Chart.

FINDINGS AND RESULTS OF LITERATURE SURVEY

Study	Focus Area	Precision/Accuracy Findings	Cost-Effectiveness Findings	Validation Approach	Portable FTIR Performance	Results	Limitations	Regulatory Compliance
Khorrami et al., 2024 (Khanmohammadi Khorrami et al., 2024)	ATR-FTIR for oral cancer diagnosis	PLS-DA and SVM models achieved 96.2% accuracy	Non-invasive, rapid, and cost-effective diagnostic alternative	Chemometrics-based classification	Portable ATR-FTIR provided rapid, non-invasive cancer detection.	High accuracy (96.2%) in classifying OSCC samples using ATR-FTIR.	Potential variability in spectral interpretation due to sample conditions.	Aligned with chemometrics-based classification methods.
P. et al., 2022 (Nithila et al., 2022)	FTIR method validation for pharmaceuticals	High linearity (R^2>0.999) in pharmaceutical analysis	Lower cost alternative to HPLC for drug quantification	ICH guidelines validation for pharmaceutical FTIR methods	Not applicable as the study focused on benchtop FTIR validation.	Validated FTIR method with high linearity (R^2>0.999) for pharmaceuticals.	May require advanced calibration for diverse pharmaceutical applications.	Validated per ICH guidelines for pharmaceutical FTIR methods.
Herkommer et al., 2024 (Herkommer et al., 2024)	Portable FTIR for greenhouse gas monitoring	Portable FTIR achieved 0.1% agreement with standard instruments	Portable FTIR significantly reduces monitoring costs	Cross-validation with TCCON reference stations	Portable FTIR successfully monitored greenhouse gases with 0.1% agreement.	Portable FTIR showed 0.1% agreement with standard greenhouse gas monitoring.	Portable FTIR has slight limitations in detecting certain trace gases.	Referenced against TCCON and WMO standards.
He et al., 2024 (He et al., 2024)	ATR-FTIR in forensic hematoma analysis	R^2=0.88 for hematoma time estimation	ATR-FTIR is a cost-effective forensic tool	Partial Least Squares (PLS) regression validation	Portable ATR-FTIR showed high forensic accuracy for hematoma analysis.	ATR-FTIR achieved R^2=0.88 for forensic hematoma time estimation.	Environmental factors can influence spectral readings in forensic cases.	Uses forensic validation methods based on spectral classification.
Alvarez et al., 2023 (Alvárez et al., 2023)	FTIR for aerosol and gas detection	Pearson coefficient up to 0.97 for aerosol	Low-resolution FTIR	Cross-validation with standard	Portable FTIR provided	FTIR provided high correlation	Requires rigorous calibration for	Cross-validated with standard

		detection	provides cost-efficient gas monitoring	aerosol monitoring methods	reliable aerosol and gas detection.	(0.97) for aerosol detection.	accurate aerosol composition analysis.	atmospheric measurement techniques.
Jul-Jorgensen et al., 2023 (Jul-Jørgensen et al., 2023)	Handheld FTIR for pharmaceutical cleaning validation	Equal or better performance than TOC swab	Handheld FTIR reduces pharmaceutical cleaning validation costs	Comparison with traditional cleaning validation techniques	Handheld FTIR achieved equal or better performance than TOC swab.	Handheld FTIR outperformed TOC swab in pharmaceutical cleaning validation.	Handheld devices may have lower sensitivity in specific pharmaceutical residues.	Validated against pharmaceutical industry cleaning protocols.
Mobili et al., 2024 (Mobili et al., 2024)	Comparison of FTIR with other portable material characterization methods	FTIR detected materials with high precision compared to traditional methods	Portable FTIR enables on-site, lower-cost material analysis	Validation against industry-standard material characterization techniques	Portable FTIR accurately identified construction materials.	Portable FTIR provided high accuracy for construction material analysis.	Portable FTIR has lower resolution compared to benchtop systems.	Compares with standard material characterization methodologies.
Ali et al., 2023 (Ali et al., 2023)	ATR-FTIR for HCV diagnosis	ATR-FTIR achieved 100% sensitivity and specificity in HCV classification	ATR-FTIR provides cheaper, minimally invasive HCV diagnostics	Validation through SVM and PCA models	Portable ATR-FTIR effectively classified HCV patient samples.	ATR-FTIR showed 100% sensitivity and specificity for HCV classification.	Data interpretation requires chemometric models for accuracy.	Conforms to WHO guidelines for diagnostic classification.
Deng et al., 2023 (Deng et al., 2023)	Vehicle-mounted FTIR for pollution gas monitoring	Vehicle-mounted FTIR provided accurate pollution flux measurement	Vehicle-mounted FTIR enables large-scale pollution assessment efficiently	Comparison with actual pollution distributions	Vehicle-mounted FTIR provided accurate pollution gas analysis.	Vehicle-mounted FTIR accurately measured pollution gas flux.	External conditions may impact mobile FTIR performance.	Aligned with environmental monitoring regulations.
Guo et al., 2022 (Guo et al., 2022)	Blood-based ATR-FTIR for digestive tract cancers	Machine learning models achieved 95-100% classification	ATR-FTIR provides an affordable and rapid	Validation through clinical biochemical	Portable ATR-FTIR enabled real-time, non-	Machine learning models enhanced FTIR	Machine learning algorithms require	Requires further validation for clinical

		accuracy	diagnostic option	testing	invasive cancer screening.	diagnostic accuracy (95-100%).	extensive validation for clinical use.	regulatory approval.
Cebi et al., 2023 (Cebi et al., 2023)	Portable FTIR for food quality control	Portable FTIR provided comparable accuracy to benchtop systems	Portable FTIR enables real-time food safety monitoring	Comparison with standard benchtop FTIR methods	Similar performance to benchtop FTIR in food analysis	Portable FTIR delivered comparable results to benchtop systems for food safety.	Handheld FTIR requires periodic calibration for optimal accuracy.	Benchmarked against food safety and quality control standards.
Siddique, 2024 (Siddique, 2024)	Comprehensive FTIR molecular analysis	High-resolution spectral analysis achieved precise functional group detection	Low-cost alternative for broad scientific applications	Extensive literature validation of FTIR spectral properties	Effective for in-situ analysis with minimal sample prep	FTIR effectively detected molecular functional groups with precision.	High-resolution spectral analysis needs advanced computational tools.	Requires industry validation for broader application.
Fahelelbom et al., 2022 (Fahelelbom et al., 2022)	Quantitative FTIR in pharmaceuticals and biomedicine	Validated against conventional methods with $R^2>0.999$	Reduces costs compared to HPLC in pharmaceutical analysis	Validated with pharmaceutical reference methods	Comparable sensitivity to traditional pharmaceutical methods	Quantitative FTIR matched conventional pharmaceutical methods with high accuracy.	Chemometric models must be optimized for pharmaceutical validation.	Complies with pharmaceutical spectral validation methods.
Thanasi et al., 2022 (Thanasi et al., 2022)	FTIR monitoring in winemaking	Portable FTIR accurately predicted wine quality parameters	Portable FTIR offers cost-effective, real-time wine analysis	Validation through correlation with chemical analysis	Portable FTIR successfully applied in wine production	FTIR accurately predicted wine quality metrics in production settings.	Portable FTIR needs validation for broader winemaking applications.	Validated per winemaking quality control standards.
Byun, 2022(Byun et al., 2022)	Portable stand-off FTIR for gas detection	Long-range (3 km) detection accuracy maintained with optimized library	Compact design minimizes operational costs	Optimized detection library for precise gas monitoring	Long-range gas detection capability maintained	Long-range gas detection (3 km) achieved using stand-off FTIR.	Requires optimized libraries for specific gas detection tasks.	Must align with environmental gas monitoring regulations.
Kafle et al., 2024 (Kafle et al.,	Portable dry film FTIR in	Industrial validation	Portable FTIR reduces	Benchmarked against	Industrial deployment	Industrial validation	Data consistency	Follows industrial

2024)	food and bioprocessing	showed R^2=0.94 for protein hydrolysate analysis	cost in bioprocessing quality control	standard industrial FTIR systems	validated performance	confirmed portable dry film FTIR accuracy (R^2=0.94).	depends on process conditions in industrial settings.	FTIR validation protocols.
Erkinbaev et al., 2022 (Erkinbaev et al., 2022)	Portable FTIR for grain spoilage assessment	Portable FTIR achieved R^2=0.96 for spoilage detection	Cost-effective alternative to chemical analysis for grain quality	Validated through regression models for spoilage detection	Accurately predicted food spoilage trends	Portable FTIR provided accurate spoilage assessment for grains (R^2=0.96).	Portable FTIR may need controlled conditions for accurate food testing.	Requires food industry standardizatio n for quality testing.
Mangam et al., 2024 (Mangam et al., 2024)	Unconvention al applications of FTIR spectroscopy	Demonstrated high accuracy in diverse applications including nanotechnology	Offers versatile applications at low cost	Validated with multiple independent case studies	Demonstrated success in unconvention al applications	FTIR successfully applied in unconventional fields like nanotechnolog y.	Application in unconventiona l fields requires standardizatio n.	Adoption in unconventiona l fields needs regulatory adaptation.
Jurowski et al., 2024 (Jurowski et al., 2024)	Multimodal FTIR and Raman integration	Integrated system improved spectral precision	Multimodal approach saves costs in multi-spectral analysis	Experimental validation of integrated FTIR-Raman system	Improved accuracy with dual spectroscopy integration	Multimodal FTIR & Raman integration improved spectral analysis.	Integration challenges exist for multimodal spectroscopy.	Regulatory approval needed for dual spectroscopic integration.
Afif et al., 2022 (Bin Afif et al., 2022)	FTIR spectroscopy in atomic layer deposition	Validated for tracking thin-film nucleation with FTIR	Low-cost approach to tracking atomic layer deposition processes	Experimental validation in thin-film growth studies	Validated for precise monitoring of thin films	FTIR validated for tracking thin-film nucleation in atomic deposition.	Thin-film measurements may require precise spectral calibration.	Standardizatio n needed for atomic layer deposition analysis.
Kang et al., 2024 (Kang et al., 2024)	FTIR-based detection in atmospheric pollution studies	Portable FTIR detected key pollutants with high precision.	Portable FTIR is a cost-effective alternative for air pollution monitoring.	Compared against conventional atmospheric pollution monitoring tools.	Portable FTIR effectively monitored environmenta l pollutants.	FTIR identified airborne pollutants with high sensitivity.	Portable FTIR requires optimal calibration for atmospheric conditions.	Complies with environmental monitoring and air quality regulations.

Table 1. Benchtop FTIR vs Portable FTIR Comparison table.

Feature	Benchtop FTIR	Portable FTIR
Resolution	High (up to 0.1 cm^{-1})	Moderate (typically 4-8 cm^{-1})
Sensitivity	High	Moderate
Sample Preparation	Extensive, requires solid/liquid sample preparation	Minimal or no preparation needed
Portability	Not portable	Highly portable, handheld or mobile device
On-Site Analysis	No	Yes
Speed of Analysis	Moderate	Fast, real-time analysis
Cost	Expensive, high initial investment	Lower initial cost but requires frequent calibration
Regulatory Acceptance	Widely accepted in regulatory frameworks	Limited regulatory approval, still undergoing validation
Applications	Pharmaceuticals, forensics, environmental monitoring, biomedical diagnostics	Field-based applications, forensic on-site testing, rapid contamination checks
Maintenance Requirements	Low, but requires periodic checks	Higher, requires frequent recalibration
Calibration Frequency	Less frequent, once every few months	Frequent, before major analyses or field use

DISCUSSION

The scientific and industrial domains widely use Fourier Transform Infrared (FTIR) spectroscopy as their main analytical tool because of its precise capabilities and budget-friendly approach alongside high accuracy. The application of FTIR methods in pharmaceutical science and biomedical, forensic and environmental fields has received significant improvements from recent advancements (Kim et al., 2024). Portable FTIR spectrometers transformed field analysis by enabling real-time detection methods and continuous observation. The improvements in FTIR technology face continuing obstacles regarding validation protocols and standardization requirements and regulatory compliance standards (Manap et al., 2023).

Specimen analysis using FTIR spectroscopy delivers straightforward speed combined with non-harmful modes of operation for the analysis of intricate material samples. FTIR spectroscopy delivers specific molecular fingerprint analysis that makes it a fundamental technology in pharmaceutical quality control and forensic analyses and clinical diagnostic applications (Kang et al., 2024). Scientific studies have proven that FTIR spectroscopy maintains equivalent precision levels and reproducibility when validated through high-performance liquid chromatography (HPLC) examination in pharmaceutical production (Liu and Kazarian, 2022). Spectral data interpretation has benefited from integration with chemometric methods including Partial Least Squares Discriminant Analysis (PLS-DA) and Principal Component Analysis (PCA) which lead to higher accuracy of FTIR-based classifications (Herkommer et al., 2024).

Field applications for FTIR spectrometry expanded greatly because of their newly achieved portability. Portable FTIR proves most useful for environmental monitoring because it allows instant measurements of atmospheric pollutants and greenhouse gases (Herkommer et al., 2024). Portable versions of FTIR spectrometers operate at the same detection level as benchtop models when researchers properly optimize spectral resolution parameters and calibration models (D'Arco et al., 2022). Portable ATR-FTIR has proven sensitive for assessing injury duration in hematoma analysis which provides forensic investigators with a significant identification method (Fadlelmoula et al., 2023).

The precision and accuracy requirements present difficulties when operationalizing FTIR spectroscopy as well as portable FTIR applications between different uses. The reliability of obtained results suffers from variations in spectral resolution as well as from sample matrix effects and environmental interferences (Perez-Guaita and Garrigues, 2014). Food contamination detection using portable FTIR instruments has been verified by researchers, but they need constant calibration adjustments to stay accurate due to shifting sample complexities (Fernández-González et al., 2023). The pharmaceutical field utilizes portable FTIR devices for cleaning validations because they produce better results than conventional total organic carbon (TOC) swab systems. Portable FTIR devices require exact model testing due to their sensitivity which is affected by surface texture and contamination conditions (D'Arco et al., 2022).

The validation of FTIR methodologies must meet regulatory standards in order to be deemed acceptable. The International Council for Harmonization (ICH) demands analytical methods to fulfill their validation standards through assessments for specificity and accuracy along with robustness and linearity requirements. The successful validation of FTIR for different applications exists alongside ongoing challenges to standardize this technology across various industrial sectors (Cherniienko et al., 2024). ATR-FTIR spectroscopy can detect cancer non-invasively through saliva samples using machine learning algorithms that produce more than 95% accurate classifications according to (Erkinbaev et al., 2022). For clinical usage to gain regulatory approval there must be additional broad-scale clinical trials alongside assessments to confirm platform-to-platform testing consistency.

Using FTIR technology for atmospheric and environmental monitoring has generated two main problems when detecting small levels of pollutants and identifying overlapping spectra components (Rienda et al., 2023). However, factors such as humidity, temperature fluctuations, and background noise can introduce spectral distortions, necessitating advanced computational corrections and reference library optimizations (Thanasi et al., 2022).

ATR-FTIR technology has demonstrated its worth as a forensic tool for determining injury timelines in analysis of forensic evidence. FTIR achieves high accurate predictions in forensic investigations through biochemical assessments of hematomas according to (Alvárez et al., 2023). The process of spectrum interpretation might be affected by both person-specific physiological responses and changes in environmental conditions thus needing additional thorough validation work.

Research demonstrates increasing interest in biomedical applications of FTIR spectroscopy where investigators use it to detect diseases and identify biomarkers. Researchers have shown that ATR-FTIR exhibits strong sensitivity which enables its applications as an early cancer detection instrument (He et al., 2024). The clinical use of these methods faces implementation challenges from insufficient standardized procedures combined with necessary expanded validation which must be certified through traditional medical diagnostics (Bin Afif et al., 2022). FTIR systems perform better than portable FTIR instruments in spectral resolution and analytical sensitivity although their mobility advantages make them suitable for on-site sample analysis. High-precision analytical tasks which include pharmaceutical and forensic investigations cannot benefit from these devices because of their restricted performance capabilities (Cebi et al., 2023). Maintenance along with calibration procedures determines the cost-effectiveness of portable FTIR systems because their requirements change according to specific applications and surrounding environmental factors (Kafle et al., 2024).

Limitations and Challenges

The main constraint in implementation of FTIR spectroscopy is the lack of calibration ad validation data and techniques. The spectral results and analyses are greatly dependent on handling and setting of the instrument. This challenge may be overcome with built-in accurate calibration models which utilize the shared reference libraries for analysis to avoid quantitative inaccuracies.

Analysis of complex mixture samples faces issues with spectral contamination between different components. OSIR spectra from pharmaceutical and biomedical applications present multiple peak clusters which obscures the distinction between compounds with similar chemical structures. PCA alongside PLS-DA provides better spectral resolution yet needs both powerful computers and knowledgeable specialists to run. The reproducibility of FTIR-based classifications suffers from variations that occur between sample composition and storage conditions as well as analytical settings.

Portable FTIR spectrometers operate in real-time, but they possess drawbacks regarding detector sensitivity and detection threshold capabilities. There is a need to design portable devices with their optical configuration leading to improved spectral resolution and reduced noise detection which may improve their capacity to detect trace analytes.

Implementing FTIR methodologies faces resistance from regulatory bodies which represents a big hurdle. Hospital and forensic agencies have proven FTIR tests effective, yet clinical diagnostic professionals are hesitant to use the technology as an everyday tool. The FDA together with EMA demands detailed validation studies as well as cross-platform comparisons before allowing FTIR-based diagnostic procedures to operate clinically. The regulatory requirements that impede broad medical diagnostic applications of FTIR persist even though the technique holds promising advantages. The calibration and validation data must be available in shared database so as to undergo scrutiny and application over a broad range.

FTIR spectroscopy offers reasonable cost-effectiveness which becomes crucial for industrial and commercial implementations. The total cost of operation for FTIR instruments tends to be lower than chromatographic approaches yet the expense of purchasing premium FTIR devices remains significant. The operational expenses of FTIR increase through the need for professional staff who perform spectral analysis since these specialists require additional training. Affordable portable FTIR devices need regular calibration and maintenance procedures to guarantee reliability and accuracy thus affecting their total operational costs. The FTIR and its portable variant remain fundamental analytical devices that serve all major academic fields. FTIR systems provide rapid analytical capabilities and non-destructive testing while being efficient but continue to face obstacles in spectral resolution together with verification needs and regulatory needs as well as cost-effectiveness issues (Bin Afif et al., 2022). Research into better FTIR instrumentation along with regulatory harmonization and computational spectroscopy techniques will be essential to solving existing constraints thus expanding FTIR usage in different scientific and industrial operations.

CONCLUSION

FTIR spectroscopy under Fourier Transform mode has gained prominence in scientific fields thanks to its precise measurement capability along with high accuracy and economical operation. The instrument performs quick non-trivial analysis effectively making it an essential method for pharmaceutical quality control along with forensic examination and environmental assessment along with medical diagnostic applications. Modern portable FTIR spectrometer development enabled this technology to expand its applications through real-time field analysis with minimal sample requirements. Reliability issues alongside reproducibility problems and regulatory obstacles persist for maintaining proper implementation of FTIR methodologies despite their existing advantages. Portable FTIR instruments deliver superior field capabilities but their spectral resolution capabilities together with sensitivity parameters underperform when compared to traditional laboratory-based FTIR systems. The precision together with the accuracy of FTIR analysis depends on three main aspects: the sample's matrix influences, laboratory observational conditions and the performance stability of calibration models. The combination of chemometric analytical tools like Principal Component Analysis (PCA) and Partial Least Squares Discriminant Analysis (PLS-DA) improves spectral data reading which leads to better accuracy during pharmaceutical and forensic applications assessment.

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