

ADVANCES AND APPLICATIONS OF INFRARED SPECTROSCOPY IN CHEMICAL AND BIOLOGICAL ANALYSIS

**Kulsum Bano, Satish Sahu, Anand Gautam, Mohd. Sufiyan, Mohammad Taufeek,
Manish Kumar¹, Shubhankit Soni*², Alok kr Shukla³**

¹Research Scholar, ²Assistant Professor, ³Professor,

Babu Sundar Singh College of Pharmacy, Nigohan, Lucknow, Uttar Pradesh (226302).

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*Corresponding Author

Shubhankit Soni

Assistant Professor, Babu Sundar
Singh College of Pharmacy,
Nigohan, Lucknow, Uttar Pradesh
(226302).



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ABSTRACT

One of the most important analytical methods in pharmaceutical sciences and bio-related research is infrared (IR) spectroscopy. It is very useful for both qualitative identification and quantitative measurements because of its ability to record distinct molecular vibration patterns, which are frequently referred to as molecular fingerprints. Fourier Transform Infrared (FT-IR) spectroscopy has become increasingly important in many scientific fields as a result of advances in instrumentation. This study provides a more comprehensive overview of the expanding uses of infrared spectroscopy, highlighting its broad relevance in biological and clinical research as well as its contributions to pharmaceutical quality assurance. IR spectroscopy is widely utilized in the pharmaceutical sector as a trustworthy method for identifying both raw ingredients and completed medicinal products. Because each compound has a distinctive absorption spectra,

chemical identity, purity, and structural consistency may all be quickly confirmed. This is essential for upholding strict quality control standards and avoiding pharmaceutical ingredient adulteration or mislabeling. Measuring moisture content is a major use of infrared spectroscopy in the pharmaceutical industry. Accurate moisture assessment is crucial because moisture has a significant impact on the physical and chemical stability of dosage forms. IR-based techniques are better to time-consuming conventional procedures like loss-on-drying because they provide a quick, non-destructive, and accurate approach.

Additionally, the quantitative measurement of active pharmaceutical ingredients (APIs) is using IR spectroscopy more and more. Analysts can precisely ascertain the quantity of medication contained in tablets, capsules, powders, and other formulations by analyzing the relationship between absorbance intensity and concentration. This expertise helps with formulation optimization, stability research, and the creation of new dosage forms in addition to supporting regular quality monitoring.

IR spectroscopy is extremely useful in the biomedical and bio-allied sciences outside of pharmaceutical study. IR spectroscopy is particularly well-suited for examining the structure, folding patterns, and interactions of biomolecules such as proteins, lipids, nucleic acids, and polysaccharides because molecular vibrations are extremely sensitive to structural and chemical changes. IR spectra are frequently used by researchers to identify changes in functional groups, chemical binding events, and conformational transitions within intricate biological matrices.

The use of IR spectroscopy for the non-invasive assessment of bodily fluids is among its most promising advances. Samples like blood, urine, saliva, and serum can be quickly and easily analyzed using FT-IR. These methods provide early illness screening and biochemical monitoring by offering useful diagnostic data. IR spectroscopy is used in hematology to evaluate blood components, identify pathological alterations, and monitor the development of illnesses.

IR spectroscopy is used in forensic research and contemporary healthcare. IR-based techniques are being utilized more frequently in oncology to identify molecular signatures associated with cancer, enabling early diagnosis and supporting treatment assessment. IR spectroscopy is used in forensic investigations to support legal processes, analyze biological evidence, and identify unknown compounds. Its use in environmental and epidemiological research has also expanded, particularly in tracking illness biomarkers and evaluating exposure to dangerous substances.

All things considered, IR spectroscopy's speed, precision, and low invasiveness continue to increase its applicability in clinical diagnostics, pharmaceutical technology, and scientific research.

KEYWORDS: biomolecular spectroscopy, protein dynamics, nucleic acid analysis, clinical diagnostics, non-invasive screening, hematology, cancer biomarker detection, infrared spectroscopy, FT-IR, pharmaceutical quality assurance, drug identification, moisture analysis, API quantification, forensic applications, vibrational analysis, molecular fingerprinting, biomedical research, analytical instrumentation.

1. INTRODUCTION

One of the most important and versatile analytical techniques utilized in many contemporary scientific fields is infrared (IR) spectroscopy. Its capacity to provide specific details about functional groups, molecular vibrations, and general chemical structure is what makes it so powerful.^[1] IR spectroscopy provides an accurate and dependable way to analyze a wide range of chemical and biological processes because various compounds absorb infrared radiation at distinctive frequencies. From early dispersive devices to sophisticated, computer-driven Fourier Transform Infrared (FTIR) spectrometers and cutting-edge IR imaging technologies that can map chemical information at microscopic scales, the technology has seen tremendous change over time.^[2]

Because IR spectroscopy is quick, non-destructive, and frequently requires very little sample preparation, its popularity is growing. These characteristics make it perfect for analyzing sensitive materials, delicate biological specimens, and complicated combinations.^[2,3] IR spectroscopy is frequently used in the chemical sciences to confirm molecular structure, identify contaminants, and track the course of reactions. It helps with formulation research, quality assurance, and drug identification in the pharmaceutical sector. IR instruments are also used by environmental scientists to monitor atmospheric gases, assess soil and water quality, and identify pollutants.^[2,4]

The method's potential has been further increased by recent technical advancements. Portable field testing is now possible thanks to miniature infrared spectrometers, and quantum cascade lasers (QCLs) offer extremely powerful and selective infrared sources for increased sensitivity.^[5] Multivariate analysis, pattern recognition, and spectrum deconvolution are examples of contemporary chemometric techniques that enable more accurate interpretation of complicated information than in the past. Together, these developments have made it possible to analyze heterogeneous materials with great precision, which previously presented serious difficulties for traditional infrared devices.^[5,6]

Integration of IR spectroscopy with computer tools like machine learning, artificial intelligence, and large digital spectrum libraries is another significant advancement. IR spectroscopy is now a potent tool for automated screening, predictive modelling, and real-time diagnostics because to this combination. Without the use of dyes, labels, or intrusive procedures, infrared (IR) approaches are becoming more and more popular in the biological sciences for disease diagnosis, tissue characterization, microbial identification, and biochemical change monitoring. These features demonstrate the increasing usefulness of IR spectroscopy in scientific and therapeutic contexts.^[4,7]

2. FUNDAMENTAL PRINCIPLES OF INFRARED SPECTROSCOPY

The fundamental idea behind infrared (IR) spectroscopy is the way molecules interact with infrared light.^[2,8] Atoms are joined by chemical bonds to form molecules, and these connections function similarly to small elastic springs. Bonds are continuously vibrating, stretching, bending, twisting, rocking, and wagging in various directions because to this spring-like behavior.^[9] Certain wavelengths of infrared light that coincide with the natural vibrational frequency of a specific bond or functional group are absorbed when the radiation travels through or impacts a molecular sample. This selective absorption results in a distinctive infrared spectrum that functions as a molecular fingerprint, providing details on the compound's identity and structure.^[9,10]

The near-infrared (NIR: 12,800–4,000 cm^{-1}), mid-infrared (MIR: 4,000–400 cm^{-1}), and far-infrared (FIR: 400–10 cm^{-1}) are the three primary regions that make up the infrared section of the electromagnetic spectrum. Because it exhibits distinct and easily comprehensible absorption bands for functional groups such hydroxyls, carbonyls, amines, alkenes, and aromatic rings, the mid-infrared area is the most frequently utilized in chemical and pharmacological study.^[11] Only vibrational modes that alter a molecule's dipole moment will result in IR-active absorption, according to the IR selection rule. This explains why some extremely symmetrical compounds exhibit little to no infrared absorption and may require other methods for full structural characterization, such as Raman spectroscopy.^[9,12]

Depending on whether the sample is solid, liquid, or gas, different IR sampling techniques are used. Diffuse reflectance spectroscopy (DRIFTS), thin solid films, and potassium bromide (KBr) pellets are frequently used for solid analysis. Because of their relatively low density, gases are analyzed using long-path gas cells to increase sensitivity, whereas liquid samples

often require liquid cells with IR-transparent windows.^[11,12,13] The introduction of attenuated total reflectance (ATR) technology is a significant sampling advancement. By enabling direct measurement of solids, semi-solids, gels, and biological tissues with nearly no sample preparation, ATR-FTIR has transformed IR analysis, saving time and lowering the possibility of sample change.^[14]

The application of the Fourier Transform (FT) technique is another significant advancement in infrared spectroscopy. Modern FTIR equipment gather an interferogram that includes all wavelengths at once and then mathematically transform it into a high-resolution spectrum rather than detecting absorption at each individual wavelength. This procedure boosts overall precision, speeds up analysis, and improves signal quality.^[15,16]

Understanding these basic concepts is essential to understanding how infrared spectroscopy has developed into a sophisticated analytical method that can accurately examine intricate chemical structures and biological components.^[17]

3. INSTRUMENTATION IN INFRARED SPECTROSCOPY

From conventional dispersive systems to extremely effective Fourier Transform Infrared (FTIR) spectrometers, modern IR spectroscopic equipment has experienced a substantial evolution. Early devices separated infrared wavelengths using gratings or prisms, but their sensitivity, speed, and resolution were all constrained. By employing an interferometer, usually the Michelson design, to concurrently gather all wavelengths and use Fourier transformation to translate the data into a spectrum, FTIR revolutionized the field. Better spectral consistency, faster scans, and an enhanced signal-to-noise ratio are all made possible by this method.^[18]

A radiation source, beamsplitter, interferometer, sample interface, detector, and computer system make up a standard FTIR apparatus. Nernst glowers and globar (silicon carbide) are common sources of broad-spectrum infrared radiation. The radiation in the interferometer is separated into two channels by beamsplitters, which are typically composed of KBr or CaF₂. The interferogram is the result of constructive and destructive interference patterns created as the moving mirror shifts positions.^[17,19]

Detectors are essential for figuring out an instrument's sensitivity. While sophisticated cryogenically cooled detectors like mercury cadmium telluride (MCT) offer higher sensitivity

for demanding jobs like biomolecular analysis or trace detection, thermal detectors like deuterated triglycine sulfate (DTGS) are extensively employed for ordinary applications.

Modern IR spectrometers include Attenuated Total Reflection (ATR) accessories in addition to conventional setups, allowing for direct examination of solids, semisolids, and liquids without sample modification. By offering tunable, high-intensity MIR light for accurate chemical imaging and trace gas monitoring, quantum cascade lasers (QCLs) have significantly improved infrared equipment.^[13,20]

Real-time and on-site investigation is now possible because to the combination of smartphone-based interfaces, portable infrared modules, and microfluidics. IR spectroscopy's use in industries such industrial process automation, biomedical diagnostics, environmental monitoring, and pharmaceutical quality control is being strengthened by these developments.^[21]

4. ADVANCED IR SPECTROSCOPIC TECHNIQUES

Infrared spectroscopy has advanced significantly beyond its traditional form thanks to continuous advancements in optics, detectors, and data processing. Researchers may now investigate molecule structures, dynamics, and interactions with much higher precision, sensitivity, and spatial resolution thanks to sophisticated IR spectroscopy techniques. IR spectroscopy is now a multifaceted analytical tool thanks to these contemporary methods. Near-Infrared (NIR) spectroscopy, which operates in the 12,800–4,000 cm^{-1} range, is one of the most notable developments. This method is very helpful for quick, non-destructive quantitative analysis, particularly in pharmaceuticals, food quality evaluation, and agricultural monitoring, even though NIR absorption bands are weaker and more complicated. It is appropriate for bulk analysis due to its capacity to reach deeper into samples.^[22]

Traditionally employed for the identification of functional groups, mid-infrared (MIR) spectroscopy has developed thanks to ATR-FTIR and sophisticated sampling techniques.

Because MIR offers distinctive absorption patterns specific to particular molecule structures, it continues to be the principal option for chemical fingerprinting. For the study of polymeric materials, inorganic complexes, and lattice vibrations, far-infrared (FIR) spectroscopy has become increasingly important. In materials science, FIR is especially useful for comprehending molecular rotation, metal–ligand interactions, and crystalline phases.^[23]

The study of ultrafast molecular dynamics has been transformed by technologically sophisticated modalities such as Two-Dimensional Infrared (2D-IR) spectroscopy. 2D-IR allows for the real-time study of coupling, relaxation pathways, and conformational changes by dispersing vibrational information along two frequency axes. This method is very effective for studying biomolecular kinetics and protein folding.

Femtosecond-scale events are captured by ultrafast and time-resolved infrared spectroscopy, providing insights into energy transfer processes, reaction mechanisms, and transient species that are not possible to study with conventional techniques.

IR imaging and microscopy, which blends spectroscopy and spatial mapping, is another innovation. Chemical distribution maps within tissues, cells, polymers, and composite materials can be created using this technique. It is frequently employed in forensic science, histology, and cancer diagnosis.^[24]

IR spectroscopy based on Quantum Cascade Lasers (QCLs) is a recent development that offers highly sensitive, adjustable, and brilliant infrared light. Because QCL-IR imaging is quicker and more accurate than traditional FTIR, it can be used for automated industrial analytics, homeland security, and trace gas identification. Lastly, the identification of monolayers and weakly absorbing molecules is made possible by Surface-Enhanced Infrared Absorption Spectroscopy (SEIRAS), which uses metallic nanostructures to amplify IR signals.

Together, these cutting-edge methods have increased IR spectroscopy's analytical capabilities and made it useful for real-time monitoring systems, nanomaterials, and extremely complicated biological systems.^[14,17,23,25]

5. DATA ANALYSIS AND CHEMOMETRICS IN IR SPECTROSCOPY

Data analysis has become more important in modern infrared (IR) spectroscopy since the method now produces big, complicated datasets that need sophisticated interpretation. High-resolution spectra produced by contemporary infrared instruments—particularly FTIR imaging systems, portable sensors, and laser-based spectrometers—cannot be fully comprehended by straightforward visual inspection. Because of this, chemometrics and machine learning are now essential parts of IR data processing, allowing researchers to find important chemical and biological information concealed in spectrum patterns.^[9,14,22,26]

Spectral preprocessing, an essential step intended to enhance data quality and reduce distortions, usually starts the analytical workflow. Unwanted fluctuations resulting from baseline drift, sensor noise, sample thickness variations, scattering effects, or atmospheric interference are frequently present in raw spectra.^[27] A number of mathematical techniques are used to address these problems. Normalization procedures standardize spectra to enable accurate comparisons between samples, smoothing techniques help eliminate high-frequency noise, and baseline correction corrects sloping or curved baselines. By separating overlapping signals, derivative transformations—particularly Savitzky–Golay derivatives—further improve peak resolution. When combined, these preprocessing techniques guarantee that the remaining spectrum data accurately reflect real chemical differences rather than artifacts of the experiment.^[28]

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Deeper insights are extracted using multivariate statistical algorithms after the data has been cleansed. One of the most popular methods for analyzing exploratory data is Principal Component Analysis (PCA). PCA helps identify underlying trends, sample grouping that occurs naturally, and possible abnormalities by condensing spectral datasets into fewer principal components. Because of this, it is very useful in fields like complex mixture categorization, authenticity research, and quality control. Another effective technique, especially for quantitative applications, is partial least squares (PLS) regression. PLS develops calibration models that establish a relationship between chemical characteristics or concentration levels and spectral intensities.^[28]

These models are widely used in food science to evaluate composition and adulteration, in pharmaceuticals to determine active ingredient content, and in environmental monitoring to find trace pollutants.^[29]

The interpretive power of infrared spectroscopy has been greatly increased by machine learning, beyond the capabilities of conventional statistical methods. Subtle spectral properties that might not be apparent to the human eye can be automatically learned by algorithms like support vector machines (SVM), random forest classifiers, artificial neural networks (ANN), and deep learning architectures. These algorithms have made it possible for IR spectroscopy to accurately identify disease-related biochemical changes, distinguish between bacterial strains, analyze metabolic fingerprints, and categorize tissues as cancerous or non-cancerous in biomedical applications. With its ability to evaluate thousands of spectra at once and produce accurate diagnostic results, deep learning in particular has demonstrated great promise in spectral imaging.^[26,27,30]

The development of extensive spectrum libraries is another significant development in data analysis. Reference spectra for a wide range of organic, inorganic, pharmacological, and biological chemicals are available in these databases. IR spectroscopy is a powerful tool for chemical fingerprinting and forensic investigation since it enables quick and accurate identification of unknown samples when combined with automated library-matching algorithms.^[31]

IR spectroscopy has been transformed from a simple qualitative technique to an intelligent, data-driven analytical platform by the combined efforts of chemometrics, machine learning, and spectral databases. IR spectroscopy is set to become even more potent as artificial intelligence develops, providing real-time interpretation, automated classification, and improved decision-making in scientific, clinical, and industrial applications.^[31,32]

6. APPLICATIONS OF IR SPECTROSCOPY IN CHEMICAL ANALYSIS

Because it may provide both qualitative and quantitative data, infrared spectroscopy is essential to chemical analysis. The identification of functional groups is one of its most common applications. Each molecule has an own infrared spectrum, which is sometimes called its "molecular fingerprint." Researchers can reliably identify the presence of alcohols, carbonyls, aromatics, amines, and many other functional groups by analyzing distinctive absorption band.^[32,33]

IR spectroscopy is frequently used in quantitative analysis to determine the analyte concentration in mixtures. Without changing the chemical makeup of the sample, methods like ATR-FTIR provide quick and non-destructive measurement. IR spectroscopy is widely used in the pharmaceutical industry for quality control purposes, such as stability testing, tablet uniformity evaluation, and raw material verification.

Additionally, IR spectroscopy is very useful for characterizing materials and polymers. It can identify the presence of additives, degradation, degree of crystallinity, cross-linking behavior, and structural changes. This makes it a vital tool for materials engineering, packaging research, and polymer processing.^[33,34]

Another important field is environmental analysis, where IR spectroscopy is used to monitor contaminants, industrial emissions, soil contamination, and atmospheric gases. Even small amounts of greenhouse gases like carbon dioxide and methane can be found thanks to sophisticated gas cells and QCL-IR methods.^[35]

IR spectroscopy is used in forensic science to identify unknown residues, fibers, pigments, narcotics, and explosives that are discovered at crime scenes. Forensic investigators may now perform real-time on-site examination thanks to portable FTIR equipment.

Furthermore, by monitoring changes in functional groups during synthesis, IR spectroscopy facilitates the monitoring of chemical reactions. Without sampling the reaction mixture, it allows researchers to examine conversion efficiency, intermediates, and reaction kinetics. All things considered, IR spectroscopy is one of the most effective methods for chemical analysis due to its speed, adaptability, and non-destructive nature. It has helped progress industrial chemistry, materials science, pharmaceuticals, and environmental research.^[34,35,36]

7. APPLICATIONS OF IR SPECTROSCOPY IN BIOLOGICAL AND BIOMEDICAL ANALYSIS

Because infrared spectroscopy can analyze complex biomolecules without the need for labels, dyes, or damaging methods, it has become a potent and popular technique in biological and medicinal research. Every biomolecule, including proteins, lipids, nucleic acids, and carbohydrates, has a distinct vibrational signature, which is why infrared spectroscopy is so

useful in biology. These signatures provide information about the chemical makeup, molecular interactions, and structural conformation of biological systems.^[37]

Protein structure analysis is one of the most important uses. Protein secondary structures including α -helices, β -sheets, and random coils are precisely described by the amide I and amide II sections of the infrared spectrum. These measurements are essential for researching medication effects on protein stability, misfolding in neurodegenerative diseases, and protein folding. DNA and RNA structures are also widely studied using infrared spectroscopy. Detecting structural alterations, binding events, and interactions with small compounds or medications is made possible by particular vibrational modes connected to phosphate backbones and nucleotide bases. This makes a substantial contribution to molecular biology, pharmacogenomics, and genomics research.^[36,37,38]

IR spectroscopy has great potential for disease detection in biomedical diagnostics, especially for cancer. IR-based techniques can accurately distinguish between normal and malignant cells by analyzing biochemical changes in tissues, blood, saliva, or serum. Breast cancer, cervical cancer, skin cancer, and other cancers can be diagnosed early and non-invasively thanks to FTIR imaging's label-free mapping of tissue architecture.

Another important use is microbial identification. Based on their metabolic profiles, bacteria, fungi, and viruses can be quickly distinguished using infrared spectroscopy. This approach is helpful in clinical microbiology and infectious disease surveillance since it is quicker and less time-consuming than conventional culture-based methods.^[39]

IR spectroscopy helps identify metabolic alterations linked to illnesses, stress, and physiological changes in metabolomics. It has been applied to research nutritional status, oxidative stress, lipid metabolism, and diabetes biomarkers.

IR imaging is also being used in tissue engineering and regenerative medicine to evaluate biomaterial interactions, cell differentiation processes, and created tissues.

All things considered, IR spectroscopy's capacity to provide quick, sensitive, and label-free biochemical insights has established it as a revolutionary tool in biology and medicine, connecting lab research with practical clinical applications.^[39,40]

8. INDUSTRIAL APPLICATIONS OF IR SPECTROSCOPY

Because of its versatility, rapidity, and capacity to analyze a broad range of materials, infrared spectroscopy has gained significant adoption in many industries. Quality control, process monitoring, safety evaluation, and product innovation have all been greatly improved by its incorporation into industrial processes. IR spectroscopy is essential in the pharmaceutical sector for authenticating raw materials, identifying contaminants, and confirming the quality of finished products. Without requiring complicated sample preparation, ATR-FTIR enables quick screening of tablets, excipients, and active pharmaceutical ingredients (APIs). Process Analytical Technology (PAT), where real-time monitoring guarantees constant product quality throughout manufacturing, also heavily relies on infrared spectroscopy.^[41]

NIR spectroscopy is widely used in the food and agriculture industries to assess the level of moisture, protein, fat, fiber, and sugar. Grain quality, adulteration, freshness, and storage conditions are all monitored by it. NIR is perfect for routine examination in the dairy, meat, beverage, and edible oil industries because it is non-destructive.

IR spectroscopy sheds light on molecular structures, polymer breakdown, oxidation, and additives in the petrochemical and polymer sectors. It encourages the creation of novel adhesives, coatings, plastics, and specialized chemicals. FIR spectroscopy is useful for analyzing copolymer composition and polymer crystallinity.^[41,42]

IR spectroscopy is also used in **nanotechnology**, where SEIRAS and advanced IR microscopy help analyse surface chemistry, nanoparticle functionalization, and interactions at the nano–bio interface. This is crucial for designing nanocarriers, sensors, and advanced materials.^[43]

Portable infrared spectrometers are used in environmental monitoring to identify chemicals in soil, hazardous gasses, pollutants, and industrial emissions. Because QCL-based systems have exceptionally low detection limits, they can be used to monitor greenhouse gases and volatile organic compounds (VOCs).^[43,44]

IR spectroscopy is used by the paper and textile industries to assess material aging, fiber composition, dye fixation, and coating quality. IR techniques are also used in the cosmetics sector for formulation analysis, stability testing, and authenticity verification.^[42,44,45]

9. RECENT ADVANCES AND EMERGING TRENDS

Innovative developments in recent years have revolutionized the capabilities and uses of infrared spectroscopy. The invention of portable and compact infrared spectrometers is one of the most significant advancements. Micro-electromechanical systems (MEMS)-powered handheld devices allow field-based analysis for industrial inspections, forensic investigations, environmental monitoring, and agriculture.^[45]

The emergence of smartphone-integrated infrared systems, which enable commonplace devices to carry out simple infrared spectral analysis using small sensors and camera-based detectors, is another significant development. By making real-time testing accessible to consumers, farmers, and healthcare professionals, this democratizes scientific instruments.^[46]

Recent innovations have transformed infrared spectroscopy's capabilities and applications. One of the most important developments is the creation of small, portable infrared spectrometers. Field-based analysis for industrial inspections, forensic investigations, environmental monitoring, and agriculture is made possible by handheld equipment driven by micro-electromechanical systems (MEMS).^[47]

Another noteworthy development is the rise of smartphone-integrated infrared systems, which allow everyday devices to do basic infrared spectral analysis utilizing tiny sensors and camera-based detectors. This democratizes scientific tools by making real-time testing available to consumers, farmers, and medical experts.^[47,48]

The detection of trace compounds and monolayers has been made possible by the much increased sensitivity of plasmonic-enhanced infrared spectroscopy, such as SEIRAS and tip-enhanced IR.

When combined, these new developments show how IR spectroscopy is quickly developing into analytical solutions that are quicker, more intelligent, more sensitive, and easier to use.^[49]

10. CHALLENGES AND LIMITATIONS

Infrared spectroscopy still has a number of issues and restrictions that affect its analytical performance, despite its many uses and impressive developments. Spectral complexity is one of the most basic restrictions, particularly when analyzing biological or diverse samples. It is challenging to obtain clear and understandable spectra due to overlapping vibrational bands, wide absorption features, and water interference. When studying aqueous biological samples,

water's substantial absorption in the mid-IR region presents a major obstacle unless sophisticated methods like ATR or computational adjustments are applied.^[50] Sensitivity is another major drawback, particularly when it comes to identifying analytes with low abundance. When compared to approaches such as mass spectrometry or fluorescence-based techniques, conventional infrared spectroscopy is less sensitive. Even though developments like surface-enhanced IR spectroscopy and quantum cascade lasers have increased sensitivity, detection limitations are still a problem in trace analysis, environmental monitoring, and biomedical diagnostics.

Preparing samples is another challenge. Certain samples need to be handled differently; for example, solids need to be formed into KBr pellets, and gases need to be placed in particular pathlength cells. Biological tissues might require sectioning or drying before analysis. These preparation steps can introduce variability or structural alterations that affect spectral accuracy.^[51]

11. FUTURE PERSPECTIVES

The future of infrared spectroscopy is exceptionally promising, as ongoing technological and computational advancements continue to broaden its capabilities. One of the most exciting directions is the deeper integration of artificial intelligence and machine learning, which will revolutionise spectral interpretation, pattern recognition, and predictive modelling. AI-enabled systems are expected to provide automated, real-time analysis with minimal human intervention, dramatically improving diagnostic accuracy and industrial process optimisation. Personalized medicine is another area where IR spectroscopy is set to make a major impact. By analysing biochemical changes associated with diseases at the molecular level, IR-based tools could support early diagnosis, treatment monitoring, and therapy customization. FTIR imaging may soon be integrated into routine histopathological workflows, enabling rapid, label-free tissue assessment in hospitals. Quantum and nanophotonic technologies will push the boundaries of sensitivity and spatial resolution. Quantum cascade lasers, plasmonic materials, and tip-enhanced nano-IR spectroscopy could allow detection of single molecules or structural changes at the nanoscale. These capabilities will deepen our understanding of biochemical processes, protein dynamics, and material interfaces.^[49,52]

12. CONCLUSION

Infrared (IR) spectroscopy has transformed remarkably from a traditional analytical method into a highly advanced, multifunctional platform used across a wide range of scientific and

industrial fields. Its core strength lies in its ability to deliver detailed molecular and structural information without the need for complex sample preparation. This simplicity, combined with its analytical accuracy, has made IR spectroscopy indispensable for both fundamental laboratory research and real-world applications. Over time, continuous technological progress has significantly strengthened its utility. Innovations such as Fourier Transform Infrared (FTIR) spectroscopy, Attenuated Total Reflectance (ATR) systems, quantum cascade laser (QCL)-based instruments, infrared imaging methods, microfluidic-integrated IR systems, and powerful machine-learning algorithms have collectively enhanced sensitivity, speed, and resolution.

In chemical sciences, IR spectroscopy plays a key role in functional group identification, allowing chemists to detect specific bonds and validate molecular structures. It is also widely used to monitor the progress of chemical reactions, assess the purity of compounds, study degradation pathways, and characterise complex materials such as polymers and composites. Environmental and forensic laboratories depend on IR spectroscopy for detecting pollutants, analysing soil and water samples, and identifying unknown substances at crime scenes. Its ability to handle diverse sample types—solids, liquids, gases, and mixtures—adds to its versatility.

In biological and biomedical fields, IR spectroscopy offers a non-invasive and highly informative approach to studying living systems. It provides valuable insights into protein folding patterns, nucleic acid structures, lipid composition, metabolic profiles, and cellular behaviour. Techniques like FTIR imaging and ATR-FTIR enable high-sensitivity analysis of tissues, cells, and biofluids, making IR spectroscopy increasingly important in medical diagnostics. Researchers are using it to identify disease biomarkers, differentiate healthy and cancerous tissues, and even detect microbial infections without chemical staining.

Industrial applications are equally significant. The pharmaceutical industry uses IR spectroscopy for drug identification, quality control, and formulation studies. Food and beverage industries employ it for adulteration detection, freshness assessment, and nutritional profiling. In nanotechnology and materials science, IR spectroscopy supports the characterization of coatings, nanoparticles, and advanced functional materials.

While challenges such as overlapping spectra, sensitivity constraints, and spectral interpretation difficulties persist, rapid advancements in instrumentation, data processing, and

nanomaterial-based sensors are helping to overcome these limitations. The future of IR spectroscopy is strongly linked to artificial intelligence, portable miniaturised sensors, and quantum-enhanced IR sources, all of which promise to revolutionise analytical workflows. Overall, IR spectroscopy remains a foundational analytical technique, continuously evolving through innovation and expanding its influence across scientific, medical, environmental, and industrial sectors.

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