

Integrating FTIR Spectroscopy into Chemistry Education: A Narrative Review of Learning Approaches, Student Competencies and Educational Innovation

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ABSTRACT

Fourier transform infrared spectroscopy (FTIR) bridges concepts of molecules and experimental spectral evidence. Generally, students can identify characteristics of adsorption bands. However, students still struggle to integrate evidence-based spectral interpretation. This narrative review synthesizes the integration of FTIR/infrared spectroscopy in chemistry education. This review focuses on learning approaches, spectroscopic competency, educational innovation, assessment, and learning transfer. A structured search of Scopus and Web of Science was carried out. A supplementary backward and forward citation tracking was also conducted. 595 records were found. 43 studies were retained for narrative and thematic synthesis after removal of duplicates, screening, and eligibility assessment. 5 interrelated themes have been discovered. 1) Bridging chemical theory and experimental evidence. 2) Approaches to teaching spectral interpretation. 3) Developing spectroscopic competencies. 4) Educational innovation and digital transformation. 5) Challenges, assessment, and future directions. The synthesis suggests that the learning approach has shifted from being teacher-centered on the recognition of peaks to more scaffolding, inquiry, collaborative sense-making, and authentic problem-solving, which enhances independent reasoning in spectroscopy. Therefore, assisted by digital and computational approaches, including virtual environments and machine-learning applications, opportunities for learning from data analysis are further expanded. However, the innovation of technology itself cannot demonstrate the effectiveness of teaching and learning. Overall, effective FTIR education should be constructed aligning with conceptual understanding, active pedagogy, authentic spectral data, digital support, and competency-based assessment. Future research should focus on directly evaluating students' reasoning. It

also needs to be further investigated whether the spectroscopic competencies acquired by students transfer to unfamiliar analytical contexts.

1. Introduction

For decades, spectroscopic techniques such as infrared (IR), nuclear magnetic resonance (NMR), and mass spectrometry have been introduced in organic chemistry lecture and laboratory curricula (Alexander et al., 1999; Vosegaard, 2018; Hapiot et al., 2025). Moreover, in undergraduate chemistry education, infrared (IR) spectroscopy may establish itself as a key component because it could indicate that molecular structure and bonding become evident through the experimentally observed spectra. Given that FTIR spectroscopy deepens this educational context, the findings suggest that students might benefit from broader exposure to instrumental methods. However, the significant evidence could demonstrate that students gain the ability to engage with instrumental analysis and vibrational spectroscopy. In light of these results, functional group-spectrum relationships appear to support that chemical identification improves through this exposure. Students learn that spectroscopy links structure to spectra.

FTIR learning requires more than memorizing and matching absorption bands with functional groups. Students need to relate spectral features to molecular vibrations and consider experimental conditions, including chemical variables. However, students must identify relevant evidence and could use it to construct defensible chemical interpretations. Previous research in chemistry education demonstrates that IR spectral interpretation involves complex reasoning (Hamilton et al., 2025). Given that these findings show this, learners might indicate that they must coordinate spectral data with relevant conceptual knowledge to construct meaningful conclusions. In light of other findings, results could suggest that Attenuated Total Reflectance (ATR)-FTIR activities for undergraduates have incorporated instrument optimization, vibrational interpretation, substance identification, spectral comparison, and chemometric analysis. Notwithstanding this observation, the evidence may demonstrate that this range of conceptual and analytical skills appears required by contemporary FTIR (Kumar et al., 2019; Zapata et al., 2021). FTIR education needs to move beyond procedural operation and peak memorization. Therefore, spectroscopy education should shift toward conceptual understanding and evidence-based spectral reasoning.

This direction in spectroscopy education aligns with broader developments in active and inquiry-oriented chemistry education. Lucas & Rowley (2011) mentioned that inquiry-based spectroscopy learning incorporates independent learning, collaborative work, problem-solving, and interpretation rather than relying exclusively on direct knowledge transmission. However, educators must clearly differentiate between students' perceptions of learning and what the evidence could indicate about demonstrated spectroscopic competency (Persky et al., 2020; Al Fulaiti et al., 2024). Given that engagement alone does not establish this, increased engagement, confidence, or satisfaction may not suggest that improvement in conceptual understanding occurred. Findings show satisfaction doesn't prove reasoning improved.

Research related to FTIR and IR spectroscopy education may demonstrate that instructional contexts appear scattered across a wide variety of approaches. Moreover, the evidence could indicate that this includes laboratory and research-based learning, structure elucidation, authentic analytical problems, multispectroscopy activities,

interactive digital environments, virtual laboratories, and computational approaches (Alavi, 2020; Cahill et al., 2024; Dunnagan et al., 2020; Jablonka et al., 2022). However, the findings might suggest that some studies directly examine student reasoning, conceptual understanding, or performance. Furthermore, the results could demonstrate that others examine reported engagement, perceptions, usability, or the design of the educational activities. The studies demonstrate that these differences may create distinct outcomes. However, the evidence might indicate that the studies cannot be treated as equivalent when evaluating FTIR-related educational approaches since the scopes are different.

This narrative review has compiled and integrated previous research on FTIR/IR spectroscopy teaching and learning in chemistry education. This review helps gain an overall understanding of previous research on teaching and learning FTIR/IR spectroscopy and identify gaps that might guide the development of more effective and transferable spectroscopic learning. For this purpose, the following three research questions have guided this review.

RQ1: How is FTIR/IR spectroscopy incorporated into chemistry education to integrate chemical theory, experimental practice, and spectral interpretation?

RQ2: How do learning approaches and innovations support students' learning of spectral interpretation, reasoning, problem-solving, and spectroscopic competencies?

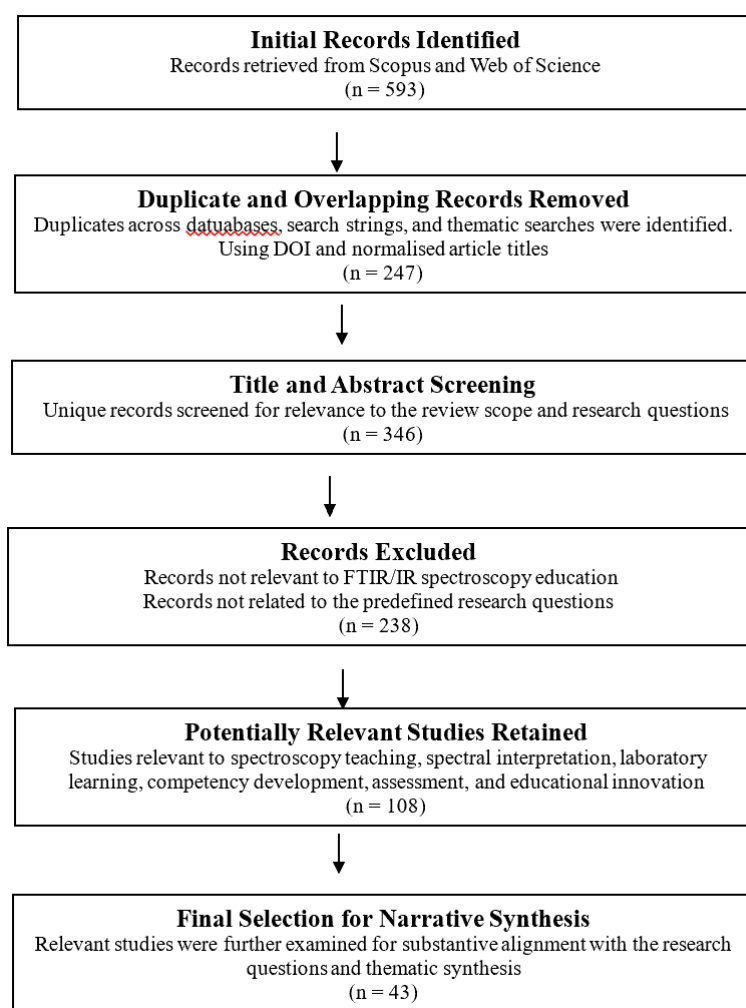
RQ3: What challenges and assessment practices are reported in FTIR/IR spectroscopy teaching and learning? What future research is needed to support transferable spectroscopic competencies?

2. Methodology

This study uses a narrative review approach to qualitatively synthesize the literature on the educational integration of Fourier Transform Infrared (FTIR) spectroscopy. Moreover, the findings may suggest that a clear narrative emerges regarding FTIR/IR as a teaching tool and how it is taught. Additionally, the evidence could indicate that the narrative covers competencies developed and how technology drives innovation in learning and teaching. Given that these results demonstrate relevant trends, the study might indicate that technology shapes pedagogy in important ways. The study also discusses challenges and future directions, offering recommendations.

The literature search and article-selection process followed the four-phase review guidance proposed by Snyder (2019). Phase 1 involves designing the review. Moreover, Phase 2 relates to conducting the review and could indicate multi-stage screening was central to the results. Given that findings emerge across phases, Phase 3 and Phase 4 might indicate that analysis, thematic synthesis, and writing the review appear tied together. Therefore, the study may establish that these key stages could demonstrate a coherent structure. Figure 1 shows steps in Phase 2.

Figure 1: Steps in multi-stage screening for conducting the review



2.1 Search Strategy

The study demonstrates that a structured literature search was conducted using Scopus and Web of Science (WoS) as the primary databases. The final search was conducted on 14 September 2026. Moreover, the search may indicate that the design aimed to identify studies addressing FTIR/IR spectroscopy within chemistry education and related teaching and learning contexts. Furthermore, search terms could suggest that the organization revolved around three concept groups: spectroscopy, education and learning, and spectral interpretation or related learning challenges. However, the core spectroscopy terms might include "Fourier Transform Infrared Spectroscopy," "FTIR," and "infrared spectroscopy." Search combined terms with education terms. Given that the results were combined using Boolean operators with education-related terms such as "education," "teaching methods," "undergraduate," "higher education," and "pedagogy," the findings could indicate that interpretation-related terms appeared to include "spectrum interpretation," "learning difficulties," and "misconceptions." Nevertheless, the search may demonstrate that the application occurred across relevant title, abstract, and keyword fields, with search combinations adapted to the requirements of each database. In light of these findings, backward and forward citation tracking of key retrieved papers might suggest that the study aimed to identify relevant literature that might not have been captured by the database searches. Results show no publication-year restriction imposed. Moreover, the review could indicate that the

purpose was to capture both foundational and contemporary developments in FTIR/IR spectroscopy education.

2.2 Eligibility Criteria and Study Selection

Studies were eligible when they addressed the teaching, learning, interpretation, application, assessment, or educational use of FTIR/IR spectroscopy. The studies either treated this as their primary focus or included it as an important component of broader multispectroscopy learning. The selection process and reasons for exclusion were documented to maintain transparency and consistency throughout the review. However, the findings may suggest that studies were excluded when FTIR/IR spectroscopy was used solely as an analytical, diagnostic, industrial, biomedical, environmental, food, geological, or materials-characterisation technique without a substantive educational component. Moreover, the evidence could indicate that studies involving functional near-infrared spectroscopy (fNIRS) were used solely as a neurophysiological measurement tool, and these were also excluded since they did not speak to teaching or learning contexts. Given that computational and machine-learning approaches often appear to lack a meaningful connection to spectroscopy education, such studies might indicate that they could not be considered core educational evidence. Results show studies excluded on this basis. Nevertheless, the significant findings may suggest that excluded studies still serve as important contextual literature for emerging technological directions.

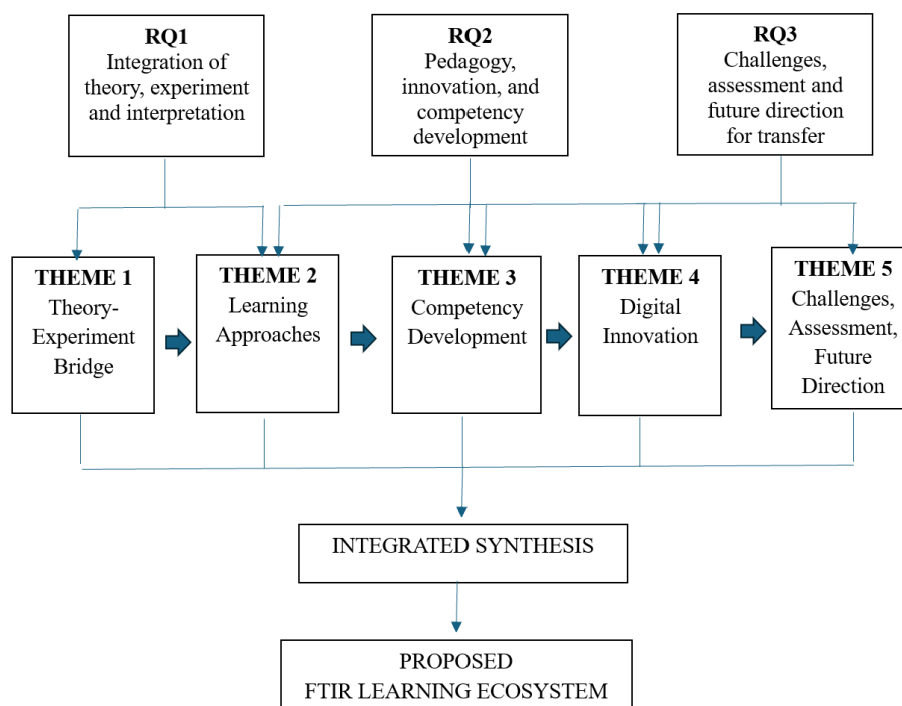
The study-selection process may demonstrate that multiple stages were important. Moreover, the database searches could indicate that 593 records were initially identified. Furthermore, the removal of 247 duplicate records might suggest that 346 unique records underwent the title screening against the review scope. Additionally, the findings reveal that 238 records were excluded because the studies were not relevant to FTIR/IR spectroscopy education. Records excluded studies not addressing research questions. However, the remaining 108 potentially relevant studies could indicate that further examination was important for substantive alignment with spectroscopy teaching. Given that spectral interpretation and laboratory learning were examined, competency development might suggest that assessment was important. In light of the findings, educational innovation may demonstrate that 43 studies were retained for the final narrative synthesis. Nevertheless, the selection process could indicate that the reasons for exclusion were documented to support the transparency (Figure 1).

2.3 Narrative and Thematic Synthesis

The 43 studies retained for final review were analysed using narrative and thematic synthesis. Rather than statistically aggregating findings, the synthesis focused on identifying recurring educational concepts, pedagogical approaches, competency outcomes, technological developments, assessment practices, and learning challenges across the literature. Findings relevant to the three research questions were compared and progressively grouped into conceptually related categories. Through iterative comparison and refinement, five interrelated themes were developed: (1) FTIR spectroscopy as a bridge between chemical theory and experimental work; (2) learning approaches for teaching FTIR spectroscopy and spectral interpretation; (3) development of student competencies through FTIR-based learning; (4) educational innovation and digital transformation in FTIR learning; and (5) challenges, assessment, and future directions for FTIR-integrated chemistry education. The themes were not treated as mutually exclusive because individual studies could contribute evidence to

more than one dimension of FTIR education. The thematic structure was subsequently mapped against the research questions. Figure 2 maps the research question (RQ) with the theme in this narrative review. RQ1 maps to Theme 1 and Theme 2, while RQ2 maps to Themes 2, 3 and 4. RQ3 maps to Themes 3, 4 and 5. This results in an excellent structure, as Themes 2, 3, and 4 serve as "bridging themes".

Figure 2: Research question (RQ) map with five themes for narrative review



3. Results and Discussion

The first theme establishes the conceptual role of FTIR in connecting molecular theory with observable evidence. Moreover, the second theme may examine that instructional approaches could support students in making this connection. Given that evidence demonstrates a learning progression, the third theme might indicate that important competencies could emerge from such experiences. However, the fourth theme could show that digital and computational technologies appear to extend these competencies further. Final theme addresses learning difficulties, assessment needs, transfer, and future development of FTIR education. Even though, the themes are discussed separately for analytical clarity, they are strongly interconnected.

3.1 FTIR Spectroscopy as a Bridge between Chemical Theory and Experimental Work

The literature demonstrates that FTIR has educational value beyond its function as an analytical instrument. Moreover, spectral interpretation may require that students connect molecular structure, bonding and vibrational behaviour with an experimentally generated symbolic representation. Findings link structure and spectra directly. Given that this connection exists, FTIR could serve as a bridge that links chemical theory, molecular behaviour, experimental observation, spectral representation and chemical interpretation.

The educational value of FTIR/IR spectroscopy extends beyond instrumental analysis. This is because interpretation requires learners to coordinate molecular structure, bonding and vibrational behavior with experimentally generated spectral representations. However, this coordination may not be automatic for many students. Students recognise wavenumber ranges without explaining why absorptions occur. Given that Hamilton et al. (2025) demonstrated that IR interpretation requires coordination of chemical knowledge with multiple pieces of spectral evidence, this suggests that peak recognition alone might indicate limited understanding. Moreover, the findings from Stambouli et al. (2023) could show that a discrepancy exists between familiarity and understanding. Nevertheless, these studies together may indicate that the findings support that peak recognition should not be treated as equivalent to integrated spectroscopic reasoning.

Table 1 shows evidence involving chemical theory, experimental work, and spectral interpretation across reviewed literature.

Table 1: Summary of FTIR educational connection in chemistry education

Educational connection	Contribution to learning	Critical interpretation	Sources
Molecular theory with spectral features	Physical modelling connects reduced mass, bond order, electronegativity, polarity and dipole behaviour with peak position/intensity.	Moves instruction beyond memorising wavenumber–functional-group associations.	Wright & Oliver-Hoyo (2019)
Molecular motion with calculated spectrum	Students manipulate structures, visualise bond vibrations and compare calculated IR spectra.	Provides a representational bridge between molecular behaviour and spectral output; it does not by itself establish independent competency.	Baliya & Morsch (2019)
Chemical question with FTIR evidence	FTIR is integrated with thermodynamic concepts in an inquiry investigation of hydrogen-bonded species.	Positions spectra as evidence for reasoning about molecular interactions rather than as an experimental endpoint.	Rodríguez Ortega et al. (2019)
Authentic material with analytical decision	Real-material experiments use spectroscopy to connect chemical knowledge with observed properties and practical interpretation.	Authenticity broadens application, but authentic context should not be equated automatically with demonstrated transfer.	Leri & Pavia (2022); Palezvan et al. (2025)

The educational value of FTIR lies partly in its ability to support movement across multiple forms of chemical representation. Students encounter the observable sample and experimental process at the macroscopic level, reason about molecular structure, bonding and vibrational behavior at the submicroscopic level, and interpret the symbolic information the FTIR spectrum shows. Moreover, this relationship could indicate that it is consistent with Johnstone's triplet of chemical representations, which emphasizes that learners need to coordinate macroscopic, submicroscopic and symbolic forms of chemical knowledge (Johnstone, 1991). Given that the framework has been revisited within chemistry education, the findings may suggest that particular emphasis falls on the cognitive demands involved when learners move between these representational domains (Taber, 2013). However, the evidence might indicate that

meaningful spectral interpretation requires coordination among these representational levels. In light of these findings, significant results could demonstrate that students must coordinate experimental observations, molecular-level explanations, and symbolic spectral representations rather than treating these forms of knowledge independently. Findings show representations link together.

Evidence suggests the following conceptual sequence:

Chemical theory → Molecular behavior → FTIR experiment → Spectral representation → Chemical interpretation → Evidence-based reasoning.

This sequence may suggest that learning does not occur in a fixed linear order. Moreover, the interpretation might indicate that students should move recursively between the molecular hypotheses and the spectral evidence. Furthermore, this important sequence could demonstrate that it establishes the foundation for the subsequent themes. Nevertheless, the FTIR interpretation may require that coordination between the theory and the evidence appears critical. Given that effective pedagogy demonstrates these requirements, structured opportunities could provide support for students to develop this coordination. Students should not rely on memorization only.

3.2 Learning Approaches for Teaching FTIR Spectroscopy and Spectral Interpretation

The reviewed literature demonstrates considerable variation in approaches used to teach infrared spectroscopy. Table 2 shows pedagogical approaches used in IR/FTIR spectroscopy education synthesized from the reviewed literature. Taken collectively, these approaches indicate a pedagogical progression. It ranges from highly structured interpretive procedures to inquiry-based, collaborative, authentic, and technology-supported learning.

For novice learners, structured instruction and scaffolding remain important (Bennett & Forster, 2010; Baxter et al., 2025). These approaches reduce the cognitive burden of interpreting a complex spectrum while establishing an initial reasoning structure. Moreover, the literature may suggest that a shift occurs from procedural scaffolding towards guided inquiry and exploratory learning. Given that evidence demonstrates this trend, these approaches might indicate that learners could construct explanations from observations rather than reproduce predetermined interpretations (Baliya & Morsch, 2019; Rodríguez Ortega et al., 2019; Beck & Miller, 2022; Iler et al., 2012). However, a further dimension involves collaborative spectral sense-making that appears to demonstrate value. Activities require students to articulate, compare, and justify interpretations, making implicit reasoning processes visible (Winschel et al., 2015; Hapiot et al., 2025).

The progression continues through authentic experimental and problem-based applications. Therefore, such tasks may differ from conventional peak-identification exercises because the significant spectrum could become part of a larger analytical decision (Accettone et al., 2022; Leri & Pavia, 2022; Palezvan et al., 2025). In light of these findings, digital and computational approaches might provide another layer of important pedagogical support (Zhang et al., 2016; Jablonka et al., (2022). Furthermore, interactive applications, calculated spectra, virtual laboratories, and data-processing environments could allow that students manipulate representations, explore spectral

relationships, and repeat analytical processes conventional laboratory access alone may not support. Tools appear in Theme 4 but support exploration here.

The literature suggests a conceptual pathway through six stages: Structured Instruction and Scaffolding, Guided Inquiry and Exploratory Learning, Collaborative Spectral Sense-Making, Authentic Experimental and Problem-Based Application, Digital, Computational and Virtual Exploration, and Independent Spectral Reasoning and Transfer. However, the findings may suggest that this progression represents a conceptual synthesis of the reviewed literature. The study shows that the sequence is not empirically validated as universal

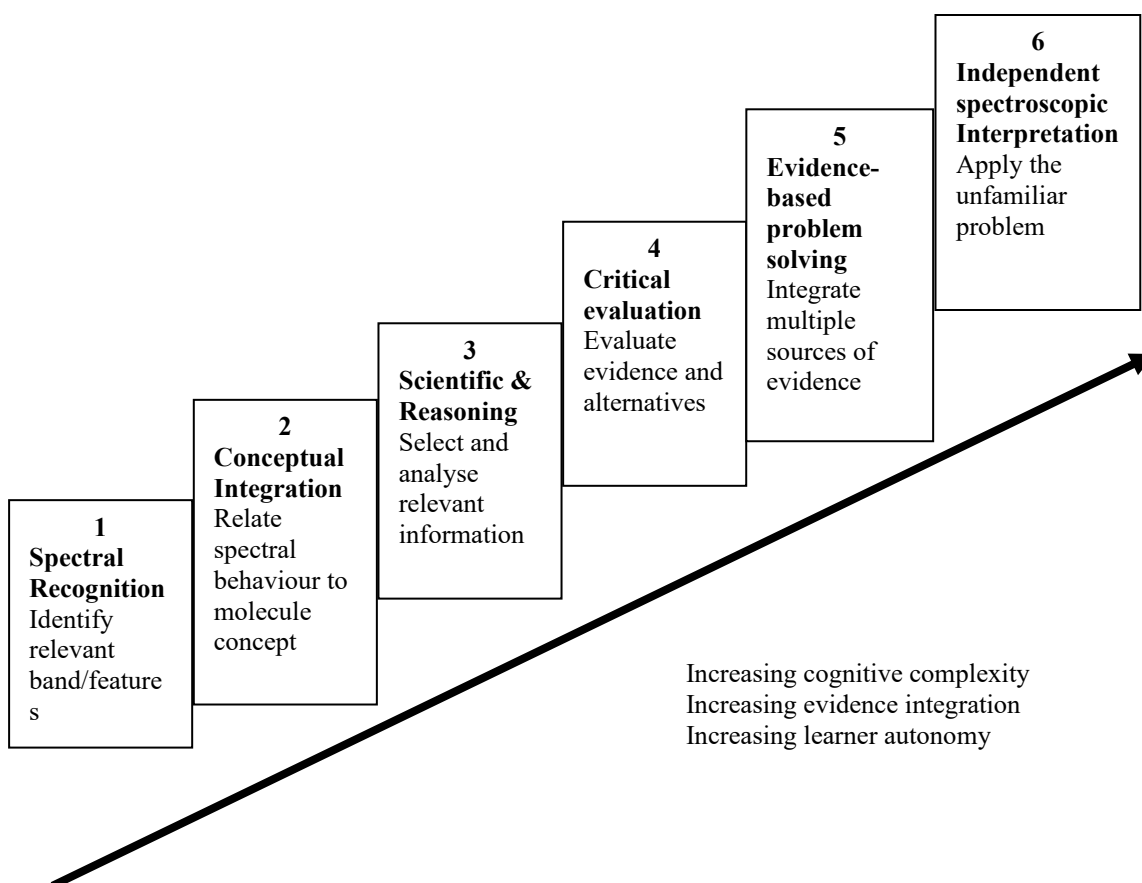
Table 2 : Pedagogical approaches used FTIR/IR specreoscopy education

Learning approach	Typical learning activity	Learner role	Intended educational function	Sources
Structured instruction & scaffolding	Guided interpretation, absorption regions, interpretation schemes	Follow and recognise	Build foundational interpretation	Bennett & Forster, 2010; Livengood et al., 2012; Baxter et al. (2025)
Guided inquiry & exploratory learning	Explore structure–spectrum relationships	Investigate and explain	Develop conceptual reasoning	Balija & Morsch (2019); Rodríguez Ortega et al. (2019); Beck & Miller (2022); Iler et al. (2012)
Collaborative sense-making	Jigsaw, peer discussion, tournament	Discuss and justify	Coordinate interpretations	Winschel et al. (2015); Schwartz et al., (2025); Hapiot et al. (2025)
Problem-based/authentic learning	Unknowns, polymers, fuels, quantitative FTIR	Analyse and decide	Apply spectroscopy to chemical problems	Kurth & Kurth, 2014; Accettone et al. (2022); Leri & Pavia (2022); Palezvan et al. (2025)
Multispectroscopy structure elucidation	IR + NMR/MS evidence	Integrate evidence	Construct structural explanations	Pavel et al. (2012); Zhang & Morrison (2021); Agnello et al. (2020)
Digital/computational learning	Web tools, molecular visualisation, simulation	Explore and manipulate	Connect representations dynamically	Zhang et al. (2016); Jablonka et al. (2022)

3.3 Development of Student Competencies through FTIR-Based Learning

The pedagogical progression identified in Theme 2 links closely to a second shift: moving from acquiring spectroscopic knowledge toward demonstrating spectroscopic competency. Moreover, across the reviewed studies, FTIR-based activities may provide contexts in which students could develop spectral interpretation, conceptual understanding, and scientific reasoning. Given that these tasks demand analytical thinking, the findings suggest that critical evaluation and problem solving also emerge through this process. Furthermore, the evidence indicates that students appear to progress toward increasingly independent interpretation as they engage with these activities. Figure 3 shows conceptual competency development through FTIR-based learning. Peak recognition is not the same as spectroscopy competency. The ability to analyze specific spectral information does not necessarily lead to a correct structural claim (Stowe & Copper, 2019; Persky et al. 2020)

Figure 3: Development of spectroscopic competency in FTIR learning



Students must grasp basic concepts at the foundational level. This includes molecular vibrations, characteristic absorption regions, and relationships between functional groups and spectral features. However, the evidence may suggest that competency requires more than possession of this declarative knowledge. Moreover, students must determine which features could indicate analytically meaningful patterns in the data. Given that findings demonstrate this need, they also need to explain how these features support or contradict a proposed molecular interpretation. Wright and Oliver-Hoyo (2019) study peak position and intensity through molecular principles.

Spectral interpretation represents the next level of competency. Given that scaffolded tasks such as those reported by Baxter et al. (2025) exist, they may provide students with the progressively complex opportunities needed to recognise patterns and apply them to unknown spectra. Moreover, inquiry-based activities could further reduce dependence on instructor-generated rules, and the findings suggest that students benefit from this reduced reliance. However, the evidence may indicate that this reduced dependence supports the development of the important pattern-recognition skills needed for unknown spectra. Balija and Morsch (2019) show students built IR-frequency chart from observations. Students analysed spectral data without prior IR experience or instructor intervention.

FTIR-based learning can also create opportunities for scientific and analytical reasoning. Accettone et al. (2022), for example, required learners to make decisions about internal-standard selection within ATR-FTIR analysis. However, the survey findings may suggest that this approach could improve perceived understanding, though these self-reported outcomes should be distinguished from direct measures of competency. Given that Rodríguez Ortega et al. (2019) designed their inquiry-based laboratory explicitly, the results might indicate that this method could develop scientific reasoning by requiring students to relate FTIR observations to thermodynamic equilibria. Analysis shows students need calibration strategies too. Moreover, in quantitative analytical contexts, the evidence may suggest that students could additionally need to evaluate evidence and make important methodological choices regarding these selections (Huffman et al., 2010).

Complex spectroscopy problems may suggest that critical evaluation appears important for problem solving, particularly when the results demonstrate that several possible interpretations must be considered. Moreover, the findings may indicate that cooperative structure-elucidation exercises involving IR together with NMR or mass spectrometry could suggest that students integrate different forms of the evidence (Winschel et al., 2015; Connor et al., 2019). Furthermore, given that computational tools appear increasingly available, similar machine-learning exercises might demonstrate that spectral analysis could extend beyond conventional visual interpretation. Nevertheless, the significant findings from Cahill et al. (2024) may indicate that combining IR spectra and Python programming could help classify regioisomers effectively. Study shows prediction of students' samples.

Importantly, findings from multispectroscopy studies should not be attributed solely to FTIR. This is because the observed reasoning may arise from integrating several analytical techniques. Similarly, studies reporting student satisfaction, confidence, or perceived usefulness should not automatically be interpreted as demonstrating objectively improved competency.

Three dimensions, cognitive complexity, integration of evidence, and learner autonomy, increase across this progression. However, the sequence may not indicate that it constitutes an empirically validated hierarchy. Students move recursively between stages. Given that technical skills, communication, and collaboration develop alongside rather than within this progression, the findings suggest that these factors influence outcomes separately. Framework shows distinction useful between students.

3.4 Educational Innovation and Digital Transformation in FTIR Learning

Digital transformation represents a key direction in contemporary spectroscopy education. However, the reviewed studies may suggest that a progression exists from static digital resources towards interactive environments, virtual laboratories, computational analysis and emerging artificial-intelligence or machine-learning applications. Given that evidence indicates basic digital resources could make spectra more accessible, results might indicate that students explore structure-spectrum relationships more dynamically than printed peak tables allow. Moreover, interactive computational activities such as those described by Balija and Morsch (2019) may enable that learners manipulate three-dimensional molecular structures and visualise vibrational modes, linking molecular movement to spectral output. Tools support conceptual bridging.

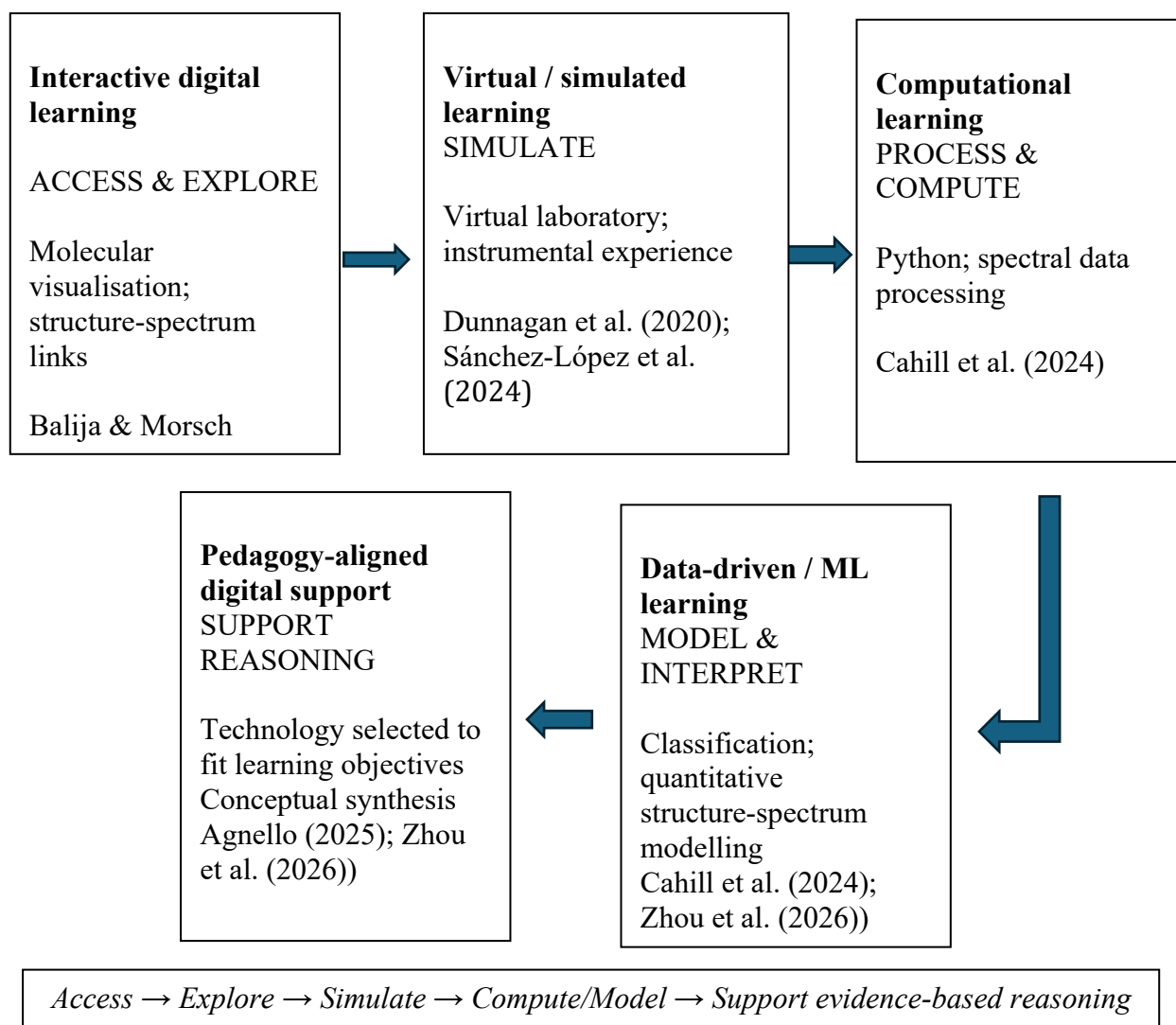
A second development involves virtual and immersive laboratory environments. Dunnagan et al. (2020) built a realistic immersive virtual-reality organic chemistry laboratory focused on infrared spectroscopy. Given that technological novelty did not automatically translate into superior learning outcomes, their findings appear important: the virtual experience offered favourable accessibility and student responses, but learning performance was not necessarily superior to conventional instruction. Moreover, this may suggest an important principle, that virtual environments should be evaluated according to the quality of learning they support rather than immersion alone. However, more recent immersive applications could indicate potential benefits under appropriately designed conditions. Results depend on design. Given that evidence from Sánchez-López et al. (2024) demonstrates this, their study evaluated immersive virtual reality in an analytical biotechnology context and reported higher performance on relevant IR-related assessment items and greater engagement for the intervention group. Nevertheless, findings from an individual course or cohort should not be generalised to all FTIR teaching contexts without replication.

The next stage involves computational and data-driven learning. Cahill et al. (2024) integrated IR spectroscopy with Python and machine learning, requiring students to process spectral information and classify molecular regioisomers. Moreover, this approach may reflect that a broader transformation is underway, in which spectra become datasets to be processed, modelled and interrogated rather than simply visual patterns to be manually inspected. Given that automated analysis and chemometrics increasingly shape the field, such experiences could indicate that these key skills appear relevant. Practice shows chemistry graduates need these tools. Emerging work extends this direction towards AI-assisted spectral learning. Recent educational studies have guided students through the construction of spectral databases, machine-learning models, experimental validation and interpretable analysis of structure-spectrum relationships (Thrall et al., 2021; Jablonka et al., 2022; Ayeni et al., 2025). For example, Zhou et al. (2026) used carbonyl stretching frequencies as a context for integrating IR spectroscopy with machine learning and SHAP-based model interpretation. Such activities may connect spectroscopy education with computational literacy and data reasoning. However, the presence of AI or machine learning does not itself demonstrate educational effectiveness; learning outcomes require independent evaluation.

Figure 4 presents the synthesized digital progression across reviewed literature. Digital transformation might indicate that it intersects with the preceding themes economically. Given that evidence demonstrates educational value, technology could indicate that it

strengthens the theory-evidence connection and supports active interpretation. Therefore, the findings may suggest that it provides authentic or otherwise inaccessible experiences and facilitates independent reasoning. Digitalisation alone shows no endpoint value. However, the desired endpoint appears to connect to a learner-centred FTIR learning environment. In light of these findings, technology may function as an enabling component that supports pedagogy and competency development. One important thing to note that increasing technological complexity does not imply increasing educational effectiveness.

Figure 4: The synthesized digital progression in FTIR learning



3.5 Challenges, Assessment and Future Directions for FTIR-Integrated Chemistry Education

Several persistent issues remain when discussions involve the expansion of pedagogical and technological approaches, Learning challenges, meaningful assessment of competency, transfer to authentic or unfamiliar problems, and the development of future-ready FTIR education, as identified across the reviewed literature. All four points are interconnected. One of the clearest learning challenges is that familiarity and understanding differ. Furthermore, Hamilton et al. (2025) demonstrate that IR interpretation requires complex reasoning processes and that students at different

levels could approach the spectral evidence differently. Given that Stambouli et al. (2023) found that students perceived IR spectroscopy as comparatively well understood, the results might indicate that knowledge of underlying concepts such as wavenumber remained limited. Therefore, several educational interventions could show that the important goal is to move students away from memorisation. Notwithstanding the key results, Wright and Oliver-Hoyo (2019) used molecular modelling to connect spectral features with chemical principles, while structured and inquiry-based approaches have sought to replace isolated peak recall with systematic interpretation (Lopes & Fascio, 2004; Balija & Morsch, 2019; Baxter et al., 2025). Findings show challenge is not whether students locate the correct absorption band but whether they explain its significance within a coherent chemical argument.

Assessment should measure more than frequency recall or functional-group identification if spectroscopy education aims to develop reasoning. Furthermore, the literature indicates that approaches may use spectral puzzles, laboratory reports, rubrics and oral examinations to evaluate how students combine evidence. Given that the results could show how students justify conclusions, the evidence might suggest that assessment provides significant data. Thus, Baxter et al. (2025), for example, provide a scaffolded assessment structure in which students progress from building pattern knowledge to applying it to unknown spectra. This distinction is critical when interpreting the existing literature. Positive perceptions of an educational activity do not necessarily demonstrate improved competence. Winschel et al. (2015), for example, reported favourable student perceptions of cooperative spectroscopy problem solving, but the primary evidence concerned use and attitudes rather than direct pre-post demonstration of spectroscopic reasoning. Future assessment should capture that interpretation involves a process. Given that this process includes how students select evidence, results might indicate that students also reject alternatives and connect spectra with molecular structure. Moreover, the key data could show that students need to defend their conclusions. Nevertheless, the findings may suggest that a student who reaches the correct answer through unsupported pattern matching appears to lack the same competency as a student who constructs a defensible evidence-based interpretation. Student defends conclusions.

The reviewed literature shows that real experimental datasets, unknown samples and industrially relevant problems appear more often. Given that these findings are present, the results could indicate that a further question needs asking about whether students can apply what they have learned to unfamiliar analytical contexts. Moreover, Palezvan et al. (2025), for example, moved from FTIR measurements of commercial hydrocarbon products to spectral-library construction and analysis of unknown fuel blends. Nevertheless, authentic spectroscopy puzzles may show that real experimental information and reaction context have been included, requiring students to integrate IR with complementary analytical evidence rather than interpret idealised spectra in isolation (Esselman et al., 2025). Palezvan et al. (2025) moved from FTIR measurements of commercial hydrocarbon products to spectral-library construction and analysis of unknown fuel blends.

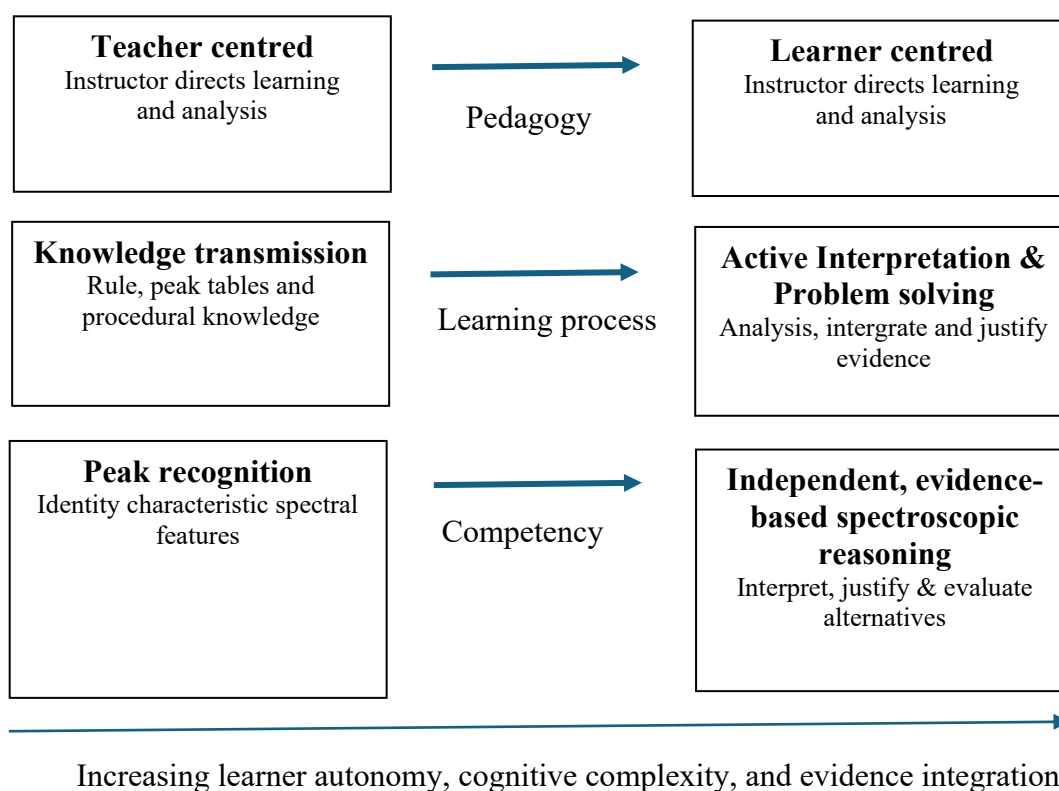
Approaches in the reviewed literature increase the authenticity of the learning environment. Moreover, this situation could indicate that opportunities emerge for students to practice independent interpretation. However, the important point is that authenticity should not be equated automatically with demonstrated transfer. Given that most studies demonstrate that learners are exposed to unfamiliar or realistic problems,

results might indicate that exposure alone appears insufficient. Few studies test transfer. Therefore, the evidence may suggest that only a few studies explicitly test whether competency acquired in one setting applies to a substantially different setting without instructional support, and this could indicate a critical gap. Nevertheless, the key findings appear to show that this represents an important research gap worth addressing. Studies should distinguish taught tasks, similar problems, and genuine transfer to unfamiliar chemical contexts.

The findings suggest that future FTIR education needs stronger constructive alignment between learning outcomes, pedagogy, authentic tasks, technology, and assessment. Given that evidence demonstrates this gap, learning outcomes should articulate more clearly to recognition of spectral features. Moreover, students should also be able to explain, evaluate, and independently interpret the evidence. Furthermore, digital and computational developments could indicate important opportunities for future-ready FTIR education. Virtual environments expand access and provide repeatable practice. Based on previous studies, machine-learning and computational approaches may suggest that students can be introduced to contemporary modes of spectral analysis (Dunnagan et al., 2020; Sánchez-López et al., 2024; Cahill et al., 2024; Zhou et al., 2026). However, the key findings indicate that technological innovation should remain subordinate to educational purpose. Therefore, the significant results might indicate that characterization should be based on the extent to which learning environments develop independent, transferable, and evidence-based spectroscopic reasoning. Quantity of technology used does not decide outcomes.

Figure 5 illustrates three broader shifts across all five themes discussed. The shifts represent a conceptual synthesis of the reviewed literature rather than an empirically validated linear progression.

Figure 5: Transformative shifts in FTIR/IR education

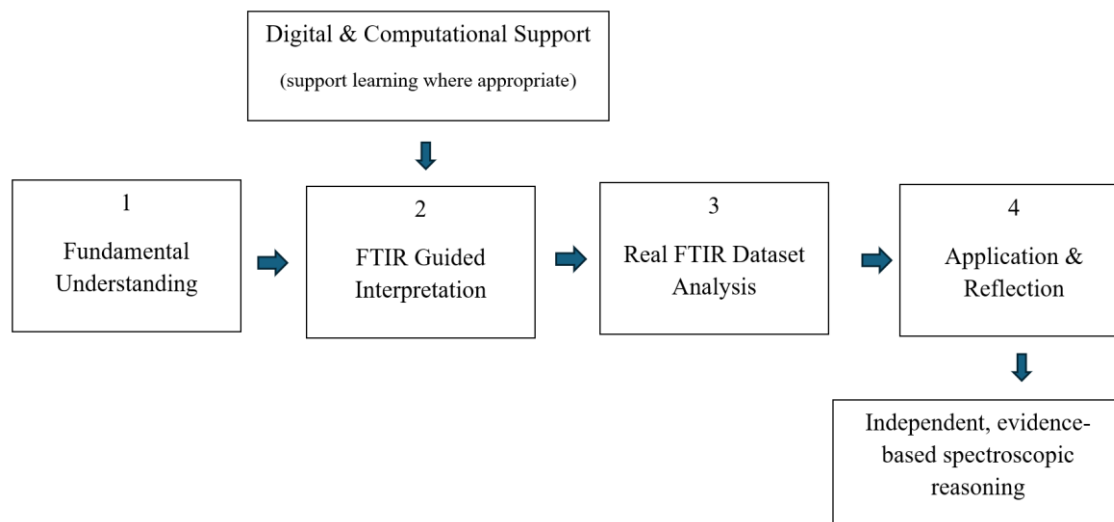


3.6 Integrated Synthesis: Towards an FTIR Learning Ecosystem

Future research needs to focus more on three areas: how students actually reason during FTIR interpretation, how spectroscopic competency can be assessed reliably, and whether that competency transfers to unfamiliar analytical problems. However, comparative and longitudinal studies may also suggest that further investigation is needed here. Moreover, the findings could indicate that certain combinations matter more than others. Given that evidence demonstrates scaffolding, authentic data, collaborative learning, and digital support each play a role. Results might indicate that some combinations promote durable and independent spectral reasoning better than others. Study shows further work determines which mix works best.

This study proposes that a conceptual basis for an integrated FTIR Learning Ecosystem (FLE) could support spectroscopic learning. Moreover, the FLE may perform better than a single teaching technique. Figure 6 illustrates the proposed FLE. Given that evidence suggests separate methods appear limited, the learning ecosystem might combine a few key items. Furthermore, the ecosystem could start with foundational theory, followed by structured scaffolding, guided interpretation, collaborative sense-making, authentic FTIR datasets and formative assessment. Digital or computational support and progressively independent analytical tasks also needed. In light of the findings, these components should not appear as isolated innovations. Their value lies in constructive alignment. This includes learning activities, technology and assessment. Additionally, the results may indicate that together they support the intended development of spectroscopic competency.

Figure 6: Flowchart of the proposed FTIR Learning Ecosystem (FLE)



4. Conclusion

The five themes show that spectroscopy education undergoes a coherent transformation. FTIR provides a representational bridge between molecular concepts and experimental evidence. This connection could support early learning. Moreover, effective pedagogy may guide students from foundational interpretation toward inquiry, collaborative reasoning, and authentic analytical application. Therefore, the learning goal appears to shift, and the findings suggest that this shift moves from knowledge acquisition toward more independent spectroscopic competency development. The

process occurs progressively. However, digital, virtual, and computational technologies could extend this progression by increasing opportunities for visualisation, experimentation, data analysis, and self-directed exploration. Nevertheless, meaningful assessment and authentic transfer may determine whether these important learning experiences result in competencies that students can demonstrate. Thus, students can apply skills beyond the immediate instructional task.

The synthesis also shows that instructional innovation differs from evidence of educational effectiveness. Many studies describe creative laboratory activities, collaborative exercises, virtual platforms or computational tools. However, the strength of evidence may still vary considerably. Given that evidence demonstrates multispectroscopy activities, results might indicate that these tasks support broader structural-analysis competency. Nevertheless, these activities still could not establish that FTIR-specific effects appear present. Findings show perceptions matter. Moreover, student confidence may suggest that engagement indicators appear meaningful, though the significant evidence could support that these indicators cannot replace direct measures of conceptual understanding or reasoning. In light of these findings, authentic problems might indicate that opportunities for transfer could emerge. Therefore, problems do not demonstrate that transfer occurs unless researchers explicitly measure it.

Overall, the reviewed literature shows that FTIR education moves beyond the traditional objective of teaching students to “read peaks”. Moreover, the broader educational potential could indicate that the findings support this shift. Furthermore, FTIR education enables learners to connect molecular concepts with experimental evidence. Given that evidence may suggest additional value, results might indicate that learners gain important benefits. However, the results could show that learners evaluate spectral information, solve analytical problems, and justify chemical interpretations. Study proposes integrated FTIR learning ecosystem aligns these dimensions. Notwithstanding the key findings, conceptual, pedagogical, technological and assessment dimensions may provide the foundation for spectroscopy-ready chemistry graduates.

Ethics Approval and Consent to Participate

The ethics committee approved the research protocol and confirmed that participants provided informed consent.

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Conflict of Interest

The authors declare no conflict of interest.

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