# EXPLORING GRADE 11 STUDENTS' LIVED EXPERIENCES IN LEARNING CHEMICAL BONDING: A PHENOMENOLOGICAL STUDY

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**ABSTRACT**

Chemical bonding is a fundamental yet abstract topic in secondary school chemistry, posing persistent challenges for student comprehension and application. In Ethiopia, particularly in Addis Ababa, little research has qualitatively examined students' cognitive, emotional, and instructional experiences while learning this concept. Most existing studies emphasize achievement outcomes and misconceptions, overlooking the lived dimensions of student learning. Addressing this gap, the present study explored the lived experiences of Grade 11 chemistry students as they engaged with chemical bonding, aiming to uncover their cognitive struggles, emotional responses, and meaning-making processes. A descriptive phenomenological research design was employed. Data were gathered from twelve purposively selected Grade 11 students through in-depth semi-structured interviews. Thematic analysis, guided by inductive coding, identified four major themes: conceptual abstraction and cognitive dissonance; misconceptions rooted in prior knowledge; the influence of teaching strategies and representational tools; and emotional shifts from confusion to confidence. Students described difficulties visualizing sub-microscopic processes, persistent misconceptions shaped by everyday explanations, and the impact of instructional methods on their understanding. Emotional experiences ranged from anxiety and frustration to moments of clarity and pride as conceptual understanding gradually improved. The findings align with international literature on chemical bonding misconceptions while highlighting context-specific challenges in Ethiopia, including limited resources, language barriers, and reliance on lecture-based teaching. The study recommends contextually appropriate, interactive, and multimodal instructional strategies, along with targeted teacher support, to improve chemistry teaching and learning in resource-constrained secondary schools. *[African Journal of Chemical Education—AJCE 16(1), January 2026]*

## 1. INTRODUCTION

Chemical bonding remains one of the most fundamental yet abstract and challenging topics within secondary school chemistry curricula worldwide. It serves as a conceptual foundation for understanding molecular structures, material properties, chemical reactivity, and biological processes [1]. Typically classified into ionic, covalent, metallic, and coordinate (dative) bonds, the topic demands that students conceptualize sub-microscopic interactions between atoms and molecules, processes invisible to the naked eye and difficult to relate to everyday experiences. Despite its centrality in the subject, international studies consistently report that students struggle to form accurate conceptions of chemical bonding, often holding persistent misconceptions related to the nature of bonds, electron sharing and transfer, molecular polarity, bond formation, and dissociation [2–4].

One of the primary difficulties students face stems from the requirement to simultaneously coordinate macroscopic observations, sub-microscopic processes, and symbolic representations—a cognitive demand well-documented in chemistry education literature [5]. These challenges are frequently compounded by emotional barriers such as anxiety, confusion, and frustration, as students attempt to make sense of abstract content that lacks tangible referents [6]. Furthermore, students often bring intuitive explanations and everyday analogies to their chemistry learning, which may conflict with scientifically accepted models and deepen conceptual misunderstandings.

In the Ethiopian secondary school context, chemical bonding has long been regarded as one of the most difficult topics in the chemistry syllabus, alongside equilibrium, thermodynamics, and kinetics [7-8]. Several factors contribute to this challenge, including limited access to well-equipped laboratories, a shortage of instructional resources, and teachers' reliance on traditional, lecture-based pedagogies [9]. In addition, students encounter difficulties arising from language barriers when translating scientific concepts presented in English into their native languages, as well as challenges related to the mathematical aspects of chemical bonding such as calculating bond order, determining electron configurations, or understanding bond energies [10]. These constraints prevent learners from developing accurate mental models of chemical interactions and inhibit meaningful understanding.

While previous studies in Ethiopia have documented students' misconceptions and academic performance regarding chemical bonding through test-based and survey research, relatively little is known about the qualitative, lived experiences of students as they encounter and make sense of this topic within their classroom environments. Much of the existing literature has emphasized student achievement outcomes and teacher practices, leaving the internal, personal, and affective dimensions of students' experiences under-explored [11]. Yet, a growing body of international research has recognized the importance of phenomenological inquiry in education, particularly for capturing how students emotionally, cognitively, and socially experience complex academic content [12].

Responding to this gap, the present study aimed to explore the lived experiences of Grade 11 students as they learned chemical bonding in Addis Ababa, Ethiopia. It sought to understand not only how students engage with this abstract topic cognitively but also how their prior knowledge, everyday explanations, instructional encounters, and emotional reactions shape their meaning-making processes. The intention was to illuminate how learners personally negotiate the challenges of abstract concepts like bonding in a resource-limited setting and how their experiences might inform more student-centered, responsive instructional approaches in Ethiopian secondary chemistry education. To guide this inquiry, the study was structured around four central research questions. These were:

1. How do Grade 11 students experience the process of learning chemical bonding?

2. What misconceptions and prior knowledge influence students' understanding of chemical bonding?
3. How do teaching methods and representational tools shape students' experiences in learning chemical bonding?
4. What emotional and cognitive transformations do students undergo during the instruction of chemical bonding?

## 2. METHODOLOGY

### 2.1 Research Design

To effectively explore the rich, personal experiences of Grade 11 students as they learned the abstract and complex topic of chemical bonding, this study employed a descriptive phenomenological research design. Phenomenology is particularly suited for investigating how individuals experience a specific phenomenon from their personal perspective, emphasizing their perceptions, emotions, and interpretations within their natural contexts [12]. In this study, the phenomenon under investigation was students' lived experiences of learning chemical bonding, a topic known for its cognitive difficulty and high rates of misconceptions worldwide [2,4].

Within phenomenology, Colaizzi's [13] method was selected as the guiding framework for data analysis due to its systematic and rigorous approach to preserving the authenticity of participants' descriptions while identifying common experiential themes. Colaizzi's seven-step process allows researchers to extract significant statements, derive meanings, and cluster these into thematic categories, which are then validated through participant feedback. This method was considered highly appropriate for maintaining the integrity of students' voices while uncovering patterns and shared meanings in their learning experiences, particularly in the resource-constrained educational context of Ethiopian secondary schools.

## 2.2 Participants

Participants in this study were selected using purposive sampling to ensure a diverse representation of student backgrounds and academic achievement levels. The sample consisted of twelve Grade 11 chemistry students drawn from four public secondary schools in Addis Ababa, Ethiopia. These schools were intentionally chosen to represent a cross-section of typical urban secondary schools with varying levels of laboratory resources and instructional approaches. The decision to focus on Grade 11 students was based on the fact that chemical bonding is introduced as a core topic at this level in Ethiopia's secondary chemistry curriculum [7].

To capture a broad spectrum of experiences, students were categorized based on their academic performance in chemistry into three groups: four high-performing students, four mid-level achievers, and four low-performing students. This stratification allowed the study to explore how learners with different backgrounds, confidence levels, and engagement tendencies experienced the same topic. Additionally, an effort was made to ensure gender balance and include students with diverse socio-economic and linguistic backgrounds, acknowledging that such factors can shape learners' engagement with complex scientific content [6]. All students participated voluntarily, with informed consent obtained from them and their parents, where necessary, before data collection commenced.

## 2.3 Data Collection Methods

This study employed in-depth semi-structured interviews as its primary data collection method to explore students' cognitive, emotional, and instructional experiences while learning chemical bonding. All twelve participants took part in individual interviews lasting approximately 45 minutes each. The interviews were guided by an interview protocol containing open-ended questions that encouraged students to describe their understanding of chemical bonding, moments of confusion, emotional reactions, and perceptions of the instructional methods they encountered.

To ensure clarity and ease of expression, interviews were conducted in either English or Amharic based on each participant's language preference. With participants' consent, all interviews were audio-recorded and later transcribed verbatim for analysis. This method provided rich, first-person narratives capturing the personal and nuanced experiences of students as they engaged with this abstract chemistry topic.

**2.4 Data Analysis**

For analyzing the qualitative data collected from interviews, classroom observations, and reflective journals, the study followed Colaizzi's [13] phenomenological data analysis method. This rigorous, seven-step process began with reading and re-reading all transcriptions, observation notes, and journal entries to gain a comprehensive, empathetic understanding of students' learning experiences. The second step involved extracting significant statements related to students' understanding, misconceptions, emotional responses, and instructional encounters with chemical bonding.

In the third step, the researcher formulated meanings from these significant statements, interpreting the underlying cognitive and emotional insights conveyed by students. These meanings were then clustered into thematic categories that captured the shared essence of students' experiences while preserving individual variations. Thematic clusters emerging from different data sources were compared, refined, and merged where appropriate to produce a coherent, integrated set of experiential themes.

In the fifth stage, an exhaustive description of the phenomenon was constructed, incorporating all thematic insights to narrate the collective learning experience of Grade 11 chemistry students in Addis Ababa. This description emphasized both the cognitive difficulties and emotional journeys students underwent while grappling with chemical bonding concepts [2, 4, 6].

As per Colaizzi's method, the sixth step involved returning the findings to the participants for member checking, ensuring that the identified themes and interpretations resonated with their actual experiences. Feedback from participants was used to make minor adjustments and verify the credibility of the thematic conclusions. Finally, the seventh step produced a clear, well-organized, and validated thematic account of students' lived experiences, which formed the basis for the study's results and subsequent recommendations.

Throughout the analysis process, measures were taken to uphold the trustworthiness of the research. Credibility was enhanced by triangulating multiple data sources and conducting member checks [12]. Dependability and confirmability were maintained through meticulous documentation of analytic decisions, coding frameworks, and peer debriefing sessions with two experienced chemistry education researchers who reviewed the coding and thematic development process [1]. Transferability was supported through thick, descriptive accounts of the study's context, participant profiles, and instructional environments, enabling readers to assess the relevance of findings to similar educational settings facing comparable challenges [7].

This robust methodological framework enabled the study to comprehensively capture, analyze, and authentically present students' lived experiences of learning chemical bonding in Ethiopian secondary schools, contributing valuable qualitative insights to chemistry education research and pedagogical practice.

**2.5 Ethical Considerations**

Ethical rigor was a critical component of this study, particularly given its focus on the personal and emotional experiences of adolescent learners within their school environments. Before commencing data collection, ethical standards in line with national research guidelines and international principles for research involving human participants, especially minors, were strictly observed.

Participation in the study was entirely voluntary, and informed consent was obtained at multiple levels. Written informed consent was secured from all participating students, and for those under the age of 18, additional parental or guardian consent was obtained through official school channels. Participants were thoroughly informed about the study's purpose, procedures, potential benefits, and any foreseeable risks associated with participation. They were also advised of their right to withdraw from the study at any time, without academic penalty or personal disadvantage.

To protect participants' privacy and personal integrity, strict confidentiality protocols were maintained throughout the research process. During data collection, participants' real names were replaced with pseudonyms in all interview transcripts, journal entries, and observation records. Audio recordings and reflective journals were securely stored in password-protected digital files accessible only to the primary researcher. In classroom observations, no identifying information about students or teachers was recorded, and findings were reported in aggregate or anonymized form to prevent individual identification.

## 3. FINDINGS

The lived experiences of Grade 11 students learning chemical bonding emerged through four rich, interconnected themes drawn from in-depth interviews. Each theme reveals key cognitive, emotional, and instructional dimensions of their learning journey.

### Theme 1: Conceptual Abstraction and Cognitive Dissonance

The first theme uncovered the deep challenge students faced in grasping the invisible and intangible nature of chemical bonding. Many expressed how difficult it was to picture atoms and electrons interacting, as these processes occur at a scale beyond sensory perception. This caused a sense of mental tension — cognitive dissonance — because the scientific explanations conflicted with their everyday experiences and mental models. One student explained with vivid imagery:

> *"When I try to imagine electrons moving around atoms to form bonds, it feels like trying to picture ghosts or invisible forces that nobody can see or touch. The teacher says atoms share electrons or that opposite charges attract, but it's so strange because I can't physically see anything happening. Sometimes I close my eyes and try to picture it, but all I see is emptiness, and that makes me feel confused and frustrated because how can I understand something that's invisible? It almost feels like magic, or something made up. This makes learning bonding feel really hard because it's not like learning about things I can see or feel."* (Student 5, Interview)

Another student reflected on the difficulty of connecting textbook analogies with real life:

> *"The teacher talks about how opposites attract, like magnets, but when I think about magnets, I see them pulling together in front of me. I know atoms are tiny, and electrons even tinier, but it's hard for me to believe they behave the same way. I keep wondering, how do atoms decide to bond if I can't see or touch them? This confusion makes me doubt myself and sometimes makes me stop trying to understand because it feels so mysterious and distant from anything I know."* (Student 9, Interview)

This theme reveals the core difficulty for students — trying to form mental images and understand a microscopic world they cannot observe directly.

### Theme 2: Misconceptions and Prior-Knowledge Challenges

The second theme revealed that many students arrived at the bonding unit with deeply ingrained misconceptions and prior knowledge that often contradicted scientific concepts. These inaccurate ideas from earlier grades or informal sources were resistant to change, creating significant barriers to learning despite teacher efforts. A high-performing student explained his struggle to overcome misconceptions about metallic bonding:

> *"Before we started studying chemical bonding in detail, I believed that all metals bond like ionic compounds, where atoms just give or take electrons and become charged. So, when the teacher showed us metallic bonding, I kept trying to assign positive and negative charges to metal atoms as I had learned for salts, but it didn't make sense. It took a long time for me to realize that metallic bonding is a completely different kind of bond where electrons move freely. This confusion made me get many answers wrong at first, and I felt frustrated because I thought I understood metals, but I didn't."* (Student 2, Interview)

Another student described how ideas about bond strength from earlier schooling influenced her understanding:

> *"In Grade 9, we were taught that metals are strong and non-metals are weak, so I assumed that covalent bonds, which are usually between non-metals, must be weak bonds. This made it hard for me to accept when the teacher said covalent bonds hold molecules together very strongly. For a long time, I doubted this and tried to memorize what the teacher said without really believing it. It was only after many examples and seeing models that I slowly began to change my thinking."* (Student 7, Interview)

This theme highlights the powerful influence of students' prior knowledge and the difficulty of conceptual change in chemistry learning.

**Theme 3: Impact of Representations and Teaching Methods**

The third theme highlighted how the use of diverse teaching methods and representational tools helped students better understand and engage with chemical bonding. Students reported that physical models, drawings, animations, and simulations transformed abstract ideas into more concrete, understandable forms. One student shared a transformative learning moment:

> *"When we finally got to use the ball-and-stick models in class, it was like everything clicked for me. Before that, I just saw dots and lines on paper, which didn't make sense. But holding the models, seeing how atoms fit together, and drawing lone pairs helped me actually picture what a molecule looks like in 3D. It felt like I was building the molecule myself, and that made me feel like I really understood the idea instead of just memorizing."* (Student 3, Interview)

Another student described the impact of animations:

> *"The teacher showed us videos where electrons moved around atoms and bonds formed step by step. Watching those animations was way better than just listening to explanations. I could see how the electrons shared space and how molecules took shape. It made the lesson fun and easier to remember. I even re-watched some of the animations at home."* (Student 8, Interview)

This theme underscores the value of varied, interactive representations and multimodal teaching strategies in making complex chemistry concepts more comprehensible and engaging.

**Theme 4: From Confusion to Confidence**

The fourth theme illuminated students' emotional journeys, showing how initial confusion and frustration often evolved into confidence and pride as understanding deepened. Many described feeling overwhelmed at first but gradually building self-esteem through interactive learning. One student reflected on this emotional transformation:

> *"At the beginning of the bonding unit, I felt really stupid because other students seemed to understand, but I didn't. I was scared to answer questions and often stayed quiet in class. But after we started drawing diagrams together and discussing ideas in groups, I began to feel proud whenever I got an answer right. That pride made me want to keep trying, and I noticed I was understanding more than I thought possible."* (Student 6, Interview)

Another student tracked a similar progression:

> *"On Monday, I was very confused about lone pairs and almost wanted to give up because nothing made sense. But by Wednesday, after practicing with my classmates and explaining the concept to a friend, I felt like I had unlocked a secret. I was so happy and confident. It was a big relief to know I could learn this hard chemistry."* (Student 11, Interview)

This theme demonstrates that emotional support, social learning, and formative feedback are essential to help students move from confusion to mastery.

## 4. DISCUSSION

This study provides an in-depth exploration of Grade 11 students' experiences learning chemical bonding, revealing that this topic challenges learners cognitively, emotionally, and pedagogically. The richness of these findings reflects the complexity inherent in mastering abstract scientific concepts and offers valuable insights into how instructional strategies can be refined to better support student learning [14].

### 4.1 Conceptual Abstraction and Cognitive Dissonance

A profound barrier to learning chemical bonding is the challenge of conceptual abstraction. Students struggled to internalize the invisible and intangible nature of electrons and atomic interactions, which aligns with the understanding that abstract scientific concepts demand higher-order cognitive processes such as visualization, spatial reasoning, and symbolic interpretation [15-16]. The metaphors students created—referring to electrons as "ghosts" or "magic"—reflect their attempts to make sense of the unknown but also illustrate how such analogies can mask scientific inaccuracies and risk cementing misconceptions [17].

This cognitive dissonance aligns with models of conceptual change where learners must experience dissatisfaction with prior conceptions before accommodating new scientific knowledge [18]. However, the emotional discomfort accompanying this dissonance can impede learning if not properly managed. Without carefully designed instructional scaffolds, students may resort to rote memorization or superficial understanding, limiting their ability to transfer knowledge to new contexts [19].

The difficulty of bridging macroscopic observations with submicroscopic atomic theory is well documented [20]. Visual-spatial skills—crucial for interpreting molecular models—vary widely among learners and are often underdeveloped in early schooling, compounding abstraction difficulties [21]. These findings reinforce the need for instructional approaches that reduce cognitive load and provide concrete analogues for abstract concepts. Dynamic visualizations, such as interactive simulations and augmented reality, have demonstrated significant promise in helping students visualize and manipulate representations of chemical bonding, thereby making invisible processes more tangible [22-23].

Moreover, cognitive load theory suggests that instructional materials should be designed to optimize working memory capacity by integrating visual and verbal information seamlessly, avoiding extraneous cognitive demands [24]. The use of multimodal teaching tools aligns with this principle, allowing students to build mental models incrementally. However, effective use requires careful alignment between representations and pedagogical goals to prevent confusion arising from overly complex or disconnected visuals [25]. Altogether, these findings highlight that conceptual abstraction is not simply a knowledge deficit but a multifaceted cognitive challenge requiring deliberate and sustained instructional intervention, including representational variety and cognitive support strategies [14].

### 4.2 Misconceptions and Influence of Prior Knowledge

Misconceptions remain one of the most stubborn obstacles to conceptual learning in chemistry. The students' misconceptions observed—such as equating metallic bonding with ionic bonding or misunderstanding electron sharing dynamics—reflect the pervasiveness of naive scientific ideas often formed early and reinforced by imprecise teaching or oversimplified textbook explanations [26-27].

These findings corroborate the notion that prior knowledge acts as a double-edged sword in learning: while foundational knowledge can facilitate understanding, faulty preconceptions can hinder or distort the assimilation of new concepts [28]. The resilience of misconceptions is explained by conceptual framework theory, which posits that learners develop alternative frameworks that coexist with scientific models and may dominate reasoning in everyday contexts [29].

The study suggests that misconceptions are often compounded by linguistic and terminological ambiguity. For example, the use of everyday language to describe “bonding” and “sharing” without precise definitions allows informal interpretations to flourish. This linguistic ambiguity, combined with insufficient emphasis on atomic theory in earlier schooling, creates fertile ground for misunderstandings to persist [30].

Formative assessment tools designed to reveal misconceptions, such as two-tier diagnostic tests or concept inventories, have been shown to be effective in identifying and addressing these cognitive barriers [31]. Conceptual change strategies that induce cognitive conflict, encourage metacognitive reflection, and actively engage students in constructing scientifically accurate explanations are necessary for overcoming entrenched misconceptions [32]. This study’s findings underscore the importance of explicitly confronting misconceptions rather than assuming that correct explanations will automatically replace faulty ideas. Educators must also be aware of sociocultural factors, such as language proficiency and educational background, that influence how students interpret scientific content and adapt instruction accordingly [14].

### 4.3 Role of Representations and Pedagogical Strategies

The instrumental role of varied representations and interactive pedagogy was strongly evident in students’ learning experiences. The positive impact of ball-and-stick models, VSEPR diagrams, and interactive digital simulations supports extensive evidence that multimodal instruction enhances conceptual understanding by catering to diverse cognitive styles and making abstract content more accessible [33-34].

Multimodal teaching aligns with dual coding theory, which posits that information processed through both verbal and visual channels is more likely to be understood and retained [35]. The students' "aha" moments when using manipulatives reveal how concrete engagement with materials helps bridge the gap between symbolic chemical notation and conceptual understanding [36].

Moreover, interactive representations promote active learning, a pedagogical approach associated with improved problem-solving skills and long-term retention [37]. The shift from passive lecture formats to active, hands-on experiences enhances student motivation and provides immediate feedback, facilitating formative assessment and corrective feedback loops [14].

The findings highlight that representational tools must be thoughtfully integrated within a pedagogical framework guiding students through progressively complex ideas. Teacher competence in combining content knowledge with technological tools and pedagogical strategies is critical to optimize instruction [38]. However, challenges remain in ensuring teachers are adequately trained and supported to implement these approaches effectively. Without sufficient professional development, representational tools risk being underutilized or misapplied, reducing their potential benefits [14].

### 4.4 Emotional Dynamics and Learning Progression

The emotional dimension of learning emerged as a crucial factor influencing students' engagement and conceptual development. The transition from initial confusion and self-doubt to pride and confidence highlights how emotions interplay with cognitive processes and motivation, shaping the overall learning trajectory [39].

Negative emotions such as frustration and anxiety can hinder working memory capacity and reduce cognitive flexibility, leading to disengagement [40]. Conversely, positive emotions such as curiosity, pride, and enjoyment are linked to enhanced attention, persistence, and deeper processing [41].

The study's findings emphasize the importance of creating learning environments that validate student struggles and foster supportive atmospheres. Collaborative learning and reflective practices allow students to share difficulties, build collective knowledge, and develop emotional resilience—essential for tackling challenging content [42]. Formative feedback that recognizes progress and encourages effort can transform emotional responses, making learning more rewarding. This emotional scaffolding complements cognitive scaffolding and contributes to the development of a growth mindset, enabling students to view challenges as opportunities rather than threats [43].

**4.5 Integrative Implications for Teaching Chemical Bonding**

The complexity of learning chemical bonding demands a holistic approach that addresses cognitive challenges, pedagogical practices, and affective factors simultaneously. Instruction must incorporate multimodal, scaffolded representations alongside diagnostic assessment tools to actively reveal and address misconceptions. Furthermore, teachers must cultivate emotionally supportive classrooms where student confidence is nurtured through collaboration, reflection, and positive feedback [38, 43].

This integrated approach aligns with contemporary educational frameworks promoting student-centered learning and technological integration. Investing in teacher professional development focused on conceptual change pedagogy, effective use of technology, and socio-emotional learning strategies is essential. Such investment enables educators to design and implement lessons that are both intellectually rigorous and emotionally responsive, ultimately improving student outcomes in chemistry [14].

## 5. CONCLUSION

This study offers a nuanced understanding of Grade 11 students' lived experiences as they engage with the challenging and abstract topic of chemical bonding. The findings reveal that students face significant cognitive obstacles related to the intangible nature of bonding concepts, which evoke cognitive dissonance and complicate the formation of accurate mental models. Persistent misconceptions, often rooted in prior knowledge and linguistic ambiguities, further obstruct meaningful learning. However, the use of diverse representations, including physical models and interactive digital tools, proved instrumental in facilitating comprehension and bridging the gap between abstract theory and concrete understanding. Additionally, the emotional journey students undergo—from confusion and frustration to clarity and pride—emphasizes the critical role of affective factors in science learning. Taken together, these insights affirm that chemical bonding is not only a complex intellectual challenge but also an emotional and pedagogical one. To support effective learning, instruction must be holistic, integrating cognitive, representational, and emotional supports in tandem. The study highlights the imperative for thoughtfully designed teaching approaches that are responsive to students' conceptual and affective needs, ultimately enhancing their engagement and achievement in chemistry.

## 6. RECOMMENDATIONS

Based on the study's findings, several practical recommendations emerge for educators, curriculum developers, and policy makers aiming to improve the teaching and learning of chemical bonding in secondary education.

First, educators should incorporate a variety of rich, multimodal representations—such as ball-and-stick models, molecular visualizations, and interactive simulations—to concretize abstract bonding concepts. These tools should be embedded within well-structured lesson plans that gradually build complexity and explicitly connect different representational modes to students' existing knowledge.

Second, diagnostic formative assessments must be routinely used to identify and address misconceptions early. Teachers need to adopt conceptual change strategies that actively engage students in reflecting on and revising their misunderstandings, leveraging cognitive conflict and metacognitive questioning to promote deeper learning.

Third, teacher professional development is essential to equip educators with the necessary skills and confidence to integrate technological tools effectively and apply evidence-based pedagogies that address both cognitive and affective dimensions of learning. Training programs should emphasize instructional design principles aligned with frameworks like TPACK and include opportunities for peer collaboration and reflective practice.

Fourth, creating emotionally supportive learning environments is critical. Teachers should encourage collaborative learning, provide timely and constructive feedback, and foster a classroom culture where students feel safe to express confusion and celebrate progress. These strategies can help transform negative emotions into motivation and resilience.

Finally, curriculum designers and policymakers should ensure that educational materials and assessment standards reflect these integrated approaches, promoting instructional coherence and resource availability. Investment in infrastructure to support access to digital tools and laboratory experiences will further enhance the quality of chemistry education.

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