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Students' Misconceptions in Chemistry Learning: A Systematic Literature Review from 2015 to 2025

Pahriah*, **I Gde Wawan Sudatha, I Kadek Suartama, Made Hery Santosa**

Study Program of Educational Sciences, Postgraduate Program, Universitas Pendidikan Ganesha, Jl. Udayana No.11, Banjar Tegal, Singaraja, Buleleng Regency, Bali, Indonesia 81116.

* Corresponding Author e-mail: pahriah@student.undiksha.ac.id

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Abstract

This study aims to identify the forms of misconceptions in chemistry learning, the methods/instruments used to detect these misconceptions, and effective instructional strategies to address them through a Systematic Literature Review (SLR) approach. The review was conducted on 24 scientific articles published between 2015 and 2025, obtained from the Scopus and Google Scholar databases (via Publish or Perish). Article selection was carried out in stages following the PRISMA flow, and the results were analyzed using a thematic content analysis approach. The review findings indicate that the topics most frequently associated with misconceptions are chemical bonding, acid-base concepts, chemical equilibrium, and reaction rates. The most commonly used instruments to identify misconceptions are three-tier diagnostic tests, followed by interviews and two-tier tests. Effective instructional strategies include the use of multiple representations, digital simulations, the 5E model, inquiry-based learning, and educational games. The study also revealed several research gaps, such as the lack of longitudinal studies, limited topic coverage in chemistry, and the underutilization of interactive digital technologies. Therefore, the development of innovative learning approaches and technology-based conceptual assessments is necessary to sustainably reduce misconceptions in chemistry learning.

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INTRODUCTION

Chemistry learning often faces challenges due to the abstract and complex nature of the subject matter, which leads to conceptual difficulties among students. Numerous studies have shown that misunderstandings of fundamental chemistry concepts, such as chemical bonding and stoichiometry, significantly impact students' low academic performance (Golestaneh & Mousavi, 2024; Mujakir et al., 2020). This indicates that students' conceptual understanding remains a crucial issue that needs to be addressed in chemistry education. Therefore, it is essential to seek more effective solutions to overcome misconceptions in chemistry learning to improve the overall quality of instruction.

Difficulties in understanding chemistry stem not only from cognitive aspects but also from the teaching approaches employed. Traditional approaches that emphasize rote memorization result in shallow and non-transferable understanding (Boateng, 2024; Adu-Gyamfi & Ampiah, 2019). The lack of integration between concepts and real-world contexts makes it difficult for students to apply what they learn, thereby exacerbating existing misconceptions.

Various studies emphasize the importance of active and interactive learning strategies, such as inquiry-based learning, project-based learning, educational games, and digital media. These approaches have been proven to enhance student engagement and improve their understanding of difficult chemistry concepts (Dewi & Wardani, 2018; Ang et al., 2020). Hence, it is necessary to design a curriculum that focuses on deep conceptual understanding through meaningful learning experiences so that students can not only comprehend chemistry concepts but also apply them in real-life situations.

Misconceptions are among the primary obstacles in learning chemistry. Concepts such as chemical bonding, stoichiometry, equilibrium, and buffer solutions are among the most prone to misconceptions (Suparwati, 2022; Islami et al., 2019; Afifah et al., 2021). Research shows that misconceptions often arise from the mismatch between students' initial understanding and scientifically accurate concepts (Zulkhairi, 2022). Therefore, effective identification methods and appropriate instructional approaches are required to address these issues.

Over the past decade, a growing number of studies have highlighted the urgency of conducting systematic reviews on misconceptions in chemistry education. These studies focus on identifying types of misconceptions, methods of identification, and the effectiveness of instructional strategies in overcoming them (Kimberlin & Yezierski, 2016; Jovero & Picardal, 2022; Islamiyah et al., 2022). Some studies even reveal that teachers may still carry misconceptions acquired during their own learning experiences (Adu-Gyamfi & Asaki, 2022). This suggests that chemistry education requires a more comprehensive approach to detect and address misconceptions at the instructional level.

Recent trends in chemistry education research show an increasing use of multiple representations and diagnostic tools, such as multi-tier diagnostic tests, to uncover hidden misconceptions (Widarti et al., 2021; Agatha et al., 2022; Gultom et al., 2019). However, misconceptions cannot be completely eliminated without a more systematic and holistic approach that addresses various aspects of education.

Given the high prevalence of student misconceptions, it is essential to conduct a thorough and systematic review to map the types of misconceptions, effective identification methods, and appropriate teaching strategies. Such a review not only enriches the academic literature but also provides practical contributions to improving the quality of chemistry education across educational levels (Prodjosantoso et al., 2019; Cai, 2022; Tümay, 2016). Therefore, this study aims to answer the following research questions:

1. What types of student misconceptions in chemistry learning have been reported in the literature from 2015 to 2025?
2. Which chemistry topics or concepts most frequently lead to misconceptions, based on studies from this period?
3. What methods or instruments have been used in research to identify students' misconceptions?
4. What instructional strategies or approaches have been reported as effective in addressing student misconceptions?
5. What research gaps remain in the study of student misconceptions in chemistry from 2015 to 2025?

METHOD

Study Design

This study employs a Systematic Literature Review (SLR) approach to identify the types of misconceptions in chemistry learning, the methods or instruments used in previous studies to detect these misconceptions, and the instructional strategies reported as effective in addressing them. The review focuses on scholarly articles published between 2015 and 2025, aiming to capture recent trends and developments in chemistry education research over the past decade.

Sources and Literature Search Strategy

The literature serving as the data source was systematically collected from two primary databases: Scopus and Publish or Perish (PoP). Scopus was chosen due to its reputation as a highly regarded index of international scientific journals, while PoP was utilized to access Google Scholar, thereby broadening the scope of academic literature searched. The main keywords used in the search were "chemical AND misconceptions." The search was restricted to journal articles that are directly relevant to misconceptions in chemistry education.

Literature Selection Process

In the screening process using Scopus, the initial search yielded 1,248 documents. Articles were first filtered based on the publication year (2015–2025), resulting in 622 documents. Further filtering based on the field of chemistry and document type (articles only) narrowed the selection to 180 documents. A more refined screening using specific keywords such as misconceptions, discrepant events, and chemical education research reduced the number to 44 documents. The selection was then limited to sources from peer-reviewed scientific journals and English-language articles, yielding 103 documents. From these, only 30 articles had full access (either open access or via subscription). A final manual screening based on titles and abstracts identified 11 articles that were highly relevant to the focus of this review.

An additional search using Publish or Perish (PoP) produced approximately 200 initial documents. After filtering based on abstracts and topic relevance, 13 additional articles were selected. Therefore, the total number of articles analyzed in this review was 24, consisting of 11 articles from Scopus and 13 from PoP.

Inclusion Criteria

Articles included in this review are those published in Scopus-indexed scientific journals (Q1 to Q4), with a primary focus on misconceptions in chemistry education. The publications must fall within the time range of 2015 to 2025, be written in English, available in full-text format, and contain empirical data, systematic analysis, or conceptual reviews relevant to the identification of misconceptions and instructional strategies.

Exclusion Criteria

Articles were excluded from the review if they did not specifically address misconceptions within the context of chemistry education, were not journal articles (e.g., editorials, proceedings, or book chapters), were not written in English or not accessible in full text, or if the articles were duplicates or lacked relevant data for further analysis.

Data Analysis Technique

All articles that met the inclusion criteria were analyzed using a thematic content analysis approach. Information extracted from each article included: the author(s) and year of publication, the chemistry topic or concept associated with the misconception, the forms of misconceptions reported, the methods or instruments used to identify the misconceptions, the instructional strategies proposed as solutions, and the journal quartile ranking according to the Scopus index. The data were compiled into a literature analysis table and then presented narratively to address the five research questions previously formulated.

The results of the illustrative analysis using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, based on articles relevant to this research study, are presented in Figure 1 below.

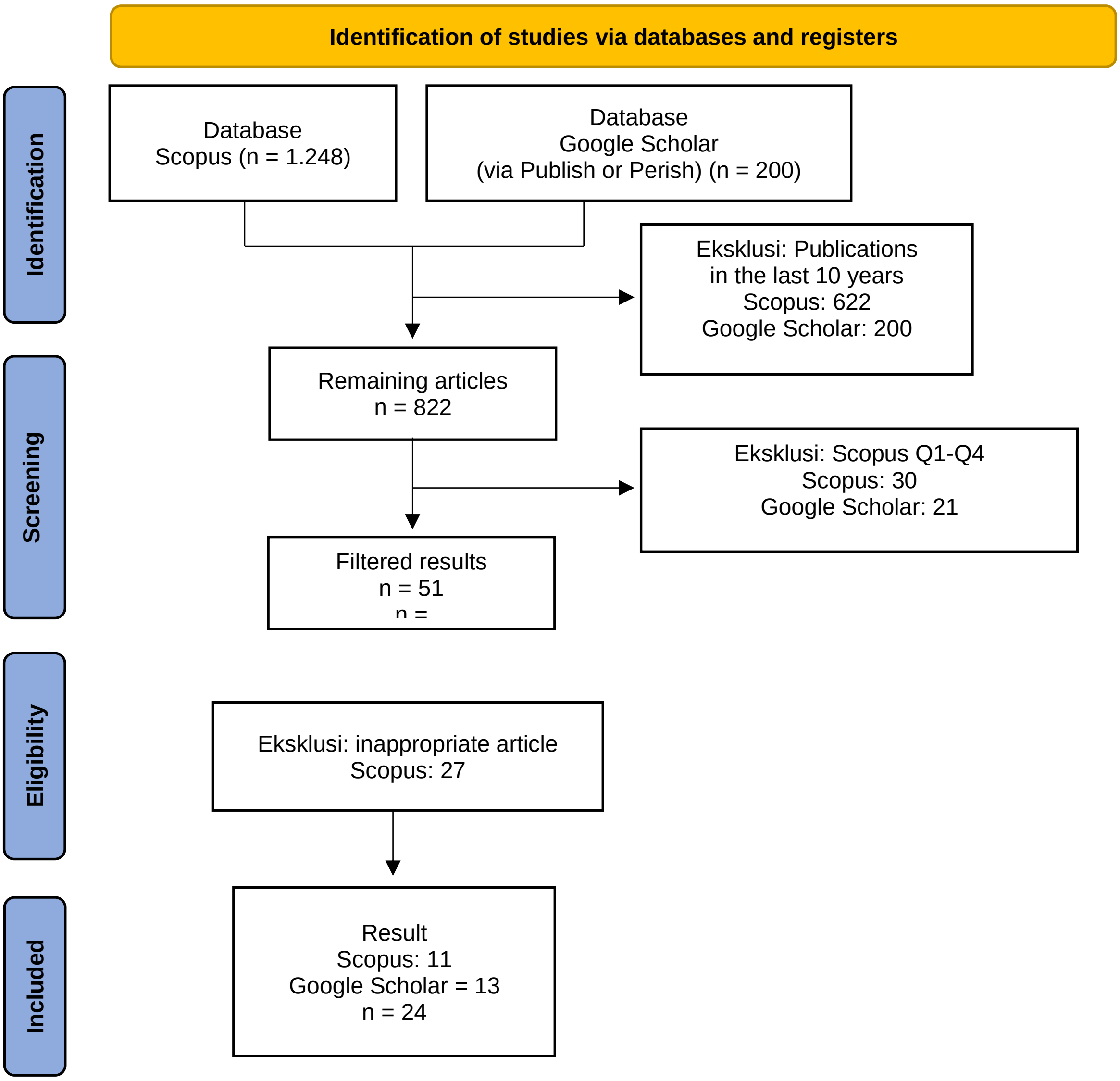

Figure 1. Flowchart Illustrating the Selection of Relevant Articles for Systematic Review

RESULTS AND DISCUSSION

Results

To gain a comprehensive understanding of the types of chemical misconceptions, the identification methods employed, and the learning strategies or approaches reported in the literature, a systematic review was conducted on research articles published between 2015 and 2025. This review aims to map various forms of misconceptions across specific chemistry topics while identifying interventions or instructional strategies that have been tested or recommended to address them. The results of this systematic literature review (SLR) are summarized in Table 1 below.

Table 1. Synthesis of Literature on Chemical Misconceptions from 2015 to 2025

No	Author & Year	Miscon ception Topic	Form of Miscon ception	Identifica tion Method/ Instru ment	Effective Strategy/ Approach	Journal Name	Sco pus Index
1	Peris (2022)	Chemical Equilibrium	Students cannot explain the direction of equilibrium shifts and merely memorize without understanding the effects of temperature, pressure, and catalysts.	Conceptual test + open-ended explanation	No explicit strategy reported	Chemistry Teacher International	Q2
2	Tsaparlis et al. (2021)	Chemical Bonding & Polarity	Considering ionic and covalent bonds as completely different; not understanding polarity from molecular electrostatic potential maps.	Exam + ESP analysis	Electrostatic visualization (ESP maps), spiral approach, and concept-based learning	Chemistry Teacher International	Q2
3	Stroumpouli & Tsaparlis (2022)	Chemical Kinetics	Incorrectly writing rate laws, errors with logarithms, and misunderstanding half-life and rate constants.	Final exam script analysis	Problem-solving based teaching, classroom discussion, laboratory experiments	Chemistry Teacher International	Q2
4	Nuić & Glažar (2023)	Matter Structure & Pure Substances	Believing solid particles do not move and natural substances like milk are pure substances.	Pre-post test + frequency analysis	Animation-based e-learning on particles, effective when guided by teachers	Journal of the Serbian Chemical Society	Q3
5	Stojanovska & Petruševski (2017)	Electrolysis & Nomenclature	Misunderstanding electrolysis reactants and naming of organic compounds.	Student competition-based multiple-choice test	No explicit strategy reported	Macedonian Journal of Chemistry and Chemical Engineering	Q4
6	Ivanoska & Stojanovska (2021)	Acids, Bases & Salts	Assuming all salts are neutral; indicators only red for acid and blue for base.	Two-tier diagnostic test + structured interviews	Multiple representations and molecular visualization	Macedonian Journal of Chemistry and Chemical	Q4

No	Author & Year	Miscon ception Topic	Form of Miscon ception	Identifica tion Method/ Instru ment	Effective Strategy/ Approach	Journal Name	Sco pus Index
					suggested as intervention	Engineering	
7	Antonucci-Durgan & Abramovich (2024)	Particle Structure & Motion	Air not considered particulate; particle movement explained by gravity or external forces.	Writing-to-Learn (WTL) + Peer Review	Spatial training, writing-to-learn, conceptual writing-based peer feedback	Journal of Chemical Education	Q2
8	Schwarz (2021)	Spectroscopy (AAS & ICP-MS)	Belief that stronger light intensity increases AAS instrument sensitivity.	Classroom Response System (CRS)	CRS with immediate formative feedback based on digital polling	Chimia	Q3
9	Müller et al. (2024)	Chemical Bonding	Bonding seen as physical connection and energy storage like a battery.	Visualization discussion + interviews	Interactive experiential learning (SCINE simulations), multi-representation exploration	Journal of Chemical Education	Q2
10	Tümay (2016)	Emergence Concepts & Bonding	Applying heuristic rules absolutely; assuming compound properties derive directly from atoms.	Literature study + interviews	Systemic learning model integrating three levels of representation; data-driven argumentation	Chemistry Education Research and Practice	Q1
11	Jusniar et al. (2020)	Reaction Rates & Equilibrium	Belief that reaction rates always increase; catalysts raise activation energy; misunderstanding dynamic equilibrium.	Three-tier test + interviews	Suggested prerequisite concept teaching; strategy not yet tested directly	European Journal of Educational Research	Q3
12	Belova & Zowada (2020)	Scientific Models & Chemical Reactions	Models seen as real replicas; chemical reactions thought to convert substances directly into energy.	Educational game "MisCoAct"	Educational game "MisCoAct" to build misconception awareness playfully	Education Sciences	Q1
13	Vrabec & Prokša (2016)	Ionic & Covalent Bonds	NaCl considered a molecule; ionic bonds formed by direct electron exchange.	Two-tier test + clinical interviews	No explicit learning strategy explained	Journal of Chemical Education	Q2

No	Author & Year	Miscon ception Topic	Form of Miscon ception	Identifica tion Method/ Instru ment	Effective Strategy/ Approach	Journal Name	Sco pus Index
14	Schmidt-Rohr (2015)	Thermochemi stry	Combustion energy assumed from fuel itself, not bond formation.	Conceptual study	Quantitative illustrations and verbal clarifications to address bond energy misconceptions	Journal of Chemical Education	Q2
15	Tseng et al. (2024)	Chromatograp hy	Belief that separation depends on weight/color, not polarity/molecular interactions.	Two-tier visual test	Reflective inquiry with TLC simulation, in-depth discussion, visual-based assessment	Journal of Chemical Education	Q2
16	Milenković et al. (2016)	Carbohydrates & Stereochemist ry	Confusion between D/L forms and optical rotation direction; misunderstanding cyclic structure.	Three-tier carbohydrate test	Learning strategies not tested; instrument prepared for diagnosis	Journal of Chemical Education	Q2
17	Mubarokah et al. (2018)	Acids, Bases & Electrolytes	All strong acids considered corrosive and all solutions strong electrolytes.	Three-tier diagnostic test + interviews	Cognitive conflict approach and multiple representations suggested	Journal of Turkish Science Education	Q2
18	Laliyo et al. (2022)	Redox Reactions	Redox only seen as oxygen transfer; difficulty calculating oxidation numbers.	Three-tier diagnostic test + interviews	No explicit learning strategies mentioned; focus on three-tier diagnosis	Journal of Baltic Science Education	Q2
19	Prodjosantoso & Hertina (2019)	Chemical Bonding	All metal compounds assumed ionic; ionic bonds seen as direct electron exchange.	Three-tier test + essay	No intervention strategies mentioned; focus on misconception identification	International Journal of Instruction	Q2
20	Supasorn & Promarak (2015)	Chemical Kinetics	Reaction rate equated with product amount; catalysts seen as increasing product quantity rather than speeding reaction.	Pre-test & post-test + reasoning	5E model combined with analogy and guided experiments	Chemistry Education Research and Practice	Q1

No	Author & Year	Miscon ception Topic	Form of Miscon ception	Identifica tion Method/ Instru ment	Effective Strategy/ Approach	Journal Name	Sco pus Index
21	Urban (2016)	Analytical Chemistry	Confusing mass sensitivity with concentration sensitivity in analytical instruments.	Literature study	Directed discussion on conceptual understanding limitations and symbolic clarification	Journal of Chemical Education	Q2
22	Prince et al. (2016)	Heat & Temperature	Heat and temperature considered the same; heat assumed to flow from cold to hot.	Pre-post test + observation	Inquiry-based learning through direct exploration and experimental activities	Chemical Engineering Education	Q4
23	Eymur & Geban (2017)	Chemical Bonding	Bonds seen only as attraction forces; no understanding of bond energy and formation.	Interviews + cooperative observation	Cooperative learning through discussion to socially dismantle misconceptions	International Journal of Science and Mathematics Education	Q1
24	Butler et al. (2015)	Environmenta l Chemical Ecology	Energy considered recyclable; microorganisms and humans ignored in food chains.	Open survey + environmental assessment	No explicit teaching strategy reported	European Journal of Teacher Education	Q1

DISCUSSION

What Are the Forms of Students' Misconceptions in Chemistry Learning Reported in the Literature from 2015 to 2025?

Based on a systematic review of 24 scientific literatures published between 2015 and 2025, various forms of misconceptions have been consistently reported in chemistry learning at both school and university levels. These misconceptions cover a wide range of chemistry topics, from basic concepts such as matter structure and chemical bonding to advanced concepts including chromatography, spectroscopy, and chemical equilibrium. In general, the forms of misconceptions can be categorized into several main themes:

a. Misconceptions about Chemical Bonding and Molecular Structure

Misconceptions in this topic were the most dominantly reported. Students often perceive ionic bonds as a result of direct electron transfer and covalent bonds as electron transfer rather than shared electron pairs (Prodjosantoso & Hertina, 2019; Vrabec & Prokša, 2016; Eymur & Geban, 2017). For instance, NaCl is frequently considered a molecule instead of an ionic crystal. Additionally, students tend to think molecules have no charge at all, while polarity strongly depends on molecular geometry and electronegativity.

b. Misunderstandings about Energy and Thermochemistry

Some students believe that the energy in combustion reactions originates from the fuel itself, rather than from bond formation in the products (Schmidt-Rohr, 2015). Other misconceptions include confusing heat and temperature, and even thinking heat can naturally flow from colder to hotter objects (Prince et al., 2016).

c. Equilibrium and Reaction Rate

A common misconception here is the lack of understanding that equilibrium is dynamic. Students often think that when a system reaches equilibrium, the reaction completely stops (Peris, 2022; Jusniar et al., 2020). Regarding reaction rates, they mistakenly believe that the reaction rate depends on the amount of product or that catalysts increase activation energy (Stroumpouli & Tsaparlis, 2022; Supasorn & Promarak, 2015).

d. Acids-Bases and Electrolytes

Students often equate acid-base strength with concentration and assume all acid or base solutions are strong electrolytes (Mubarokah et al., 2018). Furthermore, during titration processes, they misidentify equivalence points and solution pH (Widarti et al., 2017).

e. Redox Concepts and Oxidation Numbers

Classic misconceptions remain, such as believing redox reactions involve only oxygen transfer (Laliyo et al., 2022). Students also frequently err in assigning oxidation numbers to elements in complex compounds.

f. Molecular Representations and Scientific Models

Models are often seen as exact copies of reality rather than conceptual representations. This leads students to misinterpret models as "physical facts" instead of cognitive tools (Belova & Zowada, 2020; Tümay, 2016).

g. Other Specific Topic

Misconceptions are also found in more advanced topics such as chromatography (Tseng et al., 2024), where students think the weight or color of substances determines their movement, instead of intermolecular interactions. In spectroscopy, students wrongly assume that stronger light means higher instrument sensitivity (Schwarz, 2021).

From these findings, it can be concluded that misconceptions in chemistry learning tend to arise in abstract, multilevel topics requiring deep conceptual understanding, such as chemical bonding, equilibrium, and redox reactions. The main root causes include students' tendency to over-simplify by applying practical rules excessively, limitations in interpreting symbolic and microscopic representations, and incomplete understanding of the relationships between macroscopic, microscopic, and symbolic levels. Additionally, modern chemistry topics newly introduced, such as chromatography, spectroscopy, and analytical techniques like AAS and ICP-MS, are fertile grounds for new misconceptions. This is suspected to be due to the limited use of visual, conceptual, and contextual teaching approaches to fully explain these concepts to students. Therefore, it is important for educators not only to recognize the common types of misconceptions but also to evaluate and improve pedagogical approaches to effectively address the root causes of these conceptual misunderstandings.

Which Chemistry Topics or Concepts Most Frequently Lead to Student Misconceptions Based on Studies During This Period?

Based on a review of 24 literature articles published between 2015 and 2025, several topics in chemistry were consistently identified as the primary sources of misconceptions among students. Table 2 below summarizes the most frequently reported chemistry topics in these studies, along with the number of articles addressing them and the respective authors who reported them.

Table 2. Chemistry Topics Most Frequently Leading to Misconceptions Based on Studies from 2015–2025

No	Chemistry Topic	Number of Articles	Authors Reporting
1	Chemical Bonding (ionic, covalent, polarity)	7 articles	Tsaparlis et al. (2021), Müller et al. (2024), Tümay (2016), Prodjosantoso & Hertina (2019), Eymur & Geban (2017), Vrabec & Prokša (2016), Belova & Zowada (2020)
2	Acids–Bases & pH	4 articles	Ivanoska & Stojanovska (2021), Mubarokah et al. (2018), Jusniar et al. (2020), Tümay (2016)
3	Chemical Equilibrium	3 articles	Peris (2022), Jusniar et al. (2020), Tümay (2016)
4	Reaction Rate / Chemical Kinetics	3 articles	Stroumpouli & Tsaparlis (2022), Supasorn & Promarak (2015), Jusniar et al. (2020)
5	Structure of Matter & Particle Motion	3 articles	Nuić & Glažar (2023), Antonucci-Durgan & Abramovich (2024), Tümay (2016)
6	Redox Reactions & Oxidation Numbers	2 articles	Laliyo et al. (2022), Belova & Zowada (2020)
7	Titration & Salt Hydrolysis	2 articles	Ivanoska & Stojanovska (2021), Mubarokah et al. (2018)
8	Thermochemistry / Heat Energy & Temperature	2 articles	Schmidt-Rohr (2015), Prince et al. (2016)
9	Carbohydrates & Stereochemistry	1 article	Milenković et al. (2016)
10	Spectrometry / Instrumental Analysis	2 articles	Schwarz (2021), Urban (2016)
11	Chromatography	1 article	Tseng et al. (2024)
12	Scientific Models / Representations	2 articles	Belova & Zowada (2020), Tümay (2016)
13	Environmental Chemistry & Ecology	1 article	Butler et al. (2015)

The data in Table 2 indicates that several chemistry topics have consistently been reported as major sources of student misconceptions. These misconceptions span both fundamental and advanced topics and are often associated with students' difficulties in reconciling macroscopic, microscopic, and symbolic representations.

a. Chemical Bonding as the Main Source of Misconceptions

Chemical bonding (including ionic, covalent, and polarity) is the most frequently reported topic causing misconceptions, appearing in 7 out of 24 reviewed articles. Students tend to oversimplify or misinterpret the bonding process as merely a matter of exchange or attraction, without understanding concepts such as bond energy, electron configuration, or molecular structure (Tsaparlis et al., 2021; Müller et al., 2024; Prodjosantoso & Hertina, 2019). Some even believe that NaCl is a molecule or that bonds "store" energy like a battery (Vrabec & Prokša, 2016; Belova & Zowada, 2020).

b. Acids–Bases and pH: Between Theory and Practice

Acid–base and pH concepts rank as the second most reported topics related to misconceptions (4 articles). Some students mistakenly believe that all strong acids are corrosive or that all solutions are strong electrolytes (Mubarokah et al., 2018). Others assume that indicators only turn red for acids and blue for bases, without considering the actual pH range of the indicators (Ivanoska & Stojanovska, 2021).

c. Chemical Equilibrium: A Challenging Concept

Chemical equilibrium is the third most commonly reported topic for misconceptions. Students often struggle to understand that equilibrium is a dynamic process. Many believe that the reaction stops once equilibrium is reached or incorrectly predict the direction of shift due to a lack of understanding of Le Châtelier's principle (Peris, 2022; Jusniar et al., 2020; Tümay, 2016).

d. Microscopic Concepts: Structure and Particle Motion

The structure of matter and particle motion also emerge as important sources of misconceptions. Students frequently believe that solid particles do not move at all, or that air does not consist of particles (Nuić & Glažar, 2023; Antonucci-Durgan & Abramovich, 2024). These misconceptions highlight weak understanding of microscopic representations and the critical need for multi-representational approaches in teaching basic concepts.

e. Chemical Kinetics: Misunderstanding Rates and Catalysts

Reaction rates and chemical kinetics are another problematic area, where students often confuse reaction rate with the amount of product formed, or believe that catalysts increase the amount of product instead of speeding up the reaction (Stroumpouli & Tsaparlis, 2022; Supasorn & Promarak, 2015).

f. Specialized and Advanced Topics

Several other topics, such as redox reactions and oxidation numbers, thermochemistry, chromatography, scientific models, and instrumental spectroscopy, also lead to misconceptions, although they appear less frequently in the literature. However, misconceptions in these areas tend to be more complex and conceptual in nature (Schmidt-Rohr, 2015; Tseng et al., 2024; Schwarz, 2021).

These findings suggest that chemistry concepts involving abstract representations both microscopic and symbolic are particularly prone to misconceptions. Therefore, topics such as chemical bonding and acid–base chemistry warrant special attention in instructional planning. Multi-representational approaches, visual simulations, and diagnostic assessments are essential strategies to effectively identify and address students' misconceptions.

What Methods or Instruments Are Used in Research to Identify Students' Misconceptions?

Based on the review of Table 1, which covers 24 articles published between 2015 and 2025 focusing on misconceptions in chemistry education, it was found that a variety of methods and instruments have been used by researchers to identify students' misconceptions. These methods vary depending on the research approach, the depth of conceptual exploration, and the educational context in which the studies were conducted.

The following are the most commonly identified methods and instruments:

a. Three-Tier Diagnostic Test

   This is the most widely used method across multiple studies (Jusniar et al., 2020; Milenković et al., 2016; Mubarokah et al., 2018; Laliyo et al., 2022; Prodjosantoso & Hertina, 2019). The instrument consists of three parts: a multiple-choice question, a justification for the selected answer, and a confidence level. This structure allows researchers to distinguish between genuine misconceptions, lack of knowledge, and guessing. It is considered effective in providing a comprehensive picture of students' conceptual understanding.

b. Two-Tier Diagnostic Test

   Used in several studies as a simplified version of the three-tier test, this method asks students to provide an answer and a justification without indicating their confidence level (Ivanoska & Stojanovska, 2021; Vrabec & Prokša, 2016; Tseng et al., 2024). While less comprehensive, it remains effective for identifying misconceptions through analysis of the consistency between students' answers and their reasoning.

c. Interviews (Semi-Structured/Structured/Clinical)

   Interviews are widely used as a complementary method to explore students' conceptual understanding in depth and to validate the results of written tests (Tsaparlis et al., 2021; Müller et al., 2024; Eymur & Geban, 2017; Belova & Zowada, 2020). Through interviews, researchers can uncover misconceptions that written tests might not reveal, especially those related to submicroscopic representations or students' mental models.

d. Multiple-Choice Tests with Open-Ended Justifications

   Some researchers developed instruments combining multiple-choice questions with open-ended explanations, allowing for analysis of the quality of students' reasoning (Peris, 2022; Supasorn & Promarak, 2015). This approach helps identify misconceptions through logical errors present in students' explanations.

e. Pre-Tests and Post-Tests

   Pre-test and post-test instruments are commonly used to assess the effectiveness of instructional interventions (Nuić & Glažar, 2023; Prince et al., 2016). The analysis of pre-post test results is used to detect conceptual changes in students, whether as a shift from misconceptions to correct understanding or vice versa.

f. Student Writing and Text-Based Activities

   Writing-to-learn and peer review strategies have been applied in some studies to evaluate students' understanding through written expression (Antonucci-Durgan & Abramovich, 2024). Analysis of student narratives and reflections helps identify both implicit and explicit misconceptions conveyed in their writing.

g. Literature Studies and Conceptual Analysis

Some studies do not involve primary data collection but instead analyze literature sources, textbooks, or scientific concepts using theoretical approaches (Schmidt-Rohr, 2015; Tümay, 2016; Urban, 2016). Although not based on empirical student data, this approach contributes valuable insights into potential sources of misconceptions from epistemological and didactic perspectives.

h. Interactive Media and Classroom Response Systems

Studies such as Schwarz (2021) used classroom response systems (e.g., clickers) to detect misconceptions directly during instruction. Meanwhile, Belova & Zowada (2020) developed the educational game MisCoAct, which integrates conceptual assessment into gameplay, allowing for interactive identification of misconceptions.

In summary, recent studies show a growing trend toward using mixed methods (quantitative and qualitative) to detect misconceptions. The three-tier diagnostic test has become the primary instrument due to its comprehensive insight into students' conceptual understanding, while interviews and open-ended tools enrich the data with students' reasoning processes. Innovative approaches involving writing and digital media are also expanding the range of strategies used to identify misconceptions in chemistry education.

What Instructional Strategies or Approaches Have Been Reported as Effective in Addressing Students' Misconceptions?

Based on the review of Table 1 covering 24 scientific literature articles from 2015–2025, it was found that most studies not only identified misconceptions but also offered or tested instructional strategies to overcome them. The analysis reveals that instructional approaches that are multi-representational, interactive, and reflective are more effective in reducing or eliminating students' conceptual misconceptions.

a. Visualization and Multilevel Representations

This approach was most frequently reported as effective. The use of molecular visualizations, electrostatic maps, and interactive animations helps students understand abstract concepts by connecting macroscopic, microscopic, and symbolic representations. For example, Tsaparlis et al. (2021) used ESP visualizations to explain molecular polarity, while Nuić & Glažar (2023) and Ivanoska & Stojanovska (2021) emphasized the importance of animated visualizations for understanding particle structures and substance transformations.

b. Conceptual Change Approaches

Several articles recommended cognitive conflict strategies and conceptual change approaches to address deeply rooted misconceptions. These strategies involve presenting phenomena or experimental results that contradict students' predictions, as seen in Mubarokah et al. (2018) and Ivanoska & Stojanovska (2021), which prompt students to revise their thinking based on evidence.

c. 5E Model and Inquiry-Based Learning

The 5E instructional model (Engage, Explore, Explain, Elaborate, Evaluate), when combined with guided experiments and analogy-based approaches, has proven effective in enhancing conceptual understanding (Supasorn & Promarak, 2015). Inquiry-based learning, as implemented by Prince et al. (2016) and Eymur & Geban (2017), also enables students to construct understanding through exploration and group discussions.

d. Educational Games and Interactive Activities

Game-based innovations have also proven helpful in addressing misconceptions. Belova & Zowada (2020) developed *MisCoAct*, a scenario-based educational game that provides engaging and social learning experiences, allowing students to detect and correct misconceptions collaboratively.

e. Classroom Response Systems and Formative Assessment

Using Classroom Response Systems (CRS), such as clickers in chemistry classes, enables teachers to detect misconceptions in real time and provide timely formative feedback (Schwarz, 2021). This approach helps students recognize and correct their misunderstandings during the learning process.

f. Spatial Ability and Writing-to-Learn Approaches

Antonucci-Durgan & Abramovich (2024) emphasized the importance of spatial exercises and writing to learn strategies to help students form accurate mental models. Peer review in writing assignments also provides cognitive feedback that can correct misconceptions through written expression.

g. Open Conceptual Approaches and Verbal Clarification

Reflective studies such as those by Schmidt-Rohr (2015), Urban (2016), and Tümay (2016) did not test instructional strategies directly but emphasized that misconceptions can be mitigated through strengthening conceptual understanding, quantitative illustrations, and verbal clarification during classroom discussions.

Based on the literature review, no single instructional strategy has emerged as the most dominant in addressing students' misconceptions. However, approaches that consistently demonstrate effectiveness are those that integrate concept visualization, critical reflection, active student engagement, and the use of multiple representations. These approaches enable students to achieve a deeper understanding of concepts through interactive and exploratory learning experiences. Thus, instructional strategies that emphasize active thinking and conceptual interaction are key in helping students revise and eliminate pre-existing misconceptions.

Research Gaps in Studies on Students' Chemistry Misconceptions (2015–2025)

Based on an analysis of 24 articles focusing on misconceptions in chemistry education, it was found that these studies have made significant contributions in identifying various types of misconceptions and suggesting specific instructional strategies. However, this review also revealed several research gaps that still need to be addressed, both in terms of methodological approaches, topic coverage, and educational contexts. The following are key research gaps identified:

a. Limited Experimental Intervention Studies

Most studies (e.g., Jusniar et al., 2020; Mubarokah et al., 2018; Prodjosantoso & Hertina, 2019) primarily focus on identifying misconceptions using diagnostic tests and interviews, without systematically testing the effectiveness of instructional interventions. Only a few have evaluated the impact of specific teaching strategies in overcoming misconceptions, such as those by Supasorn & Promarak (2015) and Belova & Zowada (2020).

Gap: The lack of quasi-experimental or true experimental studies results in weak empirical evidence regarding the effectiveness of interventions for addressing students' misconceptions. This limits the development of research-based instructional practices in the field.

b. Lack of Longitudinal Studies

   All of the reviewed studies are cross-sectional, observing misconceptions at a single point in time. No research was found that tracked the development or persistence of misconceptions over an extended learning period.

   Gap: Longitudinal studies are needed to understand how misconceptions evolve or persist over time and across educational levels. Without such studies, intervention strategies tend to be short-term and less sustainable.

c. Uneven Coverage of Chemistry Topics

   Most studies focus on topics such as chemical bonding, acids and bases, and equilibrium. Other topics like electrochemistry, nuclear chemistry, and advanced organic chemistry are rarely addressed. Some articles did not even specify the chemistry topics investigated.

   Gap: The narrow focus of research risks overlooking potential misconceptions in other complex and abstract topics. This limits the development of comprehensive learning resources for all areas of chemistry.

d. Limited Use of Multimodal and Digital Approaches

   Although some studies have begun to explore visualizations and animations (Tsaparlis et al., 2021; Tseng et al., 2024), the majority still rely on conventional methods such as written tests and interviews. The use of advanced learning technologies such as interactive digital tools, VR/AR, or AI-based feedback remains very limited.

   Gap: The underutilization of digital and multimodal technology leads to a lack of innovative approaches that could help bridge the representational gap between macroscopic, microscopic, and symbolic levels in chemistry learning.

e. Limited Diversity of Populations and Contexts

   Most studies involve high school students or chemistry education majors. Other populations such as students with special needs, teachers, or non-chemistry students are rarely included. Geographically, the studies are mostly concentrated in Southeast Asia and Europe.

   Gap: The limited diversity of participants and cultural/geographic contexts makes it difficult to generalize findings widely. This poses challenges for developing inclusive and contextually relevant instructional practices and policies.

f. Weak Integration of Representation and Assessment

   Several studies emphasize the importance of multiple representations in chemistry learning, yet very few have developed assessment tools that explicitly measure students' understanding across levels (macro–micro–symbolic).

   Gap: The lack of multi-representational assessment tools hinders a comprehensive identification of students' misconceptions. This limits the accuracy of conceptual understanding evaluations.

Overall, although research on chemistry misconceptions has grown significantly over the past decade, several critical gaps remain. These include the lack of long-term experimental studies, limited topic coverage, underutilization of digital technology, constrained participant diversity, and the absence of comprehensive assessments. Future research should aim to address these gaps to ensure that instructional strategies are truly effective, contextually relevant, and capable of supporting deep conceptual understanding among students

CONCLUSION

This systematic review successfully identified various forms of misconceptions that frequently arise in chemistry learning, particularly in the concepts of chemical bonding, acids and bases, chemical equilibrium, and reaction rates. The findings indicate that misconceptions occur not only at the conceptual level but also in students' understanding of symbolic and microscopic representations. The most commonly used identification instrument is the three-tier diagnostic test, followed by interviews and two-tier tests, which have proven effective in uncovering students' conceptual understanding more deeply. On the other hand, several instructional strategies reported to be effective in addressing misconceptions include the use of multiple representations, visual simulations, inquiry-based approaches, the 5E learning model, and educational game-based media. This review also identified several research gaps, such as the lack of longitudinal studies and limited exploration of misconceptions in specific chemistry topics, as well as the underutilization of more interactive digital technologies in both identification and instructional interventions. Therefore, future research development is recommended to broaden topic coverage, employ technology-based approaches, and integrate innovative assessment instruments to support students' conceptual understanding in a sustainable manner.

RECOMMENDATIONS

Based on the findings of this review, it is recommended that chemistry educators pay greater attention to the potential emergence of misconceptions in fundamental topics such as chemical bonding, equilibrium, acids and bases, and reaction rates. To accurately detect misconceptions, teachers and lecturers are encouraged to use three-tier diagnostic instruments combined with interview techniques or reflective discussions. In addition, instructional strategies that emphasize the use of multiple representations, visual simulations, as well as inquiry-based and 5E approaches should be more widely applied in chemistry education across various educational levels.

Future researchers are expected to develop interactive digital technology-based learning models specifically designed to more effectively address misconceptions. Longitudinal studies and classroom action research are also needed to monitor the development of students' understanding over time. Furthermore, expanding studies to include less-explored chemistry topics is recommended to obtain a more comprehensive picture of misconceptions in chemistry learning.

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