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Analysis of High School Students' Chemical Mental Models Based on Three Levels of Chemical Representation: A Literature Study

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Abstract: This study aimed to determine the profile of the chemical mental models of high school students and to describe and explain the factors that caused the formation of alternative mental models in students' minds. This research was classified as a document analysis involving 15 theses in the Chemistry Education Study Program, Universitas Pendidikan Ganesha (Undiksha) as research subjects and students' chemical mental models as the research object. Data collection was done by using a checklist. The data collected underwent descriptive analysis. The results of the study showed that students' chemical mental models included Scientifically Correct as much as 0–28.65%; Partially Correct as much as 23.03%–90.58%; specific misconceptions reaching 0.48%–58.53%; and No Response as much as 0–49.07%. Factors causing the formation of alternative mental models in students' minds include a low understanding at the submicroscopic level, overgeneralization, ignorance of the meaning of chemical symbols, a lack of information related to the complexity of the problem at hand, a lack of understanding of prerequisite concepts, analogy errors, and errors in the learning materials. In general, alternative mental models are arise when students do not understand the submicroscopic structure underlying the properties of substances.

Keywords: Chemistry; Chemical mental models; Correct; Factors; Misconceptions

Introduction

Meaningful learning in chemistry education should not only be interpreted as success in associating newly received information with students' prior knowledge but also as success in building a complete mental model of chemistry, covering three levels of chemical representation (macroscopic, submicroscopic, and symbolic) and the interconnection of these three levels (Albaiti et al., 2022; Djoa, 2023; Murni et al., 2022). Therefore, in learning chemistry, the teacher must choose a learning strategy that is suitable for students to build their mental model of chemicals as a whole, including carrying out the accommodation process for errors in chemical concepts that already exist in students' minds. Scientifically correct mental models will contribute to students' spatial abilities, digital literacy, scientific attitude, and learning outcomes (Sari, 2021; Wildan et al., 2023; Amiruddin et al., 2025)

Learning in the tertiary institutions, lecturers often assume that students are able to transfer their knowledge from one level to another (Cahya & Surya, 2025; Lathifa et al., 2020). This assumption underlies the tendency to teach chemical concepts directly from the macroscopic to the symbolic level without relating it to understanding the submicroscopic level. This condition causes students to experience difficulties in providing explanations at the submicroscopic level related to phenomena at the macroscopic level using chemical verbal and symbolic language (Ariani et al., 2020; Atikah et al., 2023).

The results of the study indicate that first-year students of the Chemistry Education Study Program at Universitas Pendidikan Ganesha, Singaraja, Bali, still lack understanding of the chemical concepts they learned in high school. For example, the correct understanding of the three levels of chemical representation related to electrolyte and non-electrolyte

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solutions, including the macroscopic level, is 34.21%, the submicroscopic level is 27.54%, and the symbolic level is 29.47%. Only 12.46% of students' mental models were classified as conceptual models (scientifically correct), while the remaining 87.54% were classified as alternative mental models, which include 38.95% partially correct and 48.59% specific misconceptions (Suja et al., 2021). The data showed that students' understanding of the three levels of chemistry was very low and most of them have alternative mental models. The same condition was found at the Universitas Pendidikan Indonesia (UPI), where students tended to memorize chemical concepts at the symbolic level and did not understand the meaning of the symbols used in chemistry lessons. Students were unable to relate the results of observations at the macroscopic level to the symbolic level and explain them at the submicroscopic level (Amiruddin et al., 2025; Wiji & Mulyani, 2018).

The low understanding of first-year students regarding the three levels of chemical representation indicates that their mental models are incomplete and prone to errors since learning chemistry in high school. This condition can be observed from the results of research on high school students' chemical mental models, including those obtained from student theses. However, to date, there has been no comprehensive mapping of high school students' chemical mental models in Bali based on the results of a cross-analysis of student theses. Based on this, the author has conducted an analysis of student theses from the Chemistry Education Study Program that examined the chemical mental models of high school students in Bali province. The purpose of this study was to determine the profile of students' chemical mental models, as well as to describe and explain the factors that cause the formation of alternative mental models in students' minds. Information about the factors that cause the emergence of alternative mental models in more detail is new and has not been revealed in previous research. This data is needed to revitalize chemistry learning in high schools and universities.

Method

This research is a literature study conducted at the Chemistry Department Library, Universitas Pendidikan Ganesha, in February-March 2025. The subjects of the study were student theses stored in the department's library. The theses studied were written by the undergraduate chemistry education students who studied the high school students' chemical mental models for their final research project (denoted as ‘researcher’). Overall, 15 theses were found about chemical mental models as their research topic in the range of year between 2017 until 2020. Data collection was carried out using a checklist and analyzed descriptively to obtain a profile of students' chemical mental models and to describe and explain the factors that cause the formation of alternative mental models in students' minds.

Data source validation was conducted by examining the suitability of the mental model test instrument used by the thesis authors to collect data. All thesis studies used mental model tests to collect data. The tests consist of two levels: the first level consists of multiple-choice questions at the macroscopic level, and the second level consists of open-ended questions to justify the answer choices at the first level. The second-tier test requires explanations at the submicroscopic and symbolic levels. Each test was validated by two experts, followed by a try-out to determine the validity of the items and the reliability of the test instrument empirically. Methodologically, the tests were suitable for data collection. Furthermore, to enhance the validity of the collected data, the data were confirmed and rechecked by the thesis authors (Tracy, 2013).

There are similarities in the data analysis used in these theses to classify students' mental models, namely referring to the views of (Sendur et al., 2010). Students' mental models are grouped into the following three categories. First, scientifically correct mental models (SC), if the answer and explanation are scientifically correct (answers at three levels of chemical representation are correct). Second, partially correct mental models (PC), if the answer is scientifically correct, but the reasoning is incorrect, or vice versa (answers at three levels of chemical representation are some correct, some incorrect). Third, specific misconceptions of mental models (SM), if the answer and explanation are not scientifically acceptable (answers at all three levels of chemical representation are incorrect). The first type of mental model is called a conceptual model or scientific mental model, while the second and third types of mental models are grouped as alternative mental models. Apart from these three types of mental models, there is still one situation where the three criteria above are not met, namely no response (NR). This condition occurs because students do not provide answers related to the three levels of chemical representation so that their mental models cannot be measured and classified.

Result and Discussion

The fifteen theses used as research subjects were written by respective authors based on the results of their research in Bali Province can be seen in Table 1.

Table 1. Information of codes and its topic research.

Code	Research Topic	Reference
A	Thermochemical mental models	(Dewi et al., 2018)
B	Mental models of chemical bonding	(Pristya, 2020)
C	Organic chemistry mental models	(Riskadayanti, 2017)
D	Reaction rate mental model	(Santhi, 2019)
E	Mental models of intermolecular interactions	(Satriawan, 2018)
F	Mental models of molecular structures	(Sucitra, 2016)
G	Mental models of colligative properties of solutions	(Hidayah, 2018)
H	Mental models of electrolyte and non-electrolyte solutions	(Suari, 2018)
I	Electrochemical mental models	(Puspayanti, 2018)
J	Stoichiometric mental models	(Kunde, 2018)
K	Hydrocarbon mental models	(Pujiasih, 2018)
L	Mental models of the periodic properties of the elements	(Wahyuni, 2018)
M	Chemical equilibrium mental models	(Alawi, 2018)
N	Mental models of redox reactions	(Negara, 2019)
O	Mental models of salt hydrolysis	(Eky, 2019)

The data from the analysis and discussion of these theses related to the profile of students' mental models and the factors causing the formation of alternative mental models are as follows.

Profile of Students' Chemical Mental Models

Study material on students' chemical mental model research in the fifteen theses that were used as research subjects, including thermochemistry, ionic and covalent bonds, organic chemistry, reaction rates, intermolecular interactions, molecular structure, colligative properties of solutions, electrolyte and non-electrolyte solutions, electrochemistry, stoichiometry, hydrocarbons, the periodic system of elements, chemical equilibria, redox reactions, and hydrolysis of salts. Based on the results of the analysis of students' answers to the two-tier test, which contains student responses about the macroscopic level of chemistry and its explanations at the submicroscopic and symbolic levels, students' chemical models can be grouped into three, namely scientifically correct (SC), partially correct (PC), and specific misconceptions (SM) mental models. In addition to the three types of mental models, there was one condition that could not be classified, namely no response (NR). The profile of the mental model of chemistry for high school students is shown in Figure 1.

The data in Figure 1 shows that students' scientific mental models or conceptual models of the chemistry material taught in high school were classified as very low, namely 0–28.65%. Partially correct was the dominant mental model, namely 23.03%–90.58%. It happened because the students did not master the three levels of chemistry correctly. In general, students understand chemistry at the macroscopic level well, but experience difficulties related to the symbolic meanings used and were unable to explain macroscopic chemical phenomena based on the particle structure of matter at the submicroscopic level. This finding is in line with previous research which made mental models as the object of the research (Amiruddin et al., 2025; Suja et al., 2021; Wiji & Mulyani, 2018).

Specific misconception mental models reach 0.48%–58.53%. This happens because there was a reasoning error in the minds of students so the mental model that was formed is contrary to the scientific truth agreed upon by experts. In this study, this condition occurred due to student errors in predicting phenomena related to the properties of substances at the macroscopic level followed by argumentation errors at the submicroscopic and symbolic levels. Lastly, there were no responses, their mental model could not be determined with certainty. Chemistry concepts that did not get a response from students were 0–49.07%. The data shows that many students did not answer the mental model test questions given by the researcher.

The low percentage of scientific mental models in students' mind is caused by the complexity of the chemical concepts they learn, which involve both concrete (macroscopic) and abstract (submicroscopic) aspects. This abstract aspect is what causes chemistry to often be considered a difficult science. Various research results show that learning chemistry using dual representation models has been proven effective in improving students' conceptual models (Djoa, 2023). In accordance with the Dual Coding Theory (DCT) and the Cognitive Theory of Multimedia Learning (CTML), information provided in the form of words (verbal) and models (visual) of invisible aspects will form a complete and scientifically correct mental model before being stored in long-term memory (Mayer, 2009; Solso et al., 2010; Woolfolk, 2013)

Given that chemistry concepts are taught in junior high school and high school students encounter many alternative mental models, strengthening the formation of scientifically correct chemical mental models should be carried out from the time students first learn chemical concepts. This view is in line with Piaget's personal constructivist learning theory, which views students as actively reconstructing their knowledge based on their prior knowledge and new information received during the learning process (Woolfolk, 2008). Therefore, the chemistry learning process in junior high school should be carried out by science teachers who have complete mastery of the content and learning strategies of chemistry. Then, at higher levels, reviews need to be conducted to ensure that students' chemical mental models are classified as scientifically correct.

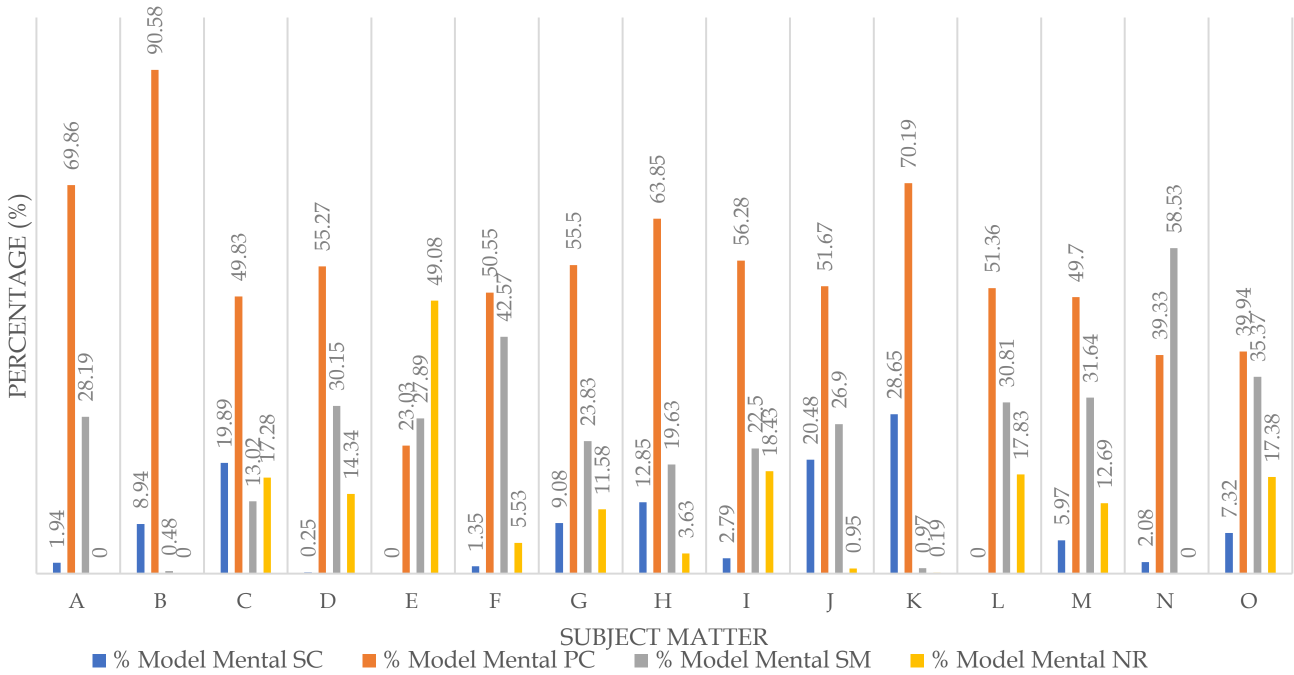

Figure 1. Profile of the Mental Model of Chemistry for High School Students

Factors Causing the Formation of an Alternative Model

Based on the analysis of the observations and interviews results conducted by researchers, as well as students' answers to the given mental model tests, it can be explained that the factors causing the formation of alternative mental models in students' minds, may come from internal and/or external factors, as explained below.

1. *Low understanding at the submicroscopic level.*

This condition was the main problem for students in learning chemistry. As a result, the mental models that were formed were unable to establish the interconnection of the three chemical levels and tend to only be partially correct mental models. For example, students know ionic compounds were hard but brittle. However, students were unable to explain the fragility of compounds based on the ionic structures (Riskadayanti, 2017). From the results of observations made by researchers, it was found that teachers tended to teach chemical concepts at the macroscopic level directly using chemical symbols, including conveying formulas and mathematical calculations without explaining what happened at the submicroscopic level. This condition almost occurs in learning all subjects of high school chemistry, especially in learning stoichiometry, redox reactions, and electrochemical cells (Kunde, 2018; Negara, 2019; Puspayanti, 2018).

In order to enhance understanding at the submicroscopic level, chemistry instruction should involve the simultaneous delivery of audio and visual information. Model-based learning or instructional videos specifically designed to help students recognize and understand the three levels of chemical representation have been shown to improve students' understanding and scientifically correct mental models (Rosmita et al., 2024; Siregar & Kurniawati, 2022; Supriadi et al., 2023; Yuanphan & Nuangchalerm, 2023).

2. *Errors in reasoning at the submicroscopic level that underlie the properties of substances.*

As an example of findings, students were able to predict the boiling point of propyne to be higher than propane, but the argument put forward was that higher energy was needed to break the triple bond in propyne (Riskadayanti, 2017). The boiling process did not involve breaking bonds between atoms, but only interactions between molecules. Conceptually, the presence of the π bond on the terminal carbon atom caused the propyne molecules to undergo charge polarization so that the dipole-dipole forces on the propyne are stronger than the London forces on the propane (Wade, 2006).

3. *Mistakes due to overgeneralization.*

With regard to the properties of the elements in the periodic system, students tend to think in general terms, without considering the characteristics of the elements in question. As an example of findings, the ionization energy of aluminum (Al) was said to be higher than that of magnesium (Mg) because in the periodic system of elements, aluminum is to the right of magnesium (Wahyuni, 2018). The general principle was that in one period the ionization energies of the elements increased from left to right because the atomic radius decreased. Meanwhile, the ease of removing electrons that underlies the ionization energy not only depends on the atomic radius, but also on the stability of the electron configuration. The two valence electrons of the Mg atom are in the 3s orbital (paired) so it was more stable than one electron in the 3p orbital of the Al atom. Thus, the ionization energy of Mg > Al (Wahyuni, 2018). Other findings, compounds containing hydroxyl groups (-OH) are thought to be basic due to the overgeneralization of Arrhenius acids and bases as also found by previous researchers (Suja & Nurlita, 2016).

4. *Ignorance about the meaning of the symbolic level.*

Symbols are very important for expressing chemical formulas, chemical reactions, states of matter, etc., including thermochemical equations (Dewi et al., 2018). Students' ignorance of the meaning of symbols in thermochemistry caused them to be unable to complete their chemical calculations and predict phenomena that occur at the macroscopic level, as was also found by other researchers (Wiji & Mulyani, 2018). The same condition also occurred in redox reactions (Negara, 2019), where students only got macroscopic and symbolic level information but did not know the meaning of the symbols used at the material particle level (submicroscopic level).

5. *Inability to draw the molecular structure of compounds.*

Students tended to draw molecular structures in two dimensions (Lewis structures) and were unable to draw three-dimensional structures. Students could not draw molecular geometric shapes by considering the number of bonding electron pairs and the number of lone electron pairs on the central atom in order to get the most stable structure. As a result, students were unable to determine the nature of organic compounds and hydrocarbons (Pujiasih, 2018; Satriawan, 2018; Sucitra, 2016).

The inability to describe molecular structures, which ultimately leads to an inability to explain the properties of compounds, was also found by Siregar and Kurniawati (2022). Their research findings showed that the group of students taught using Macromedia Flash-based learning media was more capable in describing the molecular structures of compounds than the control group. Their scientific mental model profile reached 70%, significantly higher than the control group's 37%.

6. *Lack of information related to the complexity of the problems encountered.*

As an example of findings, students determined the polarity of a compound directly from its Lewis structure. The polarity of a compound should be determined from its dipole moment, that is the vector sum of bond moments in the three-dimensional structure of the molecule, not from its Lewis structure. These data indicated a lack of student knowledge about the procedure for determining the polarity of compounds by considering the shape of the molecule, the electronegativity of the bonded atoms, and the vector sum of all bonding moments in the molecule (Satriawan, 2018; Sucitra, 2016). The findings of this study are in line with the results of research by Siregar and Kurniawati (2022), who found that the inability to draw molecular shapes will have an impact on students' low scientific mental models and inability to explain the properties of compounds.

7. *Ignorance about the type of solute particles.*

This condition caused students to be unable to write ionization/dissociation reactions of substances dissolved in the water correctly. As a result, students could not compare the electrical conductivity of solutions and the colligative properties of solutions (Hidayah, 2018; Suari, 2018).

8. *Ignorance of the macroscopic phenomena.*

Even though the students be able to memorize the basic laws of chemistry, they cannot apply the theory precisely because they do not understand the macroscopic properties of substances (Kunde, 2018). As a result, students only view stoichiometry and basic chemical laws as mathematical calculations, without understanding the physical phenomena and their explanations at the level of matter particles (submicroscopic level).

9. *Misunderstanding the concept of prerequisites.*

Students unable to determine the nature of the salt solution because they do not understand the strength of the acids and bases that make up the salt. As a result, the ions produced in salt dissolution are not followed by the correct hydrolysis reaction. The salt cations and anions both reacted with water which in turn caused the concentration of H^+ ions to equal the concentration of OH^- ions in the solution so that the nature of the salt solution becomes neutral (Eky, 2019).

10. The analogical fallacy that used in learning.

In order to explain chemistry concepts, teachers often use analogies to facilitate students' understanding. For example, to teach chemical equilibrium, the teacher used a seesaw game as an analogy (Alawi, 2018). This analogy has the potential to lead to misconceptions or alternative mental models because it only showed the macroscopic balance and not the submicroscopic changes. Meanwhile, chemical equilibrium was dynamic by involving submicroscopic changes in both directions at the same rate. This condition caused the reaction as if macroscopically it was over. On the other hand, teachers rarely use media to visualize abstract concepts at the particle level which makes learning chemistry difficult and gives rise to alternative mental models (Albaiti et al., 2022). Submicroscopic-level visualization really helped students to build a complete mental model of chemistry (Siregar & Kurniawati, 2022; Yuanphan & Nuangchalerm, 2023).

11. Mistakes in the content of teaching materials.

As an example of findings, there was a student's worksheet linking the polarity of compounds and the symmetry of their molecular shapes. It is stated that a symmetrical molecule will have a zero-dipole moment, so it is nonpolar. The statement is based on examples, such as CO_2 and $BeCl_2$ are linear, symmetrical, and nonpolar. Meanwhile, not all symmetrical molecules cause their compounds to be nonpolar, for example, in a water molecule (H_2O) with two pairs of lone electrons on the oxygen atom, the molecule is angular (like the letter V) and symmetrical (has a plane of symmetry), but the number of bond moment vectors is not the same with zero so it is polar. The findings of this study are in line with previous studies (Suja & Nurlita, 2016).

Other findings were related to exothermic and endothermic reactions using the example of changing the state of water and dissolving urea (Dewi et al., 2018). Both of these examples involved the release or absorption of heat, but no reaction occurred, so they were not suitable as examples of exothermic and endothermic reactions.

Factors causing the formation of alternative mental models in number 1 to 9 are classified as internal factors, while the last two findings are external factors. Various findings in this study about the factors that caused the emergence of alternative mental models were caused by the inability of students to build interconnections between the three levels of chemistry, as a result of a lack of understanding of the abstract submicroscopic level. The findings of this study complement the results of a literature review conducted by (Atikah et al., 2023), which stated that the formation of students' chemistry mental models is influenced by students' prior knowledge, teachers, learning resources, and learning models. The findings of this study are also in line with the view of Albaiti et al. (2022), who stated that mental model formation is influenced by internal factors, including intelligence level, formal reasoning, interest, motivation, and emotional aspects; as well as external factors, including the learning models implemented by educators and textbooks used by students and teachers. For this reason, as an implication of the findings of this study, in teaching chemistry teachers should introduce chemical concepts, covering three levels of chemical representation, and train students to solve various chemical problems by providing explanations at the submicroscopic level.

Conclusion

The results of this study showed the profiles of high school students' chemical mental models, consisting of conceptual models (0–28.65%); partially correct mental models (23.03%–90.58%), and specific misconception mental models (0.48%–58.53%), and no response which means the mental model could not be determined (0–49.07%). The main causes of the formation of alternative mental models are students' low understanding at the submicroscopic level and incorrect learning strategies. The implications of this research are finding direct teachers and lecturers to implement learning strategies that fully introduce all three levels of chemical representation, for example by using interactive video-based media so that the submicroscopic structure and dynamics of chemistry can be more clearly visualized to students.

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Author Contributions

Conceptualization, I.W.S and I.G.L.W.; methodology, I.G.L.W. and I.B.N.S.; validation, I.W.S. and I.B.N.S.; resources, I.W.S., I.G.L.W., and I.B.N.S.; data curation, I.W.S. and Q.A.H.; writing—original draft preparation, I.W.S, I.G.L.W., and I.B.N.S.; writing—review and editing, I.W.S. and Q.A.H.; visualization, I.W.S. and Q.A.H.; supervision, I.W.S.; project administration, Q.A.H. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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