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RESEARCH ARTICLE

Exploring Educational Effects of Classes Using GeoGebra for Crystal Structure Learning

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ABSTRACT

This study explored the educational value of using GeoGebra in lessons on crystal structure learning. To this end, a four-session course utilizing GeoGebra was conducted for 50 students taking Chemistry II at M Girls' High School in Jeollanam-do. The understanding of crystal structure concepts was assessed through pre- and post-tests, and changes were examined using paired sample t-test. Course satisfaction was measured in the post-test using a 5-point Likert scale and open-ended questions. The results are as follows: First, the students showed a significant increase in understanding all three crystal structures ($p<0.001$), particularly noted by the decrease in non-responding students in the post-test, indicating meaningful changes for students with lower learning levels. Second, the course satisfaction, as measured by the Likert scale, was high, ranging between 4.46 and 4.62. The students' responses highlighted that the use of GeoGebra not only aided in conceptual learning but also facilitated scientific inquiry. This study suggests the value of tools like GeoGebra in science education, particularly in utilizing sub-microscopic like the particle model.

Key words: GeoGebra, crystal structure, chemistry, sub-microscopic

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Introduction

Chemistry is a discipline that explains macroscopic phenomena at a microscopic level (Lee et al., 2023). Because the microscopic level is difficult to observe, many scholars have argued that this characteristic of chemistry makes concept learning challenging (Gilbert & Treagust, 2009; Jensen, 1998; Johnstone, 2000). Johnstone (1991) proposed the sub-microscopic level, which connects the macroscopic and microscopic levels, to address these difficulties in learning chemistry concepts. According to Chittleborough & Treagust (2007), the sub-microscopic level substitutes the unobservable microscopic level with observable models like particle models, and is recommended for use in teaching strategies to help students imagine the microscopic level.

There has been considerable research on the sub-microscopic approach in various studies of chemistry concepts. Park et al. (2020a) analyzed representations of acid-base models in

Chemistry II textbooks, noting that they presented these models at the sub-microscopic level without distinguishing between the Arrhenius and Brønsted-Lowry models. Furthermore, Park et al. (2020b) explored the ability of high school seniors to represent phenomena at the sub-microscopic level, finding deficiencies in their ability to explain macroscopic phenomena such as pH changes in buffer solutions and dissociation of weak acids at the microscopic level. They argued that frequent exposure to the sub-microscopic level is necessary to enhance students' ability to connect macroscopic and microscopic levels. This lack of ability to represent at the sub-microscopic level is not unique to South Korean students (Gkitzia et al., 2020); similar findings have been reported internationally, indicating a general need for research to facilitate students' approach to the sub-microscopic level.

Research related to the sub-microscopic approach in chemistry has often focused on reversible reactions such as dynamic equilibrium and acid-base equilibrium (Kim et al., 2019; Lee et al., 2023). The complexity of reversible reactions, which consider the simultaneous movement of particles and both forward and reverse reactions, particularly challenges students (Chiu et al., 2002). However, there is a deficiency in students' ability to approach simpler concepts at the sub-microscopic level as well, indicating that while research on complex concepts is necessary, studies on simpler concepts should also be conducted. One such simpler concept, yet lacking in sub-microscopic representation ability, is crystal structure (Choi & Paik, 2020). Both the 2009 and 2015 revised curricula address simple cubic, body-centered cubic, and face-centered cubic structures. Unlike reversible reactions, where particles move randomly, the particles in a crystal structure are fixed, making it relatively easier to approach at the sub-microscopic level. Nevertheless, Choi & Paik (2020) reported that students had difficulties understanding the three-dimensional geometric structures and positions of atoms. Current chemistry textbooks primarily use styrofoam balls to create and understand three-dimensional crystal structures at the sub-microscopic level. Kim & Paik (2021) attempted to enhance understanding of crystal structures through actual experiments using sub-microscopic approaches, but their study, which connected textbook representations of crystal structures to experiments, showed limitations in helping students independently construct and understand crystal structures at the sub-microscopic level.

The 2015 revised science curriculum suggests the development and use of models, mathematical thinking and computer utilization as functions (MOE, 2015). Jackson (1996) stated that using computers can enhance the ability to understand complex and dynamic micro-world systems in science. Furthermore, several studies have shown that educational software provides opportunities for students to design and evaluate their own models (Brady et al., 2015; Kim et al., 2019). Among these, GeoGebra is particularly advantageous for dynamically implementing geometric structures and enhancing understanding of them (Kostić et al., 2016). Programs like GeoGebra, which use particle models to construct actual crystal structures, make it very easy for students to approach crystal structures at the sub-microscopic level. Accordingly, Choi & Paik (2020) developed a teaching strategy using GeoGebra to enhance the sub-microscopic approach in crystal structures. However, their study did not investigate the educational effectiveness of the developed materials. Jeon & Kang (2021) also examined the effectiveness of teaching crystal structures using the Fusion 360 program with science high school students, finding that using the program to create particle models for crystal structures helped students' concept learning. Although this research is meaningful in examining the effects of creating crystal structures in actual classes, its results cannot be broadly interpreted to include students from general high schools who are less familiar with computer programs. Additionally, since Fusion 360 is a paid program, its use in general schools may be restricted.

This study aims to explore the educational value of using computer programs to approach crystal structures at the sub-microscopic level in general high schools. The computer program to be used is GeoGebra, which is free and widely used in math classes in schools. After conducting lessons using GeoGebra, this study will explore the value of these lessons by focusing on changes in students' understanding of crystal structures and their satisfaction with the lessons using GeoGebra.

Research Method

Participants

This study was conducted with 50 students enrolled in Chemistry II at M Girls' High School located in Jeollanam-do. Before the study began, the participants were informed about the purpose of the research and were advised that they could withdraw at any time. None of the 50 students dropped out during the study. M Girls' High School, where the participants are enrolled, is a general high school situated in an urban area of Jeollanam-do. The overall academic achievement of the participants, assessed through a nationwide academic performance test, showed an even distribution among the top, middle, and lower tiers. Among the students, three had prior experience with directly using the GeoGebra program, while the others were not familiar with it.

Lesson Design Using GeoGebra

The students participating in the study attended lessons that covered the basic concepts of crystal structures. Therefore, lessons using GeoGebra were designed and conducted for these students as shown in Table 1.

Table 1. The content of each lesson session

Session	Topic	Content
1	Introduction to GeoGebra program	-Introduction and practice on how to use GeoGebra
2	Simple cubic structure/ Body-centered cubic structure	-Creating simple cubic and body-centered cubic structures with the GeoGebra program -Characteristics of simple cubic and body-centered cubic structures (unit cell, stacking arrangement, number of adjacent particles)
3	Face-centered cubic structure	-Creating face-centered cubic structure with the GeoGebra program -Characteristics of face-centered cubic structure (unit cell, stacking arrangement)
4	Characteristics of various crystal structures	-Number of nearest neighboring particles surrounding a single particle in a crystal structure -Number of particles per unit cell in solid crystal structures -Calculation of the occupancy rate in solid crystal structures

The first session was an introduction to the GeoGebra program. Since most of the students in the study had never used the GeoGebra program before, this session provided an opportunity for them to learn and practice using it. If the students are already familiar with the GeoGebra program, this session could have been skipped.

In sessions 2 and 3, students were guided to create simple cubic, body-centered cubic, and face-centered cubic structures using the GeoGebra program. They recorded any mistakes made during the construction process, noted their corrections, and presented the characteristics of each crystal structure. To understand how particles occupy space in solids, they also discussed how circles of the same size could fill a two-dimensional space and explored the stacking and characteristics of simple cubic, body-centered cubic, and face-centered cubic structures. These sessions allowed students to directly created crystal structures using the GeoGebra program. To do this successfully, they needed to understand particle arrangement in each crystal structure, particularly the relationship between the edge length of a unit cell and the particle radius.

In the fourth session, students used the GeoGebra program to calculate the coordination number, the number of particles per the unit cell, and the occupancy rate of the crystal structures they had created. This process involved comparing which crystal structures used space more effectively and explaining why the face-centered cubic structure is represented as a more densely packed than the simple cubic and body-centered cubic structures, thereby deepening their understanding of crystal structures. If students encountered difficulties in creating crystal structures with GeoGebra, they were encouraged to seek help from their peers or refer to the supporting materials from Table 2 and Table 3.

Table 2. GeoGebra-assisted crystal structure creation support materials (Body-centered cubic)

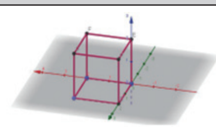
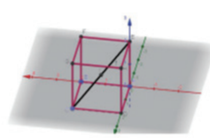
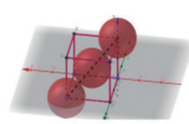
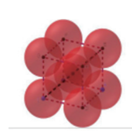
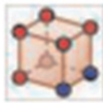
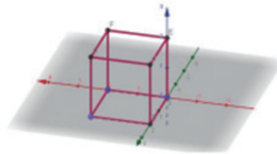
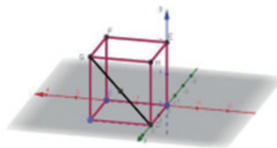
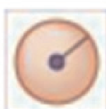
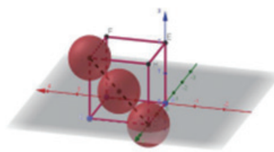
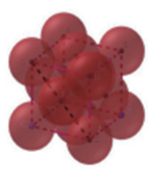
Step	Icon	3D graphics window	Explanation
1			1. Place two points to represent one edge of a cube. 2. Use the 'Cube Tool' to create a cube.
2	 		Use the 'Segment Tool' to measure the length of the cube's diagonal.
3			1. Use the 'Midpoint Tool' to create the midpoint of segment f. 2. To make the endpoints and midpoint of segment f the centers of three spheres, set the radius of each sphere to f/4. Create three spheres with a radius of f/4.
4			Create spheres with a radius of f/4 at each vertex of the cube.

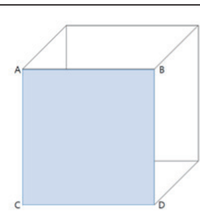
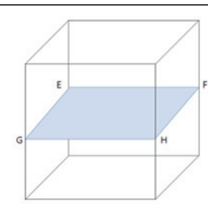
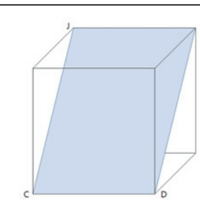
Table 3. GeoGebra-assisted crystal structure creation support materials (Face-centered cubic)

Step	Icon	3D graphics window	Explanation
1			1. Place two points to define one edge of a cube. 2. Use the 'Cube Tool' to create a cube.
2			Use the 'Segment Tool' to measure the length of the diagonal on one face of the cube.
3			1. Use the 'Midpoint Tool' to create the midpoint of segment f. 2. Set the radius of each sphere to f/4 to make the endpoints and midpoint of segment f the centers of the three spheres. Create three spheres with a radius of f/4.
4			Create midpoints on the diagonals of the remaining faces of the cube, and place spheres with a radius of f/4 at each midpoints.

Survey Tools

This study exploring the educational value of using GeoGebra in crystal structure learning employed two assessment tools. The first tool was used to measure the understanding of crystal structures, thereby gauging the effectiveness of the lessons using GeoGebra. For this purpose, a crystal structure comprehension test developed by Jeon & Kang (2021) was used, and three questions were finalized as shown in Table 4 after discussions with one field science teacher and two science education experts. Questions 1 and 2 required students to draw the arrangement of particles in three-dimensional space for simple cubic and body-centered cubic structures, after showing how the first, second, and third layers of a face-centered cubic structure are differently stacked. Question 3 asked whether particles arranged in space in a face-centered cubic structure could be represented on a two-dimensional plane after being cut along a specific cross-section; 3-1 addressed the understanding of an external cross-section, while 3-2 and 3-3 pertained to internal cross-sections.

Table 4. Test tool for understanding the concept of crystal structures

<table>
<tr><th>No.</th><th>Crystal</th><th colspan="3">Content</th></tr>
<tr><td rowspan="3">1</td><td rowspan="3">Simple cubic</td><td colspan="3">When arranging a simple cubic structure with spheres, please draw a diagram of the arrangement of spheres in each layer.</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td>First layer</td><td>Second layer</td><td>Third layer</td></tr>
<tr><td rowspan="3">2</td><td rowspan="3">Body-centered cubic</td><td colspan="3">When arranging a body-centered cubic structure with spheres, please draw a diagram of the arrangement of spheres in each layer.</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td>First layer</td><td>Second layer</td><td>Third layer</td></tr>
<tr><td rowspan="4">3</td><td rowspan="4">Face-centered cubic</td><td colspan="3">When representing the unit cell of a face-centered cubic structure as a cube, please draw a diagram showing the arrangement of spheres on the indicated cross-section.</td></tr>
<tr><td>3-1(ABCD)</td><td>3-2(EFGH)</td><td>3-3(HICD)</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td></tr>
</table>

To further explore the educational value of the lessons using GeoGebra, students' satisfaction surveys were conducted. The survey was developed with reference to the study by Kim & Kim (2021), which investigated the satisfaction with computer-based science inquiry lessons. A field science teacher and two science education experts collaborated to create an assessment tool consisting of six questions. Four of these questions used a 5-point Likert scale, while the remaining two were open-ended. The Likert scale questions assess four areas: 'recognition of lesson objectives, positive changes in spatial ability, assistance in understanding crystal structures, and support for the inquiry process and methods.' In the open-ended questions, students were asked to record the 'advantages of lessons using GeoGebra compared to traditional lessons' and 'the advantages and disadvantages compared to traditional investigations using styrofoam.' The students participating in this study had no prior experience conducting investigations using styrofoam ball. Therefore, to facilitate comparison with traditiVonal inquiry methods, videos were used to demonstrate and explain these traditional inquiry activities. Specifically, for the inquiry activities using styrofoam balls, the videos explained the process of creating three types of crystal structures and using a knife to examine their cross-sections. This approach ensured that even though the students had not experienced traditional lessons related to crystal structure learning, they were guided to enable comparisons with traditional inquiry-based lessons. After this process, the students were asked to answer questions comparing the traditional activities with the GeoGebra activity.

Data Collection and Analysis

To investigate the effectiveness of understanding crystal structures, data were collected using a pre-test and post-test single-group design. All 50 participants responded to both the pre-test and post-test. Each of the first two questions, which involved drawing the arrangement of each layer, was scored out of a maximum of 3 points, with 1 point awarded for each layer depicted. When scoring these drawings, the location of the particles relative to the vertices of the crystal structure was considered. For example, in question 1, if a student accurately drew the position of the particles at the same vertices for each layer, they received 1 point per layer. Since the crystal structure model presupposes solid billiard balls, points were deducted if the particles were drawn with gaps, similar to partial gaps that might arise. For question 3, each sub-question was scored out of a maximum of 3 points, with deductions made for any incomplete parts in the drawings similar to the examples seen in questions 1 and 2. The scoring was individually done by one science teacher and two science education experts, and discrepancies were discussed to finalize the scores, enhancing the validity of the grading. The scored results were then analyzed for significant differences using paired sample t-test, and the effect size was calculated using Cohen's d to identify which question had the greatest effect.

Regarding satisfaction with the lessons using GeoGebra, data were collected after the program concluded. For questions 1 to 4, which were on a Likert scale, basic statistics such as averages and standard deviations were calculated. Open-ended questions 5 and 6 were analyzed based on the keywords of the responses, and the classification process was repeated until saturation was reached with no further similar categorizations possible. This classification process was conducted in consultation with one science teacher and two science education experts to enhance the consistency of the results. Frequencies were calculated for responses corresponding to similar keywords. Not all 50 students responded to the open-ended questions, so the total frequency for each question was less than 50.

Results

The Effect of Lessons Using GeoGebra on Understanding Crystal Structures

The results of the paired sample t-test for the pre-test and post-test on the understanding of crystal structures related to simple cubic, body-centered cubic, and face-centered cubic structures are presented in Table 5. The post-test scores were statistically significantly higher than the pre-test scores for all three questions. Comparing the effect sizes using Cohen's d, the lessons using GeoGebra on crystal structures were relatively more effective in enhancing understanding of simple cubic and body-centered cubic structures than of face-centered cubic structure.

Table 5. The results on the understanding of crystal structure concepts

No.	Category	Sample	M(SD)	*t*	Cohen's d
1	Pre-test	50	1.63(1.10)	-6.175***	1.04
	Post-test	50	2.56(0.62)		
2	Pre-test	50	1.25(1.05)	-6.827***	1.00
	Post-test	50	2.20(0.83)		
3	Pre-test	50	1.45(1.09)	-8.640***	0.75
	Post-test	50	2.20(0.89)		

*** $p < 0.001$

In questions 1 and 2, with pertain to simple cubic and body-centered cubic structures, 9 students (18.0%) and 15 students (30.0%), respectively, scored zero in the pre-test, including non-responses. The frequency of zero scores, along with the average pre-test scores, suggests that students had relatively more difficulty understanding body-centered cubic structure. After lessons using GeoGebra, no students scored zero on question 1 (simple cubic structure) in the post-test, and only 3 students (6.0%) scored zero on question 2 (body-centered cubic structure). The significant improvement in students' understanding of crystal structures through lessons using GeoGebra is noteworthy. Additionally, it is also significant that the proportion of lower-tier students who were previously non-responsive in the concept understanding test has greatly decreased through this study.

Table 6 shows examples of student responses from the pre-test for question 1 on understanding simple cubic structure, and Table 7 shows examples from the pre-test for question 2 on understanding body-centered cubic structure. As seen in Table 6 and 7, many students lacked an understanding of how simple cubic and body-centered cubic structures are stacked in three dimensions. For example, some students depicted the simple cubic structure in an A-B-A arrangement, as shown in Student 1's response, or in an A-B-C arrangement, as seen in Student 2's response in Table 6. Similarly, many students struggled with understanding the stacking arrangement of the body-centered cubic, with some even drawing it as an A-A-A structure, as seen in student 3's response in Table 7, which also includes cases where the three-dimensional crystal structure was mistakenly represented in two dimensions. These examples highlight that students faced challenges in understanding the three-dimensional shape of crystals and the arrangement of layers. Additionally, when drawing particles of the same layer in simple cubic or body-centered cubic structures, many did not draw the particles touching each other but left spaces between them, as shown in responses of Student 2 and 4.

Table 6. The example of pre-test responses for question 1 (Simple cubic)

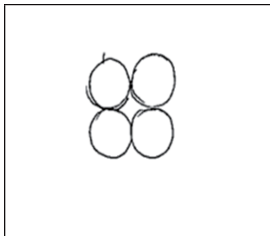
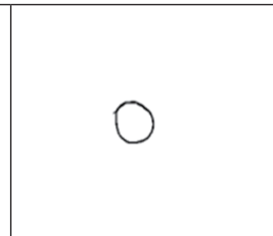
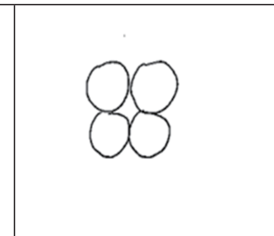
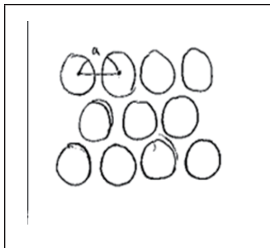
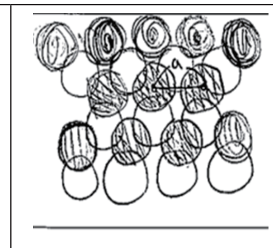
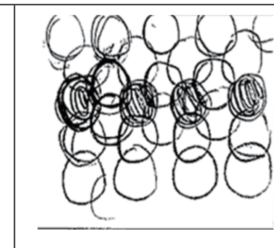
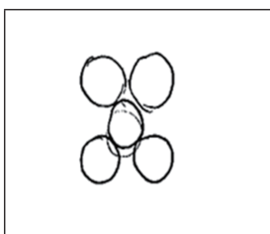
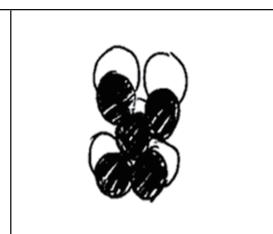
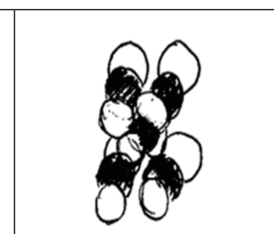
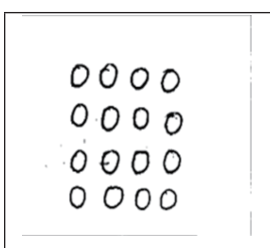
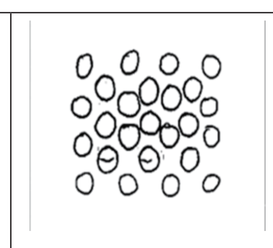
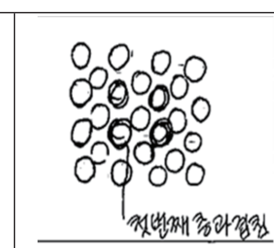
Student	Response		
(a) Student 1			
	First layer	Second layer	Third layer
(b) Student 2			
	First layer	Second layer	Third layer

Table 7. The example of pre-test responses for question 2 (Body-centered cubic)

Student	Response		
(a) Student 3			
	First layer	Second layer	Third layer
(b) Student 4			
	First layer	Second layer	Third layer

The reason students drew particles spaced apart rather than touching each other can be inferred from the way crystal structures are presented in textbooks. As shown in Fig. 1, textbooks depict the three-dimensional shapes of crystal structures in two forms. This presentation method was adopted by all six Chemistry II textbooks under the 2015 revised curriculum. The crystal structure model considers particles as solid billiard balls, stacked in various ways to represent different crystal structures (Kim et al., 2020). Therefore, illustrations that show particles touching each other and filling space represent the crystal structure model. However, the space-filling model can make it difficult to understand the three-dimensional positions of the particles. To make the arrangement of three-dimensional particles clearer, the space-filling model is sometimes simplified into a ball-and-stick model. While both presentation methods are useful for understanding crystal structures, the Chemistry II textbooks do not explain the differences between these two methods when presenting them. Consequently, it can be assumed that the students participating in this study thought the particles were separate, as reflected in their responses. In this study, when lessons on crystal structures using GeoGebra were conducted based on the space-filling model, there was an increase not only in understanding the three-dimensional stacking of particles but also in understanding how particles that touch each other form crystal structures.

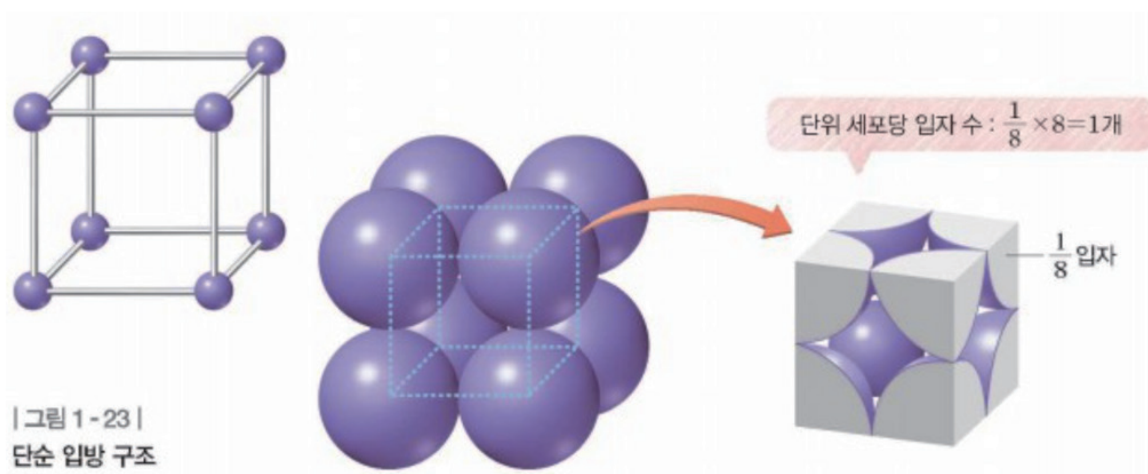


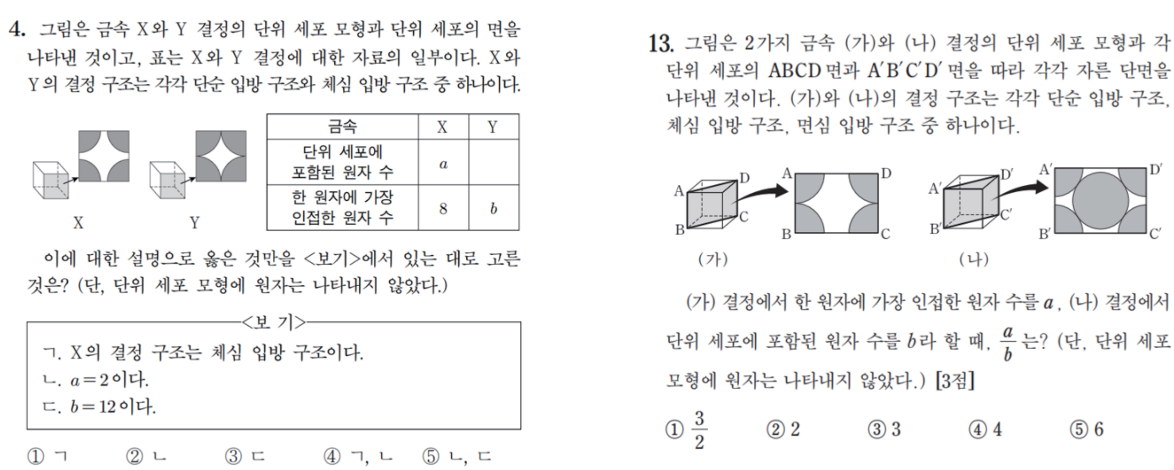
Fig. 1. The presentation method of simple cubic structures in textbooks (Park et al., 2022)

Table 8 presents the pre-test, post-test, and paired sample t-test results for question 3, which related to the face-centered cubic structure, focusing on the detailed sub-questions. The average pre-test score for sub-question 3-1, which involves predicting the external cross-section of the unit cell, was 1.94, higher than the pre-test averages for sub-questions 3-2 and 3-3, which were 1.34 and 1.06, respectively. Sub-question 3-3, which involves predicting internal diagonal cross-sections, had the lowest average score. This suggests that understanding internal aspects of crystal structures is more challenging than understanding external ones. This difficulty is not unique to the students in this study. For example, questions related to crystal structures are often included in the Korean College Scholastic Ability Test (CSAT) and mock exams, where understanding is assessed through questions about cross-sections of crystal structures, as shown in Fig. 2. While the actual correct rates for CSAT and mock exam questions issued by the Korea Institute of Curriculum and Evaluation are not publicly disclosed, the estimated correct rates provided by EBSi, based on data entered by examinees, suggest no significant difference from the results observed in this study. Fig. 2, panels (a) and (b), show different cross-sections of crystal structures; however, the approach to solving these questions is similar, as both require determining number of atoms within the unit cell and the number of nearest neighboring atoms based on the given cross-sections. Nevertheless, the 2019 CSAT Chemistry II question 4 (Fig. 2(a)), which presented an external cross-section, had a high correct rate of 83.0%, while the June 2018 mock exam Chemistry II question 13 (Fig. 2(b)), which presented an internal cross-section, had a lower correct rate of 55.3%. This suggests that a significant number of students, including those in this study, have a limited understanding of the internal cross-sections of crystal structures. Additionally, the issues of particles being drawn spaced apart and the difficulty of arranging particles in three-dimensional layers, observed in the questions on simple cubic and body-centered cubic structures were also prevalent in the pre-test responses for question 3.

Table 8. The detailed results for question 3

No.	Category	Sample	M(SD)	t	Cohen's d
3-1	Pre-test	50	1.94(1.12)	-6.034***	1.03
	Post-test	50	2.84(0.50)		
3-2	Pre-test	50	1.34(0.99)	-5.409***	0.55
	Post-test	50	1.88(0.97)		
3-3	Pre-test	50	1.06(0.97)	-8.057***	0.94
	Post-test	50	1.88(0.77)		

***$p < 0.001$


4. 그림은 금속 X와 Y 결정의 단위 세포 모형과 단위 세포의 면을 나타낸 것이고, 표는 X와 Y 결정에 대한 자료의 일부이다. X와 Y의 결정 구조는 각각 단순 입방 구조와 체심 입방 구조 중 하나이다.

금속	X	Y
단위 세포에 포함된 원자 수	a	
한 원자에 가장 인접한 원자 수	8	b

이에 대한 설명으로 옳은 것만을 <보기>에서 있는 대로 고른 것은? (단, 단위 세포 모형에 원자는 나타내지 않았다.)

<보 기>
ㄱ. X의 결정 구조는 체심 입방 구조이다.
ㄴ. $a=2$이다.
ㄷ. $b=12$이다.

① ㄱ ② ㄴ ③ ㄷ ④ ㄱ, ㄴ ⑤ ㄴ, ㄷ

13. 그림은 2가지 금속 (가)와 (나) 결정의 단위 세포 모형과 각 단위 세포의 ABCD 면과 A′B′C′D′ 면을 따라 각각 자른 단면을 나타낸 것이다. (가)와 (나)의 결정 구조는 각각 단순 입방 구조, 체심 입방 구조, 면심 입방 구조 중 하나이다.

(가) 결정에서 한 원자에 가장 인접한 원자 수를 a, (나) 결정에서 단위 세포에 포함된 원자 수를 b라 할 때, $\frac{a}{b}$는? (단, 단위 세포 모형에 원자는 나타내지 않았다.) [3점]

① $\frac{3}{2}$ ② 2 ③ 3 ④ 4 ⑤ 6

(a) 2019 College Scholastic Ability Test Chemistry II Question 4

(b) June 2018 Mock Exam Chemistry II Question 13

Fig. 2. College scholastic ability test and mock exam questions related to cross-sections of crystal structures

The use of GeoGebra in crystal structure lessons significantly improved understanding of the cross-sections of crystal structures across all three sub-questions of question 3, as indicated by statistically significant increases in concept comprehension (p<0.001). An examination of the effect size using Cohen's d showed the largest effect for understanding external cross-sections. The effect sizes for understanding internal cross-sections, specifically the horizontal and diagonal cross-sections, were 0.55 and 0.94, respectively. Although the effect size for the horizontal cross-section was somewhat lower than that for the external cross-section, there was no significant difference in the effect size for the diagonal cross-section. This suggests that lessons using GeoGebra can effectively enhance the understanding of crystal structure cross-sections.

Student Satisfaction with Lessons Using GeoGebra

The analysis of the four Likert scale questions from the satisfaction survey for the lesson where students modeled crystal structures using GeoGebra is shown in Table 9. The average satisfaction scores for the four questions ranged from 4.46 to 4.62, indicating that students positively evaluated the lessons using GeoGebra. The highest satisfaction was recorded for question 4, where students acknowledged learning about the inquiry process and methods through these lessons. The fact that using GeoGebra not only helped students improve their three-dimensional understanding of crystal structures but also allowed them to engage in scientific inquiry by modeling the structures themselves is significant. These results suggest that lessons using GeoGebra can be used not only as a tool for concept learning but also for fostering scientific inquiry.

Table 9. The results of student satisfaction with lessons using GeoGebra

No.	Content	Min	Max	Mean	SD
1	Did you clearly understand the lesson objectives during the lesson using GeoGebra?	3	5	4.60	0.63
2	Do you believe the lesson using GeoGebra led to positive changes in your spatial abilities?	2	5	4.46	0.75
3	Do you think the lesson using GeoGebra helped you understand crystal structures?	2	5	4.52	0.81
4	Do you think the lesson using GeoGebra was helpful for learning the inquiry process and methods?	3	5	4.62	0.56

This interpretation is also reflected in the results of question 5, which asked about the advantages of lessons using GeoGebra compared to traditional lessons, as shown in Table 10. The highest proportion of students (31.9%) evaluated the lessons using GeoGebra as 'inquiry-centered' compared to traditional lessons. Specific responses included: "While the worksheet involved listening and asking, I liked actually figuring out and making the structure myself.", "It's different because instead of just listening to the teacher explain, I could make the structure myself through GeoGebra and understand the principles.", and "I did not struggle to understand the difficult concepts while making the crystal structures myself."

Responses mentioning 'various modeling attempts and learning from errors' accounted for 17.0%. Specific responses included: "It wasn't just about listening to the theory but also about trying it out and thinking about mistakes and improvements.", and "Using the program to make models myself and recording the mistakes and improvements during the process made it different.". As highlighted by Kim & Kim (2021), a key feature of inquiry using computer-based programs like GeoGebra is that they allow multiple attempts, making students more tolerant of trial and error during the inquiry process and reducing the stress associated with conducting inquiries.

Furthermore, 8.5% of responses highlighted 'enhancement of scientific thinking' through self-modeling of various crystal structures. Specific responses included: "The process of creating three-dimensional structures with the program and being able to keep modeling until understanding is achieved, and later thinking about radius and occupancy rate, improved my thinking skills more than just attending lessons." and "Traditional lessons were mostly about studying from the textbook, so I often moved on without fully understanding, just by looking at pictures. However, designing with the program from the basic principles to understanding how things are structured helped me understand and design better."

These three advantages are all inquiry-related benefits and together account for over half (57.4%) of the responses, confirming the potential of GeoGebra as a tool for inquiry.

Additionally, responses such as "Understanding crystal structures and unit cells was faster when I engaged in activities compared to traditional lessons.", "I understood better while conducting the crystal structure lesson with the program instead of just sitting and listening to lessons." and "I used to just take notes while the teacher explained at the blackboard, but this time I did it myself during the lesson, which increased my focus and understanding." indicate a significant percentage (25.5%) of students observed an 'increase in concept understanding.' Other responses noted a decrease in the learning burden compared to traditional lessons (4.3%), and some indicated that the lessons sparked interest (4.3%).

Table 10. The advantages compared to traditional lessons

Content	Frequency(%)
Inquiry-centered lessons	15(31.9)
Increase in concept understanding	12(25.5)
Various modeling attempts and learning from errors	8(17.0)
Enhancement of scientific thinking	4(8.5)
Understanding of three-dimensional space	3(6.4)
Reduction in learning burden	2(4.3)
Stimulation of interest	2(4.3)
Learning the GeoGebra program	1(2.1)

The traditional method of exploring crystal structures involves using styrofoam balls to create various crystal structures. In fact, three out of the six Chemistry II textbooks under the 2015 revised curriculum present exploratory activities using styrofoam balls, while one textbook offers a similar activity using marshmallows. Of the remaining two textbooks, one includes an exploratory activity that involves interpreting crystal structures through illustrations, and the other does not include any activity related to crystal structures. Thus, current textbooks mostly offer standardized activities involving styrofoam balls for exploring crystal structures. The students' responses comparing these traditional methods to the lesson using GeoGebra are shown in Table 11.

Table 11. Advantages and disadvantages of lessons using GeoGebra compared to lessons using styrofoam

Category	Content	Frequency(%)
Advantages	Completion of structure in a short time	10(20.0)
	Ability to rotate and view from multiple directions, including the interior	10(20.0)
	Can be made more accurately and precisely	9(18.0)
	Easy to modify	8(16.0)
	Ability to create various structures	4(8.0)
	Simple preparation materials	3(6.0)
	Efficiency	3(6.0)
	Collaboration and feedback with peers	2(4.0)
	No waste produced	1(2.0)
Disadvantages	Takes time to learn the program	3(75.0)
	Eye strain	1(25.0)

Compared to traditional exploratory activities, the biggest advantage identified by students when using GeoGebra was the ability to quickly create crystal structures (20.0%). Additionally, while the traditional activity using styrofoam balls requires cutting the structure with a knife to check internal cross-sections, which ruins the structure and prevents further inspection, GeoGebra allows rotation to view cross-sections from multiple directions and inspect various internal cross-sections (20.0%). This aligns with question 3 on concept understanding, suggesting GeoGebra as a more powerful tool for comprehending crystal structures in a three-dimensional manner compared to traditional methods. Other advantages of computer-based exploration included more accurate and precise creation (18.0%), ease of modification (16.0%), the ability to create various structures (8.0%), simplicity of materials (6.0%), and efficiency (6.0%). Students also mentioned that using the program facilitated peer assistance and easy feedback (4.0%). Unlike the traditional styrofoam-based exploration, which produces waste and can be environmentally harmful, modeling crystal structures with a computer program avoids such issues.

Four students mentioned disadvantages of using GeoGebra compared to traditional methods. Three out of them (75.0%) noted the time required to learn the GeoGebra program. One student mentioned eye strain from prolonged computer use during class. These drawbacks are common in computer-based exploratory lessons and have been noted in various studies (Kim & Kim, 2023; Noh & Paik, 2015). It is important to assess students' proficiency with the program beforehand and tailor the lessons accordingly. Additionally, planning the time spent using the program during lessons is crucial to avoid issues related to excessive computer use.

Discussion

This study examined the educational value of using GeoGebra in lessons on crystal structure learning, focusing on changes in conceptual understanding and class satisfaction. The findings showed positive outcomes in both conceptual understanding and class satisfaction. Based on these results, the following discussions are presented.

Based on the concept test results, students demonstrated a statistically significant improvement. This suggests that lessons using GeoGebra can serve as an effective tool for learning sub-microscopic concepts. Several studies have highlighted the potential of GeoGebra for conceptual learning (Gökçe & Güner, 2022; Uwurukundo et al., 2024;

Zulnaidi et al., 2024). However, while its use as a conceptual learning tool has been widely explored in mathematics education, it remains relatively underexplored in science education. In the context of science education, GeoGebra studies have mostly been limited to simple experiential activities utilizing its AR features (Tomaschko & Hohenwarter, 2019). In contrast, this study utilized GeoGebra as a more active inquiry tool, enabling students to model and investigate crystal structures for conceptual understanding. Therefore, the findings of this study not only demonstrate the potential of GeoGebra for learning scientific concepts but also underscore its value as a tool for student inquiry. This value as an inquiry tool is further supported by the class satisfaction survey results involving GeoGebra (Table 9 & 10).

The use of GeoGebra in lessons has proven to be an effective tool for promoting a sub-microscopic approach in chemistry classes. In the pre-test on conceptual understanding, students struggled to derive various properties—such as the number of particles per unit cell, packing efficiency, and coordination number—related to the 3D arrangement of particles and the assumption that these particles behave like solid billiard balls. However, the significant improvement observed in the post-test results indicates that students' ability to approach crystal structures from a sub-microscopic perspective has been enhanced. Studies such as Van der Net et al. (2006) typically involve using styrofoam balls to understand the 3D arrangement of particles in crystal structures. While these traditional styrofoam balls-based investigations meet the assumptions of crystal structure models that consider particles as solid billiard balls, they pose challenges when modifying the assembled structures. In science education, modeling-based learning is emphasized to encourage active learning among students (Nielsen & Nielsen, 2021). The process of revising models through evaluation is deemed crucial (Gilbert & Boulter, 1998; Pluta et al., 2011; Schwarz & White, 2005; Snir et al., 2003). In this context, the modeling activities related to crystal structures are significant because they transcend the limitations of traditional investigations, allowing for more authentic modeling.

Moreover, traditional inquiry methods require students to cut the constructed model precisely to examine the internal cross-sectional structure, demanding a high level of accuracy. Such precision is often required in modeling activities (Chiy & Lin, 2019). The use of GeoGebra in lessons, which allows manipulation via a computer, addresses the precision challenges inherent in traditional investigations, making it a valuable tool for overcoming these limitations.

Additionally, safety concerns arise in activities that involve using knives to examine internal cross-sectional structures. As various experiments are conducted in science education, safety issues continue to emerge (Galasso et al., 2023). Utilizing computer programs like GeoGebra has been identified as a potential solution to these safety challenges.

Conclusions

This study explored the educational value of lessons where students used GeoGebra to create crystal structures themselves, focusing on understanding of crystal structure concepts and lesson satisfaction. To this end, four sessions were conducted with 50 students taking Chemistry II at M Girls' High School in Jeollanam-do. Concept understanding was measured using a single-group pre-test and post-test design, and changes were analyzed using paired sample t-test. Lesson satisfaction was surveyed using a tool consisting of Likert scale questions and open-ended questions, and the educational value was explored through basic statistics and keyword analysis. The conclusions drawn from this study are as follows:

First, GeoGebra can be utilized as one of several tools for conceptual learning in science education. In particular, students encountered greater difficulties in complex scenarios, such as understanding the cross-sectional structure of a face-centered cubic structure, compared to other structures. These complexities are challenging to address with 2D textbook illustrations or traditional styrofoam balls-based inquiry. The medium-to-large effect size observed in this study for understanding FCC cross-sections supports the argument that GeoGebra is effective in overcoming these challenges. Moreover, there was a sharp decline in the proportion of students who left questions unanswered or scored zero on the post-test compared to the pre-test. This finding suggests that GeoGebra is especially valuable for helping students with lower academic performance understand concepts in three-dimensional space.

Second, it was confirmed that GeoGebra holds value as an inquiry tool in science lessons. A key objective of science education is to cultivate scientific literacy, and scientific inquiry is an essential component for enhancing this literacy (Abd-El-Khalick et al., 1998). Due to recent changes in the educational environment, there has been a shift from traditional laboratory-based science inquiry to a variety of inquiry activities, and related research is actively being conducted. According to the research results, many students reported the advantages of using GeoGebra in lessons, particularly regarding inquiry activities. Students specifically noted that it was easy to modify the crystal structures they created, and that they could construct them with precision. These responses align with the elements of authentic inquiry proposed by Chinn & Malhotra (2002), demonstrating that GeoGebra is a useful tool for facilitating inquiry in science lessons.

Limitations and Suggestions

This study confirmed the educational value of using GeoGebra in learning crystal structures. However, there are several limitations to interpreting the results of this study.

First, while the lessons were conducted using 3D modeling with GeoGebra to facilitate student learning, the assessment tools required students to draw on 2D paper by hand, creating a mismatch between the evaluation tools and the learning tools. Even if students had a solid grasp of the concepts through 3D manipulation and modeling, such understanding might not be fully reflected in the 2D evaluation tools. This limitation suggests that the post-test results may underestimate students' conceptual understanding. Despite this potential underestimation, the statistically significant differences still demonstrate the value of lessons using GeoGebra. However, to more accurately assess the true effectiveness of these lessons, it is necessary to resolve the mismatch between the evaluation and learning tools.

Second, there are limitations in comparing the results of lessons using GeoGebra with those using traditional styrofoam balls. To minimize this issue, this study presented the traditional styrofoam ball inquiry lesson through videos, with each process explained by the teacher. However, such indirect experiences may not be equivalent to direct, hands-on experiences. Therefore, to obtain more accurate comparisons, future studies should focus on students who have directly experienced both types of inquiry.

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Conflicts of Interest

The author(s) declared no conflicts of interest.

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