Emeti Sargın
Master's degree in Chemistry Education, Chemistry Teacher
Private KOSBİ Zülfü-Mevlüt Çelik Vocational and Technical High School, Izmir, Türkiye
ORCID ID 0009-0004-7220-0287
emetti77@gmail.com

Melis Arzu Uyulgan
PhD in Chemistry Education, Professor
Dokuz Eylul University, Faculty of Education, Department of Chemistry Education, Izmir, Türkiye
ORCID ID 0000-0002-2815-2642
melis.cekci@deu.edu.tr

TECHNOLOGY-SUPPORTED 3D MODELING AND PRINTING IN CHEMISTRY TEACHER EDUCATION

Abstract. This study addresses persistent difficulties in understanding abstract chemical concepts such as hybridization, hybrid orbitals, and molecular geometry in chemistry teacher education. Due to their invisible and highly abstract nature, these topics are often associated with misconceptions and limited spatial reasoning among pre-service teachers. The study examines how technology-supported three-dimensional (3D) modeling and printing practices are incorporated into learning processes and how these practices relate to conceptual understanding. A mixed-methods research design was adopted to examine both conceptual outcomes and participants' perspectives. Quantitative data were collected through a two-tier Molecular Geometry Diagnostic Test administered before and after a semester-long instructional implementation. Qualitative data were obtained through focus group interviews. The findings indicate notable improvements in participants' understanding of hybridization, molecular structures consistent with the octet rule, and valence shell electron pair repulsion–based molecular geometries, alongside a reduction in common misconceptions. Qualitative findings revealed that interaction with both digital and physically printed 3D models supported the concretization of abstract concepts, enhanced spatial reasoning, and promoted meaningful learning through a combination of visual and tactile engagement. Participants emphasized that hands-on modeling activities helped them establish stronger connections between symbolic representations and molecular-level structures. Despite these pedagogical benefits, limitations related to technical infrastructure and insufficient prior training were identified as challenges to sustainable implementation. Overall, the results highlight the practical value of integrating 3D visualization and modeling practices into chemistry teacher education programs, underscoring the need for systematic professional development opportunities to support pre-service teachers' technological and pedagogical competencies.

Keywords: 3D printing; 3D molecular modelling; conceptual understanding of molecular structures; pre-service chemistry teachers

1. INTRODUCTION

The production of scientific knowledge and its transmission across generations have historically relied heavily on the contributions of models and modeling. Beyond being an inherent method in the NOS (Nature of Science), modeling is recognized as a fundamental tool for understanding, testing, and communicating scientific processes [1]. At the core of scientific reasoning, models are indispensable for explaining and making sense of complex, abstract, and non-observable phenomena. Scientists employ models not merely as representational tools but also as integral components of hypothesis generation, explanation, and prediction [2]. In this respect, modeling constitutes a significant learning process for students in terms of developing an understanding of the nature of science.

Within this context, the science education literature treats modeling not only as a method used by scientists but also as an effective instructional strategy. Particularly in disciplines such as chemistry, physics, and biology, where abstract concepts are prevalent, learning through

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modeling is considered highly valuable for deepening students' conceptual understanding and fostering their scientific reasoning skills [3], [4].

Model-based learning is consistent with the fundamental principles of constructivist learning theory. Rather than receiving knowledge in a passive manner, students are expected to learn through experiencing, questioning, and reconstructing knowledge [5]. Within this process, models assist students in developing mental representations and facilitate the comprehension of complex scientific concepts in more simplified and accessible forms [6]. Scientific modeling is not limited to representing objects; it also encompasses the description of processes, relationships, and mechanisms associated with these objects. Thus, modeling functions not only as a visual aid but also as a cognitive activity [7].

Recent studies in chemistry education have further emphasized the importance of modeling [8], [9]. Chemistry as a discipline is inherently intertwined with microscopic concepts such as atoms, molecules, bonding structures, and orbitals, which are not directly observable [10]. These concepts are generally represented at three levels: macroscopic (observable phenomena), microscopic (molecular/atomic level), and symbolic (formulas, equations) [11]. Presenting these three representational levels in an interconnected manner facilitates a more holistic understanding of chemical concepts [12]. However, research has demonstrated that students often struggle to establish meaningful connections across these levels, particularly in conceptualizing structures at the microscopic level [13]. Traditionally, physical models such as ball-and-stick kits have been employed in the teaching of microscopic concepts. Nevertheless, these model kits have inherent limitations, as they fail to fully capture molecular volumes or the actual size and shape of atoms; for instance, the thin rods representing bonds may lead to the misconception that electron density is localized solely between nuclei [14]. In this regard, the literature suggests the implementation of more effective modeling activities in chemistry education to minimize such misconceptions [15].

In recent years, with the widespread integration of technological tools into education, modeling practices have acquired a new dimension [15]. In their study, Grumman and Carroll [14] developed high-resolution molecular models based on van der Waals radii, alongside 3D-printed electron density isosurface models designed to kinaesthetically simulate steric interactions and reaction mechanisms. These models enable students to experience steric effects concretely and interactively, particularly those observed in bimolecular substitution (SN2) and elimination (E2) reactions. Similarly, Penny et al., [16] contributed significantly to chemistry education by designing scalable and modular molecular and orbital models. These models were structured both for large-group visual demonstrations and for hands-on manipulation in workshop settings, thereby facilitating the concretization of key chemical concepts such as stereoisomerism, hybridization, and aromaticity, while enriching the learning process.

Abdinejad et al., [10] in their study on the use of augmented reality (AR) in chemistry education, demonstrated that this technology – which superimposes virtual objects onto real-world images – substantially enhances the visualization of abstract chemical structures that students often find difficult to grasp intuitively. Through applications such as ARchemy, static textbook images are replaced by dynamic 3D models and animations, allowing students to explore molecular structures and interactions from multiple perspectives, angles, and levels of magnification. This approach enhances conceptual understanding and renders learning more interactive and enduring. Furthermore, computer-aided design (CAD) has facilitated the sharing of digital models in chemistry education, enabling researchers worldwide to generate molecular models using the same 3D printing files [17]. Platforms such as the NIH 3D Print Exchange provide accessible files for virtually any molecule. Advanced modeling capabilities, including the ability to print multifunctional materials in a single step, have paved the way for the development of interactive tools that cannot be produced through traditional methods [18].

Collectively, these technologies highlight that modeling is not limited to prototyping but plays a transformative role in developing functional tools for both chemistry research and education.

However, the effective integration of these advancements into educational contexts depends largely on the primary agents of implementation – teachers – who must be able to employ these tools both accurately and pedagogically. Teachers represent the central actors in transferring technology-based learning resources into classroom practice. Research clearly indicates that chemistry teachers can create novel types of physical models through 3D printing [14], [16]. Consequently, the sustainability of contemporary educational approaches largely hinges on enhancing teachers' knowledge and skills in technology integration. It is not sufficient for teachers merely to be familiar with the technology; they must also be capable of incorporating these tools in ways that facilitate students' understanding, which is of critical importance for effective and innovative chemistry instruction. Furthermore, integrating technological elements into lessons and providing students with opportunities for inquiry and exploration significantly contributes to conceptual understanding and knowledge transfer.

In particular, three-dimensional (3D) modeling technologies stand out as powerful tools that support learning in fields such as chemistry, where abstract concepts dominate [19]. These technologies provide students not only with the ability to visualize atomic and molecular structures but also with opportunities to interact with them and construct their own models. Among the tools afforded by technology in educational settings, 3D printers transform virtually designed models into tangible three-dimensional objects [20]. In this way, students gain the opportunity to concretize abstract structures from virtual environments and experience them directly. This process is particularly valuable in disciplines such as chemistry, where abstract concepts are often challenging to learn, as it facilitates understanding and enhances students' levels of conceptual learning. Indeed, research has demonstrated that the use of three-dimensional (3D) printing technologies in education enhances students' active participation in the learning process and contributes to making learning more meaningful and lasting by concretizing abstract concepts into tangible forms [16], [18]. Through this technology, students can directly experience concepts such as molecular geometry, bond types, isomerism, and symmetry elements by examining molecular models they have constructed themselves [21].

The effective integration of such technologies into education is directly related not only to teachers' pedagogical knowledge but also to their technological literacy. At this point, it is crucial that teachers position modeling tools not merely as visual aids but as pedagogical instruments that deepen conceptual learning, promote inquiry, and foster the development of scientific reasoning skills. However, current research indicates that many educators lack the technical expertise, time, and resources necessary to integrate 3D printing technologies into classroom practice. Song [22] noted that teachers often encounter structural limitations, such as "keychain syndrome" (remaining confined to small, trivial models), stemming from resource and material deficiencies. Such conditions frequently discourage teachers from experimenting with these tools and, consequently, hinder the adoption of 3D printing in educational settings [23]. Nevertheless, a significant gap identified in the literature is the limited availability of systematic solutions addressing the structural and pedagogical challenges that teachers face when incorporating 3D printing into instructional material development. Pre-service teachers, likewise, have pointed to inadequate professional development as a barrier to technology integration [24]. They often associate the effective use of 3D printers and technology in general with goals such as visualizing course content, increasing student engagement, teaching previously inaccessible concepts, integrating resources into curricula, and collaborating with administrators. However, their pedagogical knowledge, practical skills, and self-efficacy are not yet at the level required to achieve these goals. Consistent with this, research reveals that pre-service teachers encounter both internal barriers (lack of knowledge, insufficient competence, insecurity, reluctance) and external barriers (time constraints, lack of professional

development, access issues, maintenance problems, equipment reliability, and insufficient support from administrators and parents) in the process of technology integration [25]. In addition to gaps in knowledge and skills, pre-service teachers often experience a lack of confidence due to limited opportunities to gain hands-on experience with technology integration [26].

In this regard, the need for an educational technology course grounded in practical experiences is frequently emphasized in literature, as such training is considered to play a critical role in improving pre-service teachers' competencies in technology integration [27]. Taken together, these considerations underscore the necessity of systematically investigating how pre-service chemistry teachers' technology-supported modeling activities are reflected in both their conceptual understanding and their pedagogical approaches. However, there remains a limited number of studies that explicitly examine how technology-supported instructional processes influence pre-service chemistry teachers' understanding of abstract chemical concepts such as molecular geometry, which highlights the significance of the present study. This study, therefore, contributes to the literature by bridging the gap between the technology-supported instructional process and pre-service chemistry teachers' conceptual understanding of core molecular concepts.

The research goal. The purpose of this study is to examine pre-service chemistry teachers' conceptual understanding of hybridization, hybrid orbitals, and molecular geometries through an instructional process supported by 3D visualization technologies. As part of the instructional process, pre-service chemistry teachers actively participated in creating three-dimensional representations of chemical concepts using 3D modeling software and 3D printing tools. In this context, the study also evaluates the impact of this instructional process on pre-service teachers' understanding of chemistry concepts and their views on the use of technology in chemistry teaching.

Accordingly, the main question of the study is: What are pre-service chemistry teachers' conceptual understandings of hybridization, hybrid orbitals, and molecular geometries, and what are their views on an instructional process supported by 3D visualization technologies, including 3D modeling software and 3D printing applications?

Based on this problem statement, the following sub-questions are addressed:

1. What is the level of pre-service chemistry teachers' conceptual understanding of hybridization, hybrid orbitals, and molecular geometries after participating in an instructional process supported by 3D visualization technologies?

2. Is there a statistically significant difference between the pre-service chemistry teachers' pre-test and post-test scores on a two-tier diagnostic test related to hybridization, hybrid orbitals, and molecular geometries after participating in an instructional process supported by 3D visualization technologies?

3. What are the pre-service chemistry teachers' views regarding the instructional process supported by 3D visualization technologies in chemistry teaching?

2. RESEARCH METHODS

In this study, the impact of pre-service chemistry teachers' self-designed molecular models, produced with the aid of a 3D software program and a 3D printer, on their conceptual understanding was examined. To achieve this aim, a mixed-methods research approach was adopted. Mixed-methods research involves the collection, analysis, and interpretation of both qualitative and quantitative data to provide deeper and more holistic answers to research questions. The primary rationale for employing this approach is that different types of data complement one another, thereby enhancing the validity and reliability of research findings [28].

A concurrent triangulation design was employed in the study [28]. Within this design, quantitative and qualitative data were collected and analysed simultaneously, and the findings were interpreted together. Quantitative data were gathered through the administration of a two-tier diagnostic test and analysed using statistical methods, while qualitative data were obtained through focus group interviews and examined using thematic analysis. By capitalizing on the multifaceted evaluation opportunities offered by mixed methods research, the study provided a detailed account of the effects of modeling supported by 3D visualization technologies on pre-service chemistry teachers' conceptual understanding of hybridization, hybrid orbitals, and molecular geometries. The study employed a concurrent triangulation design, as adopted by Creswell and Plano Clark [28], as shown in Figure 1.

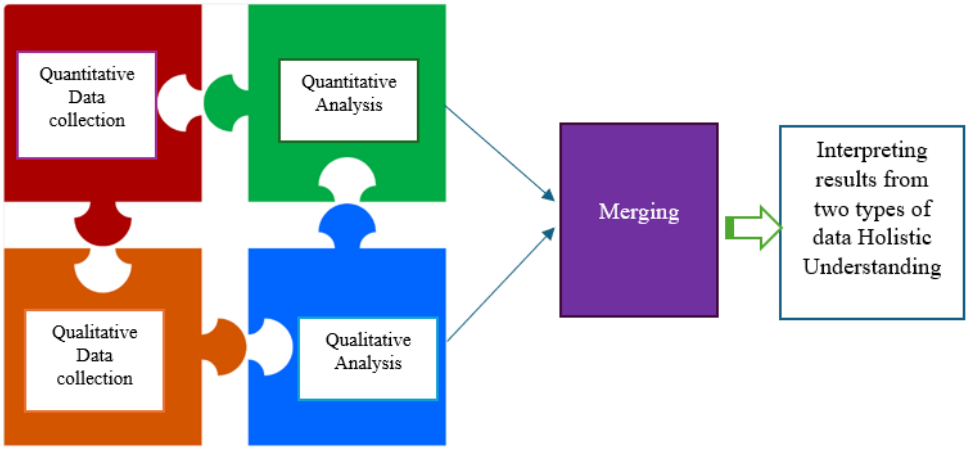

Figure 1. The concurrent triangulation design

2.1. Quantitative dimension of the study

Quantitative data were collected through a one-group pre-test–post-test experimental design. To measure the change in pre-service teachers' levels of conceptual understanding, the *Two-Tier Molecular Geometry Diagnostic Test* was administered before and after the implementation in Table 1.

Table 1

One-group pre-test–post-test experimental design of the study

Groups	**Pre-Test**	**Implication**	**Post-Test**
One-group Pre-service Chemistry Teachers (N:22)	Two-Tier Molecular Geometry Diagnostic Test	Technology-supported modeling activities using 3D software (ChemDoodle) and a 3D printer	Two-Tier Molecular Geometry Diagnostic Test

2.2. Qualitative dimension of the study

Qualitative data were obtained through focus group interviews conducted to explore in depth the participants' views on the instructional process supported by 3D visualization technologies. This method allows participants to express their opinions and perceptions in detail on a specific topic. In this study, focus group interviews were structured to elicit pre-service teachers' thoughts and experiences regarding 3D modeling and printing activities. The interviews were conducted using structured questions, audio-recorded, and analysed using thematic analysis.

By analysing quantitative and qualitative data together, the impact of the study process on the pre-service teachers' conceptual understanding was evaluated in a multifaceted manner.

2.3. Participants

The study group consisted of 22 senior pre-service chemistry teachers enrolled in the Faculty of Education at a state university in the western part of Türkiye during the spring semester of the 2023–2024 academic year. Of the participants, 77.3% were female (N=17) and 22.7% were male (N=5). Participants were selected using a purposive random sampling method. This method allows for the selection of information-rich individuals based on specific criteria while also incorporating randomness, thereby helping to reduce bias. The criteria for participant selection included being a senior student and demonstrating sufficient technological competence to participate in three-dimensional modeling activities. All participants had completed courses such as "Information Technologies" and "Instructional Technologies" during their undergraduate education, which facilitated their participation in 3D modeling and printing activities. During the study, researchers provided brief training and guidance on the necessary software and applications.

2.4. Data collection tools

The data collection process was conducted using two different instruments: the "Two-Tier Molecular Geometries Diagnostic Test" and focus group interviews. The use of multiple data collection tools increased data diversity, enabling a more comprehensive evaluation. Participation in the study was voluntary, and the researchers informed pre-service teachers to provide honest, sincere, and candid responses.

2.4.1. Two-tier molecular geometries diagnostic test (MGDT)

The "Two-Tier Molecular Geometries Diagnostic Test" (MGDT) was used to determine pre-service chemistry teachers' conceptual understanding of hybridization, hybrid orbitals, and molecular geometries. Developed by Uyulgan, Akkuzu, and Alpat [29], the two-tier MGDT consists of a total of 25 questions. In the two-tier diagnostic test format, participants are asked to provide the reasoning behind each answer they select. The test's validity and reliability analyses were conducted in previous studies. In this research, the test was used directly as a data collection instrument without any modification or adaptation of items. The test was administered twice, before and after the 3D modeling and printing activities, and the data obtained were used to evaluate changes in participants' conceptual understanding.

Two-tier diagnostic tests allow for the assessment not only of the correct or incorrect answers but also of the reasoning behind their responses. In both the pre- and post-test applications, participants were given 60 minutes to complete the test. In the first tier, participants were asked to select the answer they believed to be correct from the options given, while in the second tier, they were required to explain the reasoning for their selection. This method serves as an effective tool for identifying the pre-existing knowledge and conceptual understanding of pre-service teachers.

2.4.2. Focus group interviews

The focus group interviews were conducted to determine pre-service chemistry teachers' views on the 3D modeling and printing activities. Within this scope, participants were asked questions regarding the key components of the research, allowing them to freely express their experiences. The interview questions were carefully designed to align with the study's theoretical framework and research questions. To ensure clarity and scientific adequacy, expert opinions were consulted during the development process. Initially, relevant studies in the literature were reviewed to inform the formulation of questions that could effectively capture participants' perspectives. The interview protocol consisted of six focus group questions designed to explore changes in participants' conceptual understanding of hybridization, hybrid

orbitals, and molecular geometries. The draft questions were then reviewed and discussed by the researchers and three subject-matter experts, and revisions were made based on their feedback regarding content relevance and clarity of language. This process resulted in the final version of the interview form.

This method was employed to complement the statistical findings with participants' perspectives and to gain deeper insight into the effects of 3D modeling and printing activities on pre-service teachers. The focus group interviews were conducted face-to-face by the researchers in two sessions, with voluntary participation. Prior to the interviews, participants were informed about the study's purpose and provided written consent. With participants' permission, the sessions were audio-recorded to prevent data loss, and field notes were taken during the interviews.

2.5. Research process

The research process consisted of five main stages planned over a 12-week period. The stages and weekly workflow are presented in Figure 2.

In the first stage, pre-service teachers were provided with general information about the research's purpose, scope, and methodology. Subsequently, a pre-test was administered to determine their conceptual understanding of hybridization, hybrid orbitals, and molecular geometries. In the second stage, the ChemDoodle 3D software was introduced to the pre-service teachers for teaching hybridization, hybrid orbitals, and molecular geometries, and a hands-on training process was conducted. Since these topics are typically modelled in traditional teaching approaches using textbooks, blackboard explanations, hand drawings, or at most materials such as modeling clay, they often remain at an abstract level for learners. Within this context, the teaching process in the present study was enriched through both 3D software training and integrated 3D printer-supported applications, thereby offering an alternative, technology-based instructional method. The ChemDoodle 3D software used in the training serves as an educational digital tool that allows users to model, rotate, and examine molecular structures. Although the software offers a 14-day trial period, full functionality requires a paid license. For the purposes of this study, a one-year license was obtained through project funding, and the software was used by the researchers during the instructional implementation. Within the scope of this study, hands-on tasks were assigned to pre-service teachers using the ChemDoodle 3D program. Initially, pre-service teachers were asked to model different molecular geometries based on the VSEPR (Valence Shell Electron Pair Repulsion) theory, focusing on various AX_n types. In this context, fundamental molecular geometries such as linear (AX_2; e.g., CO_2), trigonal planar (AX_3; e.g., BF_3), tetrahedral (AX_4; e.g., CH_4), trigonal pyramidal (AX_3E; e.g., NH_3), and bent/angular (AX_2E_2; e.g., H_2O) were studied. In addition, more complex structures such as trigonal bipyramidal (AX_5; e.g., PCl_5) and octahedral (AX_6; e.g., SF_6) were also included in the modeling activities. Through this process, pre-service teachers had the opportunity to observe in a 3D environment how bonding and lone electron pairs around the central atom determine molecular geometry. They examined the 3D models by rotating, zooming, and viewing them from different perspectives, allowing for a deeper analysis of spatial arrangements. Following these structured activities on fundamental molecular geometries, they were given a more open-ended task. In this phase, they were asked to investigate and model the geometry of any molecule of their choice using the software. This task enabled them to move beyond predefined examples and explore a variety of molecular structures, facilitating the transfer of prior knowledge to new contexts and promoting a higher level of conceptual understanding. At the same time, this process encouraged independent exploration and supported the use of three-dimensional modeling tools as an active learning

resource. The training lasted 6 course hours and was structured to deepen pre-service teachers' understanding of the topics.

In the third stage, the XYZ Printing da Vinci 1.1 Plus 3D printer was used to turn the digitally produced models into tangible products. This printer was chosen due to its affordable price and user-friendly design. Physical models were created after participants received instruction on the printer's working principles, the materials utilized, and the model transfer procedures. These models were used to discuss chemical properties like molecular geometry, bond types, and bond angles.

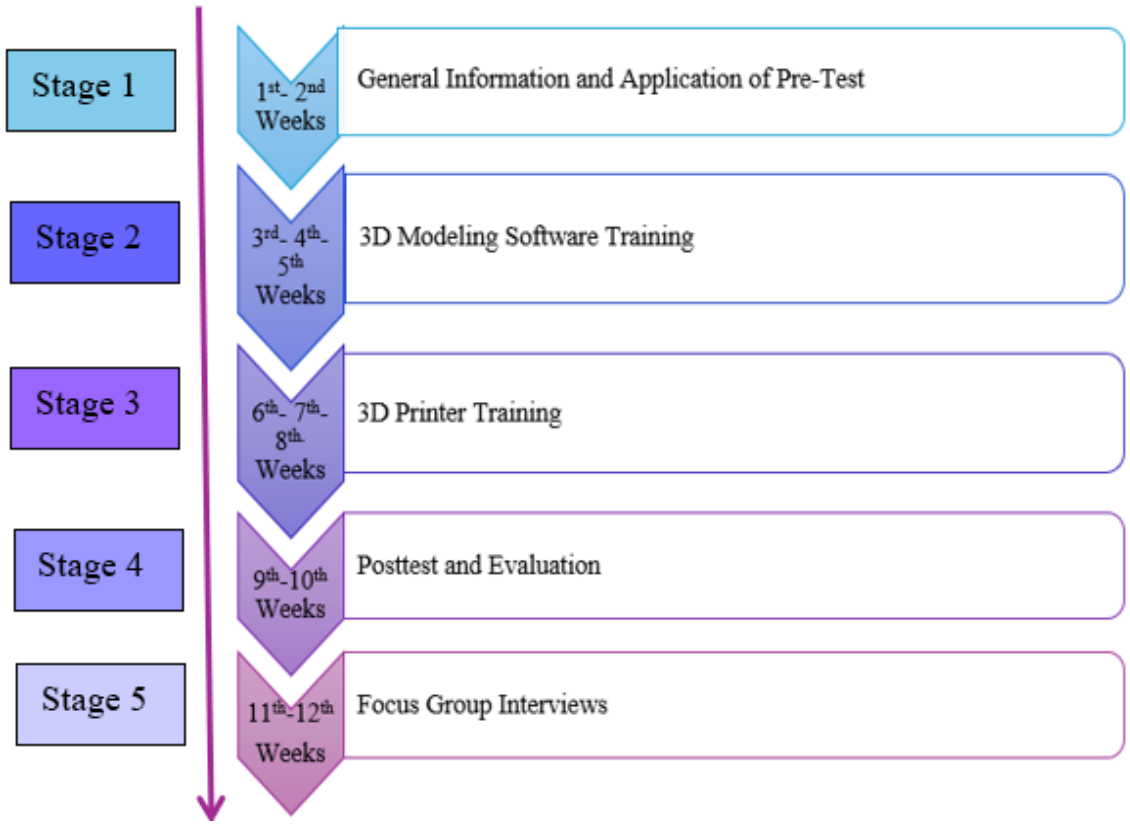

Figure 2. The research process

Figure 3 shows the design process of a Methane molecule carried out in the study. In the fourth stage, the impact of the instructional activities supported by 3D visualization technologies on conceptual understanding was assessed by administering a post-test and comparing the results with the pre-test. Finally, focus group interviews were conducted with the pre-service teachers to discuss their experiences, perceptions, and the contributions of technological applications to the field of chemistry education. These interviews also addressed challenges encountered during the three-dimensional modeling and printing process.

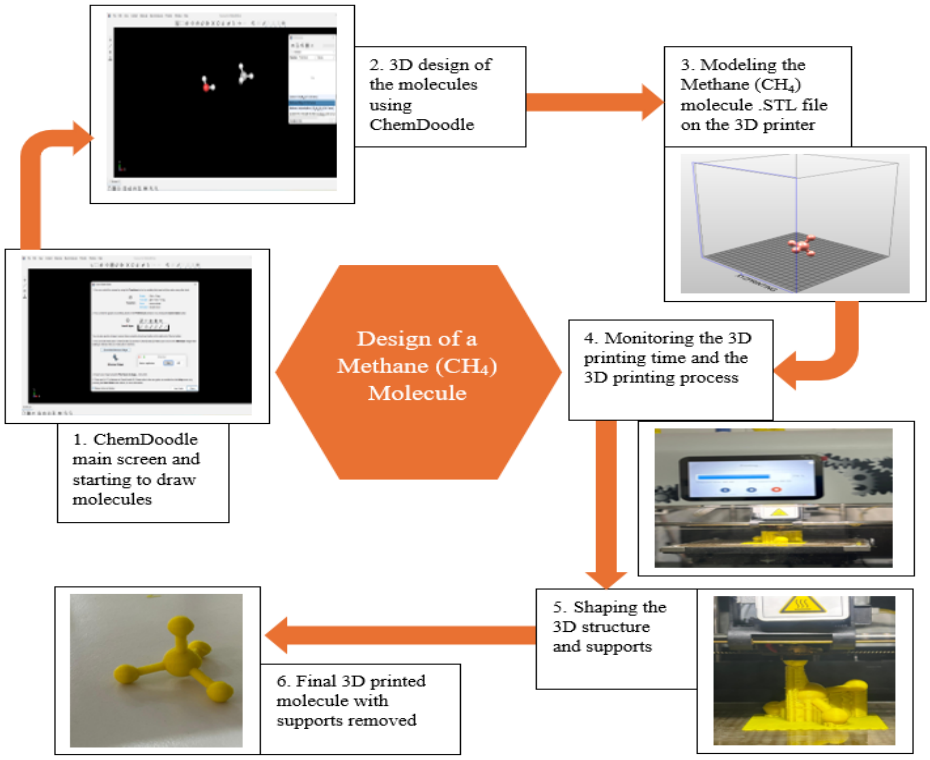

Figure 3. Design of a Methane (CH_4) molecule using 3D technologies

2.6. Data analysis

2.6.1. Analysis of the two-tier MGDT

The data analysis of the two-tier MGDT was conducted by considering both the first and second tiers. In the analysis of the first tier, responses were evaluated based on whether the chosen options were correct or incorrect. For the second tier, the explanations provided by pre-service teachers for their selected options were examined in terms of their scientific accuracy. In the combined evaluation of the two tiers, the criteria presented in Table 2 were used to categorize the responses according to their scientific value. In this process, the criteria employed by Uyulgan et al. [29] to determine levels of understanding were adapted to identify the conceptual understanding levels of pre-service teachers in this study.

Table 2

Evaluation criteria used for the analysis of the two-tier MGDT

Categories	**1st Tier**	**2nd Tier**	**Abbreviation**	**Score**
Correct Answer – Correct Explanation	Correct	Correct	CC	3
Incorrect Answer – Correct Explanation	Incorrect	Correct	IC	2
Correct Answer – No Explanation	Correct	Blank	CN	2
Correct Answer – Incorrect Explanation	Correct	Incorrect	CI	1
Incorrect Answer – No Explanation	Incorrect	Blank	IN	0
Incorrect Answer – Incorrect Explanation	Incorrect	Incorrect	II	0
No Answer – No Explanation	Blank	Blank	NN	0

According to these criteria, the maximum score that pre-service teachers could obtain for each question was determined as 3, while the minimum score was 0. The total maximum score that could be achieved from the test was 75. The scores were calculated, and based on these scores, evaluations were conducted regarding their levels of conceptual understanding in Table 3.

Table 3

Criteria and score ranges for levels of conceptual understanding

Levels of Conceptual Understanding	Score Range
Low	0–25
Medium	26–50
High	51–75

In line with the score ranges presented in Table 3, the conceptual understanding levels of the pre-service teachers were determined and classified according to their pre-test and post-test scores. To examine whether the pre-test and post-test scores conformed to a normal distribution, skewness and kurtosis values, as well as the results of the Shapiro-Wilk test (P-value >0.05), were considered. The analyses indicated that the data were normally distributed. Accordingly, a paired samples t-test was employed to examine the difference between the pre-test and post-test scores of the pre-service teachers.

To investigate the improvement in pre-service teachers' conceptual understanding, the effect size (eta-squared value) was calculated, and interpretations regarding this effect size were provided. All analyses were conducted using IBM SPSS Statistics for Windows, Version 21.0. The level of significance was set at $p < 0.05$. The findings obtained were analysed to evaluate the improvement in pre-service teachers' conceptual understanding and the impact of the 3D modeling process on this improvement from a scientific perspective.

2.6.2. Analysis of focus group interviews

The focus group interview data obtained within the scope of the study were analysed using thematic analysis. Thematic analysis is a systematic and flexible qualitative method employed to identify, analyse, and report meaningful patterns within data [30]. In this study, coding was conducted based on concepts derived directly from the data; meaningful units were identified and subsequently categorized under themes.

Researchers independently analysed the data. The coding process was conducted in accordance with the open coding approach, and concepts were derived directly from the participants' statements. The interview questions were structured around three main themes, and the responses obtained were coded and organized into categories according to these themes.

To determine inter-coder reliability, the percentage agreement method proposed by Miles and Huberman [31] was employed, resulting in an agreement rate of 89%. This rate indicates a high level of coding reliability. Furthermore, expert opinions were consulted to enhance the validity of the codes and themes, and conceptual consistency was carefully reviewed.

3. THE RESULTS

3.1. Quantitative results from the two-tier MGDT

This section presents the results of the two-tier MGDT, which was administered to address the first research question: determining the change in pre-service teachers' conceptual

understanding of hybridization, hybrid orbitals, and molecular geometries following instructional activities supported by 3D visualization technologies.

The scores obtained by the pre-service teachers from the two-tier MGDT were calculated and evaluated based on the predetermined criteria regarding their levels of conceptual knowledge. Figure 4 displays the percentage distribution of the pre-service teachers' pre-test and post-test score levels on the two-tier MGDT.

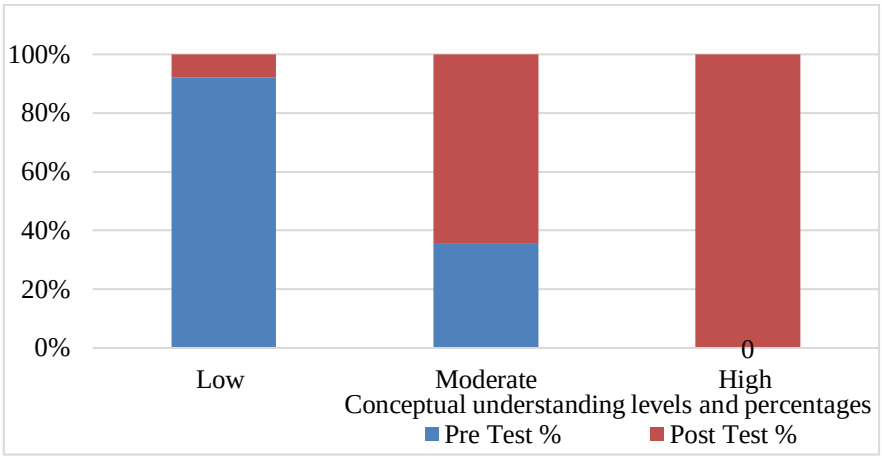

Figure 4. Percentage distribution of pre-service teachers' pre-test and post-test score levels on the two-tier MGDT

As shown in Figure 4, the distribution of pre-test scores indicated that the pre-service teachers were categorized into two levels: low (54.55%) and medium (45.45%), with none of them placed in the high category. In contrast, the distribution of post-test scores revealed a significant increase in the number of pre-service teachers at the medium (81.82%) and high (13.64%) levels. Additionally, there was a significant difference in the percentage of pre-service teachers at the low level (4.55%). This difference demonstrates that the pre-service teachers achieved higher conceptual knowledge scores in the post-test. Accordingly, it can be inferred that the 3D modeling and printing activities contributed to an improvement in their conceptual understanding.

Table 4 presents the differences between the pre-test and post-test mean scores of the pre-service teachers on the two-tier MGDT by subjects.

Table 4

Changes in pre-service teachers' pre-test and post-test mean scores on the two-tier MGDT

Subjects	**Pre-Test means scores**	**Post-Test means scores**	**Change**
Resonance	2.7	3.5	+0.8 (29.6%)
Octet Rule–Based Molecular Structures	1.3	2.6	+1.3 (100%)
Valence Shell Electron Pair Repulsion (VSEPR) Theory and Molecular Geometry	14.8	25.9	+11.1 (75%)
Hybridization	1.3	3.7	+2.4 (184.6%)
Molecular Orbitals	2.6	4.2	+1.6 (61.5%)
Intermolecular Forces	2.4	3.1	+0.7 (29.2%)
Relationship Between Lewis and VSEPR Structures	3.0	4.3	+1.3 (43.3%)

An examination of the results in Table 4 shows that the most substantial improvements occurred in the subjects of Hybridization and Octet Rule–Based Molecular Structures compared

to other areas. Overall, the findings indicate that pre-service teachers' conceptual understanding improved across all subjects. These results not only support the evidence of conceptual development during the learning process but also highlight the effectiveness of the instructional methods employed in the study.

For the second research question, the significance of the difference between the pre-service teachers' pre-test and post-test scores on the two-tier MGDT was examined. First, the normality of the pre-test and post-test data was assessed. The skewness (0.491) and kurtosis (0.953) values were within the acceptable range of -1 to +1. In addition, the Shapiro–Wilk test results ($p = .568$ for the pre-test and $p = .670$ for the post-test) indicated that the data did not significantly deviate from normality. Considering the robustness of the Shapiro–Wilk test in detecting departures from normality and its comparatively higher statistical power over other normality tests, it was concluded that the distributions of the pre-test and post-test data approximated normality. Accordingly, a paired-samples t-test was conducted to determine whether the difference between the groups was statistically significant, and the results are presented in Table 5.

Table 5

Results of the paired samples t-test for pre-test and post-test mean scores on the two-tier MGDT

Two-Tier MGDT	N	M	SD	df	t	p
Pre-test	22	25.18	9.69	21	-8.905	.000
Post-test	22	42.27	7.85			

A statistically significant difference was found in pre-service teachers' conceptual understanding of hybridization, hybrid orbitals, and molecular geometries following the 3D modeling and printing activities ($t(21) = -8.905$, $p < 0.05$). Prior to the intervention, the mean pre-test score on the two-tier MGDT was $M = 25.18$, whereas after the process, the mean post-test score increased to $M = 42.27$. This finding indicates that the instructional process was effective in enhancing conceptual knowledge and that pre-service teachers achieved a substantial improvement in their understanding of molecular geometries. It further suggests that the instructional activities supported by 3D visualization technologies have considerable potential to improve achievement in chemistry education.

The eta squared value ($\eta^2 = .790$) indicated that 79% of the total variance was explained by the independent variable. According to Cohen's [32] classification, this value corresponds to a large effect size, indicating that the independent variable had a significant and strong impact on pre-service teachers' conceptual understanding.

3.2. Qualitative findings on conceptual understanding from focus group interviews

In the focus group interviews, pre-service teachers were asked six questions related to their conceptual understanding. The findings derived from the analysis of their responses are presented in Table 6.

The findings presented in Table 6 reveal pre-service chemistry teachers' views on the molecular modeling process supported by 3D visualization technologies in relation to their conceptual understanding from multiple perspectives. The analysis indicates that the participants' experiences throughout the learning process were evaluated holistically within the framework of the overarching theme of conceptual understanding. Initially, most participants emphasized how 3D modeling can help make abstract subjects in chemistry tangible. In particular, subjects such as hybridization, hybrid orbitals, and molecular geometry – in which students often struggle with mental visualization – were reported to have become more comprehensible through the use of visual-spatial representations. In this context, modeling

supported by 3D visualization technologies not only allowed participants to visualize concepts but also to physically experience them, thereby facilitating meaningful learning.

Additionally, the participants' responses suggest that the modelling process deepened their conceptual understanding. They emphasized that molecular structures drawn in 2D on paper became much clearer when modelled in 3D, particularly with regard to bond angles, bond types, and the spatial positions of atoms. This enabled them to revisit their prior knowledge, question possible non-scientific conceptions, and correct them.

Considering that the molecular structures perceived by participants as either challenging or easy to grasp during the modeling process were closely related to their prior knowledge, the structural complexity of the molecule, and the degree of visual support available, it is clear that these factors significantly influenced their perceptions. Participants noted that larger or multi-centered molecules were more difficult to model, whereas simpler structures and those with which they were already familiar were easier to understand. This suggests that conceptual understanding is shaped by practical engagement, learners' previous experiences, cognitive load, and the quality of instructional materials. Finally, participants identified certain moments in the process as being particularly striking. Observing the 3D printer in operation and holding the printed model in their hands for the first time created a strong sense of curiosity and emotional attachment. These impactful learning moments became part of the process cognitively and effectively; the aesthetic features of the models – their colouring and realistic nature – contributed to learning retention.

Table 6

Findings regarding pre-service chemistry teachers' responses to interview questions on conceptual understanding

Theme: Pre-service chemistry teachers' opinions on molecular modeling activities supported by 3D visualization technologies and their conceptual understanding	
Question 1. In what ways did the molecular models you designed during the learning process contribute to your conceptual understanding of hybridization, hybrid orbitals, and molecular geometries?	
Codes	**Sample Statements**
Concretization of abstract concepts	"Designing molecular models helped me to visualize and concretize the concepts of hybridization, hybrid orbitals, and molecular geometries. In this way, I understood how to apply theoretical knowledge in practice." (PST19)
Visualization and spatial representation in the mind	"I was able to mentally design the spatial orientations of molecules and compounds in a more concrete way." (PST5)
Facilitation of permanent learning and meaningful understanding	"When I could visually observe that the bond length decreases as the number of bonds increases, it became much easier to remember." (PST9)
Internalization of theoretical knowledge at the conceptual level	"Through this learning process, I can say that the chemistry topics and concepts related to molecular geometries explained theoretically became much clearer." (PST10)
Question 2. How did the 3D-printed molecular models affect your understanding of the topics?	
Codes	**Sample Statements**
Enhancement of conceptual understanding through visual and tactile support	"They had a very positive impact because after seeing the molecules in 3D and holding their physical prints in our hands, we learned much more effectively." (PST4)
Support for mental visualization	"They helped me to understand structures that I had difficulty visualizing in my mind." (PST9)
Understanding conceptual details (bond angles, hybridization, geometry)	"They enabled me to think in three dimensions and better understand key concepts such as bond angles and hybridization." (PST11)
Question 3. What differences do you see between your prior knowledge and the knowledge you gained after this learning process regarding molecular geometries?	
Codes	**Sample Statements**

Reviewing and updating prior knowledge	"I realized that bond lengths and bond angles are not all the same. There were clear differences between what I knew before and what I learned after this training." (PST9)
Transition from memorization to understanding	"Instead of rote learning, we learned by doing and experiencing." (PST7)
Question 4. What was the most significant difference you experienced in your conceptual understanding between traditional 2D drawings and 3D modeling?	
Codes	**Sample Statements**
Accurate perception of bond angles and molecular geometries	"Definitely the angles! In 2D drawings, we used to see the bond angle in a methane molecule as 90 degrees. With 3D modeling, we realized the angle was actually not 90 degrees." (PST5)
Understanding of hybrid orbitals and atomic positions in space	"In 2D, we could not understand how the molecule occupies space, but in 3D it became concrete." (PST8)
Perception of spatial arrangement and depth of molecules	"For me, it was the bond lengths and bond angles. In 2D drawings, it is difficult to understand how bonds are arranged in space and their depth." (PST9)
Visual differences between 2D and 3D representations	"In 3D modeling, we could observe the product from every angle, which made a big difference." (PST16)
Question 5. During the 3D modeling activities, which specific molecular structures did you find most challenging and easiest, and why?	
Codes	**Sample Statements**
Comprehensibility of molecular geometry	"The tetrahedral structure was easier to understand because the four atoms are arranged around a central atom at equal angles." (PST15)
Presence of single, double, or pi bonds and lone pairs	"It can be difficult to identify lone pairs, and sometimes BH_3 can be confused with other structures." (PST8)
Size and complexity of the molecule	"At first, I had difficulty in understanding the structure of larger molecules such as caffeine." (PST7)
Prior knowledge and familiarity	"I did not have any difficulty with water and carbon dioxide molecules because I was already familiar with their shapes." (PST14)
Question 6. During the 3D modeling activities, which specific moments made the greatest impact on you?	
Codes	**Sample Statements**
Observing the operation of the 3D printer	"The moment we first operated the 3D printer and saw it moving around to shape the molecule was very striking for me." (PST11)
Touching/owning the physical molecular model	"The moment I held the model in my hand was the most impactful experience for me." (PST5)
First encounter with the 3D printer/excitement of discovery	"When I first saw the machine, I thought, 'What can't be done with this?' It really sparked my imagination." (PST18)
Coloured and realistic visualization	"Especially having each atom in the molecule printed in a different colour made the information much more memorable." (PST14)

The findings presented in Table 6 reveal multifaceted perspectives on the impact of molecular modeling supported by 3D visualization technologies on the conceptual understanding of pre-service chemistry teachers. The analysis indicates that participants' experiences regarding the learning process were evaluated holistically under the overarching theme of conceptual understanding.

Firstly, most participants emphasized the power of 3D modeling to concretize abstract chemistry concepts. In particular, subjects such as hybridization, hybrid orbitals, and molecular geometry – concepts that students often find difficult to visualize mentally – were reported to become more comprehensible through visual-spatial representations. In this context, technology-enhanced modeling not only enabled visual engagement with the concepts but also allowed participants to experience them physically, thereby supporting meaningful learning. Additionally, it can be inferred from the participants' statements that the modeling process enhanced their conceptual depth. They noted that while molecular structures drawn on flat 2D paper representations are limited, modeling them in 3D environments allowed them to more clearly recognize critical structural features such as bond angles, bond types, and the spatial arrangement of atoms. This awareness encouraged participants to reevaluate their prior

knowledge and identify and correct any possible non-scientific alternative conceptions. Additionally, the molecules perceived as either challenging or easy to model were associated with participants' prior knowledge, the structural complexity of the molecule, and the level of visual support provided. Notably, participants reported difficulties when modeling large or multi-centered structures, whereas simpler molecules or those with which they were already familiar were more readily understood. This finding suggests that conceptual understanding is shaped not only by the modeling activity itself but also by learners' previous experiences, cognitive load, and the quality of instructional materials employed. Finally, participants highlighted particular moments in the process that left a strong impression on them. Specifically, seeing the 3D printer in action and first-hand dealing with the manufactured model generated a great deal of interest and emotional involvement. These striking learning moments integrated affective dimensions into the learning process, in addition to cognitive ones. The aesthetic qualities of the models, their use of colour, and their resemblance to real molecular structures further contributed to the durability of learning.

4. DISCUSSION

In this study, pre-service teachers engaged in molecular modeling through technology-supported instruction, utilizing 3D software and 3D printing to create tangible materials. The production of three-dimensional physical models significantly contributed to more meaningful and lasting learning regarding hybridization, hybrid orbitals, and molecular geometries. This impact can be understood across three main dimensions.

The first dimension relates to the reduction of cognitive load achieved through the 3D modeling of complex structures. This approach allows students to optimize their mental processing. Similarly, models play a central role in supporting scientific reasoning and lowering cognitive barriers by making invisible structures accessible [1], [2]. Consistent with this, Kenneally and Bentley [33] reported that students who engaged with spatial molecular geometry content designed according to Cognitive Load Theory (CLT) principles, using augmented reality (AR) technology, demonstrated significantly lower cognitive load and higher academic achievement. This finding suggests that 3D tangible models may similarly alleviate abstract confusion in learners' minds, enabling them to focus their attention and processing capacity more effectively. In fact, students indicated that visualizing concepts in three dimensions enhanced their comprehension. This indicates that models not only facilitate comprehension but also effectively address students' alternative conceptions [15], thereby providing a solid foundation for subsequent learning [34].

Considering another dimension, in terms of multimodal representations and sensory integration, 3D materials enhance learners' visual and tactile experiences. A study featuring multi-coloured 3D-printed orbital models demonstrated that students gained a better understanding of molecular orbitals, bond types, reactivity, and transition states through interactive engagement – such as touching, rotating, and inspecting the models – rather than merely watching or reading about them [35]. Similarly, de Cataldo, Griffith and Fogarty [36] found that abstract concepts, which students often struggle to visualize, such as hybrid orbitals, became more comprehensible when represented through 3D printed models. In alignment with these findings, the current study revealed that pre-service teachers displayed a strong preference for physically interacting with models, which had a positive impact on their learning. This was particularly beneficial for students with visual and kinaesthetic learning preferences, as the rich and dynamic learning environment created by three-dimensional models made the educational experience more meaningful and engaging, while also reducing barriers to understanding [21]. Additionally, allowing students to observe and manipulate the physical models they designed added a tactile dimension to their learning, fostering deeper information processing [20]. Thus,

three-dimensional models serve as a powerful pedagogical tool that accommodates individual learning differences and promotes long-term retention. The engagement of multiple senses fosters the robust construction of concepts, ensuring that knowledge is processed not through a single channel, but through a combination of visual, tactile, and kinaesthetic components.

Additionally, the impact of tangible materials on recall and the durability of learning should be taken into consideration. Research has consistently demonstrated that technology-enhanced models foster long-term retention and support conceptual change by linking abstract and concrete domains [9], [10]. Findings commonly report that students achieve significant improvements in knowledge test scores, recall abstract topics more effectively, display more positive attitudes, develop enhanced spatial abilities, and experience reduced conceptual misunderstandings, particularly in relation to molecular structures that are difficult to visualise [37], [38]. The findings of the present study similarly demonstrated that 3D modeling and printing activities significantly improved pre-service teachers' understanding of hybridization, hybrid orbitals, and molecular geometries. Testimonies from participants further revealed that their active engagement in the digital modelling process facilitated comprehension of abstract chemical concepts, while the visual, tactile, and interactive learning experiences supported the internalization of conceptual knowledge. Consequently, the findings of this study align with those reported in the literature, collectively underscoring that three-dimensional tangible models contribute to both long-term retention and a deeper understanding of concepts.

Another significant finding was the notable improvement in pre-service teachers' conceptual understanding of hybridization, molecular structures consistent with the octet rule, the valence shell electron pair repulsion (VSEPR) theory, and molecular geometry. The high mean score for hybridization indicates that this abstract concept became more comprehensible and memorable through the use of three-dimensional modeling. Similarly, the increase in scores related to the octet rule and molecular geometry demonstrates that technology-supported instruction had a significant impact on subjects that students initially found challenging. Additional improvements were observed in areas such as molecular orbitals, resonance, and the relationship between Lewis structures and VSEPR theory, although gains in understanding intermolecular forces were more limited. These findings indicate that technological modelling, including 3D-printed models, provides substantial benefits for topics perceived as difficult by students, particularly in supporting the learning of complex structural concepts that conventional physical model sets often fail to convey [24]. In addition, anecdotal feedback from undergraduate students supports this claim, indicating that such models help clarify abstract and complex content [16].

In this context, the use of technological tools stands out as one of the most commonly used and effective methods. Technologies like 3D printers play a crucial role by transforming virtually designed models into tangible, physical objects, which significantly contribute to the learning process [16], [17]. Similarly, Endeshaw and O'Leary [35] demonstrated that three-dimensional printed molecular orbitals were effectively used to address common misconceptions in introductory university chemistry courses. Furthermore, another study highlighted that the challenge of "un-teaching" misconceptions formed from unsupported statements can be overcome by constructing accurate, evidence-based conceptual models using physical representations [8]. In the present study, participants indicated that the activities prompted them to reconsider their prior knowledge and restructure their understanding of the targeted concepts. These results suggest the potential value of expanding technology-supported instructional practices within teacher education programs, as such practices can enhance pre-service teachers' ability to integrate technology into their future classrooms while also supporting the development of both pedagogical and scientific competencies [39].

5. CONCLUSIONS AND PROSPECTS FOR FURTHER RESEARCH

The statistically significant difference identified between the pre-test and post-test results of the two-tier Molecular Geometry Diagnostic Test (MGDT) administered within the scope of this study demonstrates the effectiveness of integrating technology in learning abstract chemistry concepts. In particular, for topics such as hybrid orbitals and molecular geometries, which are often challenging for students to grasp, instructional processes supported by three-dimensional software programmes were found to exert a strong impact on the conceptual development of pre-service teachers. The statistically high effect size ($\eta^2 = .790$) confirmed that the instructional method supported by 3D visualization technologies had a powerful and substantial influence on participants' conceptual understanding. This finding aligns with previous research, which has highlighted that technology-enhanced applications significantly support the meaningful learning of complex and difficult concepts [23], [24].

In this respect, the conceptual gains achieved by pre-service teachers are expected to have positive implications for their future instructional practices, enabling their students to develop a deeper understanding of chemistry topics. Improved comprehension of abstract concepts, such as hybrid orbitals and molecular geometries, can equip these future teachers with the ability to employ more effective instructional strategies and facilitate learning by making complex content more concrete. Thus, the conceptual knowledge acquired by pre-service teachers through such technology-supported instructional processes may play a critical role in enhancing student achievement [40].

Indeed, the literature frequently emphasizes the importance of teachers' use of diverse technological tools to improve the quality of learning processes and the pedagogically grounded integration of technology into classroom practices. In this regard, technology-supported instructional applications should be regarded as an indispensable component of teacher education programmes.

Based on the findings of this study, several implications can be drawn for the effective integration of 3D printing technologies into educational settings. In light of the results, it is particularly recommended that 3D printer-supported applications be integrated into teacher education programs, especially for teaching abstract concepts such as hybridization and molecular geometries. Furthermore, it is essential to expand professional development programs that aim to enhance the competencies of in-service teachers in this field. Such programs should include training in 3D printer operation, 3D design, access to digital models, project-based applications, and the development of printed materials that support learning and educational objectives. Additionally, offering elective courses on 3D design within teacher education curricula may help increase students' awareness and engagement with these technologies.

Despite these promising findings, several limitations of the present study should be acknowledged. First, the study was conducted with a relatively limited sample consisting of 22 senior pre-service chemistry teachers. However, it should be noted that this group represents the entire accessible population within the relevant cohort, as all final-year students enrolled in the program were included in the study. Second, the research employed a one-group pre-test–post-test design without a control group due to institutional and instructional constraints, as all participants were required to engage in the same instructional process. While this design limits the ability to make strong causal inferences, integrating qualitative data through focus group interviews provided methodological triangulation and contributed to a more comprehensive understanding of the findings.

Future research should aim to address the limitations identified in this study, particularly by including larger and more diverse samples to enhance generalizability, employing experimental or quasi-experimental designs with control groups, and developing more

structured instructional frameworks for technology-supported learning environments. Comparative research across different educational levels could provide deeper insights into the effectiveness of 3D technologies in fostering conceptual understanding. Longitudinal studies are also recommended to examine the long-term effects of 3D modeling and printing on knowledge retention, conceptual change, and attitudes toward chemistry.

Interdisciplinary research should be encouraged, particularly studies that integrate 3D printing into fields such as engineering, health sciences, mathematics, and social sciences, in order to promote collaborative and cross-disciplinary learning. Moreover, future studies could compare 3D-printed models with real-world objects to better evaluate their pedagogical value. From a technological perspective, the development of simplified and user-friendly 3D design software tailored to different educational levels would increase accessibility and usability. Finally, it is recommended that 3D material development processes be systematically examined in line with instructional design principles, and that the impact of these technologies on learning be rigorously evaluated.

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ТЕХНОЛОГІЧНО ПІДТРИМУВАНЕ 3D-МОДЕЛЮВАННЯ ТА 3D-ДРУК У ПІДГОТОВЦІ ВЧИТЕЛІВ ХІМІЇ

Еметі Саргин
магістр з хімічної освіти, учитель хімії
Приватний професійно-технічний ліцей KOSBİ імені Зюльфю-Мевлюта Челіка, м. Ізмір, Туреччина
ORCID ID 0009-0004-7220-0287
emetti77@gmail.com

Меліс Арзу Уйулган
доктор філософії з хімічної освіти, професор
Університет Докуз Ейлюль, педагогічний факультет, кафедра хімічної освіти, м. Ізмір, Туреччина
ORCID ID 0000-0002-2815-2642
melis.cekci@deu.edu.tr

Анотація. Дослідження присвячене стійким труднощам у розумінні абстрактних хімічних понять, таких як гібридизація, гібридні орбіталі та молекулярна геометрія, у процесі підготовки майбутніх учителів хімії. Через свою високий рівень абстрактності ці теми часто пов'язані з поширеними хибними уявленнями студентів педагогічних спеціальностей та обмеженим розвитком їх просторового мислення. У дослідженні проаналізовано, як технологічно підтримувані практики тривимірного (3D) моделювання та 3D-друку інтегруються в освітній процес і як вони пов'язані з формуванням концептуального розуміння. Для вивчення як концептуальних результатів, так і поглядів учасників було використано змішаний дослідницький дизайн. Кількісні дані збирались за допомогою дворівневого діагностичного тесту з молекулярної геометрії, який проводився до та після семестрової навчальної реалізації. Якісні дані були отримані шляхом фокус-групових інтерв'ю. Результати засвідчили суттєве покращення розуміння учасниками процесів гібридизації, молекулярних структур, що відповідають правилу октету, а також молекулярних геометрій, пояснених на основі теорії відштовхування електронних пар валентної оболонки, поряд зі зменшенням поширених хибних уявлень. Якісний аналіз показав, що взаємодія як із цифровими, так і з фізично надрукованими 3D-моделями сприяла конкретизації абстрактних понять, розвитку просторового мислення та формуванню змістовного навчання завдяки поєднанню візуального й тактильного досвіду. Учасники наголосили, що практична робота з моделями допомогла їм встановити більш міцні зв'язки між символічними хімічними поданнями та структурами молекулярного рівня. Незважаючи на виявлені педагогічні переваги, було також визначено низку обмежень, пов'язаних із технічною інфраструктурою та недостатнім рівнем попередньої підготовки, що створюють

труднощі для сталого впровадження таких підходів. Загалом результати підкреслюють практичну цінність інтеграції 3D-візуалізації та моделювання в програми підготовки вчителів хімії та вказують на необхідність систематичних програм професійного розвитку для підтримки технологічних і педагогічних компетентностей майбутніх учителів.

Ключові слова: 3D-друк; тривимірне молекулярне моделювання; концептуальне розуміння молекулярних структур; майбутні вчителі хімії

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