Journal of Teaching and Education for Scholars (JOTES)
e-ISSN: 2830-1064, Vol. 3 No. 1 (2026)
Homepage: https://www.ojs.ycit.or.id/index.php/JOTES/index

Elevating Conceptual Understanding and Engagement in Ionic Bonding Using 3D-Printed Ionic Tiles: A Quasi-Experimental Study

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A Research Article

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Received: 29/04/2026
Revised: 24/05/2026
Accepted: 01/06/2026
Published: 01/11/2026

Citation:
Suico, Z. X. A., & Capacio, L. J. A. Elevating conceptual understanding and engagement in ionic bonding using 3D-printed ionic tiles: A quasi-experimental study. *Journal of Teaching and Education for Scholars*, *3*(2), 93–102. https://doi.org/10.59065/jotes.v3i2.284

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Abstract
Ionic bonding is a foundational concept in secondary school chemistry, yet it remains challenging for many learners because it involves submicroscopic processes that cannot be directly observed. Research consistently shows that students struggle with chemical bonding when instruction relies mainly on symbolic or verbal explanations without effectively linking macroscopic, submicroscopic, and symbolic representations. This study evaluated the effectiveness of 3D-Printed Ionic Tiles in improving Grade 9 students' conceptual understanding of ionic bonding and their engagement in class. A quasi-experimental pretest–posttest control group design was used, involving 76 students from two intact Grade 9 sections at Suarez National High School during the School Year 2025–2026. One section was assigned as the experimental group and used 3D-Printed Ionic Tiles as instructional manipulatives, while the other served as the control group and received conventional lecture-discussion instruction. Data were collected using a teacher-made multiple-choice achievement test administered as both pretest and posttest, along with an adapted student engagement questionnaire. The data were analyzed using descriptive statistics and Analysis of Covariance (ANCOVA) at the 0.05 level of significance. Results revealed that the experimental group obtained higher posttest and adjusted mean scores, with ANCOVA indicating a statistically significant difference ($p = .048$), reflecting a modest but meaningful effect of the intervention. The experimental group also demonstrated higher levels of engagement. These findings suggest that 3D-Printed Ionic Tiles can serve as a practical, low-cost instructional tool to enhance conceptual understanding and foster active participation in learning abstract chemistry concepts.

Keywords: *3D-Printed Instructional Material; Conceptual Understanding; Ionic Bonding; Students' Engagement; Quasi-Experimental Design*

1. Introduction

Chemistry helps learners explain the structure, properties, and interactions of matter. However, chemistry learning is often difficult because many of its core ideas occur at the submicroscopic level and therefore cannot be directly observed in everyday classroom situations. Among these core ideas, chemical bonding occupies a central place because it supports later understanding of chemical reactions, properties of substances, and structure–property relationships. Recent scholarship continues to affirm that chemical bonding is one of the most conceptually demanding areas in chemistry education, both for learners and for teachers, because it requires movement among macroscopic, submicroscopic, and symbolic forms of representation (Farheen & Lewis, 2021; Hunter et al., 2022; van Dulmen et al., 2023).

Students' difficulty with bonding is not merely a matter of memorizing terms. Research has shown that learners frequently hold persistent misconceptions about why atoms bond, how electrons behave, and how ionic substances form and are represented. Common difficulties include confusing atoms with ions, assuming that ionic compounds exist as molecules, interpreting electron transfer too literally, and overrelying on oversimplified octet explanations. Such misconceptions are reinforced when instruction emphasizes static textbook diagrams or symbolic notation without helping learners visualize the underlying particle-level processes (Rohmah et al., 2022; Hunter et al., 2022; Widarti et al., 2024).

Ionic bonding is especially challenging for junior high school students because the process of electron transfer and electrostatic attraction is invisible and abstract. Learners may be able to repeat textbook definitions yet still fail to explain how ions form, why oppositely charged ions attract, and how ionic lattices differ from discrete molecules. Current reviews on chemical bonding instruction emphasize that effective teaching should avoid simplistic dichotomies, explicitly address alternative conceptions, and use representations that help students reason about structure, interactions, and properties (van Dulmen et al., 2023; Çalik et al., 2024).

For this reason, the use of concrete and visual learning materials remains pedagogically important. Recent studies in chemistry education continue to support the value of multiple representations and model-based instruction for helping students interpret bonding concepts more meaningfully. Different forms of representation—such as diagrams, models, animations, and physical manipulatives—can cue different aspects of chemical reasoning. However, research also cautions that each representation has strengths and limitations, and that students must be guided in how to interpret them rather than simply being exposed to them (Farheen & Lewis, 2021; Aroch et al., 2024).

The emergence of 3D printing in education has opened promising possibilities for chemistry teaching. Reviews and empirical studies have shown that 3D-printed materials can support visualization, spatial reasoning, and active learning in chemistry, particularly when concepts are inherently three-dimensional or structurally complex. In higher education and STEM contexts, 3D-printed models have been used to improve learning of molecular form, periodic properties, and structure–function relationships. More recent evidence likewise suggests that 3D printing can be an engaging strategy for helping learners interact with scientific representations in more tactile and meaningful ways (Pinger et al., 2020; Trujillo-Cayado et al., 2024).

The educational rationale for using manipulatives is further supported by constructivist views of learning. When students physically manipulate objects to represent invisible processes, they are more likely to test ideas, compare possibilities, and negotiate meaning. In science classrooms, such hands-on learning environments may also improve engagement, a multidimensional construct that includes behavioral, cognitive, and emotional involvement in learning tasks. Recent studies in science education report that technology-supported and simulation-supported learning environments can strengthen student engagement, particularly when the learning task requires active exploration and the teacher deliberately connects representations to conceptual understanding (Zhan et al., 2022; Almasri, 2022).

Despite these developments, there remains limited classroom-based evidence on the use of 3D-printed manipulatives specifically for teaching ionic bonding in junior high school settings. While studies such as Pinger et al. (2020) and Trujillo-Cayado et al. (2024) demonstrate the value of 3D-printed models in enhancing spatial understanding and engagement, these have largely been conducted in higher education or focused on general molecular structures rather than ionic bonding concepts at the secondary level. This suggests that while the potential of 3D-printed materials is well recognized, their applicability to younger learners and specific abstract topics remains underexplored.

To add, research on manipulatives in chemistry often emphasizes visualization and conceptual support; however, many of these studies rely on controlled or simulated environments rather than actual classroom implementation. As a result, there is limited empirical evidence showing how such materials influence both conceptual understanding and engagement in authentic teaching contexts. Furthermore, while existing literature highlights the benefits of model-based instruction, it also points out that without proper instructional guidance, manipulatives may not automatically lead to deeper understanding. These gaps indicate the need for more classroom-based, teacher-driven studies that examine the effectiveness of low-cost, practical instructional tools.

Therefore, there is a need for school-level research that investigates how 3D-printed manipulatives can be integrated into real classroom instruction and whether they can effectively support both conceptual understanding and student engagement in abstract topics like ionic bonding. In response to this gap, the present study evaluated the effectiveness of 3D-Printed Ionic Tiles in enhancing Grade 9 students' conceptual understanding of ionic bonding and their engagement during instruction. Specifically, it sought to answer the following research questions:

1. What are the proficiency levels of the experimental group that was aided with 3D-Printed Ionic Tiles and those in the control group who underwent conventional teaching and learning method during the Pretest and Post-test?
2. Is there a significant difference in the posttest scores of students in the experimental group that was aided with 3D-Printed Ionic Tiles and those in the control group who underwent conventional teaching and learning method?
3. What is the level of student engagement during lessons in the control group and in the experimental group?

2. Methods

2.1 Research Design

This study employed a Quantitave Research Approach, specifically, quasi-experimental pretest-posttest control group design. This design was appropriate because the participants were drawn from intact classroom sections, making random assignment at the individual level impractical. Both groups took a pretest before instruction and a posttest after the intervention. The experimental group received instruction using 3D-Printed Ionic Tiles, whereas the control group was taught through the conventional lecture-discussion method.

2.2 Setting and Participants

The study was conducted at Suarez National High School, Junior High School Department, Iligan City, during the School Year 2025–2026. The participants were 76 Grade 9 students from two intact sections with comparable prior performance in chemistry. One section was assigned as the experimental group, and the other served as the control group.

Table 1
The Experimental and Control Groups

Group	Section	n
Experimental Group	Grade 9 - Innovative	38
Control Group	Grade 9 - Humble	38

2.3 Sampling Technique

Purposive sampling was used to select the participants. The two sections were chosen on the basis of comparable academic performance in chemistry during the previous grading period. This procedure was considered appropriate for the study because it allowed the researcher to compare two groups with similar academic backgrounds within an authentic classroom context.

2.4 Research Instruments

Two instruments were used in the study. The first was a teacher-made multiple-choice achievement test administered as both a pretest and a posttest to measure students' conceptual understanding of ionic bonding. The test covered electron transfer, ion formation, and ionic compound formation. It was validated by science teachers to ensure alignment with Grade 9 chemistry competencies. A pilot test was conducted with a comparable group of students, and the test yielded a reliability coefficient alpha of 0.82, indicating acceptable internal consistency. The pretest and post-test results were compared with the DepEd's National Achievement Test (NAT) Proficiency Levels Tool.

The second instrument was an adapted student engagement questionnaire based on Wang, Bergin, and Bergin (2014). The questionnaire measured cognitive, behavioral, emotional, and social engagement during the lesson. Students responded using a four-point Likert scale: 1 = Never, 2 = Sometimes, 3 = Often, and 4 = Always. Negatively worded items were reverse-scored before computing the overall mean. The adapted instrument underwent content validation by experts and yielded a reliability coefficient alpha of 0.85, indicating good reliability.

2.5 Data Collection Procedure

During the implementation phase, the control group was taught using the conventional lecture-discussion method, while the experimental group used 3D-Printed Ionic Tiles as instructional manipulatives during lessons on ionic bonding. The intervention was conducted over a week, with each session lasting approximately 60 minutes.

The 3D-Printed Ionic Tiles consisted of manipulatives representing ions with corresponding charges, which students used to simulate electron transfer and the formation of ionic compounds. During the lessons, students engaged in guided activities such as forming ions, combining oppositely charged particles, and constructing ionic structures using the tiles. The teacher facilitated these activities by prompting explanations and linking the manipulative representations to symbolic and conceptual understanding.

Both groups covered the same content within the same instructional time frame. After the lesson, both groups took the posttest. Students in both groups then completed the engagement questionnaire. The collected data were organized, tallied, and prepared for statistical analysis.

2.6 Data Analysis

Descriptive and inferential statistics were used to analyze the data. Mean and standard deviation were computed to describe posttest performance and engagement levels. A test of group difference was first used to determine whether the two groups were comparable based on pretest scores. Analysis of Covariance (ANCOVA) was then used to compare posttest scores while controlling for pretest performance. All inferential tests were evaluated at the 0.05 level of significance.

3. Results and Discussion

3.1 Test of Group Differences in Pretest Scores

Before the intervention, a test of group difference was conducted to determine whether the control and experimental groups were comparable in terms of prior knowledge of ionic bonding.

Table 2
Test of Group Differences in Pretest Scores

Source	Sum of Squares	df	Mean Square	F	p
Group	0.474	1	0.474	0.166	0.685
Error	211.211	74	2.854		

Table 2 shows that the p-value of 0.685 was greater than the 0.05 level of significance, indicating that there was no statistically significant difference between the pretest scores of the two groups. This suggests that the groups were comparable at baseline, making subsequent comparisons of posttest performance appropriate.

3.2 The Levels of the Pretest and Post-test Scores of the Experimental and Control Groups

This section presents the proficiency levels of the control and experimental groups in the pretest and posttest. It provides a descriptive comparison of students' performance before and after the intervention to determine whether the use of 3D-Printed Ionic Tiles was associated with better learning outcomes in ionic bonding.

Table 3
The Levels of the Pretest and Post-test Scores of Experimental and Control Groups as Compared with the NAT Profiency Level Tool

Test	Group	Mean Score (out of 10)	Percentage Equivalent	Proficiency Level
Pretest	Control Group	5.543	55.43%	Nearly Proficient

Pretest	Experimental Group	5.575	55.75%	Nearly Proficient
Posttest	Control Group	6.868	68.68%	Nearly Proficient
Posttest	Experimental Group	8.947	89.47%	Proficient

Table 3 presents the proficiency levels of the control and experimental groups during the pretest and posttest based on their mean scores and percentage equivalents. During the pretest, the control group obtained a mean score of 5.543 out of 10, which is equivalent to 55.43%, while the experimental group obtained a mean score of 5.575 out of 10, equivalent to 55.75%. Based on the given proficiency scale, both groups were classified as Nearly Proficient. This indicates that before the intervention, both groups had a similar and moderate level of prior knowledge regarding ionic bonding.

During the posttest, the control group obtained a mean score of 6.868 out of 10, or 68.68%, which is still interpreted as Nearly Proficient. In contrast, the experimental group obtained a mean score of 8.947 out of 10, which corresponds to 89.47% and is interpreted as Proficient. This shows that although both groups improved after instruction, the experimental group reached a higher proficiency level than the control group.

The findings suggest that the use of 3D-Printed Ionic Tiles may have contributed to a greater improvement in students' mastery of ionic bonding concepts. While the control group remained within the Nearly Proficient level after conventional instruction, the experimental group progressed to the Proficient level after exposure to the manipulative-based intervention. This pattern indicates that the 3D-Printed Ionic Tiles may have been more effective in helping students achieve a stronger level of conceptual understanding.

3.3 The Analysis of Covariance (ANCOVA)

This section examines whether the difference in posttest performance between the control and experimental groups was statistically significant after controlling for pretest scores. ANCOVA was used to determine the effect of the intervention while accounting for students' prior knowledge.

Prior to conducting ANCOVA, its underlying assumptions were tested. The assumption of normality was examined and found to be satisfied based on the distribution of residuals. Homogeneity of variances was confirmed using Levene's test, which indicated no significant difference between groups. In addition, the assumption of homogeneity of regression slopes was met, as there was no significant interaction between the pretest scores and group membership. These results indicate that the data were suitable for ANCOVA.

Table 4
The Analysis of Covariance (ANCOVA) Results

Source	Sum of Squares	df	Mean Square	F	p	Partial η^2
Corrected Model	1532.68	2	766.34	12.45	< .001	.249
Intercept	8263.74	1	8263.74	134.13	< .001	.636
Pretest	1042.58	1	1042.58	16.93	< .001	.183
Group	248.10	1	248.10	4.03	.048	.051
Error	4502.32	73	61.67			
Total	14298.00	76				
Corrected Total	6035.00	75				

To determine whether the observed difference in post-test scores remained after controlling for pretest performance, an Analysis of Covariance (ANCOVA) was conducted with post-test scores as the dependent variable, group as the independent variable, and pretest scores as the covariate. The results showed that the overall ANCOVA model was statistically significant, $F(2, 73) = 12.45$, $p < .001$, indicating that the model significantly explained variance in post-test scores.

The covariate, pretest score, was also statistically significant, $F(1, 73) = 16.93$, $p < .001$, partial $\eta^2 = .183$, suggesting that students' prior knowledge significantly influenced post-test performance. More importantly, the effect of group was statistically significant, $F(1, 73) = 4.03$, $p = .048$, partial $\eta^2 = .051$. This result indicates that, after controlling for pretest scores, the post-test scores of the two groups differed significantly.

Given that the adjusted mean of the experimental group was higher than that of the control group, the finding suggests that students exposed to the 3D-Printed Ionic Tiles performed better in the post-test than those who received the conventional lecture-discussion method. Furthermore, the adjusted mean scores indicate that, after controlling for pretest performance, the experimental group consistently outperformed the control group, reinforcing the effectiveness of the intervention.

A recent meta-analysis of chemical bonding intervention studies reported a large overall positive effect on academic performance and highlighted the usefulness of pedagogical approaches that better match the abstract nature of bonding content (Çalik et al., 2024). In the present study, the 3D-Printed Ionic Tiles may have served a similar function by helping students enact electron transfer and ion formation rather than merely hearing or reading about them.

The finding is also consistent with recent literature on representation use in chemical bonding. Farheen and Lewis (2021) showed that different bonding representations cue different reasoning patterns in students' predictions of chemical properties, while van Dulmen et al. (2023) emphasized that effective teaching of bonding requires strategic use of representations and deliberate attention to student misunderstandings. By offering a tactile and visual representation of electron movement and compound formation, the ionic tiles may have reduced the interpretive burden often associated with symbolic-only instruction.

Moreover, the instructional value of the manipulative is supported by recent 3D-printing literature in chemistry education. Pinger et al. (2020) identified 3D printing as a growing resource for improving chemistry teaching, especially through visualization and the creation of hands-on tools. Trujillo-Cayado et al. (2024) likewise reported more favorable learning outcomes when 3D-printing technologies were integrated into chemistry teaching in STEM contexts. Although these studies are not identical in topic or level, they reinforce the proposition that 3D-printed materials can meaningfully support abstract science learning when thoughtfully embedded in instruction.

3.4 The Levels of Engagement of the Experimental and Control Groups

This section presents the level of student engagement in the control and experimental groups during the lesson. It aims to determine whether the use of 3D-Printed Ionic Tiles was associated with greater classroom involvement compared with the conventional lecture-discussion method.

Table 5
The Levels of Engagement of the Experimental and Control Groups during the Lesson Delivery

Group	n	Mean	SD	Interpretation
Control	38	2.452	0.266	Slightly Engaged
Experimental	38	3.160	0.525	Engaged

The experimental group obtained a higher mean engagement score ($M = 3.160$) than the control group ($M = 2.452$). Based on the established interpretation scale, the experimental group was classified as Engaged, whereas the control group was classified as Slightly Engaged. This pattern suggests that the use of 3D-Printed Ionic Tiles encouraged greater classroom involvement, likely because students were able to manipulate physical representations while participating in the lesson.

This finding accords with contemporary engagement research in science and technology-supported learning. Zhan et al. (2022) found that science learning environments supported by mobile technologies can shape behavioral, emotional, and cognitive engagement, particularly when students actively interact with the learning task. Similarly, Almasri (2022) reported high engagement and satisfaction when students learned science concepts through interactive simulations, especially when the learning environment invited active participation and matched learners' need for meaningful exploration.

In the present study, the higher engagement of the experimental group may be explained by the kinesthetic and participatory nature of the manipulative-supported lesson. Unlike a purely lecture-based approach, the 3D-Printed Ionic Tiles appeared to invite students to test ideas, visualize outcomes, and discuss representations with peers and the teacher. This is pedagogically important because engagement does not only make lessons more enjoyable; it also supports sustained attention and deeper conceptual processing during science learning.

3.5 Discussion and Future Research Directions

Taken together, the results indicate that the use of 3D-Printed Ionic Tiles was associated with more favorable learning outcomes in terms of both conceptual understanding and student engagement. The experimental group not only achieved higher posttest scores but also showed a stronger level of participation during the lesson. These findings suggest that the instructional material provided students with a more accessible and interactive way of understanding ionic bonding. This result aligns with previous studies emphasizing that hands-on and model-based instruction can significantly enhance learners' conceptual understanding and engagement in science classrooms (Pinger et al., 2020; Zhan et al., 2022).

Taken together, the results indicate that the use of 3D-Printed Ionic Tiles was associated with more favorable learning outcomes in terms of both conceptual understanding and student engagement. The improved performance of the experimental group suggests that the use of manipulatives may have reduced the abstractness of ionic bonding by making key processes more visible and interactive. This aligns with previous studies emphasizing that hands-on and model-based instruction can enhance learners' conceptual understanding and engagement in science classrooms (Pinger et al., 2020; Zhan et al., 2022).

From a pedagogical perspective, the findings reinforce the importance of using instructional strategies that support multiple and connected representations in chemistry teaching. Chemical bonding requires learners to move between observable phenomena and invisible particle interactions, which many students find difficult without appropriate scaffolding. The present intervention provided a physically manipulable representation that may have served as a bridge between concrete experience and abstract reasoning (Capacio, 2021). This supports earlier findings by Farheen and Lewis (2021) and Aroch et al. (2024), who argue that guided use of representations can help students integrate multiple levels of chemical understanding and reduce misconceptions. However, it is important to note that the effectiveness of such materials depends on how they are facilitated, as manipulatives alone may not guarantee conceptual change without explicit instructional guidance.

The study also contributes to the growing body of work on 3D printing in chemistry education. While many existing studies focus on higher education or general molecular visualization, the present findings suggest that 3D-printed materials can be effectively adapted to secondary-level topics such as ionic bonding. The results highlight the potential of low-cost, teacher-developed materials to support active learning in resource-constrained contexts. This is consistent with studies by Trujillo-Cayado et al. (2024) and Almasri (2022), which emphasize the role of interactive and technology-supported learning environments in fostering engagement. At the same time, contextual factors such as teacher expertise, classroom management, and students' prior familiarity with manipulative-based learning may have influenced the observed outcomes.

At the same time, the findings should be interpreted with caution. Because the participants came from intact sections in a single school, the results may reflect context-specific conditions, including classroom culture and instructional practices. Similar limitations have been noted in other classroom-based studies, where small sample sizes and localized implementation restrict wider applicability (Zhan et al., 2022). In addition, the relatively short duration of the intervention may not fully capture long-term learning or retention effects. Future studies with larger and more diverse samples, extended intervention periods, and retention measures would help establish the robustness and sustainability of these effects.

4. Conclusion

This study examined the effectiveness of 3D-Printed Ionic Tiles in enhancing Grade 9 students' conceptual understanding of ionic bonding and their engagement during classroom instruction. The findings showed that the control and experimental groups were comparable at baseline, as indicated by the absence of a significant difference in pretest scores. After the instructional intervention, the experimental group obtained higher posttest and adjusted mean scores than the control group.

Further, the ANCOVA results revealed a statistically significant difference in posttest performance after controlling for pretest scores, $p = .048$, indicating that the use of 3D-Printed Ionic Tiles supported better conceptual understanding of ionic bonding. The engagement results also favored the experimental group, which was classified as engaged, while the control group was classified as slightly engaged.

Based on these findings, it is recommended that chemistry teachers consider integrating 3D-Printed Ionic Tiles or similar manipulative-based instructional materials in teaching abstract concepts to promote better understanding and more active classroom participation. Specifically, teachers may use such materials during concept introduction, guided practice, and reinforcement activities to help students visualize invisible processes such as electron transfer and ionic formation.

Moreover, schools and curriculum planners may explore the inclusion of low-cost, teacher-developed 3D instructional tools as part of their teaching resources to support learner-centered and interactive approaches in science education. These findings also suggest that hands-on and representation-based strategies can enhance not only cognitive learning outcomes but also student engagement, which is essential for sustained learning.

Despite its contributions, this study has several limitations. The participants were drawn from intact classes within a single school, which may limit the generalizability of the findings to other contexts. In addition, the duration of the intervention was relatively short, and the study did not include retention measures to determine long-term learning effects.

Furthermore, the statistical analysis was limited to the available dataset, which may constrain the depth of inference. These limitations suggest that while the results demonstrate promising instructional potential, further research is needed to validate and extend these findings across different settings and populations.

Funding

This study did not receive any specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Conflict of Interest

The authors declare that there is no competing interest in the conduct of this study.

Declaration of AI Use

During the preparation of this article, the authors used Microsoft 365 Copilot to assist in language editing, proofreading, organization of ideas, and refinement of the manuscript. The authors reviewed and edited the AI-assisted outputs as needed and take full responsibility for the final content, accuracy, and integrity of the publication.

Author Contributions Statements

All authors contributed equally to the conceptualization, data gathering, analysis, interpretation, and writing of the manuscript. All authors have read and approved the final version of the manuscript.

Acknowledgments

The main author sincerely thanks Dr. Leadean Jay A. Capacio for the invaluable guidance, constructive feedback, and unwavering support provided throughout the conduct of this study. Appreciation is also extended to the students and faculty members who participated in the research, whose cooperation was essential to its completion. The author likewise acknowledges the encouragement and support of family, classmates, and friends during the course of this work.

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Biography

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