JTK: Jurnal Tadris Kimiya 10, 1 (June, 2025): 11-23
Website: http://journal.uinsgd.ac.id/index.php/tadris-kimiya/index
ISSN 2527-9637 **(online) ISSN** 2527-6816 **(print)**

Integrating Digital Technology and Project-Based Learning in Secondary School Chemistry: Innovative Strategies for Conceptual Understanding

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Received: March 2025; Accepted: May 2025; Published: June 2025

Abstract

The advancement of digital technology and the growing demand for student-centered learning have prompted educators to explore more innovative approaches in science education. In chemistry, abstract concepts often pose significant challenges for learners, particularly at the secondary school level. This study aimed to examine how practising chemistry teachers integrate digital technology and project-based learning (PjBL) to enhance students' conceptual understanding. A descriptive qualitative design was employed, involving in-depth interviews with 22 secondary school teachers who are also distance education students. Thematic analysis revealed that combining video-based instruction, interactive simulations, and contextualized PjBL strategies significantly improved students' comprehension of complex topics such as atomic structure, chemical bonding, and colligative properties. For example, digital simulations enabled clearer visualization of atomic models, while hands-on projects like "Ice Cream Making to Explore Colligative Properties" successfully connected theoretical knowledge with real-life experiences. Despite the pedagogical advantages, challenges such as disparities in digital literacy and the limitations of online platforms were noted. This study contributes to the evolving field of chemistry education by offering practical insights into the implementation of digital and project-based strategies tailored to the learning preferences of Generation Z and Alpha students. The findings underscore the need for systemic teacher support, professional development, and infrastructure improvement to maximize the benefits of these transformative teaching approaches.

Keywords: digital learning, innovative pedagogy, project-based learning, student engagement

DOI: https://doi.org/10.15575/jtk.v10i1.40828

1. Introduction

Chemistry education is a vital component of the secondary school curriculum, designed to equip students with fundamental knowledge and scientific skills essential for daily life and technological advancements (Chen et al., 2024). However, chemistry learning often faces significant challenges (Boateng, 2024; Nsabayezu et al., 2022), particularly in facilitating students' understanding of abstract concepts such as atomic structure, chemical bonds, and chemical reactions (Hoai et al., 2023). Research indicates that many students struggle with these chemical materials due to their inherently abstract and complex nature (Böttcher, 2018; Chiu, 2022).

To address these challenges, innovative learning approaches are crucial. Integrating digital technology into chemistry education such as computer simulations, educational videos, interactive tools, and gamified learning platforms has been shown to enhance students' comprehension of abstract concepts while also increasing their engagement and motivation (Ali et al., 2023; O'g'li, 2024; Kusmawan, 2022). These tools enable students to visualize complex phenomena, interact with virtual environments, and engage in hands-on learning experiences that foster critical thinking skills. This aligns with contemporary paradigms that emphasize active, student-centered learning supported by technology to improve educational outcomes.

In addition, younger generations, to Gen-Z, who dominate todays' student population, demonstrate different learning styles. They are more likely to be responsive to technology-based and interactive learning methods (Chan &; Lee, 2023). Therefore, traditional teaching methods may no longer be sufficient to effectively reach and educate these learners. To effectively support their education in chemistry, educators must innovate by designing strategies that integrate technology seamlessly and foster active participation. This necessitates a comprehensive reevaluation of pedagogical practices to ensure they are adaptable, engaging, and aligned with the technological engagement tendencies and learning preferences of these young generations, thereby enhancing their motivation, understanding, and retention of complex scientific concepts.

One of the key concepts in the study of chemistry is the structure of atoms and periodic systems. Digital technologies, such as interactive applications and 3D simulations, have proven effective in helping students understand the structure of atoms and the periodic table better (Lestarani et al., 2023). In addition, the study of chemical bonds and molecular structure requires different approaches to generation Z and Alpha. A project-based approach and the use of interactive digital tools can increase student engagement and help them understand these concepts better (Masbukhin et al., 2023). Other chemical materials such as Stoichiometry, Thermochemistry, Acid-Base Solutions, Colligative Properties, and Colloidal Systems will also be explored in this who study. Various studies show that associating chemicals with everyday life can increase students' understanding and interest (Masbukhin &; Sausan, 2023).

This study investigates the experiences of Universitas Terbuka Chemistry Education students in teaching chemistry at the secondary school level, with a focus on how they apply innovative approaches to enhance learning quality. It provides an in-depth look at the teaching methods employed by students, including digital technology integration, the adaptation of project-based learning, and strategies tailored to the learning styles of Generation Z and Alpha. The insights gained are expected to shed light on the effectiveness of these innovative methods, as well as the challenges encountered and the ways students address them.

Additionally, the study explores the challenges students face when developing teaching modules and student worksheets (LKPD) for complex chemical topics such as reaction kinetics, chemical equilibrium, reactions, and electrochemistry. It compares the preparation and execution of these modules in online versus face-to-face settings to identify any notable differences. The findings are anticipated to contribute significantly to the development of innovative and effective chemistry teaching strategies suited for the digital era. Unlike earlier research, this study is distinctive because it involves Universitas Terbuka students who actively teach across various regions and institutions in Indonesia, offering practical insights into how digital and project-based methods are adapted in diverse classroom contexts.

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The problem formulation in this study encompasses several critical components. Initially, it investigates the methods employed by Universitas Terbuka students to teach fundamental chemical concepts, including atomic structure, periodic systems, and chemical bonding, to high school students. Additionally, the study examines the role of digital technology in the chemistry learning process, assessing how effectively this technology is utilized to facilitate the teaching of complex topics. Finally, it explores the application of project-based learning approaches in chemistry instruction, particularly on topics such as colligative properties and colloidal systems, and evaluates the impact of these methods on students' comprehension and understanding of the material.

2. Research Method

This study employs a descriptive qualitative research approach to explore the experiences of students from the Faculty of Teacher Training and Education (read: FKIP) at Universitas Terbuka's (UT) Chemistry Education Study Program in teaching chemistry at secondary schools. A descriptive qualitative approach was chosen to gain a deep understanding of how students use innovative teaching methods in the chemistry learning process. Sultan (2023) states that descriptive research is a type of research used to understand the existence of independent variables, either one or more variables, without trying to compare or combine them with other variables.

The research design used was an in-depth interview. Data is obtained from primary data sources through an in-depth interview process, which allows the collection of data and information directly from the research subjects. This interview is designed to explore different aspects of chemistry teaching. The interview instrument includes open-ended questions that allow the subject to give rich and detailed answers. The interview guide consists of 3 main aspects of innovative learning with a total of 9 questions. These three aspects are teaching approaches and strategies, the use of technology in learning, and curriculum planning and implementation.

To strengthen the validity of the findings, data triangulation was carried out by complementing the interview results with document analysis in the form of students' lesson plans and examples of learning activity worksheets. Although observation was not conducted due to geographical constraints, the document review helped cross-check the alignment between the students' statements and their actual planning practices.

To ensure the validity and reliability of the instrument, the interview guide was reviewed by two experts in chemistry education and qualitative research. Feedback from these experts was used to revise and refine the questions, ensuring they were clear, relevant, and aligned with the research objectives. A small-scale pilot test involving three students was also conducted to confirm the clarity and practicality of the interview items.

The subject of this study is FKIP-UT Chemistry Education students who are taking the Junior and Senior High School Chemistry Curricular Material courses in semester 5 of the 2023/2024 study period. All the subjects of this study also worked as teachers in secondary schools, so they had practical experience in teaching chemistry in the classroom. Variations in the study include differences in teaching experience in different types of schools, both in cities and regions, as well as differences in the use of technology and teaching methods. The subject selection criteria are students who are actively teaching in secondary schools and are taking courses relevant to this study.

This research was conducted at the Universitas Terbuka, a higher and distance education institution which is an important location to collect data from students. The population in this study is all FKIP-UT Chemistry Education students who meet the predetermined criteria. The sample taken was 22 students selected by purposive sampling based on their relevance to the course and teaching experience.

Data was collected through in-depth interviews with each subject. Interviews are conducted in person or through digital platforms if needed. Each interview was recorded and transcribed for further analysis. Data that have been collected from interviews are transcribed and organized systematically. Data analysis was conducted by identifying themes and patterns that emerged from interview data. The data analysis technique used is thematic analysis. Data were analysed to identify key themes related to innovative approaches in chemistry teaching. The results of this analysis are then synthesized to provide a comprehensive picture of the teaching experiences and strategies used by students.

3. Result and Discussion

This study involved 22 Universitas Terbuka Chemistry Education students who were enrolled in the Junior and Senior High School Chemistry Curricular Materials course. The demographic characteristics of respondents, as shown in Table 1, show female dominance with a percentage of 77.28%, while men are only 22.72%. This finding is in line with previous studies by Suprawata & Riastini (2022), suggesting that the teaching profession in Indonesia is predominantly filled by women, reflecting socio-cultural values that encourage women to pursue careers in education.

The age range of respondents showed that most were between 21–30 years old (50%), followed by 31-40 years (36.36%), and 41-50 years (13.64%). This shows that most respondents are young teachers who are in the early stages of their careers. Most respondents are young teachers at the early stage of their careers, supporting Murniarti et al. (2023) who stated that younger teachers are generally more open to innovation and technology, crucial for adopting new chemistry teaching strategies. Young age is often associated with openness to change and high adaptability, which are important assets in the application of new learning methods.

In terms of teaching experience, most respondents had 0–5 years of experience (54.54%), followed by 6-10 years (36.36%), and only 9.1% had 11-15 years of experience. These findings imply that the majority are early-career teachers, who, according to Tampubolon et al. (2021), are more enthusiastic and flexible in applying innovative teaching methods. This reflects positively on their readiness to adopt transformative strategies in chemistry education (Redhana et al., 2018).

Table 1. Respondents' Characteristics

Variables		∑	%
Gender	Male	5	22.72
	Female	17	77.28
Age range (years)	21-30	11	50
	31-40	8	36.36
	41-50	3	13.64
Teaching experience (years)	0-5	12	54.54
	6-10	8	36.36
	11-15	2	9.1
Employment Status	Civil Servants (ASN)	0	0

All respondents in this study have Non-ASN (Non-Civil Servant) status, which means they work as honorary or contract teachers. According to Wahyuni et al. (2023), Non-ASN teachers, while facing greater challenges in accessing professional development, tend to show higher creativity and innovation in classroom practices. This employment status of non-ASNs can encourage respondents to further innovate and adopt more effective and engaging learning approaches to maintain and improve the quality of learning.

The interview instrument in this study focused on three main aspects which include Teaching Approaches and Strategies, Utilization of Technology in Learning, and Curriculum Planning and Implementation. Interview instruments are developed based on indicators that have been set for each aspect. The first aspect, Teaching Approaches and Strategies, has four indicators covering a wide range of innovative approaches in chemistry teaching. The second aspect, Utilization of Technology in Learning, has two indicators that evaluate the extent to which respondents use digital technology in chemistry learning. While the third aspect, Curriculum Planning and Implementation, has three indicators that examine respondents' ability to plan and implement the chemistry curriculum effectively. It was developed based on frameworks from previous studies (Timilsena et al., 2022; Yaşar & Sözbilir, 2019). Each aspect contained several indicators (Table 2), which served as guidelines for thematic data analysis. To increase data validity, triangulation through document analysis of student worksheets was added. Although observations were not conducted, using LKPD reviews strengthened data credibility. Additionally, while the instrument was developed based on established guidelines, its validity was evaluated by expert judgment from two senior lecturers, and its reliability was ensured through piloting with five non-sample participants, followed by refinement.

Table 2. Dimensions of Interviews

Aspects	Number of Items
Teaching Approaches and Strategies	4
Use of Technology in Learning	2
Curriculum Planning and Implementation	3

The first aspect analyzed is the teaching approach and strategy. This aspect focuses on four main indicators to evaluate the teaching approach used by Universitas Terbuka students who also work as chemistry teachers in secondary schools. The first indicator evaluates the teacher's way of helping students understand the concept of matter and chemical properties in depth. The second indicator highlights strategies for teaching chemical bonds and molecular structure to generations Z and Alpha who have different learning styles from previous generations. The third indicator evaluates the teaching of Stoichiometry and Thermochemistry by relating them to everyday life. The fourth indicator examines how teachers teach Acid-Base Solutions using the latest learning models. The review of the 4 indicators is in line with previous research that emphasizes the importance of innovative teaching strategies as an effort to improve student learning outcomes (Rusmansyah et al., 2019).

Table 3. Teaching Approaches and Strategies

Questions	Answers
Based on your teaching experience, how can you get students to understand the concept of material and its properties more deeply?	• I divide students into discussion groups or material presentations, and add demonstrations and practicums (experiments) • I use mind maps so that students understand the material more quickly because mind maps help see the overall concept more clearly.
How do you teach chemical bonds and molecular structure to generations Z and Alpha with different learning styles?	• I use educational videos on YouTube, interactive quizzes on Instagram, or molecular structure simulation apps. • I utilize apps like 'ChemCollective' and 'PhET' to make learning fun.
How do you teach stoichiometry and thermochemistry to students by relating them to everyday life?	• I will show simple examples, for example food processing such as the process of adding baking powder to cakes and the process of burning fossil fuels in motorized vehicles. • I use a Modified Inquiry learning model with a Scientific Approach.
How do you teach acid-base solutions to students using the latest learning models?	• I use the PBL and PjBL models by inviting students to make natural indicators from several materials and test their acid-base properties. • I use an approach that integrates three levels of chemical representation to understand the concept of acid-base solutions through direct experience (macroscopic level), identification of materials using litmus paper (submacroscopic level), and introduction to acid-base theory (symbolic level).

Based on Table 3, FKIP-UT Chemistry Education students applied various innovative approaches in teaching chemistry concepts to students. Based on the interview answers, some of the strategies they used included the division of students into discussion groups and material presentations, the use of mind maps, as well as demonstrations and practicums.

One method that is often used is the division of students into discussion groups and presentations, as well as demonstrations and practicums. This approach is in line with research showing that collaborative learning can improve students' conceptual understanding. Practicums provide hands-on experience that allows students to relate theory to real practice. Malik & Ubaidillah (2021) emphasizes the importance of laboratories in science education to develop scientific thinking skills and conceptual understanding.

The use of mind maps by students is also an interesting approach that helps students understand concepts thoroughly. Hidayati & Subur (2023) states that mind maps can improve memory and understanding because visual representations help students organize and integrate information. This strategy acknowledges the visual needs of the current generation in learning, as also found in studies by Shi et al. (2023) which show that visual diagrams can improve understanding and retention of information.

In learning chemical bonds and molecular structure to generations Z and Alpha, students use educational videos on YouTube, interactive quizzes on Instagram, and molecular structure simulation applications. This is in accordance with Rahmawati et al. (2022) research that the use of digital technology in learning can increase student engagement and motivation. Apps like 'PhET' and 'ChemCollective' provide interactive and engaging simulations, which Mukama & Byukusenge (2023) suggests can improve students' conceptual understanding and problem-solving skills.

Students apply the Problem-Based Learning (PBL) model through group discussions and experiments, as well as Project-Based Learning and three-level chemical representation approaches. Compared to conventional lecture-based methods, these innovative approaches have shown a more significant impact on student learning outcomes, particularly in improving conceptual understanding, engagement, and the ability to apply chemistry knowledge to real-world contexts. This is supported by increased student participation and higher accuracy in solving contextual problems observed during classroom implementation. The project creates natural indicators and tests of acid-base properties allowing students to participate in learning actively and creatively, which is consistent with Domenici (2022) that show that project-based learning can increase student engagement and understanding.

Approaches that integrate three levels of chemical representation – macroscopic, sub - macroscopic, and symbolic – are particularly effective in helping students understand concepts holistically. Permatasari et al. (2022) emphasizing the importance of linking macroscopic representations (real phenomena) with submicroscopic (particle) and symbolic (chemical equations) representations to build a strong conceptual understanding in chemistry.

Learning chemistry requires an approach that can bridge abstract concepts to be more real and easily understood by students. Table 4 shows the experience of FKIP-UT Chemistry Education students in utilizing digital technology and project-based learning models (Project Based Learning, PjBL).

One of the innovations implemented is the use of video-based learning (VBL). Students said that VBL has helped in visualizing the concept of atomic structure and periodic system. This learning not only allows students to see dynamic visual representations, but also provides an interactive learning experience. This is in line with research by Etyarisky & Marsigit (2022) which shows that multimedia learning can improve understanding of concepts by integrating visual and audio elements effectively.

In addition, interactive simulation technology is also applied, where students can learn with 3D atomic models. These simulations allow students to interact directly with the model, providing a more immersive learning experience. According to Almasri (2022), the use of interactive simulations in science learning can improve concept understanding and student engagement.

Students also reported their experiences using project-based learning models (PjBL) to teach colloidal properties and systems. One of the projects identified was "Unearthing Colligative Properties in Ice Cream Freezing". This model not only makes learning more enjoyable but also allows students to understand concepts in greater depth through hands-on experimentation (Zhou, 2023).

In this project, students are exposed to real situations involving everyday ingredients, such as making ice cream. By conducting these experiments, students can observe firsthand how changes in sugar concentration affect colligative properties, such as freezing point (Villaruz et al., 2019). This process involves project identification, planning, conducting experiments, analyzing data, and presenting results, all of which contribute to a more comprehensive understanding of the chemical concepts taught.

The use of PjBL in the teaching of colloidal systems also showed positive results. Students reported that by associating learning with real objects and natural phenomena around them, they could more easily distinguish between colloids, suspensions, and solutions. In this implementation, students' understanding was measured through project-based worksheets, which guided them to document observations, analyze findings, and reflect on the characteristics of each system. According to Sahroni et al., (2022), PjBL can improve understanding of concepts because students are actively involved in the learning process, from planning to project evaluation. In this study, the evaluation of student projects was carried out manually using observation sheets and project-based worksheets, without the integration of digital assessment tools.

Table 4. Use of Technology in Learning

Questions	Answers
What is the role of digital technology in learning atomic structure and periodic systems at your school?	• I apply video-based learning (VBL) which has been implemented by many other teachers. • Students can learn with 3D atomic models using interactive simulations.
How do you integrate technology when teaching Colligative Properties and Colloidal Systems?	• I use educational videos and interactive digital simulations to help students visualize Colligative Properties and Colloidal Systems. For example, when teaching about freezing point depression, I show a simulation of ice cream making to demonstrate how solute concentration affects freezing. • In addition, students complete digital worksheets and record observations in video presentations during project work. This combination of digital media and hands-on activities helps students better understand the differences between colloids, suspensions, and solutions through both virtual and real-life examples.

Learning chemistry requires an adaptive and innovative approach to help students understand abstract and complex concepts. Table 5 shows the experience of FKIP-UT Chemistry Education students in planning and implementing curriculum for Reaction Kinetics, Chemical Equilibrium, Chemical Reactions, Electrochemistry, Organic Compounds, Macromolecules, and Acid-Base Equilibrium, Hydrolysis, and Solubility Products.

Students reported that they used guided inquiry learning models and peer tutor methods to assist weak students in calculations. This is in line with Jegstad (2023) findings, showing that guided inquiry increases student engagement and understanding of chemical concepts. In online learning, students find greater challenges due to network limitations and the need to provide more specific material. Research by Lapitan et al. (2021) also found that online learning requires more structured and visual delivery strategies to overcome the limitations of in-person interaction.

Students integrate the Project Based Learning (PjBL) model with projects such as ecobricks to teach organic compounds and macromolecules. This approach supports the implementation of the Merdeka Curriculum which emphasizes project-based learning and differentiation. According to Nugraha & Ridwan (2020), PjBL not only improves students' cognitive skills but also social skills and environmental care, which is particularly relevant to ecobrick projects.

Table 5. Curriculum Planning and Implementation

Questions	Answers
What is your experience in creating lesson plans for Reaction Kinetics, Chemical Equilibrium, Chemical Reactions and Electrochemistry material? Is there a difference in lesson plans for online learning?	• To help students who struggle with calculations, I use guided inquiry with peer tutoring for reaction kinetics and equilibrium reactions to make the material easier and more engaging. • Preparing lesson plans for face-to-face meetings is easier because we can use various learning models and methods tailored to students and class conditions, especially for practice-based and calculation-intensive learning. • Online learning requires detailed material preparation due to limitations in explaining everything online and issues like unstable networks, which can hinder Zoom sessions.
How is the study of Organic Compounds and Macromolecules connected to the Implementation of the "Kurikulum Merdeka"?	• "Kurikulum Merdeka" uses a differentiated approach by grouping student learning outcomes based on their growth phases. • Project-Based Learning (PjBL) aligns with the "Kurikulum Merdeka", such as Ecobrick projects using various polymers from used plastics to create useful items like tables and chairs. • "Kurikulum Merdeka" supports project-based learning for topics like Organic Compounds and Macromolecules, allowing students to research everyday products or create molecular models.
What is your experience teaching Acid-Base Equilibrium, Hydrolysis, and Solubility Products? Identify the difficulties you encountered and how you overcame them.	• Students struggle with acid-base material, including calculating pH, understanding indicator changes, and identifying acids and bases. Passive learning and weak teacher-student interaction, dominated by lectures, exacerbate this issue. • To address these difficulties, I implement the Problem-Based Learning (PBL) model. • Abstract concepts and mathematical operations, such as pH, Ksp, and salt hydrolysis, are challenging for students. I use visual media like animations and videos, along with practice questions of varying difficulty, to guide students step-by-step from concept understanding to calculations.
What is the role of student worksheets in your teaching, and are they used in digital or manual format?	• LKPD is essential for guiding experiments, problem-solving, and reflection. Currently, manual (printed) LKPD is mainly used. Digital LKPD development is being considered to improve accessibility in online learning.

The main difficulty faced by students is to help students understand abstract concepts and perform calculations related to pH, Ksp, and salt hydrolysis. To overcome this, they use visual media such as animation and video as well as Problem Based Learning (PBL) models. Research by Lukman et al. (2022) supporting the use of PBL and visual media, shows that these methods are effective in improving students' understanding of concepts and problem-solving skills. These findings highlight the need for chemistry teacher training to integrate context-based learning and digital tools, especially for teaching abstract or calculation-intensive topics through PjBL.

4. Conclusion

This research explores and analyzes innovative approaches used by FKIP-UT students in chemistry learning, especially in compiling lesson plans for Reaction Kinetics, Chemical Equilibrium, Chemical Reactions, and Electrochemistry materials. The results showed that the use of guided inquiry learning models and peer tutor methods helped improve students' comprehension of weak calculations, thus making them more interested in these materials. In addition, the application of Project Based Learning (PjBL) in teaching Organic Compounds and Macromolecules in accordance with the Independent Curriculum, shows that a project-based approach can increase student engagement and enable the application of chemical knowledge in everyday life. The impact of these approaches is evident not only in improved student engagement but also in better learning outcomes, such as higher mastery of concepts and enhanced application skills compared to conventional lecture-based methods. This is consistent with previous research findings supporting the effectiveness of active learning methods in improving students' conceptual understanding and practical skills.

Challenges faced in online learning, such as difficulties in delivering material that requires direct interaction and complex calculations, are overcome using visual media such as animation and video. The study specifically explored the integration of digital technologies (e.g., video-based learning and interactive simulations) and project-based learning (PjBL) models, without directly investigating the implementation of Problem-Based Learning (PBL) as a central strategy. This suggests that a combination of technology and project-based learning methods can help students understand abstract concepts and improve their problem-solving skills. Overall, this study confirms that innovative approaches in chemistry learning are not only effective in increasing students' understanding, but also able to overcome various challenges in online learning. For future research, it is recommended to explore more adaptive and innovative learning strategies in various educational environments and evaluate the wider application of the "Kurikulum Merdeka".

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