The Effect of Problem-Based Digital Educational Technology on Students' Achievement and Creativity in Chemistry Learning

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Abstract: This study aims to examine the effectiveness of problem-based digital learning in enhancing students' chemistry achievement and creativity. A quasi-experimental design with pretest–posttest control groups was employed. The participants were second-year undergraduate chemistry students selected through purposive sampling to ensure comparable academic backgrounds. Two intact classes were assigned as the experimental and control groups to maintain ecological validity. The research instruments included a chemistry achievement test, a chemistry creativity scale, and a learning behavior observation sheet. Data were analyzed using analysis of covariance (ANCOVA), multivariate analysis of variance (MANOVA), and thematic analysis for qualitative data. The results indicate that problem-based digital learning significantly improves students' knowledge application, problem-solving skills, and chemistry creativity, particularly in terms of the uniqueness of experimental design, flexibility in solution optimization, and cross-context knowledge transfer. However, no significant difference was found between the two groups in the mastery of basic chemical knowledge. These findings suggest that chemistry instruction in higher education should move beyond the mere transmission of concepts toward problem-based digital learning that emphasizes application, problem solving, and creativity. The integration of authentic problems with virtual laboratory environments enables students to design experiments, test solutions, and transfer knowledge across contexts. In this approach, lecturers function as facilitators, while digital tools serve as cognitive instruments that bridge theoretical understanding and innovative chemical practice.

Introduction

Chemistry serves as the foundation for the development of strategic technologies, ranging from materials engineering and renewable energy to biomedicine. The quality of chemistry education determines a country's capacity to prepare innovative talent—a need that is becoming increasingly urgent in the context of global competition and science-based industrial transformation (Wohlfart et al., 2023; Yesgat et al., 2024). Although China has established a comprehensive chemistry education system from elementary to higher education levels and implemented a core literacy-oriented curriculum philosophy, teaching practices do not yet fully reflect these requirements. The discrepancy between competency goals and learning practices is still evident in the classroom, especially in terms of assessment, experimentation, and the use of digital technology (Dewi et al., 2021) .

One of the main problems lies in the contradiction between exam orientation and scientific literacy development. Educational evaluation still focuses on memorization and algorithmic procedures, resulting in the phenomenon of "high scores but low abilities." The findings of Warmansyah(2022) confirm this gap: although Chinese students excel in science

scores, their investigative and evidence evaluation abilities are at an average level. Previous research also shows a significant gap between theoretical performance and innovative experimental skills in international chemistry competitions. This condition confirms that mastery of concepts alone does not guarantee students' ability to apply knowledge creatively and flexibly (I 2021; Prince, 2017). On the other hand, chemistry experiment learning faces a formalization dilemma. Many schools only present experiments as demonstrations or videos due to safety and time constraints. Previous studies have reported that only a small number of schools provide a full group experiment experience, so students lose the opportunity to build authentic procedural and investigative understanding (Ardhana, 2020). As a result, students may memorize the steps of the practicum but fail to design or optimize experiments independently. These findings are in line with recent research reports that highlight the weak practical application skills of students in higher chemistry education (Candra et al., 2025; Sandaram et al., 2025).

Furthermore, the adoption of digital technology in chemistry classrooms remains superficial. The use of animations, multimedia, or simulations often stops at demonstrative functions and is not integrated into the problem-solving process. Students rarely utilize digital tools to explore variables, validate hypotheses, or design new solutions. The literature shows that when technology is not guided by the right pedagogical approach, there is no improvement in the quality of learning (Constructivist et al., 2014; Ramos & Condotta, 2024; Sarwar et al., 2024) . A critical gap in current chemistry instruction lies in the loss of procedural knowledge and investigative understanding, which are essential components of scientific competence. Many students are trained to memorize experimental steps and standard protocols without understanding the underlying rationale, decision-making processes, or variable interactions involved in experimentation. This approach produces learners who can reproduce procedures accurately yet struggle to design, modify, or optimize experiments when faced with unfamiliar problems. As a result, students lack investigative understanding, including hypothesis formulation, experimental control, data interpretation, and iterative refinement. This gap becomes increasingly problematic in the context of 21st-century competency demands, where chemists are expected to solve complex, ill-structured problems and innovate under dynamic conditions. Independent experimental design and optimization require flexible reasoning, procedural fluency, and critical judgment skills that cannot emerge from rote memorization alone. Therefore, strengthening chemistry education necessitates pedagogical models that explicitly cultivate procedural and investigative understanding, enabling students to move beyond following instructions toward actively constructing and refining experimental solutions.

Although problem-based digital learning (PBDL) has been widely promoted as an innovative approach in chemistry education, existing implementations remain pedagogically insufficient in several critical aspects. Many PBDL practices emphasize problem presentation and digital tool usage but fail to articulate a coherent instructional framework that systematically integrates procedural knowledge, investigative reasoning, and creativity development. In practice, digital components are often reduced to simulations or multimedia resources that support problem discussion without guiding students through structured cycles of experimental design, testing, optimization, and reflection. Moreover, prior PBDL studies frequently treat chemistry learning outcomes as homogeneous, paying limited attention to specific cognitive domains such as experimental creativity, solution optimization, and cross-context transfer, which are central to contemporary scientific competence. In the Chinese higher education context, these limitations are further compounded by exam-oriented

traditions and rigid laboratory practices, which constrain students' opportunities for autonomous inquiry despite the availability of digital technologies. In response to these gaps, the present study develops and tests a refined PBDL model that is explicitly structured around an "investigation-verification reflection" cycle supported by virtual laboratories, molecular simulations, and collaborative digital platforms. The novelty of this approach lies in its deliberate alignment of authentic chemistry problems with iterative experimental design processes, enabling students to independently manipulate variables, evaluate evidence, and optimize solutions in low-risk digital environments. Unlike prior PBDL applications, this model operationalizes chemistry creativity into measurable dimensions and embeds them within the learning trajectory rather than treating them as incidental outcomes. Furthermore, the model is contextualized for Chinese university-level chemistry courses, addressing local curricular demands while advancing 21st-century competencies. This integrative framework provides a theoretically grounded and context-sensitive extension of existing PBDL approaches, forming the basis for the research objectives of this study(Sarwar, 2024).

Research Method

This study used a quasi-experimental design with a pretest–posttest control group model, which allowed researchers to directly compare the impact of problem-based digital learning with direct teaching in the context of chemistry learning. The research flow began with the establishment of the design, pretest implementation, intervention implementation in the experimental and control classes, posttest measurement, and quantitative and qualitative data analysis. The intervention in the experimental group used virtual laboratory devices, online collaborative platforms, and data analysis tools, while the control group received learning through teacher explanations and demonstrations (Diab et al., 2024).

The digital devices used included a virtual chemistry lab, molecular simulation devices, and a learning analytics system to monitor the students' learning process in real time. The research sample consisted of two intact classes of second-year undergraduate chemistry students at the university level. The experimental group comprised 32 students ($N_{E}=32$) who participated in problem-based digital learning, while the control group consisted of 31 students ($N_{C}=31$) who received direct instruction. This sample allocation ensured comparable academic backgrounds and maintained ecological validity, allowing a balanced comparison of learning outcomes between the two instructional approaches. The instructional interventions were implemented over a six-week period, consisting of twelve instructional sessions for both groups. Each session lasted approximately 100 minutes and was conducted twice per week within a regular university chemistry course. During this period, the experimental group engaged in problem-based digital learning activities, while the control group received direct teaching using lectures and demonstrations, ensuring equivalent instructional time across conditions. Data collection was conducted through a combination of chemistry achievement tests, chemistry creativity scales, semi-structured interviews, and non-participant classroom observations. Quantitative instruments included tests of basic knowledge mastery, application skills, and problem-solving skills, as well as a creativity scale that assessed the uniqueness of experimental design, flexibility in solution optimization, and originality in context transfer. Qualitative instruments were used to explore the dynamics of the learning process, thinking strategies, and teacher-student interactions during the intervention.
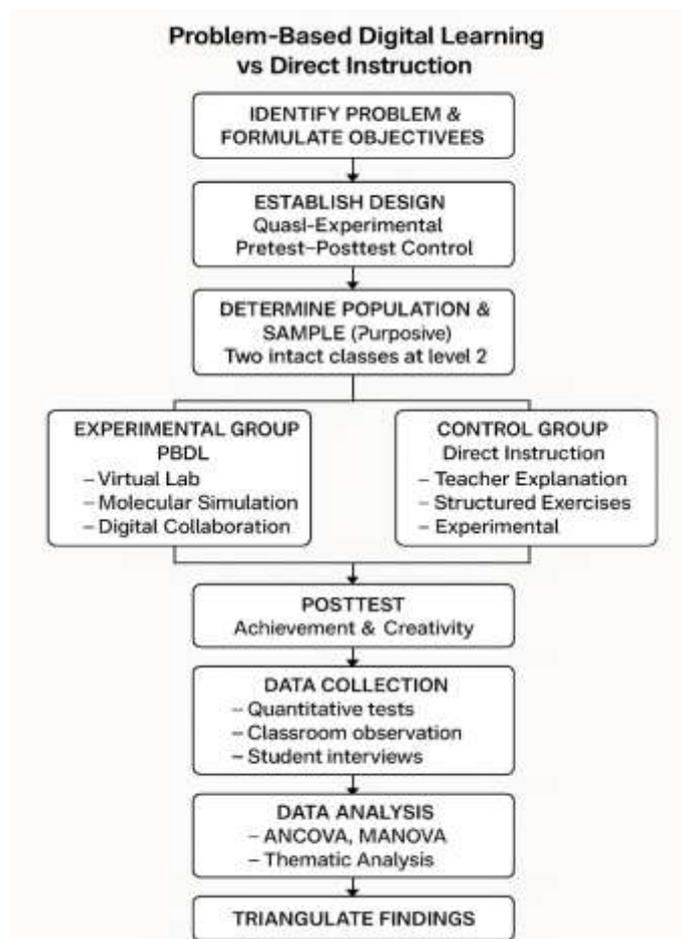
Figure 1. Research Flowchart of Problem-Based Digital Learning vs. Direct Instruction

Data were analyzed using ANCOVA statistical techniques to test post-test score differences while controlling for pre-test effects, and Prior to conducting ANCOVA and MANOVA analyses, a series of statistical assumption tests were performed to ensure the validity of the inferential procedures. Data normality was examined using the Shapiro–Wilk test, indicating that the score distributions met normality criteria. Homogeneity of variances across groups was assessed through Levene's test and showed no significant violations. For ANCOVA, the homogeneity of regression slopes assumption was also tested, confirming that the relationship between the covariate and dependent variables was consistent across groups to assess creativity dimensions simultaneously. Observation and interview data were analyzed using a thematic analysis approach to map patterns of behavior, motivation, and investigation strategies that emerged during learning. The findings were validated through method triangulation to ensure consistency between quantitative and qualitative data, resulting in a strong and credible interpretation of the mechanism of the influence of problem-based digital learning on students' chemistry achievement and creativity.

Results and Discussion

This study shows different patterns in how the two teaching models affect chemistry achievement structures. Although both the experimental and control groups experienced an increase from pre-test to post-test, problem-based digital learning (PBDL) resulted in a much greater increase in knowledge application and problem-solving abilities. As shown in Table

1, the improvement in application skills in the experimental group (10.0±3.5) was double that of the control group (5.0±3.1), while the improvement in problem-solving skills (12.3±4.0) was more than double that of the control group (5.7±3.6). Scientifically, this trend indicates that PBL forms the formation of "new cognitive pathways" through problem-based digital learning (PBDL) can be understood as a fundamental shift in how students process and use chemical knowledge, in contrast to direct teaching (DT), which primarily reinforces memory through repetition and explanation. In DT, learning is largely confined to lower cognitive levels remembering and understanding where students internalize concepts and procedures without necessarily applying them in novel contexts. By contrast, the PBDL design test revise process actively transforms conceptual understanding into application ability by engaging students in iterative cycles of hypothesis formulation, experimental design, outcome evaluation, and refinement. This process aligns closely with constructivist learning theory, which posits that knowledge is constructed through active engagement and meaning-making rather than passive reception. When students design an experiment, they must interpret concepts operationally; when they test and revise, they confront discrepancies between expected and observed outcomes, prompting cognitive restructuring. From the perspective of Bloom's Taxonomy, this cycle systematically moves learners from understanding to applying, analyzing, and creating, thereby strengthening higher order cognitive skills. Situated learning theory further explains this transformation by emphasizing that knowledge becomes functional when learned within authentic problem contexts. Through digitally mediated experimentation, abstract chemical principles are embedded in realistic tasks, enabling students to transfer concepts across contexts. Thus, PBDL does not merely enhance recall but reorganizes conceptual knowledge into flexible, actionable schemas that support problem solving and innovation. In contrast, direct teaching emphasizes memory reinforcement, which predominantly improves basic knowledge dimensions. These findings are in line with Gazali ((2025Saputri ((2025)), who state that inductive methods are superior in higher-level cognitive tasks.

Table 1. Comparison of Chemistry Achievement Scores

Variable	Group	Pre (Mean±SD)	Post (Mean±SD)	Gain
Basic knowledge	Experimental	38.2±5.6	45.6±4.9	7.4±3.2
	Control	37.8±6.1	41.3±5.2	3.5±2.8
Application of knowledge	Experiment	32.5±6.3	42.5±4.8	10.0±3.5
	Control	31.9±5.9	36.9±5.3	5.0±3.1
Problem solving	Experiment	28.6±5.7	40.9±5.1	12.3±4.0
	Control	29.1±6.0	34.8±5.5	5.7±3.6

In terms of chemical creativity, PBDL provides significant advantages in all dimensions. Table 2 shows that the experimental group produced an almost threefold increase in the uniqueness of experimental design and flexibility of solution optimization, as well as more than double the transfer between contexts. Scientifically, this pattern emerges because the "design-test-revise" cycle in virtual experiments allows students to engage in low-risk exploration, accelerate the trial-and-error process, and expand their divergent thinking space. These findings support Fit(2023Yasheni(2024) , who assert that problem-based environments strengthen deep reasoning and innovation.

Table 2. Comparison of Chemistry Creativity Scores

Variable	Group	Pre (Mean±SD)	Post (Mean±SD)	Gain
Uniqueness of experimental design	Experiment	18.3±4.2	27.6±3.8	9.3±2.9
	Control	17.9±4.5	21.2±4.1	3.3±2.5
Optimization flexibility	Experiment	16.5±3.9	25.8±3.5	9.3±2.7
	Control	16.2±4.1	19.8±3.7	3.6±2.3
Context transfer	Experiment	14.8±4.0	23.5±3.6	8.7±2.6
	Control	15.1±3.8	18.4±3.9	3.3±2.4

Qualitative findings provide a mechanistic explanation for these quantitative patterns. Table 3 shows that the experimental group spent nearly three times more time on independent exploration and had a much higher intensity of virtual experiment use (3.8 times/class compared to 0 in the control group). This pattern indicates a shift from passive learning to active knowledge construction. Students in the PBLD environment were more frequently engaged in collaborative discussions, strategy analysis, and independent variable manipulation. Byusa(2022) and Rahman(2024) found that this type of active participation increases cognitive cohesion and situational interest.

Table 3. Classroom Observation Indicators

Indicator	Experimental	Control
Independent exploration time (%)	42	15
Teacher explanation time (%)	28	55
Virtual experiment operations (times/class)	3.8	0
Traditional experimental operations	0.5	1.2
Frequency of technology use	8.6	2.3
Duration of group discussion (%)	22	10

The substantial increase in independent exploration time (42% compared to 15%) and the frequent use of virtual experiments (3.8 times per session versus none) created a learning mechanism that systematically enhanced students' problem-solving ability and creativity. Increased exploration time allowed students to exercise greater autonomy in making decisions about variables, strategies, and experimental pathways, shifting them from passive recipients of information to active constructors of knowledge. This autonomy fostered situational interest, as students perceived learning tasks as meaningful challenges rather than imposed instructions. Such a mechanism is consistent with Self-Determination Theory, which posits that autonomy-supportive learning environments enhance intrinsic motivation and deeper cognitive engagement (Deci & Ryan, 2000). When learners are intrinsically engaged, cognitive resources are allocated more efficiently, leading to deeper processing of chemical concepts. The repeated use of virtual experiments further strengthened this process by enabling rapid trial-and-error cycles without the constraints of physical laboratories, encouraging risk-taking and divergent thinking. Prior studies on virtual laboratories indicate that simulations allow learners to manipulate variables freely, test hypotheses iteratively, and visualize abstract chemical processes, thereby supporting conceptual integration and higher-order thinking (de Jong et al., 2013). As students continuously tested hypotheses and revised strategies, their conceptual understanding became more integrated and coherent, a condition referred to as cognitive cohesion. This cohesion emerges when conceptual, procedural, and

contextual knowledge are interconnected through experience rather than memorization. Consequently, students were better able to recognize patterns, transfer knowledge across contexts, and generate original solutions. The cumulative effect of increased exploration, autonomy, situational interest, and cognitive cohesion explains why higher levels of independent engagement translated directly into superior problem-solving performance and greater chemical creativity.

The findings suggest several important implications for chemistry education in the Chinese higher education context. Educators should actively promote the adoption of virtual laboratories as core instructional tools rather than supplementary media, enabling students to engage in iterative experimentation, hypothesis testing, and solution optimization. Teacher-centered explanation time should be strategically reduced to create space for independent exploration, collaborative problem solving, and guided inquiry. Lecturers are encouraged to redesign learning activities around authentic chemical problems that require students to apply concepts, manipulate variables, and justify decisions. In addition, assessment practices should shift from an emphasis on rote memorization and algorithmic procedures toward evaluating application ability, problem-solving processes, and creativity in experimental design. Formative assessments, project-based tasks, and performance-based evaluations can better capture these competencies. At the institutional level, professional development programs should support lecturers in integrating digital tools with problem-based pedagogy. Collectively, these actions can align chemistry instruction with 21st-century competency demands while respecting curricular structures within Chinese universities.

Conclusion

Based on the entire research process, it can be concluded that problem-based digital learning is a teaching model that comprehensively addresses the objectives of this study. This study proves that the integration of authentic problem situations and digital technology not only increases the depth of knowledge construction but also strengthens students' ability to apply chemistry concepts in new contexts. The cognitive mechanisms built through the "investigation-verification-reflection" cycle enable students to develop higher-order thinking skills, especially in the dimensions of knowledge application, problem solving, and chemical creativity. These advantages arise not because of increased memorization or one-way information transfer, but because of the reconstruction of learning paths that encourage independent exploration, risk-free virtual experiments, and meaningful collaboration. The student-centered learning environment strengthens situational interest and facilitates the transition from conceptual understanding to practical innovation. Thus, problem-based digital learning provides strong empirical evidence that this model can overcome the weaknesses of direct teaching in fostering innovative abilities. Overall, the findings of this study confirm that the use of problem-based digital educational technology can be a strategic path for literacy-oriented chemistry education reform, supporting the development of talents who not only master basic knowledge but are also capable of designing creative and relevant solutions to contemporary chemistry problems.

Recommendation

Chemistry teachers are encouraged to gradually integrate problem-based digital learning by combining virtual experiments with real laboratory activities. Ongoing professional development is needed to strengthen pedagogical and digital competencies. Teachers should also reflect on student learning data to refine problem design, provide timely

feedback, and sustain students' investigative skills and creativity over time. Future research should expand the implementation of problem-based digital learning to more complex chemistry contexts, such as advanced kinetic reactions or functional material design, and examine its impact on students' systems thinking and digital literacy skills. Future research should also consider variations in school technology readiness levels, differences in students' prior abilities, and teachers' competence in managing digital tools, as these factors may influence the effectiveness of the intervention. In addition, longitudinal studies are needed to assess the sustainability of this model's impact on creativity and long-term academic performance.

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