

Exploring Preservice Chemistry Teachers' Creativity in Designing Learning Media through a TPACK-STEM Framework: Evidence from Learning Artifacts and Student Perceptions

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Abstract: Despite increasing attention to technology-integrated STEM learning in teacher education, limited studies have examined how artifact-based project learning reveals pre-service chemistry teachers' creative thinking in designing media for abstract chemistry concepts. This study explored pre-service chemistry teachers' creative thinking in integrated Technological Pedagogical Content Knowledge-Science, Technology, Engineering, and Mathematics learning through teaching aid development. A descriptive-exploratory design involved 12 master's students in chemistry education. Data were collected using a student perception questionnaire, open-ended responses, documentation, and analysis of three artifacts: TyndallScope, Guess Who? Periodic Table Educational Game, and Chromatography Chamber Guide. Quantitative data were analyzed descriptively, while qualitative data were examined through artifact analysis and thematic interpretation. The results showed perceptions, with the highest mean scores in creativity ($M = 4.35$; $SD = 0.48$), relevance of integrated learning ($M = 4.29$; $SD = 0.32$), and usefulness of technology ($M = 4.25$; $SD = 0.41$). Artifact analysis showed that creative thinking was represented through originality, usefulness, flexibility, and elaboration. The products demonstrated learning innovation through colloid visualization, game-based periodic table reasoning, and guided chromatography inquiry. These findings indicate that artifact-based project learning can make creative pedagogical thinking visible and provide a meaningful context for instructional media design among pre-service chemistry teachers.

Keywords: Artifact analysis; Chemistry teaching aid; Creative thinking; Pre-service teacher; TPACK-STEM

Introduction

Chemistry education in the twenty-first century requires learning environments that help students understand abstract scientific concepts while developing creativity, critical thinking, collaboration, communication, and technological literacy (Margot & Kettler, 2019; Guo et al., 2020; Karaca-Atik et al., 2023). Chemistry is often perceived as difficult because many concepts involve invisible particles, symbolic

representations, and processes that cannot be directly observed in ordinary classroom settings (Laohapornchaiphan & Chenprakhon, 2024; Ling et al., 2024). This representational complexity requires teachers to connect macroscopic observations, submicroscopic explanations, and symbolic forms in meaningful ways (Ye et al., 2019). In teacher education, this challenge becomes more important because pre-service chemistry teachers are expected not only to understand chemistry content, but also to transform it

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into pedagogically meaningful and technologically supported learning experiences (Yamtinah et al., 2024; Nugraheni & Srisawasdi, 2025). Therefore, chemistry teacher education should provide opportunities for students to design instructional artifacts that make chemical phenomena more visible, interactive, and conceptually accessible (Pinger et al., 2019; Perna & Wiedmer, 2020).

Project-based learning, STEM integration, and technology-enhanced learning have been widely used to support authentic learning and higher-order thinking in higher education. Project-based learning can promote engagement, collaboration, problem-solving, and learning motivation when students work on authentic tasks with appropriate scaffolding (Guo et al., 2020). STEM learning encourages learners to connect scientific concepts, technological resources, engineering design, and mathematical reasoning in solving problems (Thibaut et al., 2018; Margot & Kettler, 2019). In chemistry teacher education, these approaches are relevant because pre-service teachers need to design media, teaching aids, games, or experimental tools that are not only attractive but also conceptually accurate and pedagogically useful. However, technology in chemistry learning is often treated as a technical tool rather than as part of integrated pedagogical reasoning. Digital media, sensors, educational games, and 3D-printed objects may appear innovative, but their educational value depends on their alignment with chemistry content, instructional strategy, and learning context (Gonscherowski & Rott, 2025; Yamtinah et al., 2024).

The Technological Pedagogical Content Knowledge (TPACK) framework provides a relevant basis for guiding pre-service teachers in integrating content, pedagogy, and technology in instructional design (Mishra & Koehler, 2006; Koehler et al., 2013). In chemistry teacher education, TPACK helps shift technology use from technical operation to pedagogical design with technology (Kartal & Dilek, 2021). However, developing chemistry teaching aids also requires design, construction, testing, and revision. These activities are closely related to STEM-oriented learning because students need to use scientific knowledge, technological tools, engineering design processes, and mathematical reasoning to produce functional instructional artifacts (Margot & Kettler, 2019; Yüksel, 2025). Thus, the integration of TPACK and STEM can provide a productive framework for helping pre-service chemistry teachers transform abstract chemistry topics into usable learning media.

Creative thinking is central to this process because designing instructional artifacts requires students to generate, develop, and refine ideas into products that are original, useful, flexible, and elaborated. Creativity is

commonly understood as the production of ideas or products that are both original and effective or useful in a particular context (Runco & Jaeger, 2012). In educational settings, creativity is also reflected in flexibility and elaboration because learning products should be adaptable to classroom needs and sufficiently developed for instructional use (Alabbasi et al., 2022; Syawaludin et al., 2024). These dimensions are important in chemistry teacher education because a creative learning medium should not only be novel, but should also represent chemical concepts accurately, support meaningful learning activities, and be applicable in real classroom contexts.

Previous studies have examined TPACK development, STEM implementation, project-based learning, digital fabrication, technology-enhanced learning, and creativity in teacher education. However, these areas are often investigated separately. Many studies focus on measuring teachers' TPACK, examining students' perceptions of STEM learning, or evaluating project-based learning outcomes (Gonscherowski & Rott, 2025; Guo et al., 2020; Margot & Kettler, 2019). Fewer studies analyze the actual learning artifacts produced by pre-service chemistry teachers as empirical evidence of creative thinking. Moreover, although technologies such as digital fabrication, sensors, and Internet of Things devices are increasingly relevant in science learning, the present study does not position technology as the main variable to be evaluated. Instead, technology is treated as part of a broader instructional design context in which students use available tools and media to represent chemistry concepts pedagogically.

Based on this gap, this study aims to explore pre-service chemistry teachers' creative thinking in integrated TPACK-STEM learning through the development of technology-oriented chemistry teaching aids. The study focuses on students' perceptions and three learning artifacts: a Tyndall effect visualization tool, a periodic table educational game, and a chromatography chamber guide. The novelty of this study lies in its artifact-based analysis of creativity within a TPACK-STEM framework. Rather than claiming causal improvement, this study examines how creative thinking is represented through originality, usefulness, flexibility, and elaboration, and how these dimensions appear in the integration of chemistry content, pedagogy, technology, and STEM elements. The contribution of this study is to provide an artifact-based approach for evaluating creative pedagogical thinking in pre-service chemistry teacher education and to offer a basis for developing TPACK-STEM learning designs that support innovative instructional media development.

Method

Research Design

This study employed a descriptive-exploratory design with a design-based learning orientation to examine how pre-service chemistry teachers expressed creative thinking through the development of chemistry teaching aids in an integrated TPACK-STEM learning environment. The design was appropriate because the study did not test causal effects or measure improvement through pre-test and post-test comparison, but explored students' perceptions, learning processes, and artifacts produced during the project. Creative thinking was examined through students' responses and learning artifacts rather than standardized creativity tests.

The learning design was grounded in the Technological Pedagogical Content Knowledge framework, which emphasizes the integration of content, pedagogy, and technology in teaching (Mishra & Koehler, 2006). STEM principles were also applied because students connected scientific concepts, technological resources, engineering design, and mathematical reasoning in developing instructional artifacts (Margot & Kettler, 2019). Since project-based learning supports authentic tasks, product development, collaboration, and reflection (Guo et al., 2020), the methodology was designed to capture both students' perceptions and the quality of their creative artifacts.

Research Context and Participants

The study was conducted in a graduate chemistry education course at Universitas Negeri Semarang, Indonesia. The participants were 12 master's students in Chemistry Education who were enrolled in a course related to technology integration and chemistry learning design. The participants were selected through purposive sampling because they had completed prerequisite chemistry education courses, had relevant academic backgrounds in chemistry education, and were directly involved in the TPACK-STEM instructional design project. This sampling technique was considered appropriate because the study required participants who had experienced the learning activity and had produced artifacts that could be analyzed as evidence of creative pedagogical thinking. The participants represented pre-service or prospective chemistry educators who were expected to develop the ability to design instructional media for chemistry learning.

The learning activity was implemented as a project in which students were asked to design chemistry teaching aids that integrated chemistry content, pedagogical considerations, and technological elements.

During the project, students worked collaboratively to identify chemistry concepts that are often difficult for school students, design instructional media, develop physical or digital artifacts, prepare user guides, and reflect on the pedagogical function of the products. The artifacts produced by the students included a Tyndall effect visualization tool, an educational periodic table game, and a chromatography chamber guide. These artifacts were used as evidence for examining creative thinking because they represented students' ability to transform chemistry concepts into instructional products.

Learning Procedure

The learning procedure followed a project-based sequence consisting of orientation, problem identification, design planning, artifact development, presentation, and reflection. Students were first introduced to the TPACK framework, STEM learning principles, and examples of technology-enhanced chemistry teaching aids to build a shared understanding that effective media should align technology with chemistry content and pedagogical goals (Koehler et al., 2013). They then selected abstract or difficult chemistry topics, including colloidal systems and the Tyndall effect, periodic properties of elements, and chromatographic separation. Each group planned and developed a teaching aid by considering the target learners, represented chemistry content, technological features, and classroom use. This process reflected STEM-oriented learning because students connected scientific concepts with product design, usability, and problem-solving. The final artifacts included a Tyndall effect visualization tool, a periodic table educational game, and a chromatography chamber guide. In the presentation and reflection phase, students explained the product function, chemistry concepts, learning activities, and limitations of their design. The overall learning procedure is illustrated in Figure 1.

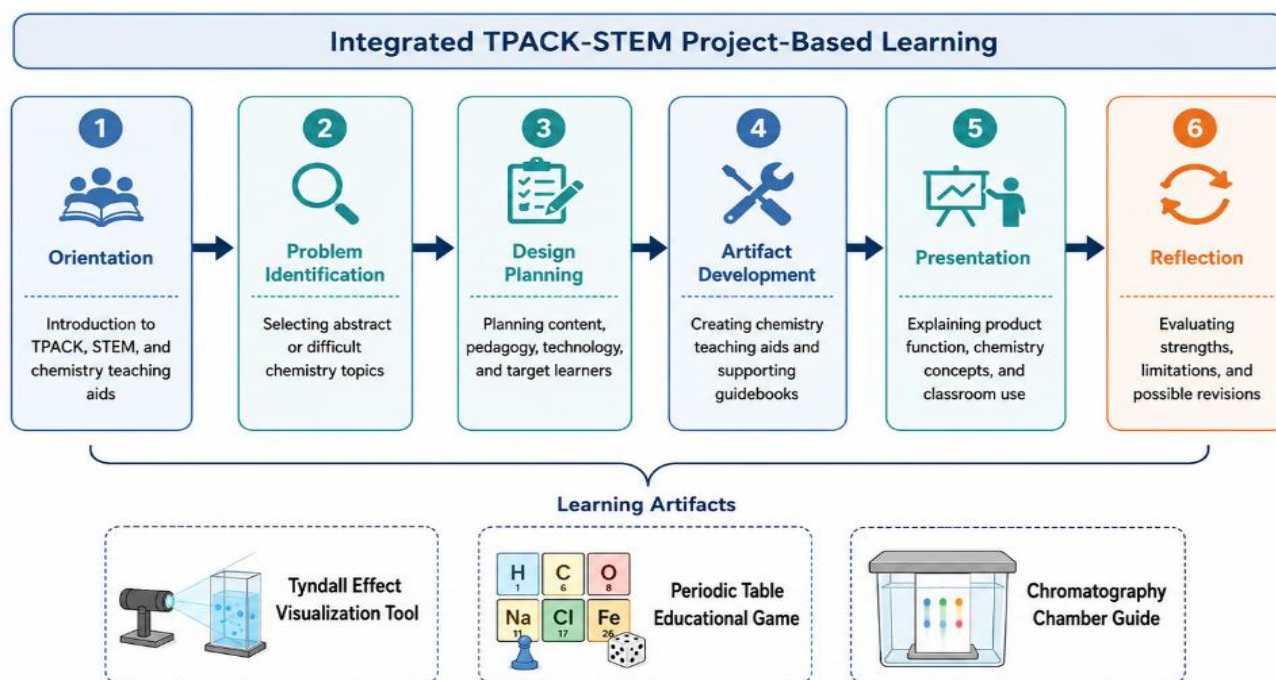
Data Collection and Instrument Validation

Data were collected from four sources: a student perception questionnaire, learning artifacts, open-ended responses, and observation documentation. The questionnaire was administered after the learning activity using a five-point Likert scale and consisted of 32 main items and two attention-check items. The items covered eight constructs: creativity in learning, engagement and motivation, collaboration, critical thinking and inquiry, technology usefulness, ease of technology use, TPACK-STEM relevance, and satisfaction. These constructs were adapted from previous studies on creativity, technology integration, TPACK, STEM learning, and project-based learning (Alabbasi et al., 2022; Guo et al., 2020; Margot & Kettler,

2019; Runco & Jaeger, 2012). Content validity was reviewed by two chemistry education experts based on item clarity, relevance, theoretical alignment, and suitability for pre-service chemistry teacher education. The questionnaire showed acceptable internal consistency, with a Cronbach's alpha coefficient of 0.814. One negatively worded item was reverse-coded before analysis.

Artifact data were obtained from three student products and their guidebooks. The artifacts were analyzed as representations of creative thinking using four dimensions: originality, usefulness, flexibility, and

elaboration. Originality referred to the novelty of the idea or instructional representation; usefulness referred to conceptual accuracy and relevance to chemistry learning; flexibility referred to adaptability across learning activities; and elaboration referred to the completeness of the product, guidebook, procedures, worksheets, and learning scenario. Observation and documentation were conducted by the research team using an observation sheet focusing on students' participation, collaboration, idea development, technology use, product development, presentation, and reflection.



Students collaboratively transform chemistry concepts into pedagogically meaningful teaching aids.

Figure 1. Project-based TPACK-STEM learning procedure for developing chemistry teaching aids

Data Analysis

Quantitative data from the questionnaire were analyzed descriptively by calculating the mean and standard deviation for each construct. The descriptive analysis was used because the sample size was small and the purpose of the study was exploratory rather than inferential. No causal statistical test was conducted because the study did not use a control group or pre-test and post-test design. The interpretation of mean scores was used to identify the general tendency of student perceptions toward the learning experience.

Qualitative data from learning artifacts were analyzed using an artifact analysis rubric. The rubric combined three analytical lenses: TPACK, STEM, and creativity. The TPACK lens examined how each artifact represented chemistry content, pedagogical strategy, and technological use. The STEM lens examined how

each artifact reflected science, technology, engineering, and mathematical elements. The creativity lens examined originality, usefulness, flexibility, and elaboration. Each creativity dimension was assessed using a four-level scale: 1 = low, 2 = moderate, 3 = high, and 4 = very high. The score interpretation was based on the degree to which the artifact showed novelty, pedagogical relevance, adaptability, and completeness.

Two chemistry education experts independently analyzed the learning artifacts using the rubric. Differences in interpretation were discussed through peer debriefing until agreement was reached. This procedure was used to strengthen the credibility of the artifact analysis and reduce the subjectivity of qualitative interpretation. Open-ended responses were analyzed thematically to identify recurring patterns related to perceived learning benefits, technological

challenges, collaboration, and suggestions for improvement. The results from the questionnaire, artifact analysis, open-ended responses, and observation documentation were then compared to support triangulation. Table 1 summarizes the data sources and analytical focus used in this study.

Table 1. Data Sources and Analytical Focus of the Study

Data source	Type of data	Analytical focus	Analysis technique	Contribution to the study
Student perception questionnaire	Quantitative data from a five-point Likert scale	Students' perceptions of creativity, engagement, collaboration, critical thinking and inquiry, usefulness of technology, ease of technology use, relevance of TPACK-STEM integration, and satisfaction with the learning process	Descriptive statistics using mean and standard deviation; one negatively worded item was reverse-coded before interpretation	Provides an overview of how students perceived the TPACK-STEM project-based learning experience and its role in supporting creative learning
Open-ended questionnaire responses	Qualitative written responses	Students' perceived benefits, challenges, and suggestions regarding the development of chemistry teaching aids in the TPACK-STEM learning context	Thematic analysis to identify recurring patterns in students' responses	Supports interpretation of the quantitative data and explains why students perceived the learning process positively or experienced certain difficulties
Learning artifacts	Student-developed products and supporting guidebooks	Evidence of creative thinking represented in the products, including originality, usefulness, flexibility, and elaboration	Artifact analysis based on creativity dimensions and TPACK-STEM integration	Provides concrete evidence of how students transformed chemistry concepts into pedagogically meaningful teaching aids
Tyndall Effect Visualization Tool	Chemistry teaching aid and guidebook	Representation of colloidal system concepts, visualization of the Tyndall effect, inquiry-based learning potential, and use of digital/3D design technology	Artifact analysis using TPACK, STEM, and creativity lenses	Shows how students designed a visualization tool to make an abstract chemistry concept more observable and meaningful
Periodic Table Educational Game	Game-based chemistry learning media and guidebook	Representation of periodic table concepts, student interaction, questioning strategy, classification of elements, and game-based learning design	Artifact analysis using TPACK, STEM, and creativity lenses	Shows how students transformed periodic table content into an interactive game that supports communication, reasoning, and conceptual understanding
Chromatography Chamber Guide	Practical chemistry teaching aid and guidebook	Representation of separation techniques, chromatography procedure, Rf calculation, observation, and laboratory-based inquiry	Artifact analysis using TPACK, STEM, and creativity lenses	Shows how students designed a practical guide and apparatus to support experimental learning and data-based reasoning
Observation and documentation	Observation sheet, field notes, product photos, presentation records, guidebooks, and product documentation	Students' participation, collaboration, idea development, use of technological tools, product development process, presentation, and reflection during the learning activity	Descriptive qualitative analysis and triangulation with questionnaire data, open-ended responses, and artifact analysis	Provides contextual evidence of the learning process and strengthens the interpretation of how students developed chemistry teaching aids in the TPACK-STEM project

Research Trustworthiness and Ethical Considerations

To enhance trustworthiness, the study used multiple sources of evidence, including questionnaire data, student artifacts, guidebooks, open-ended responses, observation notes, and product documentation. Artifact analysis was used because student perceptions alone may not fully reveal how creative thinking is represented in actual instructional products. By combining perception data, artifact

evidence, open-ended responses, and observation documentation, the study provided a more balanced interpretation of students' creative thinking in TPACK-STEM learning. The analytical categories were derived from established literature on TPACK, STEM education, project-based learning, and creativity to maintain theoretical consistency. Expert validation, peer discussion, and triangulation were also used to strengthen the credibility of the findings.

The study followed institutional ethical guidelines for educational research. Participation was conducted in the context of regular course activities, but students were informed that their responses and learning artifacts would be used for research purposes. Informed consent was obtained from all participants, and the analysis focused on learning patterns rather than personal evaluation. Student identities were anonymized and not reported in the manuscript to maintain confidentiality. The study acknowledges that its findings are context-specific and should not be generalized statistically; however, the exploratory evidence provides useful insight into how pre-service chemistry teachers express creative thinking through the development of technology-oriented chemistry teaching aids in a TPACK-STEM learning environment.

Result and Discussion

The findings are presented by integrating three sources of evidence: student perception questionnaire, artifact analysis, and open-ended responses. This integrated presentation is important because the study did not aim to test the causal effect of integrated TPACK-STEM learning, but to explore how pre-service chemistry teachers expressed creative thinking through the development of chemistry teaching aids. The questionnaire data provided an overview of students' perceptions, while the artifacts offered concrete evidence of how chemistry concepts were transformed into instructional products. This approach is consistent with the view that creativity should be examined not only through self-reported perception, but also through products that demonstrate originality, usefulness, flexibility, and elaboration (Alabbasi et al., 2022; Runco & Jaeger, 2012).

The questionnaire results showed that students perceived the integrated TPACK-STEM learning experience positively. As shown in Table 2, the highest mean score was found in creativity in learning ($M = 4.35$; $SD = 0.48$), followed by relevance of TPACK-STEM integration ($M = 4.29$; $SD = 0.32$) and perceived usefulness of technology ($M = 4.25$; $SD = 0.41$). These findings indicate that the project provided a meaningful space for students to generate ideas, design learning media, and connect chemistry content with pedagogical and technological considerations. The high creativity score may be explained by the nature of the task, which required students to move beyond understanding chemistry concepts and to redesign those concepts into visible, interactive, and usable learning artifacts. This finding is in line with Alabbasi et al. (2022), who emphasized that creativity in education involves the development and refinement of ideas into meaningful

products, and with Guo et al. (2020), who found that project-based learning supports active engagement, collaboration, and product-oriented learning when tasks are authentic and appropriately scaffolded.

The relevance of TPACK-STEM integration also received a very high score, suggesting that students recognized the importance of combining content, pedagogy, technology, and STEM-oriented design in learning media development. This finding supports the central idea of TPACK that technology becomes educationally meaningful only when it is connected to subject matter and instructional strategies (Koehler et al., 2013). It is also consistent with Margot et al. (2019), who reported that STEM integration requires teachers to connect disciplinary knowledge with problem-solving and instructional design. In the present study, students did not treat technology merely as a tool; rather, they used it as part of a design process for representing abstract chemistry concepts in pedagogically meaningful ways.

The lowest mean score was found in ease of technology use ($M = 3.62$; $SD = 0.23$). Although this score was still categorized as high, it indicates that students experienced some technical difficulties when transforming ideas into functional products. This result is important because it shows that students valued technology but still needed technical and pedagogical scaffolding (Tondeur et al., 2019). The challenge may have emerged from the need to design physical components, prepare guidebooks, align products with chemistry content, and ensure that the media could be used in classroom activities. This finding is consistent with Guo et al. (2020), who emphasized that project-based learning requires clear guidance and scaffolding, particularly when students work on complex and authentic tasks. Therefore, the lower score for ease of technology use should not be interpreted as a weakness of the learning model, but as evidence that technology-oriented instructional design requires structured support (Tan & Chen, 2022).

Table 2. Students' Perceptions of Integrated TPACK-STEM Learning

Construct	Mean	SD	Interpretation
Creativity in learning	4.35	0.48	Very high
Engagement and motivation	3.98	0.65	High
Collaboration	4.10	0.39	High
Critical thinking and inquiry	3.85	0.38	High
Perceived usefulness of technology	4.25	0.41	Very high
Ease of technology use	3.62	0.23	High
Relevance of TPACK-STEM integration	4.29	0.32	Very high
Satisfaction and intention for further use	4.06	0.24	High

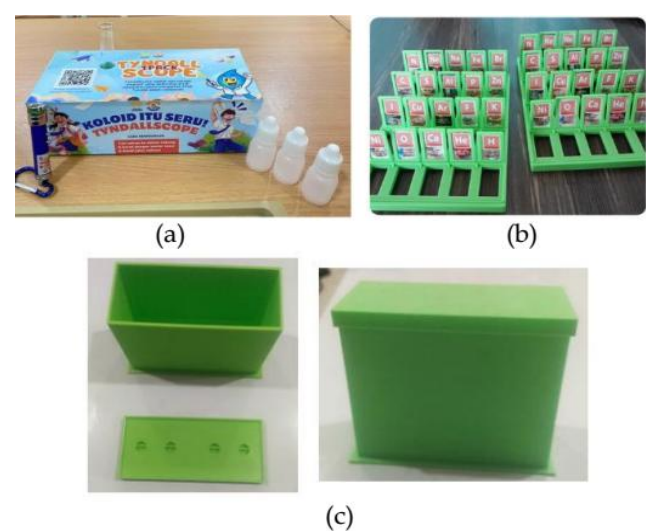


Figure 2. Student-developed chemistry teaching aids: (a) TyndallScope for visualizing the Tyndall effect in colloidal systems, (b) Guess Who? Periodic Table Educational Game, and (c) Chromatography Chamber Guide

The artifact analysis provided more direct evidence of how creative thinking was represented in students' products (Irawan et al., 2024). As shown in Figure 2 and Table 3, the three artifacts represented different forms of chemistry teaching aids: a Tyndall effect visualization tool, a periodic table educational game, and a chromatography chamber guide. These products

showed that students were able to translate chemistry content into different pedagogical formats, including visual demonstration, game-based learning, and laboratory inquiry (Li et al., 2023; Rahayu & Sari, 2023; Stieff, 2019). The diversity of these artifacts indicates that creativity appeared not only in the novelty of the products, but also in the students' ability to select appropriate representations, design learning activities, and connect the media with chemistry learning objectives.

The TPACK-STEM analysis showed that each artifact contained a different configuration of chemistry content, pedagogical orientation, technological element, and STEM representation (Cetin-dindar et al., 2018). The TyndallScope emphasized visual observation of colloidal phenomena, the Guess Who? Periodic Table Educational Game emphasized questioning and conceptual classification, while the Chromatography Chamber Guide emphasized practical inquiry and data-based reasoning. These findings suggest that students did not merely produce attractive media, but engaged in pedagogical transformation of chemistry content (Aydin-gunbatar & Akin, 2022). This is important in chemistry teacher education because pre-service teachers need to learn how to convert abstract concepts into teachable representations that can support students' understanding (Graulich & Caspari, 2021; Seery et al., 2017).

Table 3. TPACK-STEM Analysis of Student-Developed Chemistry Teaching Aids

Artifact	Chemistry content	Pedagogical orientation	Technological element	STEM representation
TyndallScope	Colloidal systems, Tyndall effect, distinction among true solution, colloid, and suspension	Inquiry-based observation and visual demonstration	3D design, physical model, light-based visualization, and QR-supported guide	Science through colloid phenomena; technology through digital and physical media design; engineering through prototype construction; mathematics through dimensions, spatial layout, and comparison
Guess Who? Periodic Table Educational Game	Periodic table, groups, periods, electron configuration, and periodic properties	Game-based learning, questioning strategy, peer discussion, and formative review	Visual card design, printed game components, and structured game board	Science through element properties; technology through media design; engineering through game mechanism; mathematics through classification patterns and periodic trends
Chromatography Chamber Guide	Separation techniques, paper chromatography, solvent movement, and Rf value	Laboratory inquiry, guided experimentation, observation, and data-based discussion	Designed chamber, practical guide, and structured worksheet	Science through separation principles; technology through apparatus design; engineering through chamber construction; mathematics through Rf calculation and comparison

The creativity categories in Table 4 were derived from the artifact analysis rubric described in the Method section. Each artifact was analyzed using four dimensions: originality, usefulness, flexibility, and elaboration. Originality referred to the novelty of the

product idea or instructional representation; usefulness referred to conceptual accuracy, relevance to chemistry learning objectives, and classroom function; flexibility referred to the possibility of using the product in different learning activities; and elaboration referred to

the completeness of the product design, guidebook, procedure, worksheet, and learning scenario (Bolden et al., 2020). Thus, the labels moderate, high, and very high did not represent subjective impressions, but were based on the degree to which each artifact fulfilled the rubric indicators (Cheng, 2018; Long et al., 2022).

Table 4 shows that the three artifacts were generally strong in usefulness and elaboration. The TyndallScope was categorized as high in originality, usefulness, and elaboration because it transformed an abstract colloid concept into a visual and observable classroom demonstration. The Guess Who? Periodic Table Educational Game received high ratings across the four dimensions because it adapted a familiar game structure into a chemistry-specific medium that supported questioning, classification, peer discussion, and formative review. This finding is consistent with Hu et al. (2022), who reported that game-based learning in chemistry can support interaction and conceptual learning when the game mechanics are aligned with learning objectives. It is also in line with Naaim et al.

(2024), who showed that periodic table learning can be strengthened through game-based approaches that promote motivation and active participation.

The Chromatography Chamber Guide showed very high usefulness but moderate originality and flexibility. This pattern indicates that educational creativity does not always require radical novelty. A product may still be pedagogically creative when it adapts existing laboratory principles into a more accessible, structured, and usable learning tool. In this study, the chromatography artifact was valuable because it supported laboratory inquiry, procedural understanding, and data interpretation. This finding extends the concept of creativity in teacher education by showing that creative products may emerge through refinement, contextual adaptation, and instructional structuring, not only through completely new inventions. This interpretation is consistent with Runco & Jaeger's (2012) definition of creativity as requiring both originality and effectiveness.

Table 4. Creativity Analysis of Student-Developed Artifacts

Artifact	Originality	Usefulness	Flexibility	Elaboration	Main interpretation
TyndallScope	High	High	Moderate	High	The product creatively visualized an abstract colloid concept through a physical demonstration tool and guidebook
Guess Who? Periodic Table Educational Game	High	High	High	High	The product transformed periodic table learning into an interactive game that supported questioning, classification, and peer discussion
Chromatography Chamber Guide	Moderate	Very high	Moderate	High	The product provided a practical apparatus and structured guide for experimental learning and data interpretation

The open-ended responses supported the questionnaire and artifact findings (Mardiah et al., 2022). As summarized in Table 5, students reported that the project helped them understand how abstract chemistry concepts could be made more concrete through teaching aids. They also perceived that technology and designed media could make chemistry learning more attractive and easier to explain. Collaboration was another important theme because group discussion helped students improve product ideas and solve design problems (Backfisch et al., 2023; Mcdougall & Phillips, 2024). These responses help explain why creativity, relevance of TPACK-STEM integration, and collaboration received high scores in the questionnaire. Creativity in this context was not only an individual cognitive ability, but also a situated process shaped by collaboration, negotiation, technical constraints, and pedagogical decision-making (Wong et al., 2021).

At the same time, students' responses also revealed challenges in technical procedures and the need for clearer guidance. This finding explains why ease of

technology use had the lowest mean score among the questionnaire constructs. Students needed support not only in operating technological tools, but also in aligning product design with chemistry content, learner characteristics, classroom activities, and assessment possibilities. Therefore, TPACK-STEM learning should not only ask students to create products, but should also provide structured scaffolding, examples of good learning media, technical guidance, and reflection activities. This finding is consistent with studies emphasizing that technology integration in teacher education requires pedagogical support rather than technical exposure alone (Koehler et al., 2013; Yamtinah et al., 2024).

The findings have several practical implications. For chemistry teacher education curriculum developers, artifact-based projects can be integrated into courses related to chemistry learning media, instructional design, or technology integration (Dewi et al., 2022; Diamah et al., 2022). Such projects can help pre-service teachers connect chemistry content knowledge with

pedagogical reasoning and product development (Fang et al., 2025; Lin et al., 2021). For lecturers who teach TPACK, STEM, or chemistry education courses, the findings suggest the importance of providing design rubrics, technical scaffolding, peer feedback, and opportunities for presentation and reflection (Papanikolaou et al., 2022). For learning media development, the study indicates that products should

be evaluated not only based on visual attractiveness or technological sophistication, but also on conceptual accuracy, pedagogical usefulness, flexibility of classroom use, and completeness of supporting materials (Da et al., 2021). In this sense, artifact-based analysis can serve as a practical model for evaluating creative pedagogical thinking in pre-service chemistry teacher education (Jue & Haiying, 2024).

Table 5. Themes from Students' Open-Ended Responses

Theme	Summary of students' responses	Interpretation
Chemistry concepts became more teachable	Students stated that the project helped them think about how abstract chemistry concepts could be made more concrete through teaching aids	The activity supported the transformation of content knowledge into pedagogical representation
Technology supported learning design	Students perceived that technology and designed media could make chemistry learning more attractive and easier to explain	Technology was viewed as useful when connected to learning goals and classroom use
Collaboration supported idea development	Students reported that group discussion helped them improve product ideas and solve design problems	Creativity emerged through social negotiation and shared problem-solving
Technical procedures remained challenging Further guidance is needed	Students mentioned difficulties in design, tool construction, and technological operation Students suggested clearer instructions, more examples, and better preparation before product development	Technical scaffolding is needed to support students in technology-oriented project work Project-based TPACK-STEM learning requires structured support to optimize creative outcomes

This study has several limitations. First, the study involved only 12 master's students from one university, so the findings should not be generalized statistically to broader populations. Second, the descriptive-exploratory design did not use a control group or pre-test and post-test comparison; therefore, the findings should not be interpreted as evidence that students' creativity increased. Third, the analysis focused on students' perceptions and the artifacts they produced, but did not examine the implementation of the teaching aids in real school classrooms. Future research should involve larger and more diverse participants, apply validated creativity rubrics with stronger inter-rater agreement, and investigate how student-developed teaching aids influence school students' chemistry learning, engagement, and conceptual understanding.

Overall, the findings indicate that integrated TPACK-STEM learning provided a meaningful context for exploring the creative thinking of pre-service chemistry teachers. The principal contribution of this study is its artifact-based approach to examining creativity in chemistry teacher education. The three student-developed products showed that creative thinking can appear as conceptual visualization, game-based transformation, and laboratory apparatus adaptation. Rather than positioning creativity as an abstract trait, this study shows that creative pedagogical thinking can be made visible through instructional

artifacts that are original, useful, flexible, elaborated, and aligned with chemistry learning needs.

Conclusion

This study demonstrates that integrated TPACK-STEM project-based learning provides a meaningful context for exploring pre-service chemistry teachers' creative thinking through the development of chemistry teaching aids. Students' perceptions were generally positive, especially regarding creativity, relevance of TPACK-STEM integration, and usefulness of technology. Artifact analysis further showed that creative thinking was represented through three instructional products: TyndallScope for visualizing the Tyndall effect, Guess Who? Periodic Table Educational Game for supporting conceptual classification and questioning, and Chromatography Chamber Guide for facilitating laboratory-based inquiry. Unlike studies relying primarily on self-reported creativity, this study combines perception data with artifact-based evidence to examine how creative thinking appears in instructional media design. This study contributes to chemistry teacher education by demonstrating that artifact-based analysis provides a practical approach for making pre-service teachers' creative pedagogical thinking visible within integrated TPACK-STEM learning. The findings support the integration of artifact-based project learning into chemistry teacher education

programs to foster innovative instructional media design. However, because this study used a descriptive-exploratory design with a small number of participants and no pre-test-post-test comparison, the findings should not be interpreted as evidence of increased creativity. Future research should involve larger samples, validated creativity rubrics with inter-rater agreement, and classroom implementation of the developed teaching aids to examine their impact on students' chemistry learning.

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Author Contributions

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Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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