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# Development of inquiry competence through STEM-based nanotechnology education among future physics teachers

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**Abstract**

The pedagogical potential of STEM-based research-oriented learning activities for enhancing future physics teachers' research competence and interest in nanotechnology has not been sufficiently investigated empirically. In this regard, the aim of the study was to determine the impact of a STEM-based nanotechnology learning module on future physics teachers' interest in nanotechnology and research competence. The study employed a quantitative quasi-experimental design. N = 108 students enrolled in physics teacher education programs at three universities participated in the study. Participants were divided into experimental group (EG) (n = 53) and control group (CG) (n = 55). The intervention was conducted for seven weeks. STEM-based project-oriented and research-oriented learning activities, digital visualization and a system of situational tasks were implemented in the EGs, while traditional teaching methods were used in the CGs. A questionnaire on a 5-point Likert scale consisting of 20 statements and a system of situational tasks for assessing research competence were used for data collection. The questionnaire demonstrated high internal consistency (Cronbach's alpha = 0.87). In addition, students' research competence was assessed using the inquiry competence index (ICI). Data were analyzed using the Shapiro-Wilk test, Mann-Whitney U test, Wilcoxon signed-rank test, effect size (r), and normalized gain coefficient (g). The results demonstrated significant improvements in students' interest in nanotechnology and research competence in the EGs. In the EGs, the interest scores increased from 55-57 to 83-86 points, while the ICI scores increased from 45-48% to 69-72%. In addition, large $r$ values (≈ 0.88) and moderate $g$ values (= 0.41-0.48) were observed in the EGs, whereas the $g$ values remained substantially lower in the CGs. The findings suggest that STEM-based, research-oriented nanotechnology learning activities can positively influence the development of subject interest and research competence in future physics teachers. The results of the study support the pedagogical importance of integrating STEM-based nanotechnology education into teacher training programs.

**Keywords:** STEM education, STEM-based learning activities, nanotechnology education, inquiry competence index, future physics teachers

## INTRODUCTION

At present, the rapid development of science and technology places new demands on education systems. Industry 4.0, digitalization, artificial intelligence and the expansion of high-tech industries require the modernization of the content of training specialists in the field of natural sciences (Nugraha et al., 2023; Zhai et al., 2023). One such strategically important areas is nanotechnology. Nanotechnology is considered an


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**Contribution to the literature**

- This study provides multi-university quasi-experimental evidence on the effects of STEM-based nanotechnology education on the inquiry competence and subject interest of future physics teachers.
- It introduces an approach that combines project- and inquiry-oriented activities, digital visualization, and situational tasks, while using the inquiry competence index to assess students' scientific reasoning and research skills.
- The findings demonstrate the value of systematically integrating STEM-based nanotechnology activities into physics teacher education and offer practical guidance for developing research-oriented courses in higher education.

interdisciplinary scientific field that contributes to the development of many areas, such as medicine, electronics, energy, bioengineering, materials science and robotics (Lamberti, 2008; Schmid et al., 2023). Since its content is based on the interaction of physics, chemistry, biology, computer science and engineering sciences, nanotechnology education is becoming an important component of the development of a modern scientific worldview.

In the modern education system, the training of future teachers should not be limited to theoretical instruction alone. Teaching natural sciences in the current context requires the formation of students' scientific research culture, analytical thinking, experimental skills and research competence (Gümüş & Bozkurt Altan, 2025; Kuzmenko et al., 2023). Research competence is considered a complex pedagogical competence that includes the ability to define a scientific problem, propose a hypothesis, conduct research, analyze experimental results and draw scientific conclusions. In this regard, nanotechnology teaching is an important area for improving the research and practical training of future physics teachers. Nanotechnology content enables students to explain complex physical phenomena in a modern scientific context, understand interdisciplinary connections and actively participate in scientific research activities (Skakov & Nurizinova, 2021). In recent years, the science, technology, engineering, and mathematics (STEM) educational approach has been widely considered as one of the effective pedagogical models for teaching natural sciences. The STEM approach allows for the connection of theoretical knowledge and practical activities, the use of engineering design elements, and the development of research activities (Zeng et al., 2025; Zhan & Niu, 2023). In particular, STEM-based project learning contributes to the development of students' inquiry-based learning skills, scientific research activity, and problem-solving abilities. Project and laboratory work organized in a STEM environment allows students to independently analyze scientific problems, conduct experiments, and interpret the obtained results. In addition, the use of STEM technologies increases the interactivity of the learning process and positively influences students' research motivation (Shoiynbayeva et al., 2024).

Although the issue of integrating nanotechnology education and STEM approaches has been actively studied in the international scientific literature, much of the existing literature remains theoretical or methodological in nature. Although many studies describe the general pedagogical effectiveness of STEM technologies, their impact on inquiry competence and research skills of future physics teachers has not been sufficiently empirically studied (Hu et al., 2025; Schmid et al., 2023). In addition, the number of quasi-experimental investigations conducted at several universities, based on the comparison of experimental group (EG) and control group (CG), is limited. In particular, there is limited research that quantitatively assesses the impact of STEM-project teaching on students' research activity, experimental thinking, and changes in inquiry competence indicators (Tenekecigil & Kariper, 2025). In this regard, the main problem of the study is to determine the impact of STEM-project teaching on the level of inquiry competence and research skills of future physics teachers. The study aimed to empirically assess the changes in students' research competence through the use of STEM-based project tasks, analysis of scientific problems, and inquiry-oriented learning activities within the course "nanotechnology and nanomaterials".

The following research questions (RQs) were considered within the framework of the study:

**RQ1.** Does STEM-project teaching affect the level of inquiry competence of future physics teachers?

**RQ2.** Does STEM-based teaching contribute to the development of students' research skills and scientific research activity compared to traditional teaching?

**RQ3.** Does the STEM-project approach contribute to the development of students' experimental analysis, hypothesis formulation, and problem-solving skills?

The main hypothesis (H) of the study was formulated as follows:

**H1.** STEM-project teaching leads to a statistically significant increase in the indicators of inquiry competence and research skills of students in the EG.

The scientific contribution of the study is determined by empirically substantiating the impact of STEM-based nanotechnology education on the level of inquiry competence and research skills of future physics teachers. The research results will demonstrate the pedagogical effectiveness of integrating STEM project-based learning into physics teacher training programs and contribute to improving the research-oriented model of nanotechnology education.

## RELATED WORK

In recent years, the STEM education approach has been widely regarded as one of the effective pedagogical models for teaching natural sciences. The rapid development of science and technology, Industry 4.0, digital transformation and the expansion of high-tech industries require education system to develop not only theoretical knowledge, but also research, engineering and technological competencies (Nugraha et al., 2023; Organization for Economic Co-operation and Development [OECD], 2023). In this regard, the STEM approach allows students to connect subject knowledge with practical activities, comprehensively analyze scientific problems and develop interdisciplinary thinking.

Current research shows that the STEM environment plays an important role in developing students' research activity, critical thinking and problem-solving skills. In particular, project-based learning and inquiry-based learning models increase students' active participation in the learning process and strengthen their abilities to conduct scientific reasoning and independent inquiry (Zeng et al., 2025). During STEM project-based learning, students acquire theoretical knowledge by solving real scientific and practical problems, which contributes to the development of their scientific thinking, analysis and conclusion-making skills.

The integration of STEM education with digital technologies has become an important directions of modern pedagogical research. OECD (2023) considers the development of STEM competencies and increasing digital literacy as one of the strategic tasks of 21$^{st}$ century education. In addition, a meta-analysis conducted by Öztop (2023) showed that STEM education supported by digital technologies is more effective than traditional teaching models. The author notes that interactive tasks and practice-oriented activities in the STEM environment positively influence students' scientific reasoning and research engagement.

Digital modeling and interactive visualization have become increasingly important in the digital STEM environment. Valeeva et al. (2023) reported that modeling enables students to better visualize complex scientific phenomena and support deeper conceptual understanding and scientific reasoning. According to the authors, digital visualization is an effective tool, especially in explaining abstract scientific concepts. In addition, Gunawan et al. (2025) demonstrated that a project-based learning model supported by e-modules significantly improved prospective physics teachers' creative thinking, engagement, and participation in learning activities. These findings emphasize the importance of digital resources in STEM environments for developing scientific thinking and research-oriented learning.

In addition, although the overall effectiveness of STEM education has been widely studied, most of the existing research has focused on general STEM competencies, creative thinking, or academic achievement. There remains a limited number of quasi-experimental and quantitative studies that assess the changes in prospective physics teachers' research competence and scientific research skills based on a STEM-project intervention.

Nanotechnology is one of the highly interdisciplinary fields of modern science, and its content is based on the integration of physics, chemistry, biology, engineering, and computer science (Lamberti, 2008). Since nanotechnology is widely applied in medicine, energy, materials science, electronics, and bioengineering, the importance of integrating this field into educational systems continues to grow (Grand View Research, 2024). Furthermore, nanotechnology content is considered an important component in the formation of a modern scientific worldview.

However, nanotechnology education is considered one of the most challenging areas from a pedagogical perspective. The abstract nature of nanoscale processes, difficulties in visualization, and the interdisciplinary scientific content complicate students' conceptual understanding (Schmid et al., 2023). A systematic literature review conducted by Schmid et al. (2023) revealed that major challenges in nanotechnology education include difficulties in understanding nanoscale phenomena, limitations in visualizing complex concepts, and insufficient inquiry-oriented learning activities. The authors emphasized the importance of active learning strategies, laboratory experiments, and research-oriented teaching approaches in improving students' conceptual understanding and scientific literacy.

Recent research demonstrates the effectiveness of digital resources and interactive visualization in nanotechnology and STEM education. Kefalis et al. (2025) found that digital simulations and interactive visualization tools improve students' conceptual understanding, engagement, and scientific reasoning skills in STEM learning environments. Interactive modeling and multimedia tools facilitate the explanation of complex nanostructured processes and promote students' active participation in research activities. In addition, Skakov et al. (2026) showed that the introduction of electronic educational resources into the course "nanotechnology and nanomaterials" facilitates understanding of complex theoretical content and strengthens students' scientific analysis and research activities.

The integration of nanotechnology with STEM approaches plays an important role in the development of students' research competence and inquiry-oriented thinking. Shoiynbayeva et al. (2024) demonstrated that STEM-oriented nanotechnology instruction contributes to students' interdisciplinary understanding of scientific concepts and increases their engagement in inquiry-based and research-oriented learning activities. The authors emphasized the importance of integrating practical modeling, experimentation, and digital visualization into nanotechnology education. In addition, Yıldırım (2024) found that the use of TRIZ-STEM approaches enhances creative problem-solving, scientific reasoning, and innovation skills in STEM education. Begmatova et al. (2024) demonstrated that STEM-oriented nanotechnology instruction supported by educational technologies contributes to the development of students' scientific reasoning skills, interdisciplinary understanding, and creative approaches to scientific problem-solving.

Presenting nanotechnology in an interactive and hands-on format can increase students' engagement in inquiry-oriented activities. Begmatova et al. (2024) demonstrated that educational technologies, visualization tools, and practice-oriented STEM activities enhance students' scientific understanding and participation in inquiry-based learning. Similarly, Kefalis et al. (2025) emphasized that digital simulations and interactive visualization improve students' engagement and conceptual understanding in STEM education. However, most of these studies have been conducted in school classrooms or within short-term educational interventions.

In general, although existing studies have shown the effectiveness of integrating STEM and nanotechnology, most of the studies have focused on school students, creative thinking, or general STEM skills. There is a lack of studies that experimentally evaluate the changes in research competence and research skills of prospective physics teachers based on long-term STEM-project interventions.

In the modern education system, the preparation of future teachers is not limited to subject knowledge alone, but also requires the formation of their research, technological and interdisciplinary competencies. In particular, in the training system of physics teachers, the integration of nanotechnology content with STEM approaches is considered one of the important areas of professional training (Shoiynbaeva et al., 2024).

The NEST program developed by Sorge et al. (2017) aimed to develop teachers' subject knowledge and research competencies in the field of nanotechnology. The authors demonstrated that inquiry-based and research-oriented learning activities facilitate the effective integration of nanotechnology concepts into STEM educational environments. In addition, Blonder et al. (2026) emphasized that effective professional development in nanotechnology education should move beyond theoretical instruction toward interactive, research-oriented, and practice-based pedagogical applications. According to the authors, such approaches improve teachers' ability to integrate complex nanoscale concepts into STEM learning environments.

The introduction of nanotechnology content into the curriculum directly depends on the subject-specific and pedagogical preparation of teachers. Park and Yoon (2023) found that teachers' readiness to implement a nanotechnology curriculum is associated with their ability to organize STEM content in a practical and interdisciplinary format. Furthermore, Wang (2024) showed that STEM project activities and electronic resources play an important role in developing teachers' research and professional competencies in the context of digital transformation.

Recent studies have demonstrated the effectiveness of interdisciplinary STEM approaches in developing students' scientific understanding and teachers' pedagogical competencies. Nguyen et al. (2025) showed that STEM project-based learning contributes to the development of teachers' professional competencies, interdisciplinary instructional skills, and scientific problem-solving abilities. In addition, Gunawan et al. (2025) found that project-based learning supported by electronic modules significantly enhances prospective physics teachers' creative thinking, scientific reasoning, and active participation in research-oriented learning activities.

Shoiynbaeva et al. (2024) proposed methodological and didactic principles for incorporating nanotechnology content into the curriculum during the training of future physics teachers. The authors emphasized the importance of interdisciplinary STEM approaches, digital visualization, and inquiry-oriented learning activities in developing future teachers' scientific understanding and professional competencies.

Nevertheless, most existing research has focused on teacher training or general STEM competencies. Studies that experimentally and quantitatively assess the impact of STEM project-based learning on the development of future physics teachers' inquiry competence are still limited.

## Research Gap and Contributions

The existing scientific literature shows that STEM approaches have a positive impact on students' inquiry-oriented learning, scientific thinking, and professional competencies. In addition to this, teaching

**Table 1.** Comparative analysis of STEM and nanotechnology education studies related to inquiry-oriented learning, teacher competencies, and research skills

| Study | Educational context | Participants | Research design | Main focus | Key findings | Limitations |
|---|---|---|---|---|---|---|
| Schmid et al. (2023) | Nanoscience and nanotechnology education | Literature sources | Systematic literature review | Challenges in nanoscience education | Identified difficulties related to visualization, interdisciplinarity, and inquiry-oriented learning in nanoscience education | No empirical intervention or quantitative assessment |
| Begmatova et al. (2024) | Nanophysics and nanotechnology teaching | Students | Educational technology intervention | Educational technologies in nanotechnology learning | Educational technologies supported conceptual understanding and active learning in nanotechnology education | Limited focus on inquiry competence and teacher preparation |
| Yıldırım (2024) | TRIZ-STEM teacher education | Pre-service teachers | Innovative pedagogical intervention | TRIZ-STEM pedagogy and creative problem-solving | TRIZ-STEM approaches improved creative problem-solving and inquiry-oriented learning skills | No nanotechnology-specific learning context |
| Shoiynbaeva et al. (2024) | Future physics teacher education | Future physics teachers | Methodological and pedagogical analysis | Methodological foundations of nanotechnology teaching | Demonstrated the pedagogical value of integrating nanotechnology into STEM-oriented physics teacher education | Mainly theoretical and methodological focus |
| Gümüş and Bozkurt Altan (2025) | STEM teacher professional development | Science teachers | Professional development study | STEM lesson planning and interdisciplinary teaching | Improved interdisciplinary teaching competencies and STEM lesson implementation skills | Did not examine nanotechnology-specific applications |
| Nguyen et al. (2025) | Interdisciplinary STEM teaching | Secondary school teachers | Systematic synthesis | Teacher competencies in interdisciplinary STEM education | Highlighted the importance of interdisciplinary competencies and inquiry-oriented teaching practices in STEM education | General STEM focus without nanotechnology context |
| Gunawan et al. (2025) | Project-based learning with e-modules | Pre-service physics teachers | Experimental study | Project-based learning and creative thinking | Enhanced creative thinking and active participation in inquiry-oriented learning activities | No direct nanotechnology integration |
| This study (2026) | STEM-project-based nanotechnology course | Future physics teachers | Multi-university quasi-experimental study | Development of inquiry competence and research skills through STEM-based nanotechnology education | EG demonstrated significant improvement in inquiry competence, scientific analysis, and research-oriented skills | Conducted within a specific nanotechnology course and future physics teacher population |

nanotechnology in a STEM educational environment facilitates understanding of complex scientific concepts and expands the possibilities for research-oriented learning.

Nevertheless, the literature review revealed several important scientific gaps. First, the majority of studies are focused on school audiences or on general STEM competencies. Second, the number of studies examining the impact of STEM-project-based learning on the development of research skills in the context of training future physics teachers is limited. Third, there is a lack of multi-university quasi-experimental studies based on comparisons of EG and CG. In addition, there are few comprehensive studies that assess the change in students' research competencies using quantitative measures.

In this regard, this study aims to empirically assess the impact of STEM-project-based learning on the development of research competencies of future physics teachers on a quasi-experimental design. The study examines the impact of STEM-based project activities on scientific reasoning, inquiry, and problem-solving skills by comparing EG and CG.

A review of existing studies indicates that STEM-based nanotechnology education has been investigated in various pedagogical contexts. However, most studies have primarily focused on general STEM competencies, creative thinking, interdisciplinary teaching, or teacher professional development. In addition, few studies have quantitatively examined the development of inquiry competence and inquiry-oriented skills among prospective physics teachers through multi-university

**Table 2.** Lesson topics

| Week | Main learning content |
|---|---|
| 1 | Definition of nanotechnology, basic concepts and history of nanotechnology development |
| 2 | Physical and chemical foundations of nanotechnology and types of nanomaterials |
| 3 | Methods for studying nanoobjects and nanostructures |
| 4 | Low-dimensional structures and fundamentals of nanoelectronics |
| 5 | Elements of molecular electronics, spintronics and nanoengineering |
| 6 | Application of nanotechnology in the fields of energy, biotechnology and engineering |
| 7 | Preparation and presentation of STEM-based project works |

quasi-experimental designs. **Table 1** provides a comparative overview of the current study in relation to previous research.

Table1As shown in **Table 1**, previous studies have mainly emphasized interdisciplinary STEM learning, digital educational technologies, creative thinking, and professional development in science education. Although several studies addressed nanotechnology integration and inquiry-oriented learning, few studies specifically investigated the development of inquiry competence and research skills among future physics teachers using quantitative and quasi-experimental approaches. Therefore, the present study contributes to the existing literature by empirically evaluating the impact of STEM project-based nanotechnology education on prospective physics teachers' inquiry competence, scientific reasoning, and inquiry-oriented learning skills.

## MATERIALS AND METHODS

The study employed a quantitative quasi-experimental design. The aim of the study was to examine the impact of a STEM-based nanotechnology learning module on the development of research competence of future physics teachers. The outcomes of the EG and CG were compared and the effectiveness of STEM-project teaching was assessed.

Since the study used pre-existing academic groups, random assignment of participants to groups was not carried out. In this regard, the study was considered quasi-experimental in nature. This approach is widely used in educational research to preserve the natural learning environment. To reduce the potential impact of selection bias, academic groups with similar subject preparation and curriculum were selected.

The main analysis of the study was based on quantitative data. The results of pedagogical observations were used as supplementary data to describe the learning process and complement the interpretation of quantitative results. In this regard, the study was considered a quantitative quasi-experimental study with qualitative descriptive elements, rather than a fully developed mixed methods design.

The intervention was implemented over seven consecutive weeks. Instruction was delivered once per week, with each weekly session consisting of two consecutive 50-minute class periods (100 minutes in total). The EGs participated in STEM-based project-oriented and inquiry-oriented learning activities, whereas the CGs received traditional instruction following the regular curriculum. Each weekly session was conducted according to the nanotechnology topics presented in **Table 2**.

A total of 108 prospective physics teachers participated in the study. Of these, 53 students were in the EG and 55 in the CG.

The study was conducted among students enrolled in the Physics teacher education program of the educational program 6B015 – "natural sciences". The study was organized at the following higher education institutions:

- East Kazakhstan University named after S. Amanzholov,
- South Kazakhstan Pedagogical University named after O. Zhanibekov, and
- International Kazakh-Turkish University named after Khoja Akhmet Yassawi.

Participants were selected using the purposive sampling method. The main selection criteria were:

1. education in the field of physics,
2. the presence of natural science and mathematics subjects in the curriculum,
3. willingness to participate in STEM-based learning activities, and
4. voluntary consent to participate in the study.

The study protocol was approved by the Ethics Committee of Khoja Akhmet Yassawi International Kazakh-Turkish University (protocol no. 46, 22.10.2025). The study was conducted in accordance with the ethical principles for research involving human participants and the relevant institutional regulations. All participants provided written informed consent prior to data collection.

The educational institutions included in the study were selected based on the ability to implement STEM-based nanotechnology content into the educational process and the similarity of pedagogical educational programs in the natural science direction. As part of the study, a special STEM-based nanotechnology learning module for prospective physics teachers was developed and implemented in the EGs.

Since the EG and CG were organized on the basis of different academic groups, some differences in year level were observed. This factor was considered one of the potential limitations of the study. In this regard, the baseline scores of the groups before the intervention were statistically compared. The results of the preliminary analysis showed that there were no statistically significant differences between the EG and CG ($p > 0.05$).

In addition, since the second and third year students included in the study had similar subject preparation within the same educational program, their educational content and academic structure were at a comparable level.

Since the study was conducted at different universities, the instructional staff also differed. In order to ensure the consistency of the intervention, common methodological guidelines, the same task structure, and a unified STEM-based instructional content structure were used across all educational institutions.

Since the structure of the curricula and the content of natural science subjects at the three universities were similar, the data were analyzed in a combined manner. Baseline equivalence across the three participating universities was assessed using the Kruskal-Wallis test based on the pre-test scores. The analysis revealed no statistically significant differences among the universities ($H = 4.83$, $df = 2$, $p = 0.090$), indicating comparable baseline levels prior to the intervention. However, institutional differences, differences in course level, and instructor-related factors were considered as limitations that could have influenced the results.

As part of the study, a STEM-based nanotechnology learning module was developed for future physics teachers. The main goal of the intervention was to develop students' research competence, scientific reasoning skills, and research skills.

In the EGs, the learning process was based on STEM methods, and students were involved in analyzing scientific research, analyzing scientific information, conducting inquiry activities, and performing project tasks. The intervention was delivered by senior lecturers with more than five years of experience in teaching physics and experience in STEM education and the integration of digital learning technologies. Throughout the intervention, the instructors primarily acted as facilitators, guiding students during inquiry-based learning activities and project work.

Digital visualization, scientific modeling, presentation materials, and project analysis were systematically used throughout the intervention. The learning process was based on scientific explanation, inquiry-oriented tasks, and digital educational resources rather than relying on complex nanolaboratory equipment. To ensure intervention fidelity across the participating universities, all instructors followed a common methodological guide, used standardized instructional materials and learning tasks, and participated in regular online coordination meetings before and after instructional sessions to maintain consistency in implementing the STEM-based nanotechnology learning module. The intervention structure was organized into weekly stages (**Table 2**).

Table2STEM-based project-based, inquiry-based, and digital visualization elements were systematically used across all topics. During the course, students completed inquiry-oriented assignments focused on analyzing, comparing, and interpreting scientific information, defining a scientific problem, and drawing evidence-based conclusions. In addition, students were involved in comparative analysis of multiple scientific sources, interpreting research results, and developing STEM-based project work.

Figure1**Figure 1** shows the basic methodological structure of the STEM-based nanotechnology learning module. The model was aimed at ensuring the simultaneous development of students' cognitive interest and research competence through STEM-based research-oriented learning activities.

Traditional teaching methods were used in the CGs. Theoretical explanations, analysis of text materials, and standard classroom tasks dominated in these groups.

### Data Collection

A specially designed questionnaire was used as the main data collection tool for the study. The questionnaire was aimed at assessing changes in inquiry competence and research-oriented skills in the context of a STEM-based nanotechnology learning module.

The questionnaire consisted of 20 statements and was rated on a 5-point Likert scale, where 1 indicated "strongly disagree" and 5 means "strongly agree".

The questionnaire items were developed using international scientific literature on STEM education, research competence and nanotechnology education. The initial version consisted of 24 statements. Later, as a result of expert evaluation, statements containing repetitive or unclear content were removed, and the questionnaire was reduced to 20 statements.

In order to ensure content validity, the tool was evaluated by three experts in the field of STEM education, physics pedagogy and research methodology. In addition, the questionnaire was tested in a small pilot group, as a result of which the wording of several items was refined.

The internal consistency of the questionnaire was assessed using Cronbach's alpha coefficient. As a result, the instrument demonstrated high reliability (Cronbach's alpha = 0.87).

To further examine the construct validity of the questionnaire, an exploratory factor analysis was

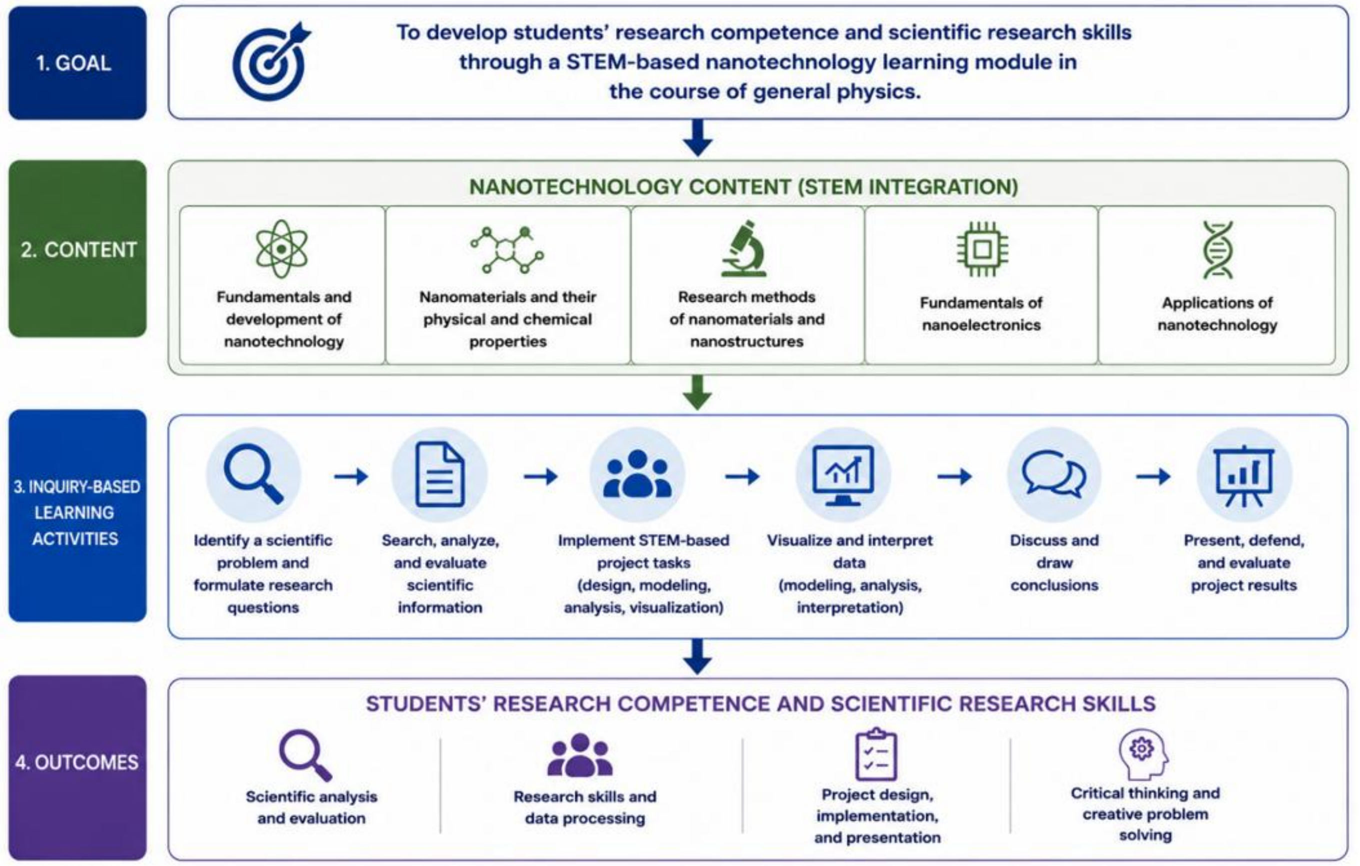


**Figure 1.** Methodological structure of a STEM-based nanotechnology learning module aimed at developing research competence (developed by the authors)

performed using principal component analysis with Varimax rotation. The Kaiser-Meyer-Olkin measure of sampling adequacy was 0.811, indicating good suitability of the data for factor analysis. Bartlett's test of sphericity was statistically significant ($\chi^2 = 576.429$, df = 190, $p < 0.001$), confirming that the correlation matrix was appropriate for factor extraction. Six factors with eigenvalues greater than 1 were extracted, explaining 58.62% of the total variance. The obtained factor loadings ranged from 0.45 to 0.76, providing additional evidence for the construct validity of the questionnaire.

The questionnaire consisted of items designed to assess students' cognitive interest, engagement in scientific information analysis, motivation for research-oriented learning, and the degree of participation in STEM-based learning activities.

In addition to the main questionnaire, a set of situational tasks was used to assess students' research competence. A total of 10 situational tasks were used in the study. The tasks were aimed at assessing the ability to identify a scientific problem, analyze and compare information, draw conclusions, and propose evidence-based solutions.

The assessment was carried out according to the following criteria:

- scientific validity,
- quality of theoretical explanation,
- level of scientific reasoning, and
- validity of the proposed solution.

Each criterion was assessed on a 0-3-point scale:

- 3 points – a complete and scientifically justified answer,
- 2 points – a partially sound answer,
- 1 point – a superficial answer, and
- 0 points – incorrect answer or no answer.

The maximum score for one task was 12 points. The total possible score for ten tasks was 120 points. According to the accumulated scores, the levels of research competence of students were divided into three categories:

- high level (90-120 points),
- medium level (50-89 points), and
- low level (0-49 points).

This assessment system allowed researchers to determine the ability of students to analyze scientific information, explain research problems and propose evidence-based solutions.

To calculate the inquiry competence index (ICI), the percentage of the total points scored by students to the maximum possible score was used.

$$ICI = \frac{S}{120} \times 100, \quad (1)$$

where $S$ is the student's total score and 120 is the maximum possible score for the tasks.

The ICI allowed for a comprehensive assessment of the level of development of students' skills in defining a scientific problem, analyzing scientific information, interpreting research results, and drawing evidence-based conclusions. In addition, the ICI allowed for a comprehensive quantitative assessment of the impact of STEM-based research-oriented learning activities on students' inquiry-oriented skills.

The questionnaire and sample situational tasks are presented in the additional section (**Appendix A**).

### Data Analysis

Data were analyzed using quantitative statistical methods. Descriptive statistics are presented as mean (M) ± standard deviation (SD). In addition, 95% confidence intervals (CIs) were calculated and reported for the M values of the ICI. Data normality was assessed using the Shapiro-Wilk test. The results indicated no significant deviations from normality for either the pre-test or post-test ICI scores in the EG (pre-test: $W = 0.974$, $df = 53$, $p = 0.312$; post-test: $W = 0.978$, $df = 53$, $p = 0.444$) or the CG (pre-test: $W = 0.994$, $df = 55$, $p = 0.992$; post-test: $W = 0.990$, $df = 55$, $p = 0.927$). Although the Shapiro-Wilk test indicated no significant deviations from normality, non-parametric statistical methods (Mann-Whitney U and Wilcoxon signed-rank tests) were applied because the questionnaire responses were based on a five-point Likert scale and the study employed score-based educational assessments. In addition, the use of non-parametric methods ensured methodological consistency across all analyses.

The Mann-Whitney U test was used to compare the results of the EG and CG. The Wilcoxon signed-rank test was used to determine the differences in the initial and final indicators within the group.

To assess the practical significance of the results of the Wilcoxon signed-rank test, the effect size ($r$) was calculated using the formula:

$$r = \frac{Z}{\sqrt{N}}, \quad (2)$$

where $Z$ is the Wilcoxon test statistic and $N$ represents the number of paired observations included in each Wilcoxon signed-rank test for the corresponding EG or CG.

In order to further evaluate the effectiveness of the intervention, the normalized gain coefficient ($g$) was determined.

$$g = \frac{Post-pre}{100-pre}, \quad (2)$$

where $pre$ is pre-intervention score and $post$ is post-intervention score.

The normalized gain coefficient was used to estimate the level of growth resulting from the STEM-based intervention.

Data from the three universities were analyzed in a combined manner because they used a common curriculum and a unified intervention design. However, institutional differences, differences in course level, and instructor-related factors were considered as limitations that could have influenced the results.

## RESULTS

The results of the study showed that STEM-based research-oriented learning activities had a positive impact on students' interest in nanotechnology and research competence of students in the EG. When comparing the results of the preliminary and final assessments, a clear positive trend was observed in the EGs in terms of the ability to analyze scientific information, interpreting research results, and drawing evidence-based conclusions.

The increase in interest in nanotechnology topics in the EGs was associated with systematic work with STEM-based project and research-oriented tasks. In particular, tasks aimed at comparative analysis of scientific information, explanation of practical problems, and evaluation of research results increased students' learning engagement. Although certain positive changes were also observed in the CGs, their dynamics remained at a low level compared to the EGs.

In addition, students in the EG showed high results in terms of identifying a scientific problem, drawing conclusions based on several sources, and proposing evidence-based solutions when performing situational research tasks. This showed that STEM-based learning activities contributed not only to the development of students' cognitive interest, but also to the development of their ability to engage in inquiry-oriented activities.

**Table 3** presents the descriptive statistics for the interest score and ICI. M ± SD values are reported for all variables, whereas 95% CIs are additionally presented for the ICI M values.

Table3The results presented in **Table 3** demonstrate a clear increase in the interest scores and the research competence index in the field of nanotechnology in the EGs of all universities. The interest scores of the EGs increased from 55-57 points in the pre-test stage to 83-86 points in the post-test stage. At the same time, the research competence index also increased from 45-48% to 69-72%.

Although positive changes were observed in the CGs, their level of improvement was significantly lower compared to the EGs. While the interest scores in the CGs remained at the level of 60-65 points in the post-test stage, the ICI indicators did not exceed 50-53%.

**Table 3.** Dynamics of interest indicators and research competence index in the EG and CG

| University | Group | n | M ± SD | | | ICI pre-test 95% CI | M ± SD | ICI post-test 95% CI |
|---|---|---|---|---|---|---|---|---|
| | | | Interest score pre-test | Interest score post-test | ICI pre-test (%) | | ICI post-test (%) | |
| Sarsen Amanzholov East Kazakhstan University | EG | 15 | 57.06 ± 4.8 | 83.93 ± 3.5 | 47.6 ± 4.0 | 45.4-49.8 | 69.9 ± 2.9 | 68.3-71.5 |
| | CG | 24 | 53.25 ± 4.2 | 60.13 ± 3.9 | 44.3 ± 3.8 | 42.7-45.9 | 50.1 ± 3.2 | 48.7-51.5 |
| O. Zhanibekov South Kazakhstan Pedagogical University | EG | 18 | 57.16 ± 4.1 | 83.05 ± 3.2 | 47.8 ± 3.5 | 46.1-49.5 | 69.2 ± 2.7 | 67.9-70.5 |
| | CG | 10 | 55.00 ± 3.9 | 60.10 ± 4.1 | 45.8 ± 3.3 | 43.4-48.2 | 50.4 ± 3.4 | 48.0-52.8 |
| Khoja Akhmet Yassawi International Kazakh-Turkish University | EG | 20 | 55.05 ± 4.5 | 85.95 ± 3.1 | 45.9 ± 3.7 | 44.2-47.6 | 71.6 ± 2.6 | 70.4-72.8 |
| | CG | 21 | 57.95 ± 4.4 | 65.09 ± 4.0 | 47.1 ± 3.6 | 45.5-48.7 | 53.0 ± 3.3 | 51.5-54.5 |
| Overall | EG | 53 | 56.30 ± 4.5 | 84.40 ± 3.4 | 47.0 ± 3.8 | 46.1-48.1 | 70.2 ± 2.8 | 69.4-71.0 |
| | CG | 53 | 55.00 ± 4.3 | 61.80 ± 4.0 | 45.6 ± 3.8 | 44.7-46.7 | 51.2 ± 3.3 | 50.3-52.1 |

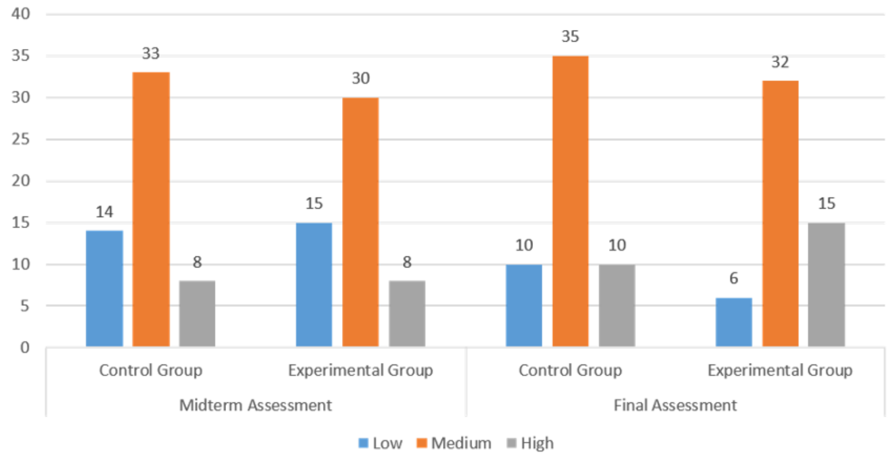


**Figure 2.** Dynamics of changes in the levels of research competence in the EG and CG (developed by the authors)

Analysis of the survey results showed that STEM-based learning activities increased students' interest in nanotechnology topics but also contributed to their motivation to participate in inquiry-oriented activities. In particular, the EG students demonstrated high agreement with statements such as "I have increased my interest in studying issues related to nanotechnology" and "My ability to interpret scientific information has improved."

The results of the ICI revealed that the EG students showed significant progress in the indicators of identifying a scientific problem, comparative analysis of scientific sources, and drawing evidence-based conclusions. In particular, high results were observed in the tasks of comparing several scientific sources and providing scientific explanations for practical problems.

Although certain positive changes were also detected in the CGs, the level of growth in the EGs was clearly higher in all indicators. This indicated that STEM-based research-oriented learning activities had a positive pedagogical contribution to the simultaneous development of students' cognitive interest and research skills.

In addition, the changes in the levels of research competency are shown in **Figure 2**. The results of the preliminary assessment showed that the initial levels of the EG and CG were relatively similar. During the final assessment period, the proportion of low-level students in the EGs decreased, and the proportion of high-level students increased. And although changes were detected in the CGs, their dynamics remained at a low level compared to the EGs.

Figure1The results of **Figure 2** show that the proportion of low-level students in the EGs decreased and the proportion of high-level students increased. In addition, it was observed that some of the medium-level students moved to the high-level. Although some positive changes were also detected in the CGs, their dynamics remained at a lower level compared to the EGs.

## Results of Inferential Statistical Analysis

The results of the inferential statistical analysis showed that STEM-based research-oriented learning activities contributed to increases in inquiry competence and interest in nanotechnology in the EGs. In particular, in the EGs, a high level of statistical significance was observed in the differences between the pre-test and post-test scores. The results of the inferential statistical comparison of the EG and CG are shown in **Table 4**.

The results presented in **Table 4** demonstrate that the differences between the pre-test and post-test scores were statistically significant in both the EG and CG. However, the normalized gain coefficients were

**Table 4.** Results of inferential statistics for the EG and CG

| University | Group | Z | p | r | g |
|---|---|---|---|---|---|
| Sarsen Amanzholov East Kazakhstan University | EG | 3.422 | < 0.001 | 0.880 | 0.43 |
| | CG | 4.336 | < 0.001 | 0.885 | 0.10 |
| O. Zhanibekov South Kazakhstan Pedagogical University | EG | 3.738 | < 0.001 | 0.880 | 0.41 |
| | CG | 2.889 | 0.0039 | 0.910 | 0.09 |
| Khoja Akhmet Yassawi International Kazakh-Turkish University | EG | 3.937 | < 0.001 | 0.880 | 0.48 |
| | CG | 4.102 | < 0.001 | 0.895 | 0.11 |

Note. $p$ is the statistical significance level

consistently higher in the EGs than in the CGs, indicating greater improvement following the STEM-based intervention. Large $r$ values were observed across all Wilcoxon signed-rank tests.

The results of the normalized gain coefficient also showed similar dynamics. In the EGs, the g coefficient was determined in the range of 0.41-0.48, indicating that STEM-based research-oriented learning activities had a moderate to high level of improvement in developing research competence. In the CGs, this indicator remained in the range of 0.09-0.11, indicating a low level of improvement.

The observation of statistically significant changes in the CGs can also be explained by the influence of the general learning process, systematic work with subject content, and the university academic environment. In addition, the interdisciplinary and applied nature of nanotechnology topics is likely to have a certain impact on students' interest in the subject.

However, the normalized gain coefficients were consistently higher in the EGs across all universities, indicating that STEM-based research-oriented learning activities provided greater educational improvement than traditional instruction. This finding suggests an additional pedagogical contribution to the simultaneous development of students' interest in nanotechnology and inquiry competence.

The results of the Mann-Whitney U test showed that there were statistically significant differences between the EG and CG at the final stage ($p < 0.001$). This suggests that STEM-based inquiry-based learning activities produced stronger outcomes than traditional teaching methods.

## DISCUSSION

The effectiveness of STEM-based research-oriented learning activities is closely related to the concepts of constructivist learning, inquiry-based learning, and project-based learning in the modern scientific literature. These approaches are aimed at developing active cognitive engagement by independently analyzing scientific problems, comparing evidence, and drawing scientific conclusions, rather than students passively receiving ready-made knowledge. In this regard, the STEM-based nanotechnology learning activities used in our study created a comprehensive pedagogical environment that contributed not only to the development of students' subject knowledge, but also to their inquiry-oriented thinking.

The results of the study showed that STEM-based research-oriented learning activities contributed to the simultaneous development of students' interest in the field of nanotechnology and their research competence. In particular, the increase in students' ability to analyze scientific information, interpreting research results, and drawing evidence-based conclusions in the EGs indicated that the STEM approach contributed to the enhancement of cognitive engagement. These results are consistent with previous studies demonstrating that STEM-based inquiry-oriented and project-based learning activities contribute to the development of scientific reasoning and inquiry competence (Gunawan et al., 2025; National Research Council, 2012; Yıldırım, 2024; Zollman, 2012).

The results are also consistent with studies that have shown that digital visualization and inquiry-oriented learning activities contribute to a deeper understanding of scientific concepts. In particular, the findings about the role of virtual and hands-on laboratory activities in the development of scientific reasoning are consistent with our results (De Jong et al., 2013). In addition, previous studies have shown that STEM-based inquiry activities enhance students' scientific reasoning, problem-solving abilities, and active participation in learning activities, which supports the findings of the present study (Cavdar et al., 2024).

Previous studies have also shown that the use of digital modeling, visualization, and modern educational technologies in teaching nanophysics and nanotechnology positively influences students' scientific interest and understanding of interdisciplinary connections (Begmatova et al., 2024). In our study, STEM-based inquiry-based tasks also contributed to the development of students' abilities to synthesize information from multiple sources, evaluate scientific information, and provide scientific explanations for practical problems. In addition, the results of the study showed that the STEM environment has a significant impact on the development of future physics teachers' ability to connect inquiry activities with practical applications.

The results obtained are also consistent with previous empirical studies that have shown that STEM-based activities increase students' subject-related interest and scientific engagement (Aderibigbe, 2021; Haagen-Schützenhöfer & Joham, 2018). It was observed that, especially in an inquiry-based learning environment, students' active participation in cognitive activities contributes to an increase in learning motivation.

In addition, the literature also shows that the effectiveness of the STEM approach is not equally effective in all contexts. Some studies note that the effectiveness of STEM-based activities depends on the learning environment, teacher experience, intervention duration, and students' initial level of academic preparation. This suggests that the effectiveness of STEM approaches may depend on the quality of pedagogical implementation. In this sense, differences in institutional characteristics and course levels between the three universities in our study may have contributed to the results to some extent.

The observation of statistically significant positive changes in the CGs can be explained by several factors. First, these changes are likely to be associated with the influence of the general academic environment, systematic work with subject content, and natural cognitive development in the learning process. Second, the pre-test itself may have increased students' attention to nanotechnology topics, creating a testing effect. In addition, the influence of the Hawthorne effect cannot be completely ruled out, since students knew that they were participating in the research process. However, although large $r$ values were observed in both groups, the normalized gain coefficients and improvements in inquiry competence were substantially greater in the EGs. This indicates an additional pedagogical contribution of STEM-based research-oriented learning activities.

The lack of full equivalence in year levels was also considered as a potential confounding factor in the study. Students in different courses may not have the same academic experience and scientific training levels. However, the observation of similar positive dynamics in the EGs at all universities indicates a relative consistency of the findings.

Overall, the results indicate that STEM-based inquiry-based learning activities not only increase prospective physics teachers' interest in nanotechnology but also contribute to the development of their skills in scientific reasoning, interpretation of research results, and presentation of evidence-based solutions. Furthermore, the results highlight the importance of systematic integration of STEM-based inquiry-based learning activities into prospective physics teacher training programs.

### Limitations

Several limitations of this study should be noted. First, because the study was quasi-experimental, the participants were not randomly assigned. This may affect the generalizability of the results to some extent.

Second, because the study involved students from different course levels, there may have been differences in their initial academic preparation and research experience. This factor was considered a confounding variable that could have influenced the study results.

Third, students' interest and motivation to learn were mainly determined through self-assessment questionnaires. Therefore, the possibility of social desirability bias and response bias cannot be completely ruled out.

Fourth, because the study was conducted at several universities, institutional differences may have influenced the results to some extent.

Another limitation concerns the possible novelty effect. Since the STEM-based nanotechnology learning module introduced a new instructional format that combined project-based learning, digital visualization, and inquiry-oriented activities, part of the observed improvement may have been influenced by students' increased motivation associated with experiencing a novel learning environment. Although the intervention lasted seven weeks, future longitudinal studies are needed to determine whether these positive effects are sustained over longer periods.

In addition, although the intervention was standardized through a common methodological guide, unified instructional materials, and regular coordination among instructors, instructor-related differences cannot be completely excluded. Variations in teaching style, classroom interaction, and facilitation of inquiry-based activities may have influenced students' learning outcomes despite the measures taken to ensure intervention fidelity across the participating universities.

In addition, the qualitative component of the study was limited. It is recommended that future studies use extended qualitative data collection methods to examine students' inquiry-oriented learning experiences in greater depth.

Future studies using long-term follow-up, random sampling, and a fully developed mixed-methods design will allow for a more in-depth evaluation of the pedagogical impact of STEM-based nanotechnology education.

## CONCLUSION

The results of the study showed that the use of STEM-based research-oriented learning activities is associated with an increase in subject interest and inquiry competence of future physics teachers in the field of nanotechnology. In the EGs, a clear positive trend was observed in terms of interest scores, the ICI, as well as the ability to analyze scientific information, interpreting research results, and drawing evidence-based conclusions. In addition, the results of inferential statistical analysis showed that the differences between the EG and CG were statistically significant.

The scientific novelty of the study lies in the examination of STEM-based nanotechnology education in relation to inquiry competence in the context of training future physics teachers. The study used a system of situational tasks and the ICI to assess students' inquiry-oriented learning skills. This approach enabled a comprehensive assessment of the impact of STEM-based learning activities not only on subject interest, but also on the development of scientific reasoning, investigative thinking, and scientific information interpretation abilities.

From a practical perspective, the results obtained highlight the importance of systematically incorporating STEM-based research-oriented learning activities into future physics teacher training programs. In particular, combining nanotechnology content with project tasks, digital visualization, modeling elements, and research-oriented learning activities can contribute to increasing students' cognitive engagement. In addition, the proposed approach provides conditions for the development of future teachers' capacity to analyze scientific information, understand interdisciplinary connections, and provide scientific explanations for practical problems. In this regard, the results of the study can be considered when designing STEM-based physics courses in higher education institutions. At the same time, when interpreting the results of the study, it is necessary to consider its quasi-experimental nature. Since the participants were not randomly assigned, differences in year levels and institutional characteristics may have influenced the results to some extent. In addition, the observation of statistically significant positive changes in the CGs also indicates the need to consider the effect of the STEM-based intervention not as an absolute causal factor, but as one of the pedagogical factors associated with increases in inquiry competence and subject interest.

Future research suggests that fully developed qualitative methods and factorially validated instruments should be used in future studies. In addition, longitudinal studies, digital modeling, virtual labs, and AI tools should be integrated into STEM-based nanotechnology education to provide deeper insight of the pedagogical potential of this field.

Overall, the results suggest that STEM-based research-oriented nanotechnology learning activities may positively contribute to the development of subject interest and inquiry competence in future physics teachers. This suggests that STEM-based nanotechnology education demonstrates considerable pedagogical potential in the system of training future physics teachers.

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## APPENDIX A: SAMPLE QUESTIONNAIRES AND SITUATIONAL TASKS USED IN THE STUDY

### Part A. Survey Findings

The following findings were aimed at assessing the level of research competence and research skills in the context of a STEM-based nanotechnology learning module. All findings were rated on a 5-point Likert scale: 1 – strongly disagree, 2 – disagree, 3 – neutral, 4 – agree, and 5 – strongly agree.

1. I can analyze scientific information related to nanotechnology.
2. I can compare multiple sources when identifying scientific problems.
3. I am willing to perform STEM-based tasks.
4. I am interested in researching scientific problems related to nanotechnology.
5. I can evaluate the reliability of scientific information.
6. I can analyze complex scientific problems.
7. I can relate nanotechnology topics to other natural sciences.
8. I rely on evidence when making scientific conclusions.
9. I am willing to perform research tasks.
10. I can use digital visualization elements when understanding scientific information.
11. I can interpret scientific information.
12. I am interested in performing project tasks related to nanotechnology.
13. I can consider multiple approaches to solving scientific problems.
14. I can relate nanotechnology topics to everyday life.
15. I am capable of scientific analysis.
16. I am willing to participate in scientific discussions.
17. I can critically evaluate information related to nanotechnology.
18. I can work in a team when carrying out scientific projects.
19. I am interested in completing research assignments.
20. I can independently investigate scientific issues related to nanotechnology.

### Part B. Sample Situational Tasks

#### *Task 1. Scientific analysis of the uses of nanoparticles*

Silver nanoparticles are widely used in medicine as an antibacterial material. Some studies have proven their effectiveness, while other scientific works contain opinions about their possible effects on the human body.

**Analyzing the given scientific situation:**

- Identify the main advantages of silver nanoparticles
- Describe their possible risks
- Present a scientifically based conclusion

**Evaluation criteria:**

- Scientific validity
- Comparative analysis of information
- Correct use of scientific terms
- Justification of the conclusion

#### *Task 2. Nanotechnology and energy*

Currently, scientists are using nanostructured materials to improve the efficiency of solar panels. Nanomaterials enhance the ability to absorb light and increase energy efficiency.

Based on the given situation:

- Explain the advantages of using nanomaterials

- Describe their importance in the energy sector
- Suggest possible ways to study this problem using the STEM approach

**Evaluation criteria:**

- Quality of theoretical explanation
- Level of scientific analysis
- Use of STEM methods
- Validity of the proposed solution

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