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Enhancing Student Engagement in Nanotechnology through STEM-Based Instruction: Evidence from a Quasi-Experimental Study in Higher Education

Bakdaulet Anas [1*], Mazhyn Skakov [1], Sherzod Ramankulov [2] and Ali Coruh [3]

[1] Department of Physics and Technology, Higher School of IT and Natural Sciences, Sarsen Amanzholov East Kazakhstan University, Ust-Kamenogorsk 070004, Kazakhstan;
[2] Department of Physics, Faculty of Natural Sciences, Khoja Akhmet Yassawi International Kazakh-Turkish University, Turkistan 161200, Kazakhstan;
[3] Department of Physics, Faculty of Arts and Sciences, Sakarya University, Sakarya 54187, Türkiye.

* **Corresponding author:** banas@vku.edu.kz.

ABSTRACT: The integration of STEM-based instructional approaches into advanced scientific fields such as nanotechnology is increasingly recognized as essential for improving student engagement and conceptual understanding in higher education. However, empirical evidence on its effectiveness in physics education remains limited. This study examines the impact of STEM-oriented, project-based instruction on undergraduate students' interest in nanotechnology. A quasi-experimental design was implemented involving 108 second- and third-year physics students from three universities in Kazakhstan. Participants were divided into an experimental group ($n = 53$), which received STEM-based project and laboratory instruction, and a control group ($n = 55$), which was taught using traditional lecture-based methods over a 15-week semester. Student interest in nanotechnology was measured using a validated 20-item Likert-scale questionnaire with high reliability (Cronbach's $\alpha \geq 0.80$), administered before and after the intervention. Pre-test results confirmed no statistically significant differences between groups ($p > 0.05$), ensuring baseline equivalence. Post-test findings demonstrated a marked improvement in the experimental group (+28 points) compared to the control group (+7 points). Statistical analysis using the Mann–Whitney U test confirmed a significant difference between groups ($p < 0.001$), with a large effect size ($r \approx 0.78$). These results provide strong evidence that STEM-based, inquiry-driven instruction significantly enhances student engagement and interest in nanotechnology. The study contributes to STEM education literature by highlighting the effectiveness of experiential and interdisciplinary teaching strategies in fostering motivation toward emerging scientific fields. The findings also offer practical implications for curriculum developers and educators seeking to modernize science education through active learning methodologies.

Keywords: STEM-based instruction, Nanotechnology education, Student engagement, Quasi-experimental study, Physics education innovation.

I. INTRODUCTION

The achievements of high technologies inevitably lead to progressive changes in medicine, electronics, robotics, industry and other fields of human activity. At the same time, great hopes are pinned on nanotechnology, which encompasses and integrates physics, biology, chemistry, computer science, and cognitive sciences. The interdisciplinary nature of nanotechnology is inherent in postclassical science as a whole, and in the case of nanotechnology it is particularly striking and fundamental [1]. The abbreviation NBIC technology, widely used in the Western scientific school (nano-bio-information and cognitive technologies), is also widespread in Kazakhstan.

The modern education system must be modernized taking into account such modern achievements of science and technology. Therefore, it can be said that the study of nanotechnological concepts and patterns in physical content courses at the university corresponds to the principle of professional orientation of teaching and can significantly affect the knowledge of the methodological foundations of modern science by a future teacher [2, 3]. Enriching the content of physics courses with nanotechnology concepts will help to increase students' interest and develop their analytical and research skills. Gaining practical and project experience in the field of nanotechnology will enable future physics teachers to use new pedagogical methods in their professional activities. This, in turn, will allow students to deepen their knowledge by increasing their interest in the subject. The professional cycle includes general professional subjects, core disciplinary courses, and specialized elective courses [4].

At the same time, nanotechnology education should not be limited to theoretical content. Current pedagogical research shows that the STEM (Science, Technology, Engineering, Mathematics) approach is important in increasing students' interest in the subject, developing research skills, and forming the ability to apply knowledge in practical situations. STEM project-based learning is aimed at solving interdisciplinary problems, developing engineering thinking, and forming a culture of scientific research. Analysis of scientific literature and works has shown that the specific quantitative impact of introducing a STEM project approach to the nanotechnology course on students' interest in the subject in the context of training future physics teachers has not been sufficiently empirically studied. Although many works provide methodological or theoretical justification, the number of quasi-experimental studies that compare changes in the level of interest using initial and final measurements is limited. In particular, studies conducted at several universities and compared with a control group are rare.

Given this gap, the aim of the study is to experimentally assess the level of interest of future physics teachers in the field of nanotechnology by introducing STEM-project learning within the framework of the course "Nanotechnology and Nanomaterials". During the study, students' interest was measured using a questionnaire based on a 5-point Likert scale before and after the learning process. The scores obtained were classified into four levels: low interest, situational interest, exploratory interest and cognitive interest. The results of the experimental and control groups were analyzed comparatively. Thus, the study aimed to determine whether the teaching of nanotechnology in the STEM-project format in the system of training future physics teachers is statistically related to students' interest in the subject.

II. RELATED WORK

In recent years, the integration of nanotechnology content with the concept of STEM education has been widely considered as a means of developing students' research skills, increasing interest in the subject, and deepening the mastery of complex scientific concepts. In particular, interdisciplinary and practice-oriented teaching methods are recognized as effective ways to improve the quality of education, and a number of domestic and foreign studies have been conducted in this area. The studies reviewed below are intended to analyze the pedagogical possibilities and limitations of teaching nanotechnology in a STEM environment. Previous studies have demonstrated that integrating nanotechnology into STEM education through active learning methods improves student engagement and conceptual understanding. Although this study demonstrates the effectiveness of STEM–nanotechnology integration, it is limited to a general student audience and does not specifically address the formation of subject interest and professional competencies within future physics teacher training programs [5].

Recent bibliometric analyses of data from the Web of Science (WoS) and Scopus databases provide a broad overview of research trends in nanotechnology education, indicating the expansion of this field in the educational context [6]. These studies demonstrate high-level publication patterns, offer valuable guidance to researchers and educators who aim to develop nanotechnology education, but do not provide specific pedagogical inputs or empirical evaluations in teacher training programs. Similarly, pilot studies investigating the educational importance of nanoscience–nanotechnology at the elementary school level indicate that teachers and students generally recognize its value. This pilot study aimed to examine whether teachers and students trained in nanoscience–nanotechnology recognize the need to incorporate Nanoscience–Nanotechnology content into the school context [7], but they do not provide evidence for the effectiveness of integrated STEM–nanotechnology curricula in higher education.

Domestic scholars have identified methodological foundations for teaching nanotechnology in the process of training future physics teachers and have proposed structural and didactic approaches to integrating subject content into the curriculum [8]. While this study makes an important theoretical and methodological contribution in the context of teacher training, there has been no large-scale empirical or quantitative evaluation of the effectiveness of the proposed models. In addition, a number of studies have shown that the use of STEM approaches in physics education effectively connects theoretical knowledge and practical activities, increasing academic achievement and interest in the subject [9]. Although these studies have shown that STEM technologies improve the quality of education through project and laboratory tasks, they are mainly limited to school audiences.

Studies that consider the interdisciplinary nature of STEM education and its potential for knowledge formation often fail to describe specific methodological mechanisms for its inclusion in the curriculum and note the inconsistency of implementation strategies [10, 11]. In the context of training future teachers, the positive impact of STEM models on the development of professional competence has been demonstrated [12]. In addition, a systematic literature review on nanotechnology education identifies the need for additional pedagogical and experimental research in this area [13]. Although practice-based studies have shown that future teachers improve their attitudes toward nanotechnology, these studies are short-term and do not comprehensively assess the impact of a full-length training course [14]. In general, while existing literature has demonstrated the effectiveness of STEM approaches and the educational potential of nanotechnology content, these areas are often considered in isolation. There is a lack of comprehensive studies that systematically evaluate the direct impact of STEM projects on interest in nanotechnology in a population of prospective physics teachers, based on quantitative and qualitative data, within a specific university course. This highlights a significant scientific gap addressed by the present study.

The issues of teaching nanotechnology and the introduction of STEM approaches into the educational process have been actively studied in recent years. However, the majority of existing works focus on only one of two directions: on the one hand, the scientific, technical or engineering content of nanotechnology is considered, and on the other hand, the general pedagogical effectiveness of STEM technologies is described. Moreover, these studies are often focused on general school students or mixed audiences, and a comprehensive assessment of the impact of teaching in the context of training future physics teachers, within a specific university course, as well as through the systematic integration of STEM projects is not sufficiently considered [15]. In particular, there is a limited number of empirical studies that experimentally demonstrate the impact of the systematic introduction of STEM projects within a specific university course on students' interest in nanotechnology, research skills, and professional competencies across multiple educational institutions. Comprehensive assessment methods that combine quantitative and qualitative data and demonstrate real changes in learning motivation are also insufficiently represented in the literature. Thus, the real impact of integrating STEM approaches with the content of the nanotechnology course on the interest in the subject and research competencies of future physics teachers remains insufficiently investigated. This situation creates a gap between theoretical proposals and actual pedagogical practice and determines the relevance of this study. This study makes the following main contributions:

- Methodological contribution: A structural and methodological model of STEM-based teaching, consisting of lecture-laboratory-project-assessment stages, was developed for the course (Nanotechnology and Nanomaterials).
- Pedagogical contribution: A system of practical tasks aimed at developing students' research and design skills (microscopic visualization of nanostructures, study of the Tyndall and lotus effects, analysis of water

composition, assessment of the biological effect of silver nanoparticles, monitoring the properties of liquid crystals, etc.) was introduced into the educational process.

- Empirical contribution: By comparing the initial and final surveys, the positive dynamics of the level of interest of students in nanotechnology was quantitatively proven (lack of interest decreased, and the level of cognitive interest significantly increased).
- Practical contribution: The proposed methodology is suitable for inclusion in the training programs of future physics teachers and offers ready-made pedagogical solutions that allow for the effective integration of STEM elements into natural science subjects.

Thus, the study theoretically and practically substantiates the effectiveness of integrating nanotechnology content with STEM approaches in the professional training of future teachers.

III. MATERIALS AND METHODS

The study aimed to assess changes in subject interest among students studying nanotechnology within the «Physics» specialty under the educational program 6B015 – «Natural Sciences». The context of training future teachers was considered as the research environment, and the level of interest of students was taken as the main outcome indicator. A total of N = 108 students participated in the study. Participants were divided into an experimental group (n = 53) and a control group (n = 55). The study was conducted at three higher education institutions:

- S. Amanzholov East Kazakhstan University - n = 39 (control group 24, experimental group 15);
- O. Zhanibekov South Kazakhstan Pedagogical University - n = 28 (control group 10, experimental group 18);
- Khoja Akhmet Yassawi International Kazakh-Turkish University - n = 41 (control group 21, experimental group 20).

At these institutions, second- and third-year students enrolled in the specialized course «Nanotechnology and Nanomaterials», in addition to core courses such as «General Physics», participated in the study. The selection of participants was carried out using the purposive sampling method, the main criteria of which were the subject relevance of the specialty, the presence of physics and mathematics in the curriculum, as well as the students' voluntary willingness to participate in research activities.

The aim of the quantitative analysis was to determine the statistical relationship between STEM-project-based learning and the change in the subject interest of future physics teachers in the field of nanotechnology. The level of interest was measured using a specially designed questionnaire consisting of 20 statements. Each statement was rated on a 5-point Likert scale (1 strongly disagree, 5 strongly agree). All responses were added up and a total score (normalized to a scale of 0–100) was calculated for each student.

The total scores were classified into four levels: 0–40 lack of interest, 41–60 curiosity, 61–75 inquisitiveness and 76–100 cognitive interest. The internal consistency of the questionnaire was assessed using the Cronbach's alpha coefficient:

$$\alpha = k/k - 1\,(1 - \sum \sigma_i^2/\sigma_T^2) \quad (1)$$

The internal consistency of the questionnaire was high (Cronbach's $\alpha \geq 0.87$), which confirmed the reliability of the measurement instruments.

1. DATA COLLECTION

Data collection consisted of several stages based on the pre-test post-test logic. In the first stage, a diagnostic assessment was conducted to determine the initial interest, level of understanding and motivational orientation of students in the field of nanotechnology. The results of the questionnaires and interviews helped to determine the initial research profile of the students. At this stage, a questionnaire based on the Likert scale was used. The questionnaire consisted of 20 statements and was rated on a 5-point Likert scale. The total scores were summed and classified into four levels of interest (low, situational, exploratory, cognitive). The internal consistency of the questionnaire was satisfactory (Cronbach's $\alpha \geq 0.80$). This questionnaire was administered to the experimental and control groups in the same version, ensuring comparability of the results. The second stage was the introduction of the learning module. During this stage, a specialized course program that included lectures, laboratory work and research tasks based on STEM project learning. While interdisciplinary laboratory and project tasks of a more general nature were systematically used in the experimental group, traditional teaching methods were used in the control group.

The third stage focused on students' research and project work. The work was carried out in two phases: initially, the teacher proposed research topics, and in the second, the students independently selected the topic and determined the goals and objectives of the research. At this stage, the teacher acted as a facilitator or mentor. The results of the pre-test showed that there were no statistically significant differences between the groups ($p > 0.05$), which confirmed the equality of the initial level (baseline equivalence).

2. RESEARCH DESIGN

The research methodology was organized in a mixed-methods quasi-experimental pre-test post-test design and allowed for the integrated use of quantitative and qualitative data. While the quantitative component was aimed at identifying the initial and final levels of students' interest in nanotechnology, the qualitative component was used to provide a deeper interpretation of the results obtained.

Quantitative data collection was carried out using the same questionnaire in two stages: before and after the experiment. Since the research used established academic groups, the distribution of participants was non-random. In this regard, the study was considered a non-randomized quasi-experimental design. Although the lessons were conducted by different teachers at each university, a single syllabus, lesson plans, laboratory tasks, and methodological instructions were used to ensure consistency across institutions. Thus, the difference was limited only to the teaching method. The collected data were analyzed using descriptive indicators as well as inferential statistical methods. The Mann–Whitney U test was used to determine differences between groups, and the Wilcoxon signed-rank test was used to compare pre-test and post-test results. In addition, the effect size and 95% confidence intervals were calculated. The qualitative component identified the pedagogical component of the study and examined students' research activities, project work, analytical skills in the learning process, and interpretation of experimental results. The methods used included observation, semi-structured interviews, content analysis of documents and project materials, and modeling of pedagogical situations.

In addition to traditional laboratory equipment for general physics, optical microscopes, atomic force microscopes, scanning probe microscopes such as the Nanopedagogy model, which allows visualization of nanostructures, and electron microscopes were used as material and technical resources. The educational process was provided with the curriculum of the elective course «Nanotechnology and Nanomaterials», teaching aids, practical tasks, and tools for students' individual research projects. Liquid crystals, nanoparticles (Ag, SiO_2), biological models (yeast cells), polymeric materials, and natural water samples were used for experimental work. Working with these materials allowed students to observe the manifestations of nanostructures at the macro and micro levels and to explain their potential applications.

Data analysis included quantitative and qualitative analytical methods. Quantitative analysis was conducted on the basis of descriptive and inferential statistics, and qualitative data were systematized using content and thematic analysis methods. These methods allowed for a comprehensive assessment of the relationship between STEM-project learning and students' interest in nanotechnology. Participation in the study was voluntary. All students provided informed consent. Data were collected anonymously and used for scientific purposes only. Personal data were kept confidential.

IV. DATA ANALYSIS

In this section, qualitative and quantitative data collected during the study were systematically analyzed. The main goal of the analysis was to empirically assess the relationship between STEM-project-based learning and students' interest in the field of nanotechnology. Qualitative data were analyzed using content analysis to identify behavioral and cognitive changes during the learning process.

An important component of nanotechnology education is the integration of nanotechnology knowledge with practical teaching experience. This requires creating opportunities for the practical application of nanotechnology knowledge in everyday, technical, and professional contexts (Figure 1). If these qualities are present, in the future, it will not be difficult for a specialist to develop an increased interest in the field of nanotechnology and to provide examples and specific practical opportunities for the use of nanotechnology in school work practice.

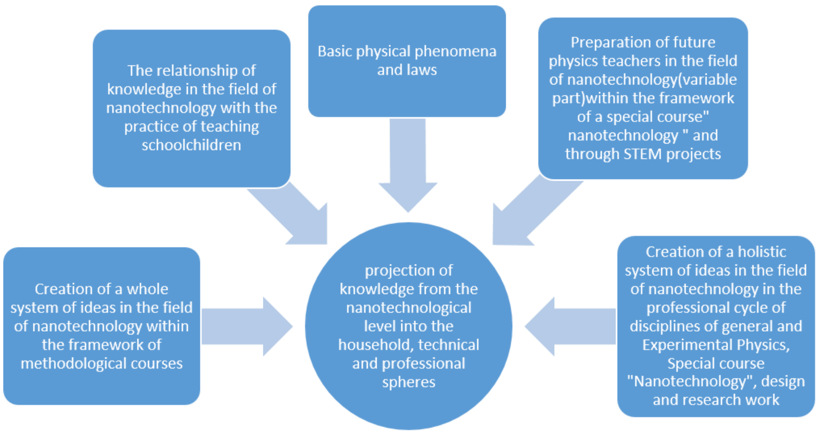

FIGURE 1. System of implementation of nanotechnology concepts in the educational environment of schools and universities.

The final stage of the scheme (closed-loop stage) implies the process of introducing nanotechnological concepts into the general fundamental conceptual framework in which a modern specialist, including a teacher, works and acts. The closed-loop stage emphasizes the cyclical nature of the processes that occur in any new science: it arises, complements and becomes part of fundamental science. Involving students in research activities allows them to participate in an educational environment focused on their interests and needs, allows them to express themselves, increases the level of knowledge, identifies knowledge gaps and areas for improvement. The participation of students in research and design work is carried out within the framework of the modern scientific understanding of the material and discrete nature of physical reality. Such research projects can be focused on experiments with the nanoscale, which will allow students to understand model objects, the conditions of their existence, to better understand the material studied in the main school course.

The research stage in mastering nanotechnology includes individual research projects, laboratory work, as well as research and design work carried out by a group of students. Within the framework of the special course Nanotechnology and Nanomaterials, the design and research work of students involves independent conduct of research, as well as its analysis and protection. Many types of design and research work carried out by students are available in both instrumental support and training. They do not require in-depth knowledge in a specific field of nanotechnology or other special disciplines. Many of the phenomena of the nanotechnology industry are well expressed at the level of the microcosm and macrocosm. To visualize them, it is enough to use the following equipment (i) optical microscope; and (ii) scanning probe microscope, atomic force microscope (AFM), or scanning tunneling microscope (STM). As an example, we can cite the design and research work presented within the framework of a special course:

- obtaining an image of an atomic force microscope using a scanning probe microscope NanoEducator in semi-contact mode.
- the influence of different types of sugar on the growth and development of yeast.
- study of the lotus effect.
- study of the composition of water from various sources.
- study of the mechanism of elastic and plastic deformation of nanostructures.
- the memory form effect.

- Tyndall effect.
- study of the properties of liquid crystals.
- the effect of silver nanoparticles on bacterial growth and development and other activities.

Students carry out educational, research and design work within the framework of the special course nanotechnology and nanomaterials in two stages:

- the implementation of work within the framework of the topics and directions established by the teacher with the initially chosen research trajectory;
- the implementation of a project related to the independent choice of the topic, the definition of the direction and objectives of the research. At the second stage, the teacher acts as a mentor and tutor in the framework of the ongoing design and research work. These stages allow students to participate in the implementation of work with different levels of complexity.

The project method, educational and research activities of students in the field of nanotechnology, have a lot in common, and the use of any design method makes it possible to realize the process of mastering new physical phenomena and processes at a fairly serious scientific level. The general characteristics of research and project activities include the following characteristics: setting a problem, formulating a goal, choosing tools and methods that meet the goals; planning work on a project, carrying out design work or research work; recording the results of work in accordance with the intended goals; presenting the results. In accordance with the real possibilities of introducing the basics of nanotechnology with the help of the design method and educational and research activities into the process of teaching students, the list of acquired skills that allow students to work productively on a project (research) includes:

- analysis of scientific research by preliminary description-highlighting the problem, tools, tools and technical capabilities used to conduct research, determining the list of scientific results planned to be obtained;
- according to the proposed description of the experiment, to give a definition of the observed phenomenon, to indicate the branch of modern science or the section of classical physics to which this phenomenon belongs, to propose its interpretation, technical devices based on this phenomenon, and to determine the scope of its application;
- ability to formulate questions for the project manager to clarify the direction of information search, its theoretical basis and the field of science to which it belongs;
- ability to understand the essence of the discussed problem situations, to independently formulate questions related to the situation that has arisen;
- distinguish unreliable facts from reliable, opinion assessment;
- have experience in using different research methods to explain the facts that arise.

1. QUALITATIVE DATA ANALYSIS

Qualitative data were used to describe the changes in students' cognitive activity, research skills and attitudes to the subject during the learning process. As a result of observation and project work, a clear development of the skills of conducting independent research, formulating a problem, presenting a hypothesis and interpreting results was observed in the experimental group students. Qualitative data were collected through observation, semi-structured interviews, and content analysis of students' laboratory and project work. Students in the experimental group actively formulated research problems, planned experiments, worked with tools and interpreted results. During the learning process, practical tasks and projects allowed them to connect theoretical knowledge with real professional situations.

In the control group, learning activities were mostly reproductive in nature, and research independence was observed at a low level. Thus, qualitative analysis showed that STEM-project learning is positively correlated with students' cognitive interest in nanotechnology and professional motivation. In the control group, learning activities were mostly reproductive in nature, and the frequency of research activity and independent decision-making remained at a low level. Thus, qualitative observations confirmed the relationship between STEM project-based learning and students' career-oriented interest and provided additional evidence for interpreting quantitative results.

2. QUANTITATIVE DATA ANALYSIS

In order to initially characterize the results of the study, descriptive statistics were calculated on the students' interest scores. The mean values (M), standard deviation (SD), and growth index (Gain = post−Pre) were determined for each group in the pre-test and post-test periods. This analysis allowed a preliminary assessment of preliminary assess the overall dynamics of STEM project-based learning and the differences between the experimental and control groups. The results are presented in Table 1.

Table 1. Descriptive statistics (M, SD, Gain) of nanotechnology interest scores in the experimental and control groups at pre-test and post-test stages for each university.

University	Group	n	Pre (M±SD)	Post (M±SD	Δ (Gain)
S. Amanzholov East Kazakhstan university	Experimental group. 2nd year students	15	57.06±4.8	83.93±3.5	+26.87
	Control group. 3rd year students	24	53.25±4.2	60.13±3.9	+6.88
U.Zhanibekov South Kazakhstan Pedagogical University	Experimental group 3rd year students	18	57.16±4.1	83.05±3.2	+26.89
	Control group 2nd year students	10	55.00±3.9	60.10±4.1	+8.10
International Kazakh-Turkish university named after Khoja Ahmed Yasawi	Experimental group 2nd year students	20	55.05±4.5	85.95±3.1	+30.90
	Control group 3rd year students	21	57.95±4.4	65.09±4.0	+7.14
General experimental group		53	56.3±4.5	84.4±3.3	+28.1
General control group		55	55.0±4.3	61.8±4.0	+6.8

In all three universities, the increase in the experimental groups was observed in the range of 25–31 points, and in all cases $p < 0.001$. This indicates that the STEM-project approach has a stable effect in different academic contexts. Additional analysis was conducted to check the stability of the results across different academic levels. The study involved 2nd and 3rd year students, but the distribution of groups varied between universities. The course level did not fully match the experimental situation (in one university, the experimental group was in the 3rd year, in two universities, there were 2nd year students), which allowed for a natural control of the course factor.

This indicates that in the STEM-project learning condition, students' cognitive and professional interest in the subject increased at a much higher rate than in traditional learning. However, since descriptive statistics alone do not establish statistical significance, inferential statistical analysis was conducted. Inferential statistical methods were used to test the statistical significance of the observed differences between groups. The pre-test and post-test results within groups were compared using the Wilcoxon signed-rank test, and the differences in growth between groups were compared using the Mann–Whitney U test. The effect size was calculated using the formula $r = Z/\sqrt{N}$. The effect size (r) and 95% confidence intervals were also calculated. These methods allow assessment of both the statistical significance and practical importance of the observed training effects. The results of the calculations are presented in Table 2.

The results presented in Table 2 show that the differences between pre-test and post-test in the experimental groups were statistically significant at all universities ($p < 0.001$). Comparison of growth rates between groups also revealed significant differences ($p < 0.001$). The high level of effect size ($r = 0.81–0.87$) indicates that STEM-based project-based learning has a large practical impact. The location of the 95% confidence intervals far from zero confirms the stability and reliability of the results. Thus, the obtained data demonstrate that STEM-based learning is associated with an increase in students' interest in the field of nanotechnology.

Table 2. Descriptive statistics (M, SD, Gain) of nanotechnology interest scores in the experimental and control groups at pre-test and post-test stages for each university.

University	Comparison	Test	Result (Z)	p	Effect size (r)	Gain difference (Exp–Ctrl), points	95% CI
S. Amanzholov East Kazakhstan university	Exp: Pre–Post	Wilcoxon	3.39	0.000709	0.87	–	–
	Contr: Pre–Post	Wilcoxon	4.30	0.000017	0.88	–	–
	Gain: Exp vs Control	Mann–Whitney	5.22	<0.001	0.84	19.99	[18.17; 21.75]
U.Zhanibekov South Kazakhstan Pedagogical University	Exp: Pre–Post	Wilcoxon	3.71	0.000207	0.87	–	–
	Contr: Pre–Post	Wilcoxon	2.77	0.005635	0.88	–	–
	Gain: Exp vs Control	Mann–Whitney	4.31	<0.001	0.81	18.79	[17.48; 20.10]
International Kazakh-Turkish university named after Khoja Ahmed Yasawi	Exp: Pre–Post	Wilcoxon	3.94	0.000083	0.88	–	–
	Contr: Pre–Post	Wilcoxon	4.03	0.000055	0.88	–	–
	Gain: Exp vs Control	Mann–Whitney	5.52	<0.001	0.86	23.76	[22.98; 24.50]
General	Gain: Exp vs Control	Mann–Whitney	8.99	<0.001	0.87	21.20	[20.26; 22.10]

The majority of respondents believe that the introduction of nanomaterials and nanotechnologies will soon affect their lives. However, the initial survey indicated that students' interest is scattered, disorganized, and does not correspond to the level of interest or curiosity. In Table 3, we additionally present the results of the analysis of the results of the survey conducted among students on a Likert scale in order to determine the initial and final level of interest in the topic of nanotechnology, not as an experimental or control group, but as a whole, across universities.

Table 3. Results of the initial and final survey to determine the level of interest in the topic «nanotechnology and nanomaterials».

Level of interest	Percentage of respondents with the appropriate level of interest					
	S. Amanzholov East Kazakhstan university		U. Zhanibekov South Kazakhstan Pedagogical University		International Kazakh-Turkish university named after Khoja Ahmed Yasawi	
	initial	final	initial	final	initial	final
Lack of interest	30%	10%	25%	5%	30%	10%
Level of «curiosity»	25%	25%	25%	25%	20%	20%
Level of «inquisitiveness»	20%	30%	22%	32%	22%	32%
Level of cognitive interest	25%	35%	28%	38%	28%	38%

When analyzing the results of the study, an increase in the interest of students in the topic of nanotechnology in general can be observed. If at the beginning of the educational experiment, the level of interest of the majority of respondents corresponded to the level of interest and knowledge, then after using the method, many respondents showed a level of cognitive and theoretical interest. After the experiment, the number of students who showed a very high level of motivation to form nanotechnology knowledge in order to gain in-depth knowledge and improve their skills in the future profession increased by 10%, while the number of students with low interest decreased in all universities.

In general, the results of the quantitative analysis showed that the scores of interests in nanotechnology in the experimental groups where the STEM-project approach was used increased statistically significantly and with a large effect size, while in the control groups where traditional teaching was carried out, the changes were weaker. This trend was observed equally in all three universities and at different course levels, that is, confirming the stability of the results obtained. As a comparative analysis with the literature shows, the present study complements the previous qualitative conclusions about the effectiveness of STEM-based learning with quantitative empirical evidence. In this regard, STEM-project-based learning can be considered as a pedagogical approach that is positively related to students' interest in the subject. The following section discusses the pedagogical interpretation and theoretical significance of the obtained results.

3. ERROR ANALYSIS

Since the results of the study were based on students' self-reported interest in the subject through a questionnaire, possible sources of measurement errors and distortions were taken into account when interpreting the data.

First, the self-report method is subjective. Students may overestimate or underestimate their interest, and may also strive to provide socially desirable responses due to social desirability bias. This factor may lead to an overestimation of the results. In order to reduce this risk, the survey was conducted anonymously, and it was explained in advance that the answers would not affect the academic assessment. Second, the novelty effect of the intervention may have influenced the results. Since STEM-project learning is a new format for students, it is possible that a temporary increase in interest may be observed. To reduce this effect, the training was organized systematically over a full semester (15 weeks), rather than a short-term training, which allowed for the formation of a lasting pedagogical impact. Third, since the study was conducted at several universities, differences between instructors may have affected the results. To limit this potential instructor effect, all institutions used a single syllabus, the same laboratory assignments, common methodological guidelines, and standardized learning materials. Thus, the difference was limited only to the teaching method (traditional vs. STEM-project-based). Fourth, when dividing interest levels into four categories (lack of interest, situational interest, exploration, cognitive interest), classification error may occur due to the cutoff values. Therefore, categorical distributions were used for descriptive purposes only in statistical analyses, and testing of the main hypotheses was carried out on the basis of continuous Likert scores. Given these limitations, the study results should be interpreted as a positive association between STEM-project-based learning and students' subject interest, rather than as a cause-and-effect relationship.

4. COMPARATIVE EVALUATION WITH STATE OF THE ART

In order to compare the results obtained with current research in the field of STEM project-based teaching, a literature review was conducted. Comparative analysis showed that the magnitude of the increase in interest identified in our study is consistent with the results of previous studies aimed at training future physics teachers. In particular, a number of studies have reported that teaching based on practical and project activities is associated with increased student participation in the subject and motivation. Our data also showed a clear increase in interest scores in the experimental groups that included STEM project-based learning, indicating a positive association of the STEM approach with subject interest.

Table 4. Comparative description of research on nanotechnology STEM project-based learning.

Research	Context	Sample size (N)	Duration	Rating indicator	Main result
Haagen-Schützenhöf	Future physics teachers, experimental work	~60	1 semester	Participation, professional	Active hands-on work has been shown to increase

er & Joham (2018) [16]				training (qualitative)	student engagement in the subject.
Shoiynbaeva et al. (2024) [8]	Nanotechnology methodology in the training of future teachers	~50–70	1 semester	Methodological/pedagogical analysis	The pedagogical value of incorporating nanotechnology into the curriculum has been proven (no quantitative measure)
This study (2026)	Future Physics Teachers, STEM-Project Nanotechnology Course	108	1 semester	Interest score (Likert, pre/post)	+26–31 points increase in the experimental group, +7–8 points in the control group; a clear increase in interest in the STEM approach was observed

The comparison results show that while previous studies were mostly limited to qualitative or methodological description, in the present work the quantitative change in interest was assessed using inferential statistics. The large effect size observed in the experimental groups ($r > 0.7$) indicates a stable relationship between STEM-project-based learning and interest in the subject, and these results are consistent with international practice.

V. DISCUSSION

Analysis of the research results showed that the application of STEM project-based learning was associated with a statistically significant increase in students' subject interest in nanotechnology. According to the quantitative data, the average increase in interest scores in the experimental groups ranged from 26 to 31 points, whereas in the control groups the increase was limited to only 7–8 points (Table 1). The differences between the groups were found to be significant using the Mann–Whitney U test ($p < 0.001$), and the effect size was high ($r \approx 0.70$–0.80), indicating the practical pedagogical significance of the STEM approach. Initial survey results indicated that the majority of students demonstrated only moderate or superficial levels of interest in nanotechnology. However, by the end of the study, a significant number of them had risen to the level of cognitive and theoretical interest. This change suggests that the use of STEM projects in the educational process improves students' thinking skills, research culture, and understanding of interdisciplinary connections.

The results obtained are consistent with the findings of previous studies. For example, while the empirical work of the aforementioned scholars [16] qualitatively demonstrated that it increases future teachers' engagement with the subject, domestic scholars [9] justified the methodological significance of integrating nanotechnology into pedagogical training. Our study complements these findings with quantitative data, demonstrating a significant statistical change in interest indicators in a pre/post format and a large effect size. Thus, this work provides further evidence supporting the effectiveness of the STEM approach. Furthermore, the results were consistent across all three universities and at various course levels, indicating the generalizability of the intervention's impact. Therefore, the observed changes may be attributable not only to the characteristics of an individual instructor or academic team, but also to the content and methodological structure of STEM project-based learning. Overall, the data suggest a positive relationship between STEM project-based learning and students' subject interest. However, as the study was quasi-experimental in nature, the results should be interpreted as evidence of association between pedagogical approach and motivational indicators, rather than as causal evidence.

Several limitations should be acknowledged. First, the study employed non-random sampling, which may limit generalizability. Second, although baseline equivalence between groups was verified statistically, complete group matching cannot be guaranteed. Third, interest was measured using self-report questionnaires, which may introduce social desirability and response biases. Fourth, implementation across multiple universities may have involved slight instructional variability. Finally, the study assessed only interest outcomes and did not include achievement or skill-based performance measures. Future studies should incorporate randomized designs and broader outcome indicators.

VI. CONCLUSION

The results of the quasi-experimental study showed that the 'Nanotechnology and Nanomaterials' course, organized on a STEM project-based approach, was associated with an increase in the interest scores of prospective physics teachers. While the experimental groups showed a marked increase in interest scores, the changes in the control groups, where traditional teaching was used, were limited. This provides quantitative empirical evidence for the potential of the STEM approach in enhancing learning motivation. The scientific novelty of the study lies in its comprehensive evaluation of nanotechnology teaching in a STEM project format within teacher training, and in the quantitative measurement of interest indicators using a pre–post design and inferential statistics. The proposed methodological system creates conditions for developing students' research activity, critical thinking skills, and ability to solve practical tasks by integrating nanotechnology content with interdisciplinary STEM projects. In this regard, the study complements the empirical evidence on the pedagogical effectiveness of applying the STEM approach in teacher training programmes. The practically designed tasks and project-based work are adapted for use in the higher education learning process and can be directed towards enhancing the professional preparation of future teachers. This approach contributes to establishing the methodological basis for integrating elements of nanotechnology into school practice.

As the study was quasi-experimental in nature, the results should be viewed not as definitive causal evidence, but as a positive correlation between STEM project-based learning and subject interest. Future research should assess learning achievements, practical skills, and long-term impacts, as well as expand nanotechnology education by integrating digital modelling, virtual laboratories, and artificial intelligence tools. Thus, STEM project-based nanotechnology instruction represents an effective pedagogical mechanism for fostering scientific motivation and increasing exploratory and cognitive interest in nanoscience among future physics teachers.

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Author Contributions

Conceptualization, B.A., M.S., Sh.R., and A.C.; methodology, B.A. and Sh.R.; software, A.C.; validation, M.S.; formal analysis, M.S. and A.C.; investigation, B.A. and Sh.R.; resources, B.A.; data curation, B.A.; writing—original draft preparation, B.A. and Sh.R.; writing—review and editing, B.A. and A.C.; visualization, A.C.; supervision, M.S.; project administration, B.A.; funding acquisition, B.A. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

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

Data Availability Statement

The data supporting the findings of this study include anonymized questionnaire responses, pre- and post-test raw scores, coded datasets, and statistical analysis outputs. Due to ethical and confidentiality restrictions involving student participants, the data are not publicly available. Anonymized data may be provided by the corresponding author upon reasonable request for research purposes.

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Ethical Considerations

This study was conducted in accordance with the ethical standards of higher education research. Participation was voluntary. All students were informed about the purpose of the study and provided informed consent prior to participation. No personal identifiers were collected, and all responses were anonymized. The study involved minimal educational risk and therefore did not require formal medical ethical approval in accordance with institutional guidelines. All data were stored securely and used exclusively for research purposes.

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