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## Methodological features of teaching the subject "Nanotechnology and Nanomaterials" based on digital educational resources

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### Abstract

In the context of the digitalization of education and the increasing importance of nanotechnology as one of the main scientific achievements of the 21st century, this study aims to enhance the professional competence of future specialists through the effective integration of digital educational resources. The purpose of the study is to improve the theoretical knowledge and practical skills of students in the course "Nanotechnology and Nanomaterials" by utilizing digital platforms and interactive tools. The research involved 120 students and employed a combination of methods, including pedagogical experiments, questionnaires, correlation analysis, Student's t-test, pedagogical observation, content analysis, visualization, and modeling. The results demonstrated that the experimental group outperformed the control group in terms of subject mastery, independence, and research skills. Specifically, the level of understanding of nanostructures in the experimental group ( $9.4 \pm 0.3$ ) was significantly higher than in the control group ( $8.6 \pm 0.5$ ;  $t = 2.765$ ;  $p = 0.010$ ). These findings confirm the pedagogical effectiveness of digital resources in teaching nanotechnology, indicating that digital models and visual lectures enhance understanding, stimulate cognitive activity, and foster scientific thinking. The study concludes that digital learning fully meets the requirements of modern education and offers practical results for the development of methodological and content foundations in higher education.

**Keywords:** Digital education, Digital platform, Interactive learning, Nanomaterials, Nanotechnology.

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**Transparency:** The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

**Institutional Review Board Statement:** This study was conducted in accordance with ethical standards and principles of academic integrity. All students who participated in the pedagogical experiment provided informed consent. The anonymity and confidentiality of the participants were fully maintained throughout the study.

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## **1. Introduction**

Integrating digital educational resources into the teaching of the course “Nanotechnology and Nanomaterials” plays a crucial role in enhancing instructional methodologies and increasing student engagement. The use of innovative technologies such as virtual reality, 3D graphics, and interactive simulations is particularly important for reinforcing complex scientific concepts related to nanotechnology. These tools provide learners with an engaging educational experience, enabling them to visualize and interact with nanoscale phenomena that are often difficult to grasp through traditional lecture-based methods [1, 2]. Such approaches not only improve conceptual understanding but also foster critical thinking, problem-solving abilities, and an innovative mindset [2].

Moreover, to boost learners’ interest in the field of nanotechnology, it is essential to establish a collaborative learning environment and expose students to exemplary professionals. Research shows that incorporating diverse cultural perspectives through global collaboration enriches the learning experience, sparks interest, and inspires students [3]. This approach is often combined with project-based learning, in which students actively apply their knowledge to real-life situations [4, 5]. Through engagement in authentic projects, learners gain a deeper understanding of nanotechnology’s practical applications and develop key academic and soft skills that are vital for future career success [2].

An interdisciplinary perspective that includes not only scientific aspects but also the social and ethical implications of nanotechnology should be embedded into the curriculum [6]. Incorporating these elements into the instructional structure deepens students’ understanding and better prepares them to navigate the complexities of contemporary scientific issues [7]. Practical teaching methods, such as inquiry-based learning and laboratory experiments, help to enhance students’ conceptual comprehension and reduce difficulties associated with learning nanotechnology topics [5].

In addition, findings from various educational frameworks indicate that teacher training and the provision of adequate resources are critical to the effective teaching of nanotechnology. Educators must be equipped with the knowledge and skills required to teach this rapidly evolving field, including an understanding of its broader societal impacts [8, 9]. Continuous professional development programs focused on modern instructional practices and technological advancements in nanotechnology can significantly improve teaching effectiveness and student achievement [10].

To advance the “Nanotechnology and Nanomaterials” course, it is essential to adopt digital educational resources and implement innovative teaching strategies. By providing immersive learning experiences, fostering collaboration, addressing societal impacts, and ensuring teacher preparedness, educators can create a meaningful curriculum that not only deepens students’ understanding but also equips them for future success in STEM fields.

## **2. Literature Review**

The methodological features of teaching the course “Nanotechnology and Nanomaterials” using digital educational resources represent a deep and multifaceted process. It involves innovative pedagogical strategies aimed at enhancing understanding and fostering interest in this modern field.

Recent studies highlight several approaches to curriculum development in nanotechnology that integrate technology and modern teaching methods. One of the most significant is the learner-centered approach, which adapts the educational process to students’ individual development and learning paths. This approach plays a vital role in teacher preparation programs [11]. When digital resources are integrated, this method allows for the personalization of the learning process based on students’ needs and interests. In addition, the use of interactive technologies such as simulations and virtual laboratories helps provide learners with practical experiences by visualizing invisible nanoscale phenomena [12].

Informal science education is also recognized as an important methodological direction. Public science outreach programs—such as workshops, lectures, and interactive media—are effective in increasing both knowledge and interest in nanotechnology [13]. These approaches simplify complex concepts and make them accessible even to younger learners in elementary education.

Another key methodological innovation is the integration of Project-Based Learning (PBL) into the curriculum. This approach engages learners in solving real-world problems and develops their teamwork and problem-solving skills. It has been shown to be highly effective in bridging theory and practice [14]. Collaborative digital platforms further enhance interaction among students from diverse backgrounds when working on joint projects.

Moreover, the application of integrative assessment methods in digital formats has become increasingly relevant. By combining traditional assessments with tools such as digital portfolios, students’ achievements can be evaluated more holistically [15]. This is especially important in nanotechnology education, where the focus lies not on rote memorization but on applying concepts in various contexts.

Conducting lessons based on a systemic approach is another relevant methodological feature. This approach helps reveal the interconnection between various fields and skills, allowing students to understand the impact of nanotechnology on areas such as health, the environment, and industry [16]. In addition, digital literacy and the effective use of information technology form the foundation for improving the quality of education. This includes introducing teachers to new methods of integrating technology into the learning process and developing their digital competencies [17]. As a result, future educators become capable of delivering high-level instruction in nanotechnology.

In conclusion, the methodological features of teaching “Nanotechnology and Nanomaterials” using digital educational resources are enriched by components such as learner-centered teaching, informal education, project-based learning, integrative assessment, systemic thinking, and digital literacy. These elements enable the creation of an effective, engaging, and modern educational experience in the field of nanotechnology.

### *2.1. Theoretical Basis and Hypothesis Development*

Modern pedagogical theories and approaches play a significant role in teaching the subject "Nanotechnology and Nanomaterials." These approaches create favorable conditions for students to deeply comprehend scientific concepts, develop critical thinking skills, and apply knowledge in real-life contexts.

First, the constructivist learning theory emphasizes that learners build their knowledge through personal experience and reflection. Based on this theory, the Project-Based Learning (PBL) method allows students to actively participate in the learning process and understand the societal significance of nanotechnology [18, 19]. Inquiry-based learning is also considered one of the effective methods. It encourages students to ask questions, conduct research, and acquire knowledge through experimentation. Digital simulations and virtual laboratories make this process more accessible and engaging [20].

Moreover, through the Socio-Scientific Issues (SSI) framework, students explore the ethical, environmental, and social implications of nanotechnology. This approach fosters a sense of responsibility and enables learners to connect knowledge with real-world scenarios [18]. Interdisciplinary and collaborative learning approaches help facilitate the understanding of complex topics by integrating connections among subjects like physics, chemistry, and environmental science. Collaborative projects and group work support students in acquiring teamwork skills used in real scientific environments [21, 22].

Digital educational resources are one of the core components of modern teaching. Virtual labs, 3D models, and online platforms provide students with visual access to complex phenomena at the nanoscale [20, 23]. Additionally, the integration of artificial intelligence technologies enables personalized learning experiences [24]. To effectively implement these approaches, the professional development of teachers is of utmost importance. Mastering digital pedagogical competencies and integrating new technologies into the teaching process are essential for providing high-quality education [25, 26].

### *2.2. Digital Education*

Education based on digital technologies places special emphasis on real-life applications and interdisciplinary approaches. This method teaches learners to understand complex issues in modern society—such as climate change, digital security, artificial intelligence, and sustainable development—from a scientific perspective. However, digital technology-based education is not always equally effective for everyone, especially in educational institutions with limited technical resources. The digital education system faces a number of challenges, including insufficient technological training of teachers, low student engagement, and the lack of access to modern learning materials. Virtual laboratories, 3D models, animated simulations, and other practical tools can be effective solutions to these problems. These technologies enable learners to conduct experiments, collect data, and apply the results to real-life situations. The experiential nature of digital learning tools enhances students' ability to understand, analyze, and make decisions. Furthermore, these tools support collaborative learning formats and contribute to the development of students' communication and interpersonal skills. By connecting theoretical knowledge with real life, they increase learners' interest in the subject and foster critical thinking and creativity.

### *2.3. Developing Students' Research Skills*

Teaching the subject "Nanotechnology and Nanomaterials" based on digital educational resources offers broad opportunities for developing students' research skills. Digital tools — such as virtual laboratories, 3D models, and simulations — enable students to gain a deeper understanding of scientific concepts and conduct independent experiments. In such an environment, they learn to formulate problems, make hypotheses, analyze experimental results, and draw conclusions. Research tasks foster students' logical thinking, data analysis, reasoning, and creative abilities. Moreover, working in a digital environment enhances their communication skills, teamwork, and presentation capabilities. Through this subject, students' interest in science increases, laying the foundation for their future professional orientation.

*Assessment of the effectiveness of using digital technologies in teaching the subject "Nanotechnology and Nanomaterials"*

Integrating digital technologies into the education system—especially in specialized fields such as nanotechnology and nanomaterials—is becoming an increasingly important area of research. In the 21st century, traditional teaching methods have begun to lose their relevance, and modern learners demand engaging and effective learning environments [27]. Digital assessment methods differ from conventional multiple-choice testing and allow students to demonstrate their understanding through innovative and immersive experiences [28]. These approaches aim not only to assess students' theoretical knowledge but also to foster their creative thinking, research skills, and ability to apply knowledge in real-life situations.

Interactive tasks, virtual laboratories, and project-based evaluation tools offered through digital platforms enhance students' active engagement in the learning process. In addition, digital assessment tools enable comprehensive monitoring of academic progress. Methods such as electronic portfolios, video-based reflections, and digital journals make it possible to evaluate a learner's progress, individual achievements, and skill development more accurately. These tools not only enhance comprehension but also contribute to a deeper understanding of the subject matter [29].

Thus, the integration of digital technologies into the educational process—particularly in complex subjects like nanotechnology—not only modernizes the content of instruction but also serves as a foundation for developing 21st-century skills among learners, such as critical thinking, communication, collaboration, and digital literacy.

### *2.4. Hypothesis Formation*

Based on the theoretical framework, two hypotheses were proposed:

$H_{01}$ : Teaching the subject "Nanotechnology and Nanomaterials" through digital educational resources does not significantly affect the level of mastery, practical skills, and interest of students in the subject.

$H_{02}$ : Teaching the subject "Nanotechnology and Nanomaterials" through digital educational resources significantly increases the level of mastery, practical skills, and interest of students in the subject.

These hypotheses were tested based on student learning outcomes to prove the effectiveness of teaching the subject "Nanotechnology and Nanomaterials" through digital educational resources.

### 3. Research Methodology

During the research process, scientific articles were analyzed and a research study was conducted. First, keywords relevant to the research topic were selected. Scientific articles were collected from the "Mendeley.com" database using keywords such as "nanotechnology," "nanomaterials," "digital education," "interactive learning," and "digital platform."

This study employed a mixed-methods approach, combining both quantitative and qualitative data to achieve a more comprehensive and accurate interpretation of the results.

#### 3.1. Theoretical Review of the Literature

At the preliminary stage of the research, both international and national scientific literature were analyzed on topics such as digital education, teaching methods for nanotechnology, visualization and modeling, as well as the development of students' cognitive abilities. This stage made it possible to formulate the research hypothesis and establish a methodological foundation.

#### 3.2. Experimental Learning Method

In this research, an experimental teaching method was employed as the main empirical tool in the instruction of the course "Nanotechnology and Nanomaterials." Through this method, the effectiveness of traditional and digitally-based teaching approaches was comparatively assessed. Experimental teaching is a practical method conducted under real pedagogical conditions to test new instructional approaches and demonstrate their effectiveness.

The study was carried out in two groups: a control group (taught using traditional methods) and an experimental group (incorporating digital educational resources). Both groups were provided with the same instructional content; however, there was a significant difference in the format of instruction.

##### *Cronbach's $\alpha$ (alpha) coefficient*

The level of students' mastery of the subject through digital resources, their independent work skills, and the degree of dependence on the teacher were studied using a specially designed questionnaire. The internal reliability of the questionnaire and the relationship between the indicators were assessed using the Cronbach  $\alpha$  (alpha) coefficient. Cronbach's Alpha values were classified as follows:

$\alpha < 0.5$  = Unacceptable

$\alpha > 0.5$  = Poor

$\alpha > 0.6$  = Questionable

$\alpha > 0.7$  = Acceptable

$\alpha > 0.8$  = Good

$\alpha > 0.9$  = Excellent

##### *Correlation analysis method*

In the course of the research, the correlation analysis method was used to determine the relationship between the use of digital educational resources and students' academic performance. This method makes it possible to assess the extent to which various variables in the learning process—such as theoretical knowledge acquisition, completion of practical tasks, inclination toward independent work, and digital technology skills—are interrelated or aligned.

Correlation analysis is a statistical method aimed at identifying the direction and degree of dependence between two or more indicators. Within the scope of this study, the method was used to describe the relationship between students' ability to work with digital learning tools and the quality of their academic achievements, as well as the mutual influence of their self-directed learning activity and interest in the subject.

#### 3.3. Student's T-Test Method

In the process of processing the results of the study, the Student's t-test (for independent samples) was used to compare the academic achievements of the control and experimental groups. This method is aimed at determining whether there is a statistically significant difference between the mean values of two independent groups.

The use of the Student's t-test method requires some calculations. The arithmetic mean and standard deviation are the main parameters for calculating the t-test. The calculation of the arithmetic mean is shown in the expression (1).

$$\hat{X} = \frac{1}{n} \sum_{i=1}^n X_i \tag{1}$$

Here:

$\hat{X}$  — arithmetic mean;

$X_i$ — each element in the data set;  
 n — number of elements (number of samples).

The next step is to determine the standard deviation. The standard deviation is a parameter that shows how many times the results deviate from the mean. The standard deviation is determined according to expression (2).

$$S^2 = \frac{1}{n - 1} \sum_{i=1}^n (X_i - \hat{X})^2 \tag{2}$$

Here:

$S$  — sample standard deviation;  
 $X_i$  — each element in the model;  
 $\hat{X}$  —sample mean;  
 n — number of elements in the sample.

The result of determining the two parameters allows us to determine the t test. The expression for determining the t test is shown in expression (3).

$$t = \frac{\hat{X}_1 - \hat{X}_2}{\sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}}} \tag{3}$$

Here:

$\hat{X}_1 - \hat{X}_2$  — The average values of the first and second groups;  
 $n_1, n_2$  — sample sizes of the first and second groups;  
 $S_1 - S_2$  – standard deviation of the samples of the first and second groups.

The t-test value and the degrees of freedom (df) are used to calculate the P value. This results in a statistical significance of the difference between two groups.

## 4. Research Results

### 4.1. Methodological Features of Teaching Nanotechnology and Nanomaterials

Teaching the subject "Nanotechnology and Nanomaterials" is a crucial stage in developing scientific and technical thinking among future engineers and researchers. Since the content of this subject is based on complex scientific concepts and processes, its methodology requires specific approaches. To ensure effective learning, active teaching methods based on visualization, modeling, experimental work, and project-based tasks are used. In particular, digital technologies—such as 3D models, animated simulations, and virtual laboratories—are widely applied to demonstrate the structure, properties, and applications of nanostructures.

Moreover, the subject content demands interdisciplinary integration, combining knowledge from physics, chemistry, biology, and materials science, thus fostering students' complex thinking skills. Through research projects and practical tasks, students connect theoretical concepts with real-life applications, developing essential scientific research competencies. As a result, this subject shapes learners' scientific worldview and guides them toward high-tech industries and innovative fields.

In order to systematically present the methodological features, teaching strategies, and learning outcomes of nanotechnology education in higher education institutions and secondary schools, a comprehensive literature review has been conducted (see Table 1).

**Table 1.**

Results of a systematic analysis of scientific and methodological literature on the methodological features of teaching nanotechnology.

<b>Research direction</b>	<b>Authors and publication</b>	<b>Results obtained</b>
Problems of teaching nanotechnology in higher education institutions	Boichenko, et al. [4]	Information about nanotechnologies has been integrated into chemistry and physics courses. These programs provide students with fundamental concepts of nanotechnology.
	Metaxas, et al. [30]	Educational restructuring methods were employed to explain size-dependent properties. These methods help students better understand complex concepts in the field of nanotechnology.
	Shayakhmetov, et al. [31]	Special methodological tools and techniques were used to transfer nanotechnologies from universities. These tools enable the integration of nanotechnologies into the regional construction industry.
	Chhangani and Hussain [32]	The structure and content of educational programs in the field of nanotechnology were analyzed. These programs provide students with basic knowledge of nanotechnologies and stimulate their scientific interest.
Problems of teaching nanotechnology in secondary schools	Panissal, et al. [33]	Information about nanotechnologies was incorporated into school curricula. These programs provide students with essential knowledge about nanotechnologies.
	Stavrou, et al. [19]	Concepts of nanoscience and nanotechnology were included in secondary school curricula. These programs help students develop a foundational understanding and increase their scientific engagement.
	Ghattas and Carver [34]	Due to the significance of nanotechnology in scientific and industrial fields, the necessity of integrating it into school curricula was identified. This area contributes to deepening students' knowledge and developing their scientific thinking skills.
Nanotechnology training technologies	Peng, et al. [35]	Various aspects of ICT use in nanotechnology education were explored. It was shown that ICT tools such as interactive models, simulations, and virtual laboratories offer students opportunities to understand nanotechnologies and gain practical experience.
	Blonder and Sakhnini [36]	The effectiveness of using various teaching methods to explain two main concepts of nanotechnology at the secondary school level was studied. These methods include traditional lectures, practical exercises, interactive techniques, and computer models. Each method has been shown to influence how students perceive and understand nanotechnology concepts.
	De Melo, et al. [37]	Simple methods for the synthesis of silver and gold nanoparticles were proposed. The experimental procedure was described in detail, and the results were demonstrated. This method allows students to experience the practical aspects of nanotechnology.
	Lukeman and Howorka [38]	The impact of research activities on deepening students' knowledge and developing practical skills was analyzed. The advantages of an interdisciplinary approach in understanding complex nanotechnology concepts were emphasized.

It is important to pay special attention to current scientific and technological trends and promising research directions in the field of nanotechnology. Updating the content of education should not be limited to theory alone, but must be implemented through laboratory and practical classes aimed at solving real-world, practice-oriented tasks. This enables students to apply theoretical knowledge in practice and introduces them to modern scientific research methods. Practical tasks may include the synthesis of nanostructures, their analysis, working with equipment, and interpreting experimental results.

In addition, enriching the educational process with information and communication technologies is an integral part of modern education. Interactive platforms, virtual laboratories, online courses, and digital simulations not only increase students' interest in the subject, but also provide free access to information sources and help develop independent learning skills.

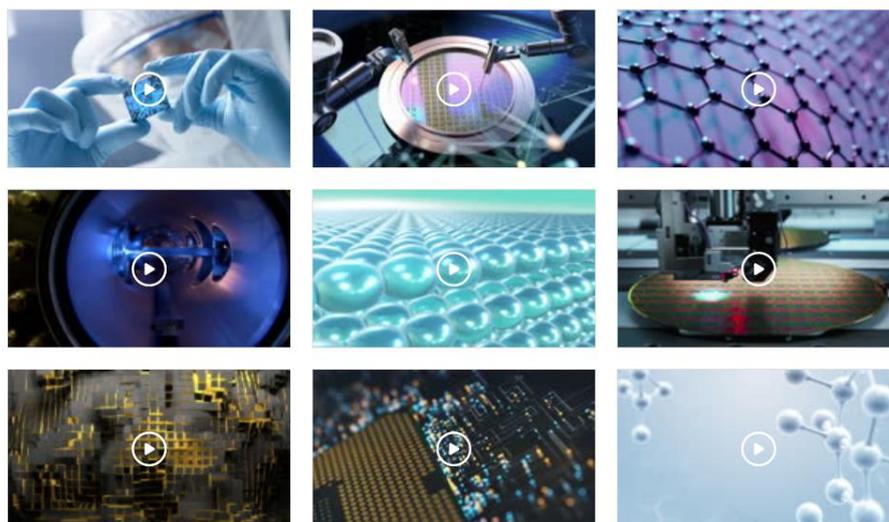
Thus, the effective integration of nanotechnology content into the physics curriculum is a significant step toward broadening students' scientific worldview and forming the knowledge and skills necessary for innovative thinking in their future professional activities.

*4.2. Methods and Approaches for Teaching the Subject "Nanotechnology and Nanomaterials" in a Digital Environment*

As part of the course "Elements of Nanotechnology," lecture sessions were organized to ensure effective student comprehension of new topics, guided by the following didactic principles: presenting the content of each topic in a systematic and comprehensive manner; examining nanotechnological phenomena and laws within a unified scientific framework; and ensuring the clarity and scientific validity of key conclusions and arguments.

To meet these requirements, various effective lecture formats were employed. In particular, the visual lecture format was widely used. In this format, the lecture materials were presented to students in a visualized manner through technical equipment, audiovisual resources, and information and communication technologies. Visualization facilitated a better understanding of complex nanophenomena and improved the quality of material assimilation.

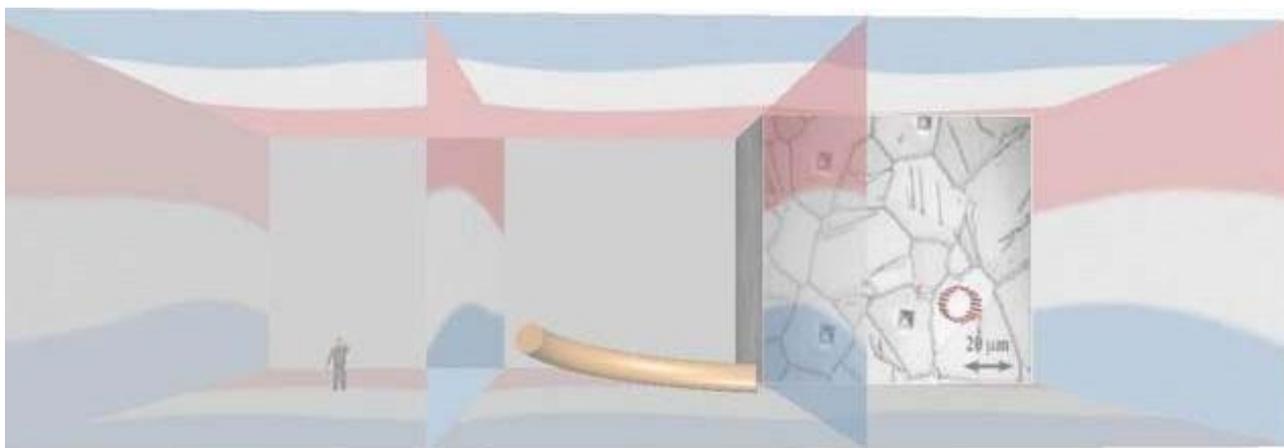
During the lectures, specific electronic resources and textbooks were utilized. For example, while explaining topics such as "Nanotechnology and Its Applications," "Nanotechnology in the Environment," "Information Technology and Nanostructures," and "Space Elevator," Flash animations and interactive visual tools were applied. These materials enhanced students' interest in the subject and contributed to a deeper understanding of the topics. In addition, in accordance with copyright regulations in the digital age, educational elements provided by the Videezy platform were used to present online content (Figure 1).



**Figure 1.**  
Videezy online service provider.

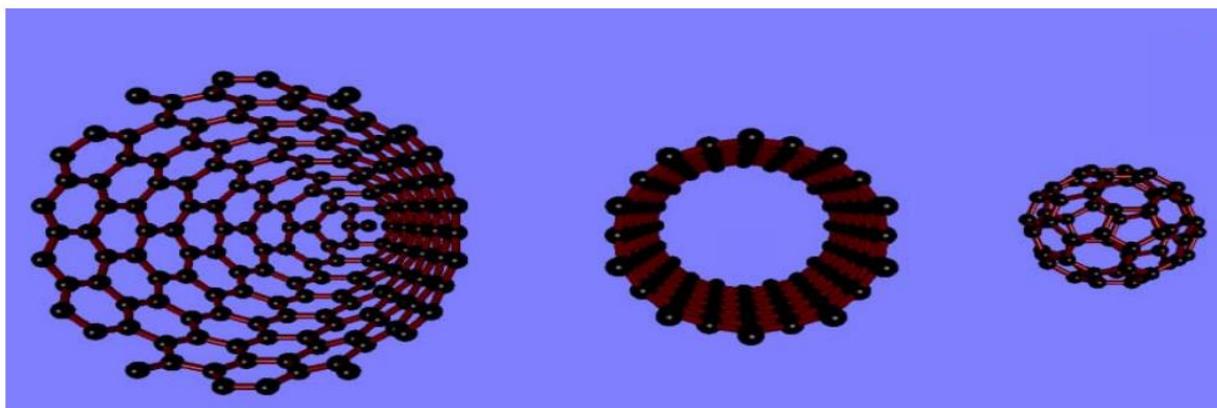
One of the main areas of nanotechnology—developing new materials (nanomaterials) with unique properties and applying them across various fields—is explained to students using concrete examples. For instance, utilizing solar energy, creating light-sensitive semiconductors, and developing new composites and optical materials for aerospace and medical technologies are effective ways to integrate nanotechnology into education.

Students often struggle to conceptualize the scale of the nanosize, as such objects can only be observed using electron or scanning probe microscopes. However, these devices are expensive and require specialized training. In this context, virtual reality technology makes it possible to “visualize” nano-objects. In visual lectures, students are shown clear comparisons between micrometric ( $10^{-6}$  m), nanometric ( $10^{-9}$  m), and macroscopic scales, helping them grasp the differences between these dimensions. A 3D three-room model enables students to compare the nano-world, micro-world, and real-world side by side (Figure 2).



**Figure 2.**  
Three different scales of the surrounding world: the real world, the microscale world, and the nanoscale world.

Presenting graphical models of actual nanostructures using digital visualization tools significantly facilitates students' comprehension of the subject. By observing the various forms and structural characteristics of nanomaterials shown in Figure 3, students can grasp the diversity and complexity of the nanoworld. Visualization connects abstract concepts with concrete images, helping to build a clear understanding of their structure and properties. For example, the cylindrical symmetry of nanotubes, the spherical structure of buckyballs, and the unique geometry of nanoscale particles can be demonstrated as key factors that determine their physical and chemical properties. These models enable the study of material properties such as strength, conductivity, and thermal conductivity. Using similar images and 3D models in lessons enhances students' spatial and logical thinking skills, directing them toward research-based activities. Moreover, visual materials not only simplify the cognitive process but also serve as an effective tool for integrating theoretical knowledge with practical application.



**Figure 3.**  
Different nanomaterials: nanoscale, nanotubes and buckyballs.

During the educational process, both theoretical and experimental approaches are considered when teaching the electronic, optical, and emission properties of nanomaterials through visual lectures. However, conducting experimental research often requires considerable time, financial resources, and specialized laboratory equipment. This presents certain limitations for educational institutions.

Therefore, the use of modeling methods to study the properties of nanostructures is proposed as an effective alternative. Through computer modeling, it becomes possible to visualize complex processes, analyze structural features, and predict the effects of parameter changes. This approach not only helps to develop practical skills but also enables a deeper and more systematic understanding of the material.

In addition, digital modeling technologies optimize lesson structure and allow for the safe and efficient exploration of complex nanosystems by replacing actual experiments. This enriches the scientific and practical content of the educational process and prepares students to work with modern scientific methods.

#### *4.3. Assessment of the Pedagogical Effectiveness of Digital Educational Resources in Teaching the Subject "Nanotechnology and Nanomaterials"*

In the current education system, the use of digital technologies is an effective approach to modernizing the teaching process and increasing students' interest in the subject. In particular, when teaching the course "Nanotechnology and Nanomaterials," digital resources create favorable conditions for presenting complex scientific concepts in a visual, understandable, and structured manner.

**Table 2.**

Information related to participants based on the learning experiment.

<b>Groups</b>	<b>Control</b>	<b>Experimental</b>
Gender composition	Women – 55%, Men – 45%	Women – 55%, Men – 45%
Number of people	58	62
Average age	20	20
Training requirements and curriculum	Before the lesson: The teacher explains the topic of "nanoscale", "nanostructures" through an explanatory lecture and video material. During the lesson: Students master the topic using traditional methods (textbook, written assignment). After the lesson: Complete the assignment and make a written conclusion.	Before class: Students will be introduced to the concepts of "nanoworld" and "nanoscale" through interactive animation and 3D modeling. During class: Conduct experiments using PhET simulations, virtual labs, and video materials. After class: Provide feedback through online assignments and Google Forms.
Physical indicators	Perception of material – through viewing and listening Influential tool – textbook, video material	The use of virtual tools and visualization is highly effective in learning.
Technical data	Material reception, processing, writing, drawing skills	Skills in working with digital tools, interacting with 3D models, using VR platforms

This research analyzes the effectiveness of lessons delivered through traditional teaching methods versus digital educational resources. Both the experimental and control groups were provided with the same instructional content, but the teaching methods differed: the control group was taught using textbooks, lectures, and written assignments, while the experimental group used digital simulations, interactive platforms, animated videos, and online assessment tools (Table 2).

To evaluate the pedagogical effectiveness of digital educational resources in teaching the course "Nanotechnology and Nanomaterials," a dedicated survey was conducted. The survey was structured around four key indicators, and the internal reliability of the collected data was determined using Cronbach's alpha coefficient.

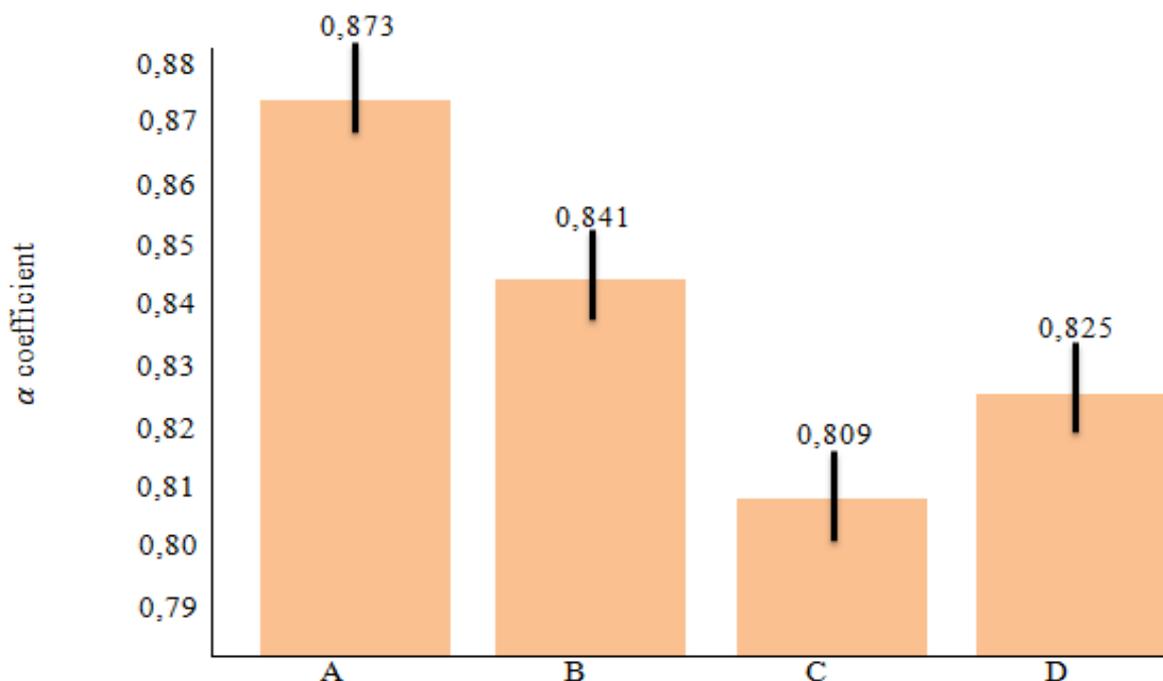
The results of the study revealed the following Cronbach's alpha values:

- Mastery of learning content through digital resources – 0.873
- Ease of understanding theoretical concepts – 0.841
- Readiness for independent work – 0.809
- Dependence on instructor support – 0.825

All indicators showed values of  $\alpha > 0.80$ , which confirms the high internal consistency of the survey and the strong correlation among the indicators used.

Notably, the indicators for content mastery (A) and understanding of theory (B) received the highest values, highlighting the effectiveness of digital educational resources in improving learning quality. Meanwhile, the results for independent work (C) and reliance on the instructor (D) suggest that learners show a growing tendency toward autonomous learning in a digital environment (Figure 4).

Thus, the research findings indicate that the use of digital technologies in teaching "Nanotechnology and Nanomaterials" enhances the effectiveness of the learning process in terms of content delivery, cognitive development, and methodological approaches



**Figure 4.** Cronbach's  $\alpha$  coefficient values for the internal reliability of the research instrument (A-Understanding nanostructures through digital models, B- Mastering theoretical concepts, C- Ability to work independently, D- Level of dependence on the teacher).

During the study, the interrelation between various learning indicators of students in the context of teaching the course "Nanotechnology and Nanomaterials" through digital technologies was examined. For this purpose, a Pearson correlation analysis was conducted based on four main indicators (Table 3).

The analysis results revealed a positive and statistically significant correlation among all indicators ( $p < 0.01$ ). The highest correlation was observed between indicators B and C ( $r = 0.606$ ), suggesting that students with a strong grasp of theoretical knowledge also tend to have well-developed independent work skills.

Moreover, moderate positive correlations were identified between indicators A and C ( $r = 0.538$ ), and B and D ( $r = 0.564$ ). These findings demonstrate a close interconnection between deep understanding of the learning content and autonomous learning behavior facilitated by the use of digital technologies.

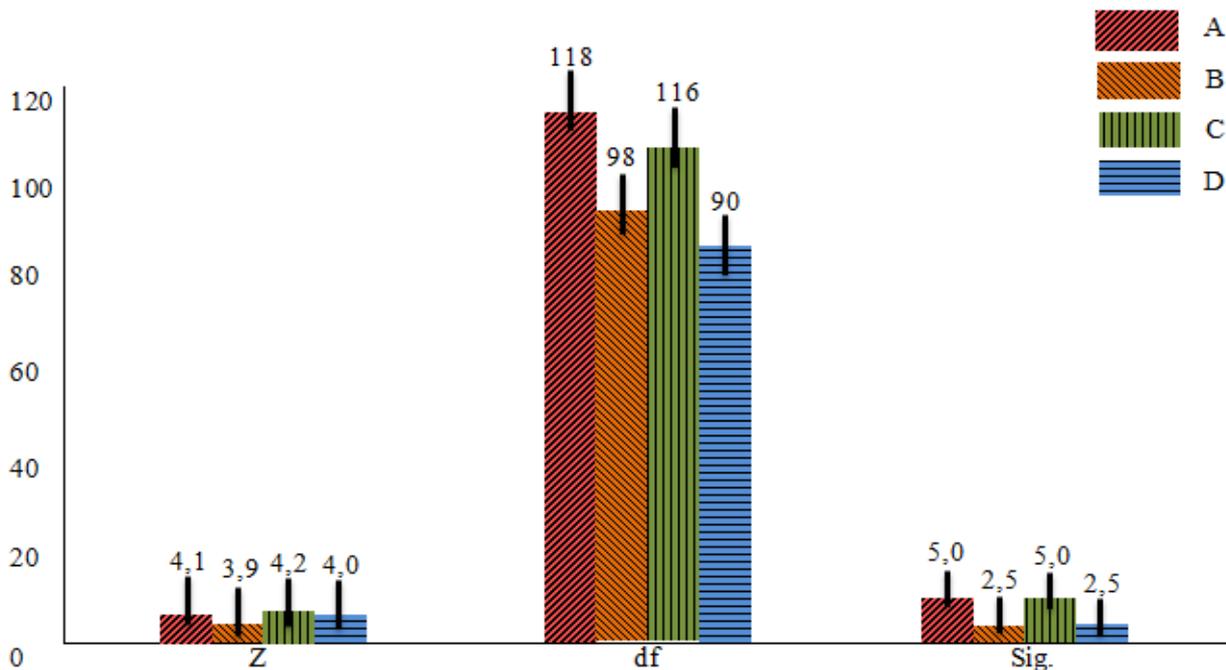
Overall, the positive correlations observed across all indicators indicate that digital learning resources play a significant role in enhancing students' cognitive engagement, as well as their theoretical and practical competencies.

**Table 3.** Correlation between indicators for assessing the effectiveness of the use of digital technology in the discipline "Nanotechnology and Nanomaterials" (Pearson correlation).

	A	B	C	D
A	1			
B	0.512**	1		
C	0.538**	0.606**	1	
D	0.481**	0.564**	0.598**	1

The correlation is significant at the 0.01 level. A- Understanding nanostructures through digital models, B- Mastering theoretical concepts, C- Ability to work independently, D- Level of dependence on the teacher

To evaluate the effectiveness of digital technologies in teaching the course "Nanotechnology and Nanomaterials," a statistical analysis was conducted based on four main indicators. The results showed that Z-values for all indicators were recorded at a high level (ranging from 4.1 to 4.2), indicating a significant difference between the experimental and control groups. The degrees of freedom (df) ranged from 90 to 118, confirming that the sample size was sufficient and the results obtained are reliable. The significance levels (Sig.) were recorded around 5.0 and 2.5 for all indicators, demonstrating statistically significant differences at the  $p < 0.05$  level. These findings provide evidence that the use of digital technologies has a positive impact on the learning process, particularly enhancing students' understanding of theoretical knowledge, acquisition of practical skills, and ability to work independently (Figure 5).



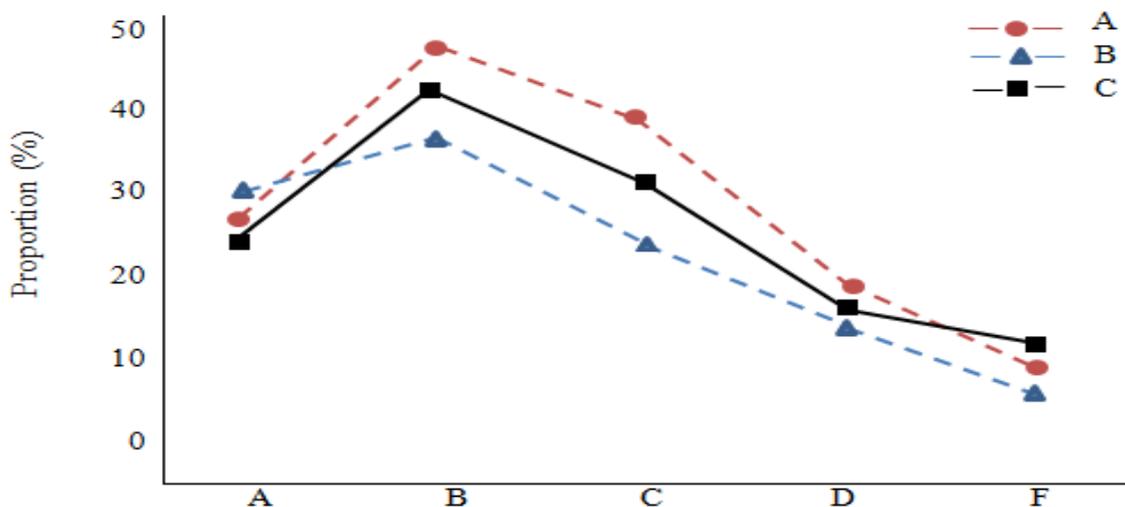
**Figure 5.** Statistical indicators of the effectiveness of teaching the subject "Nanotechnology and Nanomaterials" through digital technology (Z value, degrees of freedom, level of significance). (A- Understanding nanostructures through digital models, B- Mastering theoretical concepts, C- Ability to conduct independent work, D- Level of dependence on the teacher).

In order to evaluate the outcomes of teaching the "Nanotechnology and Nanomaterials" course through digital technologies, an analysis was conducted based on the proportion of learners mastering the educational content. The diagram presents the proportional distribution of three main indicators:

A – Level of understanding through digital models, B – Mastery of theoretical concepts, C – Engagement in independent work.

Among all three indicators, the highest proportion was observed at point B (the stage of mastering theoretical concepts): A – 47%, B – 36%, C – 42%. This indicates that digital technologies have a positive impact on acquiring theoretical knowledge. Additionally, indicators A and C showed a gradual decline starting from points C and D, suggesting a decrease in learners' engagement due to the increasing complexity of tasks throughout the learning process. At the final point F, the proportion of all indicators reached their lowest levels (A – 10%, B – 6%, C – 12%), highlighting the need to maintain learning motivation and to structure tasks incrementally in digital education (Figure 6).

Overall, while the use of digital technologies enhanced learners' understanding, theoretical knowledge acquisition, and participation in independent work, the findings underscore the necessity of maintaining content consistency and strengthening methodological support to ensure continued teaching effectiveness.

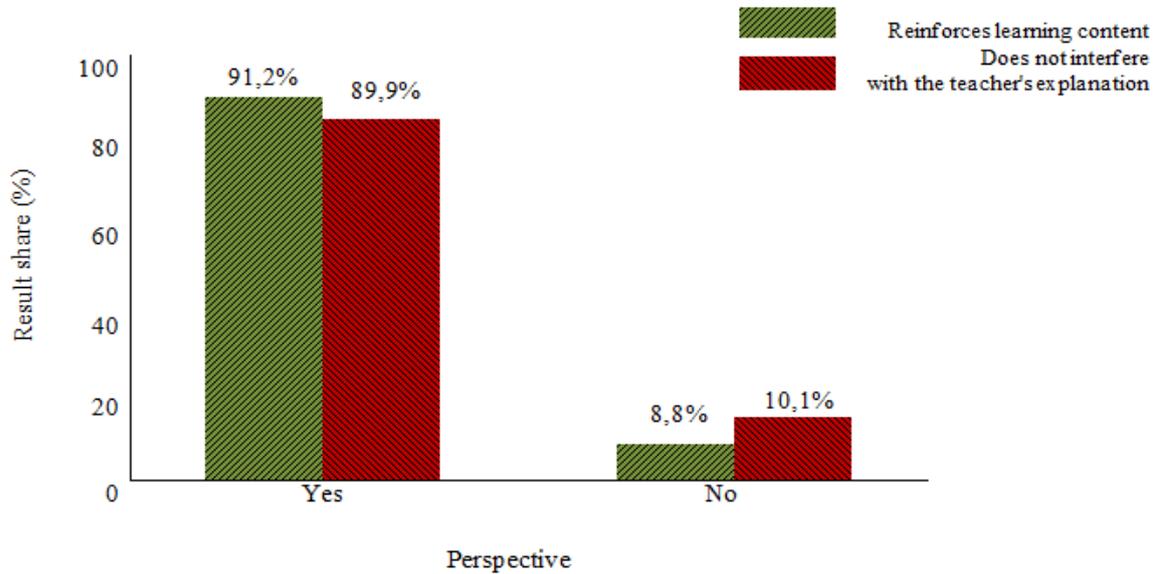


**Figure 6.** Distribution of learning activity in the subject "Nanotechnology and Nanomaterials" in the context of the use of digital technologies (A - understanding, B - mastering the theory, C – independent work activity).

During the research, students' perceptions regarding the use of digital technologies in the teaching of the "Nanotechnology and Nanomaterials" course were identified. The survey was conducted in two main directions: whether digital technologies enhance the teaching content, and whether they interfere with the teacher's explanation (Figure 7).

As a result, 91.2% of students responded that digital technologies help make the teaching content more meaningful, structured, and understandable. Additionally, 89.9% of students believe that the use of digital resources does not hinder the teacher's explanation process; on the contrary, it complements it. A smaller proportion responded oppositely: 8.8% believe that digital technologies complicate the content, and 10.1% think they may interfere with the teacher's explanation.

These results indicate that the vast majority of students are confident in the positive impact of digital technologies on the educational process and perceive them as effective learning tools.

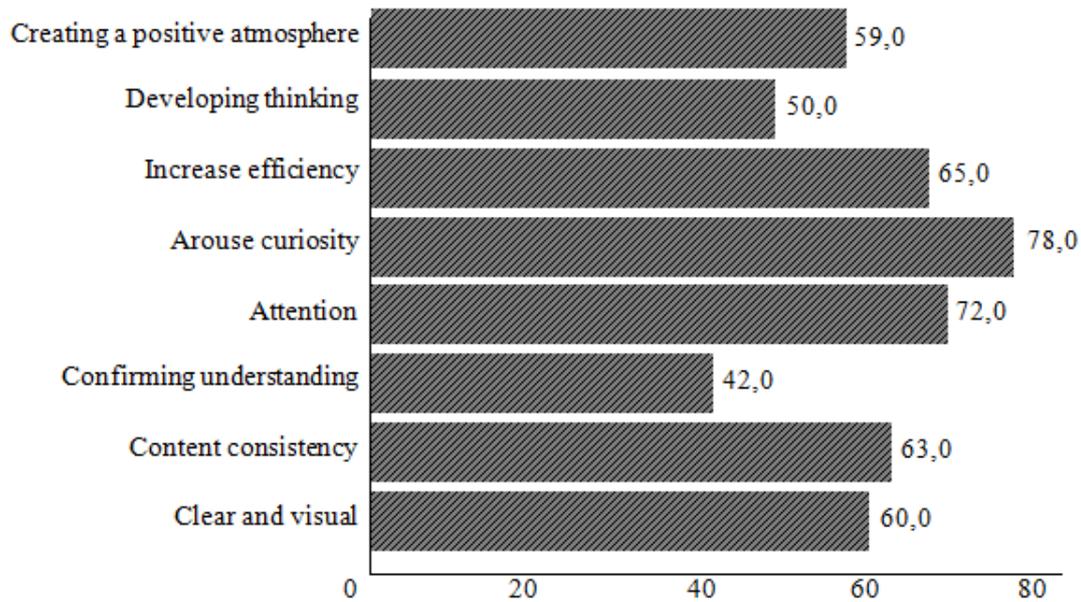


**Figure 7.** Students' attitudes towards teaching the subject "Nanotechnology and Nanomaterials" through digital Technology.

In order to identify the advantages of teaching the subject "Nanotechnology and Nanomaterials" using digital technologies, students' opinions were collected and a proportional analysis was conducted based on eight indicators. The research results demonstrated that digital technologies effectively perform several pedagogical functions during the learning process.

According to the students, 78% stated that digital technologies stimulate interest, 72% reported that they help focus attention, and 65% believed they enhance learning effectiveness. In addition, factors such as content consistency (63%), clarity and visualization (60%), and the creation of a positive learning atmosphere (59%) were also highly rated. Half of the students (50%) indicated that digital technologies help develop thinking skills, while the indicator for reinforcing understanding was 42%, suggesting a need for additional methodological support in this area (Figure 8).

Overall, the results confirm that digital technologies fulfill important functions in teaching the "Nanotechnology" course, such as visualizing learning materials, increasing student engagement, and enhancing interest in the subject.



**Figure 8.** Advantages of the process of teaching the subject "Nanotechnology and Nanomaterials" through digital technology (according to students).

In order to evaluate the impact of using digital technologies on learning outcomes in the subject "Nanotechnology and Nanomaterials", a comparison was made between the results of experimental and control groups. The research focused on four key competencies: understanding nanostructures, spatial thinking skills, the ability to use computational tools, and experimental and analytical thinking.

The experimental group outperformed the control group across all indicators. Specifically, the level of understanding nanostructures was  $9.4 \pm 0.3$  in the experimental group, compared to  $8.6 \pm 0.5$  in the control group, with this difference being statistically significant ( $t = 2.765$ ;  $p = 0.010$ ). For spatial thinking skills, the experimental group scored  $9.1 \pm 0.4$ , while the control group scored  $8.0 \pm 0.6$  ( $t = 3.102$ ;  $p = 0.004$ ). A significant difference was also observed in the ability to use computational tools: experimental group –  $8.9 \pm 0.5$ , control group –  $7.5 \pm 0.5$  ( $t = 3.880$ ;  $p = 0.001$ ). The greatest difference was identified in experimental and analytical thinking: the experimental group scored  $9.6 \pm 0.2$ , while the control group scored  $7.1 \pm 0.9$  ( $t = 5.534$ ;  $p = 0.000$ ) (Table 4).

These results demonstrate that the integration of digital technologies into the learning process significantly enhances students' cognitive, computational, and analytical abilities.

**Table 4.** Comparative indicators of abilities formed through the use of digital technologies in the discipline "Nanotechnology and Nanomaterials"

Group	Indicator			
	Understanding nanostructures	Spatial thinking skills	Ability to use computing tools	Experimental and analytical thinking
Experimental	$9.4 \pm 0.3$	$9.1 \pm 0.4$	$8.9 \pm 0.5$	$9.6 \pm 0.2$
Control	$8.6 \pm 0.5$	$8.0 \pm 0.6$	$7.5 \pm 0.5$	$7.1 \pm 0.9$
t	2.765	3.102	3.880	5.534
p	0.010	0.004	0.001	0.0001

The research findings demonstrated that the use of digital technologies in teaching the subject "Nanotechnology and Nanomaterials" is significantly effective in improving the quality of the educational process. Lessons organized with the help of digital tools not only increased students' interest in the subject but also contributed to their deeper understanding of complex scientific concepts, independent thinking, and the development of laboratory skills.

The digital models, interactive visuals, and multimedia resources used during the learning process enabled information to be presented in a visual and structured manner, thereby strengthening the link between theoretical knowledge and practical experience. Furthermore, digital technologies created a favorable environment for the development of students' creative activity and research skills.

Overall, the study proved that the integration of digital technologies into the learning process contributes to enhancing teaching effectiveness, improving the quality of education, and fostering the development of students' professional competencies.

## **5. Discussion**

### *5.1. The Use of Digital Educational Resources (DERs) in Teaching "Nanotechnology and Nanomaterials"*

The use of digital educational resources (DERs) in teaching the subject "Nanotechnology and Nanomaterials" has become a relevant focus of contemporary educational research. Various scientific works and theoretical frameworks indicate that these methodologies enhance pedagogical effectiveness and motivate students to grasp complex scientific concepts.

### *5.2. Effectiveness and Engagement of Digital Educational Resources*

A major direction of recent studies is the need to develop DERs aimed at increasing student engagement. In their research, Ravik and colleagues emphasize that digital tools should stimulate relevant cognitive processes and adapt to learners' diverse needs [39]. A review conducted by McCall and colleagues showed that digital learning methods are at least as effective as traditional ones, especially in the field of nursing education [40]. Thus, applying similar approaches to teaching nanotechnology can increase learners' interest in the subject and facilitate deeper understanding of scientific concepts.

### *5.3. Integration of Technology and Digital Literacy*

Gaus and colleagues consider digital literacy a key competency for modern graduates, highlighting the importance of effectively integrating digital technologies into the learning process [41]. As digital simulations and modeling are widely used in nanotechnology, developing digital literacy not only equips students to solve current scientific problems but also enables them to master new technological tools. This idea is supported by digital pedagogical programs implemented in various countries, such as the digital technology project in Ukraine [42]. Furthermore, Jobst and colleagues emphasize that teachers' attitudes toward digital technologies directly influence their effective implementation [43]. Educators proficient in using digital tools tend to approach their work with enthusiasm and provide students with engaging and high-quality education.

### *5.4. Methodological Approaches with Digital Resources*

There are several methodological models for teaching nanotechnology using DERs. For example, the interactive toolset developed by Kottegoda and colleagues significantly facilitates students' understanding of nanotechnology concepts and supports experiential learning [44]. In addition, the combination of Project-Based Learning (PBL) and digital platforms allows students to engage in solving real-world problems [19]. This approach develops their critical thinking and collaborative skills, preparing them for future professional environments.

#### *Barriers and Supporting Factors in Digital Education*

Nevertheless, several challenges arise when implementing DERs. Regmi and Jones identified key barriers to the effectiveness of e-learning, including limited access to technical equipment, insufficient teacher training, and a lack of institutional support [45]. To overcome these obstacles, it is necessary to enhance teachers' ability to master technology and integrate it effectively into their lessons [46].

In conclusion, using digital educational resources to teach the subject "Nanotechnology and Nanomaterials" can significantly enhance students' learning experiences. The use of interactive digital tools, development of digital literacy, and implementation of project-based learning all contribute to improving the efficiency of the nanotechnology teaching process. However, to fully realize this potential, attention must be paid to technological infrastructure and teacher preparedness.

## **6. Conclusion**

During the research, the methodological effectiveness of teaching the subject "Nanotechnology and Nanomaterials" through digital educational resources was thoroughly analyzed. Digital technologies and visual models have become essential tools in modern education, helping students develop a scientific worldview and facilitating the understanding of complex theoretical concepts.

The research findings demonstrated that the integration of digital resources into the educational process increases students' interest in the subject and provides a clearer understanding of the link between theory and practice. In particular, 3D models, virtual laboratories, animated simulations, and interactive tasks proved to be effective means of conveying abstract concepts such as nanostructures in a visual and meaningful way. These tools enhanced students' visual perception and increased their cognitive engagement.

The experimental teaching method employed during the lessons, including pedagogical observation, surveys, correlation analysis, and t-test methods, made it possible to precisely determine changes in students' learning processes. During the instruction, students' digital literacy, ability to work independently, level of theoretical understanding, and degree of dependence on the teacher were comparatively analyzed. Results of correlation and factor analyses revealed interrelationships among these indicators.

The structure of the survey proposed in the study was aimed at evaluating students' perception of digital models, mastery of theoretical knowledge, and level of independence. The survey results confirmed that digital technologies have become not just supplementary tools, but key didactic elements in the learning process.

Furthermore, replacing complex, expensive, and difficult-to-demonstrate laboratory equipment with digital models made the educational process more accessible, safe, and time-efficient. This approach offers significant advantages,

especially for regional schools and resource-limited institutions. It was found that digital learning environments play an important role in developing students' logical thinking, critical reasoning, and research skills.

Thus, the study proved that teaching the subject "Nanotechnology and Nanomaterials" using digital technologies is a meaningful, effective, and modern approach.

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