

Developing Professional Competencies Of Physics Teachers In The Context Of Digital Education Transformation: International Experience And Comparative Analysis

Turakhonov Fozil Bobonazarovich

PhD, associate professor, Denov institute of entrepreneurship and pedagogy, Department of general physics and civil engineering, Uzbekistan

Received: 22 December 2025 **Accepted:** 12 January 2026 **Published:** 18 February 2026

ABSTRACT

This article examines the pedagogical and technological foundations of developing professional competencies of physics teachers in the era of global digital transformation. During the study, the experience of developed foreign countries in physics education was comparatively analyzed and optimal models for specialized schools were proposed. The article covers the stages of teachers' transition from ICT literacy to digital pedagogical level.

Keywords: Digital transformation, physics education, professional competence, simulation, virtual laboratory, TPACK model, STEM, comparative analysis.

INTRODUCTION

In the context of global information, physics education requires not only the provision of theoretical knowledge, but also the formation of modeling and research skills in students. In this process, the teacher plays the main "driver" role. However, the imbalance between traditional methods and modern digital capabilities creates the need to raise the professional competence of teachers to a new level.

In the modern world, the competitiveness of countries is directly determined by the degree to which intellectual potential and high technologies are integrated into the educational process. As the President of the Republic of Uzbekistan Shavkat Mirziyoyev noted: "We have set ourselves the priority task of radically reforming the education and upbringing system, raising our children in the spirit of modern knowledge and experience, national and universal values" [1].

Accelerating digital transformation processes, especially in

the teaching of physics, is an integral part of the "Digital Uzbekistan - 2030" strategy [2]. Raising the quality of teaching natural sciences to a new level in the system of specialized schools, developing critical thinking and engineering skills in students directly depends on the level of adaptation of pedagogical personnel to the digital educational environment [3].

Specialized schools (Presidential schools, Al-Khwarizmi schools, etc.) as the "locomotive" of the education system place high demands on the professional competence of teachers. The fundamental nature of physics and its integration with digital modeling require a fundamental rethinking of teacher training in this field.

Although today's specialized schools are equipped with modern digital laboratories and ICT tools, many teachers lack the methodological skills to use these tools for didactic purposes, synchronize virtual experiences with real experiments, and develop students' research competence in a digital environment.

Table 1. Research stage algorithm

Stage	Content
Stage I	Study of theoretical foundations and formulation of the problem.
Stage II	Collect data on international experience (PISA, TALIS studies).
Stage III	Analyze the current situation of physics teachers using the example of Uzbekistan.
Stage IV	Identify shortcomings and develop recommendations for developing competencies.

The purpose of the research is to study international experience in improving the professional competencies of physics teachers in a digital educational environment and to develop a comparative methodological model acceptable for specialized schools.

LITERATURE REVIEW

The issue of transforming teacher competence in a digital learning environment has been a focus of attention for the global pedagogical community over the past decade. A review of the literature shows that research in this area can be divided into three main areas.

The most influential model for analyzing teachers' technological knowledge is the TPACK (Technological Pedagogical Content Knowledge) model developed by P. Mishra and M. Koehler [4]. This model assumes that a physics teacher not only knows about technology, but also determines which digital tool can most effectively explain a physical law (for example, electromagnetic induction).

Also, the DigCompEdu (Digital Competence Framework for Educators), developed by the European Union, divides teachers' digital skills into 6 levels (from A1 to C2) [5]. It is an important source for defining the qualification requirements for teachers in specialized schools.

Since physics is an experimental science, the role of virtual laboratories has been widely discussed in the literature. Studies within the PhET project, founded by C. Wieman and his team, have shown that interactive simulations can

be more effective than real laboratories in helping students create a visual model of physical processes [6].

R. Trumper emphasizes in his work that the physics teacher should play the role of a "coordinator" when using computer models in the lesson, and that this is the basis of the "inquiry-based learning" methodology [7].

Among Uzbek scientists, U.Sh. Begimkulov developed a pedagogical theory of informatization of education [8], while in the field of physics teaching methodology, M. Kurbonov and N.Sh. Turdiyev studied the issues of developing students' logical thinking through digital tools in specialized schools [9].

The issue of developing the professional competencies of physics teachers in the context of digital education transformation is being widely studied in the international scientific community within the framework of the conceptual framework of "Technology-Enhanced Learning" (TEL).

International research suggests that teacher competence is moving from traditional ICT literacy to "Digital Pedagogical Content Knowledge" (DPCK). According to a meta-analysis by H. Crompton et al. (2023), digital competence for physics teachers refers not only to the use of equipment, but also to the ability to choose technologies to manage cognitive load [10].

In recent years, the number of studies on the effectiveness of artificial intelligence (AI) and virtual reality (VR) in physics teaching has increased significantly. S. Chen et al.

(2024) in their study proved the role of virtual laboratories in creating conceptual change in specialized education, finding that virtual experiments are 35% more effective in understanding microworld phenomena (quantum physics, atomic structure) than real experiments [11].

The SAMR model (Substitution, Augmentation, Modification, Redefinition) proposed by G. Puentedura is considered the main criterion for evaluating the performance of physics teachers [12]. This model measures the teacher's competence in using technology not simply as a substitute for textbooks, but as a tool that fundamentally changes the educational process.

Comparative studies published in Scopus (e.g., M. Mullis, 2023) based on PISA and TIMSS results show that the achievements of physics teachers in countries such as South Korea and Estonia are related to their level of "Adaptive Expertise." That is, teachers in these countries are constantly transforming their teaching methods in response to changes in the digital ecosystem [13].

F.B. Turakhanov's work is mainly aimed at forming the professional competence of future physics teachers using information and communication technologies, modernizing teaching processes, and implementing distance learning technologies [14].

The analysis of the literature shows that in the context of digital transformation, the professional competence of a physics teacher is not just a set of technical skills, but a complex system of interconnected technological, pedagogical and scientific content. International experience proves the high efficiency of the digital environment in visualization and modeling, serving as a methodological basis for adapting it to educational standards.

METHODOLOGY

The research methodology is based on the international TPACK (Technological Pedagogical Content Knowledge) and DigCompEdu models of computer competences of physics teachers. The study was conducted using indicators of the level of improvement of the specific features of physics education in Uzbekistan and foreign countries - virtual laboratories, dynamic modeling and digital measurement. Data collection was carried out through questionnaires among more than 20 physics teachers as a result of direct observation of lesson processes, which

clearly illustrates the integration of theoretical knowledge with practical application.

The obtained statistical data were processed using descriptive analysis and SWOT-matrix, and the system of obstacles and growth points in the professional development of teachers were classified. The methodological basis of the study is the comparison of the methodology for the development of systematic production, ICT literacy, visualization of complex physical experiments in a computational environment and cognitive activity of students. A professional model of teachers adapted to computer transformations for the national education system based on international standards was formed and recommendations were developed.

The article was based on a systematic approach and a competency-based approach. In the context of digital transformation, the teacher's work was seen not only as imparting knowledge, but also as a synthesis of technological and methodological skills.

Technological Knowledge (TK). Starting with the top circle, Technological Knowledge (TK) refers to a teacher's understanding of technology and how to use it. This includes knowledge of hardware, software, and the ability to troubleshoot common technical problems. In the context of TPACK, it's not just about knowing how to use technology, but also about thinking critically about its potential and limitations in an educational setting.

Content Knowledge (CK). To the right is Content Knowledge (CK), which is the teacher's knowledge of the subject matter they teach. This is the "what" of teaching. It includes understanding the facts, concepts, theories, and procedures of a given subject, as well as knowing how knowledge is created and organized within that field.

Pedagogical Knowledge (PK). On the left is Pedagogical Knowledge (PK), which is the teacher's deep knowledge about the processes and practices of teaching and learning. This includes understanding different teaching methods, classroom management strategies, assessment techniques, and how students learn. This is the "how" of teaching.

Technological Content Knowledge (TCK). Where Technology and Content overlap, we find Technological Content Knowledge (TCK). TCK is the understanding of how technology and content influence and constrain one another. It involves knowing how to use technology to

represent and communicate content in new ways, such as using simulations to teach scientific concepts or digital mapping tools for geography.

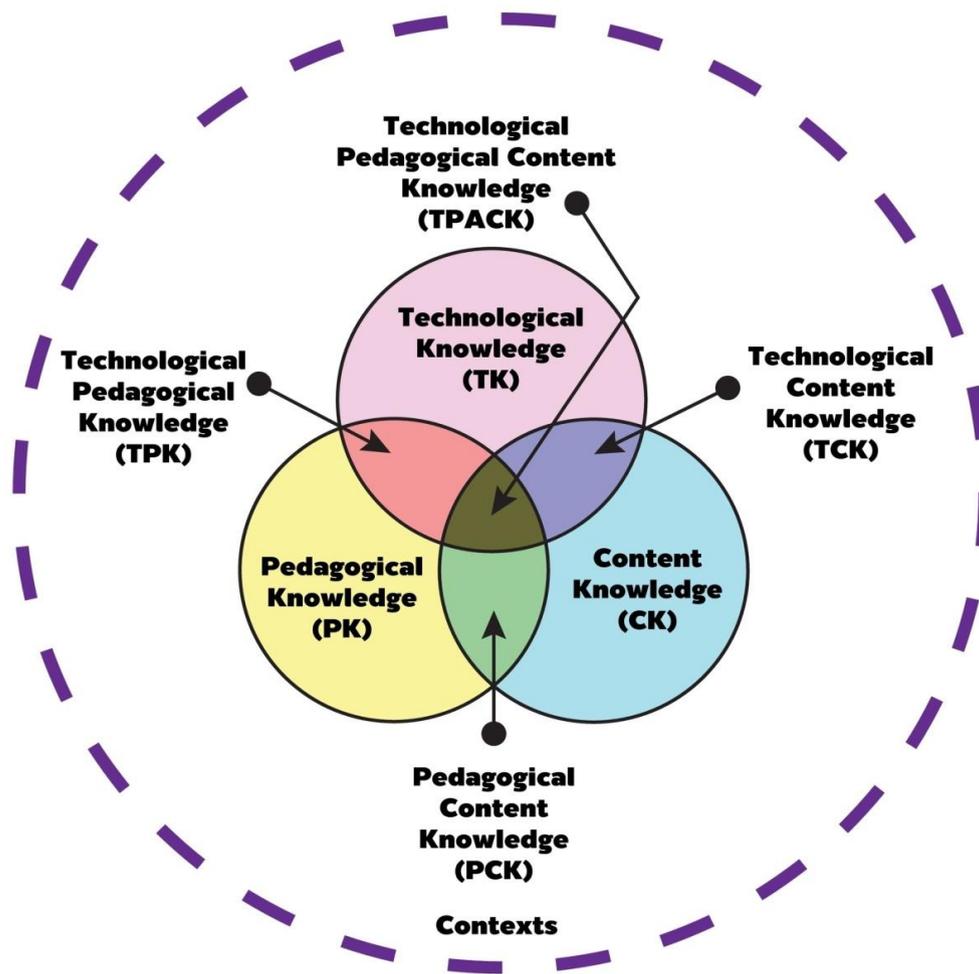
Pedagogical Content Knowledge (PCK). The intersection of Pedagogy and Content creates Pedagogical Content Knowledge (PCK). This is the specialized knowledge of how to teach a particular subject. It includes knowing the best ways to explain difficult concepts, anticipate student misconceptions, and use appropriate examples and analogies to make the subject matter understandable and engaging.

Technological Pedagogical Knowledge (TPK). The overlap between Technology and Pedagogy results in Technological Pedagogical Knowledge (TPK). TPK is the understanding of how teaching and learning can change

when particular technologies are used. It involves knowing how to use technology to support different pedagogical approaches, such as using online discussion forums to facilitate collaborative learning or educational apps for individualized instruction.

Technological Pedagogical Content Knowledge (TPACK). At the heart of the diagram, where all three circles intersect, is Technological Pedagogical Content Knowledge (TPACK). This is the ultimate goal, representing the synthesis of all three knowledge types. A teacher with strong TPACK can select and use technology in a way that is both pedagogically sound and appropriate for the specific content being taught, leading to effective and transformative learning experiences.

Technological Pedagogical Content Knowledge (TPACK)



RESULTS

The analysis shows that the "technological gap" in the computer competences of physics teachers is mainly evident at the stages of modeling complex processes and data analysis. While in international experience, teachers have focused more on introducing a student-centered

digital environment, in national experience it remains at the level of demonstration based on laboratory tests. The low indicators in artificial intelligence and adaptive learning systems (1.5 points) give a high level to targeted qualification courses in this area.

Level of qualification and competence of physics teachers (comparative analysis)

Table 2. Uzbek and international averages (on a 5-point scale according to DigCompEdu criteria).

Competency areas	International average (Top-10)	Uzbekistan (Research Result)	Difference (%)
Uploading from virtual simulations (PhET, Algodoo)	4.8	3.2	-33%
Receiving digital lesson plans (TPACK)	4.5	3.5	-22%
Data processing and analysis	4.2	2.8	-33%
Integrating artificial intelligence (AI) action into the lesson	3.9	1.5	-61%

International experience:

In foreign countries, the digitalization of physics education has focused not only on providing technology, but also on "Digital Pedagogy".

Finland: "Phenomenon-based learning" has been introduced in physics classes. In this, students learn real physics outside of the laboratory to develop sensors and data collectors.

Singapore: The Smart Nation program places great emphasis on computer modeling in physics education. Instead of memorizing complex formulas, students build

models of physical processes in special programs.

Estonia: Physics is integrated with programming and robotics through the "ProgeTiger" program. This helps to understand the laws of physics from a practical (engineering) perspective.

A comparative analysis of progress shows that the competence of physics teachers in the countries is not limited to the loading of production resources, but is lost in supporting a STEM-integrated environment (Instructional Design). In industry, international experience, teachers work more effectively with Mobile Data Logging technology in the process of integrating real and virtual laboratory data during the lesson.

Table 3. Digital transformation gap between physics teacher competencies and those in the education system.

Criteria	Finland, Singapore, Estonia	Uzbekistan (Current status and processes)
The teacher's competency	is well-versed in the TPACK model; it seamlessly links technology with science methodology.	IT literacy is increasing, but work needs to be done on integrating technology into physics methodology (TFB).
Lab work	Virtual (VR/AR) and remotely controlled real-world labs.	Mainly traditional labs; similar updates to PhET and similar simulations.
STEM integration	Physics, mathematics, and engineering are taught in one subject.	STEM centers are being established, and new lessons are being created on interdisciplinary connections.
Assessment (Feedback)	Artificial intelligence - based analytical systems track the dynamics of a student's mastery of physical characteristics.	There are electronic diaries and testing systems, but producing a laboratory view of the student is still traditional.

The main transformation process of the Uzbek study is at the stage of visualizing theoretical materials, which requires a new level of methodological support to transfer the trajectory of teachers' professional management from the level of "consumer" to the level of "digital content creator".

CONCLUSION

Digital transformation, but also the development of professional competence of physical education teachers, requires physical technical literacy, the integral integration of technology, pedagogy and science content based on the TPACK model. International comparative studies show that in educational systems that have achieved effective results, the teacher has risen from a consumer of finished products to a producer and virtual creative designer. To accelerate the process of transition to software in Uzbekistan, teachers should conduct artificial laboratory work in the lesson process, clarify the transfer of virtual laboratories and data processing programs, and should be a firm direction of the pedagogical strategy.

It is necessary to introduce a special "Digital Mentoring"

for physics teachers, and enrich qualification programs with subject-specific digital modules. Integrating simulations such as PhET and Algodoo into national curricula, training teachers to effectively use open educational resources (OER), and using hybrid (real and virtual) laboratory methods in lessons will take the quality of education to a new level.

REFERENCES

1. Mirziyoyev, Sh.M. (2020). New Uzbekistan Strategy. – Tashkent: “Uzbekistan” Publishing House.
2. Decree of the President of the Republic of Uzbekistan. (2020). Decree No. PF-6079 "On approval of the strategy "Digital Uzbekistan - 2030" and measures for its effective implementation."
3. UNESCO. (2018). ICT Competency Framework for Teachers. Version 3.0.
4. Mishra, P., & Koehler, M. J. (2006). Technological Pedagogical Content Knowledge: A Framework for Teacher Knowledge. Teachers College Record, 108(6), 1017-1054.

5. Redecker, C. (2017). European Framework for the Digital Competence of Educators: DigCompEdu. Joint Research Center (JRC).
6. Wieman, C. E., et al. (2008). Teaching Physics Using PhET Simulations. *Physics Teacher*, 46(7).
7. Trumper, R. (2003). The physics laboratory: A historical overview and future perspectives. *Science & Education*.
8. Begimkulov, U.Sh. (2007). Theory and practice of organizing and managing informatization of pedagogical educational processes. *Ped. fan. doc. diss.*
9. Turdiyev, N. Sh. (2021). Modern methodology of physics teaching. Tashkent.
10. Crompton, H., & Burke, D. (2023). Artificial intelligence in higher education: The state of the field. *Computers and Education: Artificial Intelligence (Scopus Q1)*.
11. Chen, S., et al. (2024). The effectiveness of virtual reality in physics education: A meta-analysis. *Physical Review Physics Education Research (Scopus Q1)*.
12. Hamilton, E. R., Rosenberg, J. M., & Akcaoglu, M. (2021). The SAMR Model as a Framework for Evaluating Teachers' Digital Competence. *Journal of Research on Technology in Education*.
13. Mullis, IVS, et al. (2023). TIMSS 2023 Encyclopedia: Education Policy and Curriculum in Mathematics and Science. International Association for the Evaluation of Educational Achievement (IEA).
14. Turakhonov F.B, Kurbonov M. Analysis of software with the opportunity to model physical processes in specialized schools // *American journal of social and humanitarian research // AJSHR*, Vol. 2, No. 10, desember 2021 – pp. 313 - 321.