

Advancing Science and Technology-Based Distance Learning through Artificial Intelligence, Interactive Navigation, and Cluster-Based Learning for Sustainable and Inclusive Education

Gavhar Saparovna Abdullayeva^{1*}, Zebunniso Bakhtiyor Atamirzayeva¹, Abdimumin Ibragimovich Rasulov², Dilshoda Chorshanbievna Mamatraimova³, Muhammadrasul Abdimumin Ibragimov², Hemlata Gaikwad⁴, Gulruh Shoikrom Buvorayeva⁵, Abduvali Abdullayevich Burxanov⁵, Odina Kobil Ozodova², Prayoga Bestari^{6**}

¹Chirchik State Pedagogical University, Chirchik, Uzbekistan

²Uzbekistan National Pedagogical University, Tashkent, Uzbekistan

³Termez State Pedagogical Institute, Termez, Uzbekistan

⁴Symbiosis Institute of Management Studies, Symbiosis International (Deemed University), MH, India

⁵Tashkent Institute of Irrigation and Agricultural Mechanization Engineers National Research University, Tashkent, Uzbekistan

⁶Universitas Pendidikan Indonesia, Bandung, Indonesia

gavhar@inbox.ru; yogabestari@upi.edu

Abstract—This study aims to advance science and technology-based distance learning by integrating artificial intelligence (AI), interactive navigation, cluster-based learning, and inclusive educational approaches within a sustainable education framework. A mixed-methods approach combining pedagogical experimentation, system-based implementation, and evaluation of technology-supported learning activities was applied. The main pedagogical experiment involved 444 university students in higher education environments associated with teacher preparation, with experimental and control groups used to compare ICT competence development and learning performance. Additional learning-interaction data from an AI-supported interactive distance-learning platform were adopted from a previous study to extend the evaluation of student engagement, theoretical learning, practical activities, and assessment processes. The data were analysed using descriptive and comparative approaches, including comparison of competence-level distributions, participation frequencies, response submissions, assessment completion, and practical learning activities between the experimental and control groups. The findings demonstrate improvements in ICT competence, professional readiness, learning autonomy, and the integration of theoretical and practical learning. AI-enabled feedback and structured navigation also enable adaptive learning pathways and more responsive assessment processes. The combination of educational clusters, smart technologies, interactive navigation, and inclusive pedagogical methods offers a holistic view of technology-enhanced education. The proposed framework supports the Sustainable Development Goals (SDGs), particularly on education, and contributes to the development of inclusive, equitable, and sustainable digital education.

Keywords—artificial intelligence; cluster-based learning; distance learning; ICT competence; inclusive education; interactive navigation; sustainable development goals.

I. INTRODUCTION

The rapid development of information and communication technology (ICT) has made distance learning an important component of modern higher education. The integration of science and technology into digital learning environments offers opportunities to enhance accessibility, flexibility, and student-centered learning, while supporting theoretical understanding and practical skill development (Jadhav et al., 2022; Ibrahim et al., 2025; Ayinde et al., 2026; Sanni, 2023). These developments are particularly relevant to teacher education. This is because future teachers require sufficient ICT competence to design, implement, and evaluate technology-supported learning activities.

Artificial intelligence (AI) is making distance learning even better. AI offers adaptive guidance, automated assessment, real-time feedback, and customized learning paths. In recent years, the higher education sector has seen a shift of AI-powered information systems from standalone automated systems to integrated learning, information management, decision-making, and institutional systems (Karin et al., 2025). AI-assisted approaches are also increasingly being explored for structured analytical and interpretive tasks, further highlighting the broader potential of AI in supporting intelligent decision-making (Nandiyanto, 2026). However, there are some disadvantages of online learning, such as lack of social interaction, technological complexity, communication problems with teachers, limitations in acquiring practical skills, and issues regarding the effectiveness of assessment (Pikhart et al.,

¹Gavhar Saparovna Abdullayeva, Prayoga Bestari⁵

¹Chirchik State Pedagogical University, Chirchik, Uzbekistan

⁵Universitas Pendidikan Indonesia, Bandung, Indonesia

¹gavhar@inbox.ru

⁵yogabestari@upi.edu

2023; Zaki, 2022; Stecuła and Wolniak, 2022; Talebian et al., 2014; Yuhanna et al., 2020). These limitations suggest that effective distance learning is much more than access to digital resources. As part of a learning process, students need to be taken through theory, assessment, feedback, and practical activities in a systematic and integrated manner. The effectiveness of technology-enhanced learning also depends on the teachers' ability to use ICT in a diverse educational setting. This is especially important in inclusive education, where pedagogical approaches need to be adapted to different learning needs and functional conditions. Cluster-based educational models that unite higher education institutions, schools, and supporting organizations to work together, share resources, and implement practical solutions can help in this process (Khimmatiev et al., 2025). The integration of AI, assistive technologies, and adaptive systems can further facilitate flexible learning and support technology-based educational decisions according to different learner needs (Abdullayeva, 2024; Mulyana et al., 2025).

Technology-enhanced education is also closely related to sustainable development. Digital learning can contribute to the Sustainable Development Goals (SDGs), particularly SDG 4, by supporting inclusive and equitable access to quality education. Community-based AI and digital-literacy frameworks can further strengthen technological participation, digital inclusion, and sustainable educational development, particularly among underserved groups (Karmaker, 2027). However, sustainable digital transformation requires the integration of technological innovation with teacher competence, pedagogical accessibility, institutional collaboration, and effective learning processes. Therefore, AI, ICT competence, interactive learning, inclusive education, and institutional support should be considered interconnected components of a sustainable educational system.

Previous studies have examined ICT integration, online learning, AI-supported education, inclusive education, adaptive technologies, and cluster-based teacher training (Karin et al., 2025; Pikhart et al., 2023; Zaki, 2022; Stecuła and Wolniak, 2022; Talebian et al., 2014; Yuhanna et al., 2020; Khimmatiev et al., 2025; Abdullayeva, 2024; Mulyana et al., 2025; Karmaker, 2027). Usually, the components have been studied in isolation. There is not much research on integrating AI-assisted interactive navigation, ICT skills improvement, cluster-based learning, theoretical and practical activities, and inclusive education in a science and technology-focused distance learning environment. It is especially important to fill this gap for future teachers who are expected to use digital technologies efficiently and to respond to the needs of diverse learners.

The study focuses on fostering science and technology-based distance learning via AI, interactive navigation, cluster-based learning, development of ICT competence, and principles of inclusive education within an SDGs-oriented framework. The novelty lies in the integration of a cluster-based approach to the development of ICT competence of future teachers with an AI-supported interactive learning environment, which systematically connects theoretical

learning, practical activities, assessment, and feedback. This integrated approach provides a framework for the development of adaptive, inclusive, and sustainable technology-enhanced learning.

II. LITERATURE REVIEW

A. ICT Competence and Technology-Enhanced Teacher Education

The use of digital technologies in teaching, assessment, communication and learning management is growing, and so ICT competence is a basic requirement for teachers of the future. ICT integration can be effective for teaching and learning, especially where digital resources are associated with curriculum requirements and practical activities in the classroom (Jadhav et al., 2022; Ibrahim et al., 2025; Ayinde et al., 2026; Sanni, 2023). ICT competence in teacher education means not only technical competence, but also the ability to select suitable technologies, organize digital learning activities, and support students with different learning needs. Developing ICT competence is particularly important for inclusive education. Inclusive learning environments need flexible pedagogical approaches that accommodate different abilities, accessibility needs, and learning conditions. Assistive technologies and adaptive digital systems can help meet these requirements by offering alternative access to learning materials and more individualized forms of interaction (Abdullayeva, 2024). The successful use of such technologies is very much related to teacher readiness and the linking of technological competence with pedagogical practice.

B. AI and Adaptive Learning

AI is an important element of technology-enhanced education as it offers adaptive learning, intelligent feedback, automated assessment, and personalized educational pathways. AI-based systems analyze students' answers and provide guidance to them as they move through their learning. Better decision-making and trust in applications in the educational context can also arise from transparent AI approaches (Mulyana et al., 2025). AI-based information systems in higher education are evolving from isolated automated applications to integrated systems that facilitate learning, information management, decision-making, and institutional processes. (Karin et al., 2025). This wider development further reinforces the potential for AI to support adaptive and responsive educational environments. AI-assisted approaches are also increasingly being considered for structured analytical and interpretive work. For example, AI-assisted interpretation has been proposed for complex material-characterization data, demonstrating the potential for intelligent systems to support systematic analysis and guided decision-making (Nandiyanto, 2026). But AI-based education should not be deployed without pedagogical structures. Its effectiveness depends on the quality of the connection between intelligent systems and learning objectives, instructional design, assessment processes, and professional competence of teachers.

C. Distance Learning and Interactive Navigation

Distance learning allows for more access to educational resources and flexibility, but still carries a number of limitations. Less interaction between people, Difficulties in maintaining communication with teachers, Problems with technology, Lack of practical skills development, Limitations in online assessment (Pikhart et al., 2023; Zaki, 2022; Stecula and Wolniak, 2022; Talebian et al., 2014; Yuhanna et al., 2020). These issues are particularly important when students have to find their way alone between theoretical materials, practical tasks, and evaluation activities. Such limitations can be overcome by providing interactive navigation through learning activities in the form of structured pathways. A guided learning system can lead students from theoretical materials to assessment and practical activities and give immediate feedback at different stages. This type of navigation is particularly useful for students who experience difficulties in identifying the appropriate sequence of learning activities. The integration of interactive navigation with AI offers a mechanism for creating more adaptive and organized distance-learning environments.

D. Cluster-Based Learning and Inclusive Education

Cluster-based educational models serve as a mode of organization to link universities, schools, training institutions, and other educational stakeholders. Such models facilitate cooperation, exchange of knowledge and resources, and pragmatic realization of educational innovations (Khimmatiev et al., 2025). Cluster-based learning in teacher education can strengthen the link between theoretical preparation and professional practice (Usarov et al., 2025). The cluster approach is also relevant for inclusive education, as inclusive learning requires coordination between teachers, educational institutions, specialists, and technology providers. Cluster-based models can support assistive technologies, adaptive learning environments and ICT-based instructional practices through the integration of pedagogical, technological and organizational components, cluster-based models can support assistive technologies, adaptive learning environments, and ICT-based instructional practices. This structure can improve the professional readiness of future teachers by providing wider opportunities for practical interaction and collaborative problem-solving.

E. Sustainable Education and the SDGs

Technology-enhanced education has been strongly correlated with sustainable educational development. Inclusive, equitable and quality education are at the heart of the SDGs, notably SDG 4. The achievement of these goals can be aided by digital technologies, which can increase access to learning resources, improve the flexibility of education, and address diverse educational needs. But sustainable digital education is more than simply applying technology. This requires institutional cooperation, the competence of teachers, accessibility, and pedagogical efficiency. AI-supported education can also help support

sustainability beyond formal institutional contexts. Community-based AI frameworks have been proposed to enhance online literacy, cybersecurity awareness, technological participation, and sustainable community development, especially for underserved populations (Karmaker, 2027). This view highlights that sustainable digital education should be a mix of technological innovation and accessibility, inclusion, and community empowerment. The integration of AI, ICT competence, inclusive education, and cluster-based learning can therefore contribute to sustainable education by connecting technological innovation with institutional and pedagogical development. Such integration supports learning environments that are adaptive, accessible, and responsive to changing educational needs.

F. Research Gap

Previous studies have addressed ICT integration, AI-supported learning, online education, inclusive education, adaptive technologies, cluster-based teacher training, and sustainable digital education from different perspectives (Karin et al., 2025; Pikhart et al., 2023; Zaki, 2022; Stecula and Wolniak, 2022; Talebian et al., 2014; Yuhanna et al., 2020; Khimmatiev et al., 2025; Abdullayeva, 2024; Mulyana et al., 2025; Karmaker, 2027). However, these components are generally examined independently. Limited attention has been given to the development of a unified framework that integrates ICT competence development, AI-supported interactive navigation, cluster-based learning, inclusive education, theoretical and practical learning, and sustainability within a single distance-learning environment.

As shown in Table I, an integrated approach remains necessary to connect technological, pedagogical, institutional, inclusive, and sustainability dimensions. Therefore, the present study combines AI-supported interactive navigation with ICT competence development, cluster-based learning, and inclusive education within a science and technology-based distance-learning framework.

III. METHODOLOGY

A. Research Design and Participants

This study employed a mixed-methods approach combining a pedagogical experiment, system-based analysis, and evaluation of technology-supported learning activities. The main pedagogical experiment involved 444 university students in higher education environments associated with teacher preparation and examined the development of ICT competence through cluster-based learning, AI, and adaptive technologies. Experimental and control groups were used to compare changes in competence development and learning performance.

The research was implemented within higher education environments associated with teacher preparation. The experimental activities focused on the integration of ICT-based learning, inclusive educational practices, cluster-supported learning, and intelligent technologies. The research stages included identification of educational

requirements, implementation of the pedagogical model, experimental application, evaluation of ICT competence, and comparative analysis of learning outcomes.

The available source data specify the sample size and experimental/control-group design but do not report the exact participant-selection technique. Therefore, no unsupported sampling method was assigned in the present study.

B. Research Procedure

Figure 1 presents the stages and algorithmic flow of the pedagogical experiment. The procedure consisted of sequential activities beginning with the identification of educational and technological requirements, followed by the implementation of ICT-supported learning activities and evaluation of student competence. The experimental process incorporated cluster-based interaction, adaptive technologies, and AI-supported educational tools.

The organizational structure of the learning process is presented in Figure 2. The Pedagogical Education Innovation Cluster is an educational environment of integration of higher education institutions, schools, educational organizations and other supporting units. Such a structure enables collaboration, resource sharing, practical training, and implementation of technology-supported inclusive education.

Beyond the cluster-based pedagogical model, an AI-powered interactive distance-learning system was incorporated into the analytical framework. The structure of the interactive navigation system is shown in Figure 3. The system provides a structured navigation mechanism to guide students through knowledge acquisition, theoretical activities, assessment, and practical skill development.

C. Student Learning Outcome

The integrated learning framework was structured around four main components: ICT competence development, cluster-based institutional interaction, AI-supported learning, and inclusive adaptive technologies. The development of ICT competence was focused on the ability of future teachers to identify technological tasks, select the appropriate resources, make adaptive decisions, and use digital resources to solve professional educational problems. The cluster-based component connected theory with practice in educational environments. AI-supported tools provided adaptive guidance, feedback, and evaluation, while assistive and adaptive technologies supported the implementation of inclusive educational practices. Interactive navigation further organized movement between theoretical learning, assessment, and practical activities. Table II summarizes the major methodological components and their corresponding evaluation focus.

TABLE I
SUMMARY OF PREVIOUS RESEARCH AREAS AND IDENTIFIED RESEARCH GAPS.

Research area	Main contribution	Limitation identified	Gap addressed in this study
ICT integration in education	Improves digital teaching and learning practices	Often emphasizes technology use rather than integrated competence development	Integration of ICT competence with AI, inclusion, and cluster-based learning
AI-supported education	Enables adaptive learning, intelligent feedback, and automated assessment	Often implemented as an isolated technological component	Integration of AI with structured learning pathways, teacher competence, and institutional support
Distance learning	Improves flexibility and access	Limited interaction, practical activities, navigation, and assessment	Interactive navigation connecting theory, practice, assessment, and feedback
Inclusive education	Supports diverse learner needs	Requires stronger technological and pedagogical integration	Integration of adaptive technologies with future teacher preparation
Cluster-based learning	Strengthens institutional collaboration and practical interaction	Limited integration with AI-supported distance learning	Combination of cluster structures with intelligent and interactive learning
Sustainable education	Promotes inclusive and equitable education	Frequently addressed at policy or conceptual levels	Operational integration of technology, pedagogy, inclusion, community participation, and SDGs

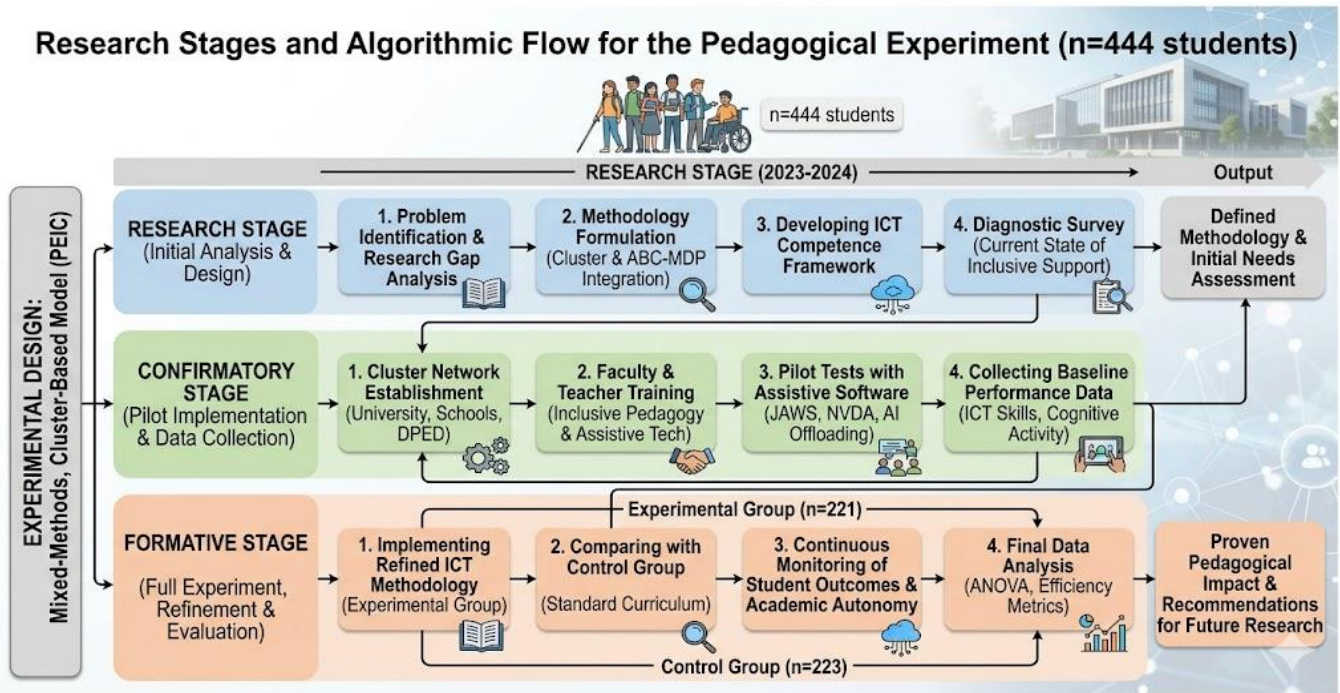


Fig. 1. Research stages and algorithmic flow for the pedagogical experiment.

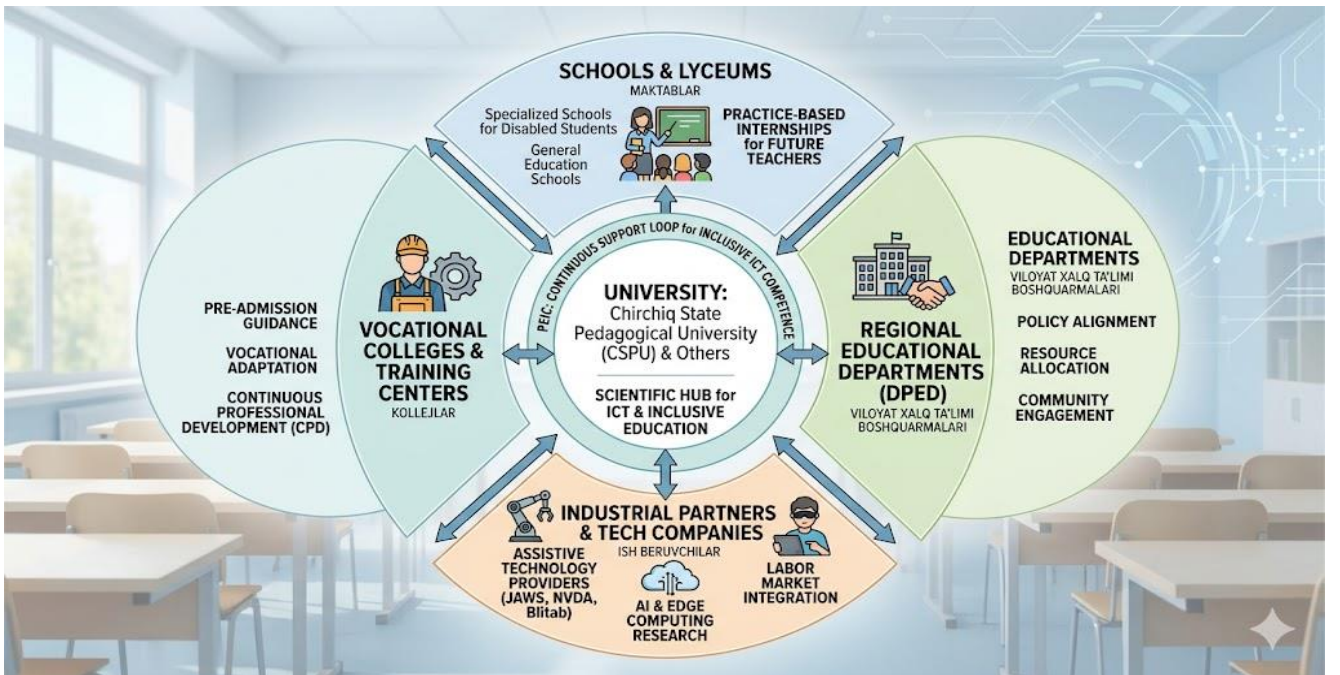


Fig. 2. Organizational mechanism of the Pedagogical Education Innovation Cluster (PEIC).

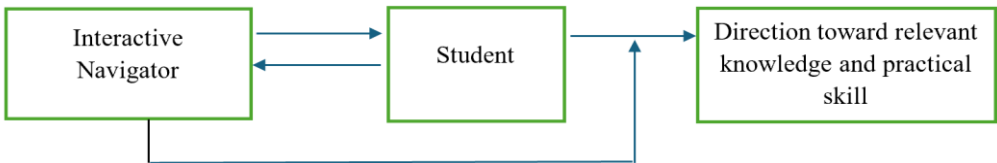


Fig. 3. Schematic representation of the AI-supported interactive navigation system adopted from Ref. (Samiyeva et al., n.d.).

TABLE II
RESEARCH COMPONENTS AND EVALUATION FOCUS

Component	Implementation	Evaluation focus
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ICT competence development	ICT-based pedagogical activities	Competence level and professional readiness
Cluster-based learning	Collaboration among educational institutions	Integration of theory and practice
AI	Adaptive guidance and intelligent evaluation	Learning responsiveness and feedback
Interactive navigation	Structured theoretical and practical learning pathways	Student interaction and activity completion
Inclusive technologies	Assistive and adaptive learning tools	Responsiveness to diverse educational needs
Sustainable education	Integration of technological and pedagogical approaches	Contribution to inclusive and quality education

D. Data Collection

Primary data were collected through performance assessment, observational analysis, pedagogical experimentation, and system-based evaluation. ICT competence was evaluated according to different levels of development, enabling comparison between the experimental and control groups. Additional learning-interaction data were adopted from Samiyeva et al. (n.d.) and included student responses to theoretical questions, number of theoretical responses submitted and assessed, practical assignment submissions, assessment completion, and instructor feedback. The adopted dataset was used to examine how interactive navigation and AI-supported evaluation complemented the cluster-based ICT competence framework.

E. Data Analysis

The analysis consisted of descriptive and comparative evaluation of the experimental and control groups. Changes in ICT competence were examined by comparing the proportions of students classified at high, medium, and lower levels before and after implementation of the pedagogical approach. The experimental-group results were also compared with the control-group results at the end of the intervention. For the adopted distance-learning dataset, participation, response submission, assessment completion, and practical activity indicators were compared between experimental and control groups. Percentage distributions and frequencies were used to characterize differences in student participation and learning activity. The analysis therefore considered two complementary dimensions: ICT competence development and interaction within an AI-supported distance-learning environment. This combination enabled evaluation of both pedagogical competence and technology-mediated learning activity within the proposed framework.

IV. RESULTS AND DISCUSSION

A. ICT Competence Framework for Inclusive Education

The implementation of the proposed framework indicates that ICT competence in inclusive education requires the integration of technological, pedagogical, and adaptive capabilities (Jadhav et al., 2022; Ibrahim et al., 2025; Ayinde

et al., 2026; Sanni, 2023; Khimmataliev et al., 2025; Abdullayeva, 2024; Mulyana et al., 2025). As illustrated in Figs. 1 and 2, competence development is supported not only through individual learning activities but also through interaction among educational institutions within the Pedagogical Education Innovation Cluster. Cluster-based education can strengthen ICT competence by connecting theoretical preparation with practical implementation and collaborative learning environments (Khimmtaliev et al., 2025).

Table III presents the core requirements used to characterize ICT competence within an inclusive educational environment. Task identification represents the ability to recognize different technological requirements, whereas resource mapping concerns the availability and allocation of computational resources for assistive technologies. Adaptive decisions emphasize responsiveness to students' functional limitations, while creative criteria reflect the ability to evaluate model adequacy and apply mathematical software to professional problems.

TABLE III
CORE REQUIREMENTS FOR THE INCLUSIVE ICT COMPETENCE FRAMEWORK.

Code	Parameter	Success indicators
RE1	Task Identification	Ability to identify task types (telemetry, streaming, real-time) for inclusive classrooms
RE2	Resource Mapping	Measuring availability of CPU and memory resources from IoT devices and edge servers for assistive technologies
RE3	Adaptive Decisions	Producing ICT-based decisions based on the student's specific functional limitations
RE4	Creative Criteria	Ability to assess model adequacy and apply mathematical software for modeling professional issues

B. Development of ICT Competence

The pedagogical experiment demonstrated measurable changes in ICT competence after implementation of the cluster-based and technology-supported approach. The results were analysed descriptively and comparatively by examining changes in the proportions of students at high, medium, and lower competence levels and by comparing the final experimental-group distribution with that of the control group. The results are presented in Table IV.

TABLE IV
COMPARATIVE RESULTS OF PEDAGOGICAL EXPERIMENTAL WORK.

Level of development	Experimental group (Start, %)	Experimental group (End, %)	Control group (End, %)
High	22.7	35.7	23.3
Medium	40.2	46.2	39.9
Lower	37.1	18.1	36.8

As shown in Table IV, the proportion of students at the high competence level increased from 22.7% to 35.7%, representing an increase of 13.0 percentage points. The medium level increased from 40.2% to 46.2%, whereas the lower competence level decreased substantially from 37.1% to 18.1%. At the end of the experiment, the control group

contained 23.3% of students at the high level, 39.9% at the medium level, and 36.8% at the lower level.

The comparative distribution shows that the experimental group had a higher proportion of students at the high competence level (35.7 versus 23.3%) and a substantially lower proportion at the lower competence level (18.1 versus 36.8%) than the control group at the end of the intervention. These descriptive differences indicate a shift from lower toward medium and high ICT competence in the experimental group.

The observed pattern supports the relevance of connecting digital competence development with pedagogical practice and institutional collaboration. Cluster-based education provides opportunities to connect theoretical knowledge with practical implementation and interaction among educational institutions (Khimataliev et al., 2025). AI-supported and adaptive systems can additionally provide mechanisms for flexible educational decision-making (Karin et al., 2025; Mulyana et al., 2025). These technological capabilities are particularly relevant to inclusive education, where teachers must respond to diverse learner requirements (Abdullayeva, 2024).

C. AI-Supported Interactive Navigation

Figure 3 presents the navigation structure through which students progress from knowledge acquisition toward theoretical and practical learning activities. Students enter the learning process through knowledge acquisition and subsequently move toward theoretical knowledge or practical skill development. Structured navigation is relevant to distance learning because students may experience uncertainty when moving among learning materials, assessments, and practical activities (Pikhart et al., 2023; Zaki, 2022; Stecuła and Wolniak, 2022; Talebian et al., 2014; Yuhanna et al., 2020). Previous studies have also identified limitations related to interaction, communication, practical skill acquisition, and assessment in online learning environments (Pikhart et al., 2023; Zaki, 2022; Stecuła and Wolniak, 2022; Talebian et al., 2014; Yuhanna et al., 2020).

Figure 4 presents the platform interface integrating independent work, theoretical activities, practical components, and assessment processes.

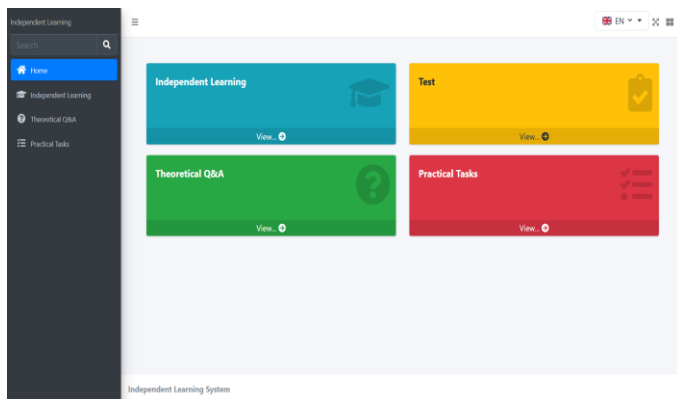


Fig. 4. Platform interface displaying integrated learning elements, including student activities and assessments, adopted from Ref. (Samiyeva et al., n.d.).

The organization shown in Figure 4 demonstrates how theoretical learning, independent activity, and assessment can be connected within a unified digital environment. Rather than presenting these activities as isolated components, interactive navigation provides a defined pathway through the learning process. This structure addresses several organizational challenges reported for online learning (Pikhart et al., 2023; Zaki, 2022; Stecuła and Wolniak, 2022; Talebian et al., 2014; Yuhanna et al., 2020).

D. Theoretical Learning, Assessment, and AI Feedback

The integration of response submission and AI-generated evaluation establishes a direct connection between student activity and feedback. AI-driven information systems are increasingly used in higher education to support learning, information processing, and decision-making (Karin et al., 2025). Transparent AI approaches can also improve the interpretability of automated decisions (Mulyana et al., 2025). The increasing use of AI-assisted approaches for structured analytical and interpretive tasks further illustrates the potential of intelligent systems to support systematic evaluation (Nandiyanto, 2026).

E. Practical Skill Development and Learning Performance

Table V presents the quantitative learning outcomes associated with the interactive distance-learning system. All numerical data presented in Table V were adopted from Ref. (Samiyeva et al., n.d.) and were analysed using frequencies and percentage distributions to compare participation, response submission, assessment completion, and practical activities between the experimental and control groups. All 44 students (100%) in the experimental group responded to theoretical questions, compared with 36 students (78%) in the control group. The experimental group submitted 609 theoretical responses compared with 475 responses in the control group. In addition, 42 students (95%) in the experimental group were assessed for theoretical responses, compared with 35 students (76%) in the control group.

TABLE V
COMPARATIVE RESULTS OF INDEPENDENT LEARNING OUTCOMES ADOPTED FROM REF. (SAMIYEVA ET AL., N.D.)

Metrics	Experimental group	Control group
Number of students responding to theoretical questions	44 (100%)	36 (78%)
Total number of theoretical responses submitted	609	475
Number of students assessed for theoretical responses	42 (95%)	35 (76%)
Total number of grades awarded for theoretical answers	584	452
Number of students submitting practical assignments	40 (90%)	33 (71%)
Total number of practical assignment submissions	73	27
Number of students assessed for practical assignments	40 (90%)	27 (58%)

Total number of grades awarded for practical assignments

72

25

Differences were also observed for practical activities. Forty students (90%) in the experimental group submitted practical assignments compared with 33 students (71%) in the control group. The experimental group generated 73 practical submissions compared with 27 in the control group. Moreover, 40 students (90%) in the experimental group were assessed for practical assignments compared with 27 students (58%) in the control group. These numerical data were adopted from Ref. (Samiyeva et al., n.d.).

The higher participation indicators in the experimental group are consistent with the importance of structured and interactive learning environments in addressing limitations associated with distance education (Pikhart et al., 2023; Zaki, 2022; Stecula and Wolniak, 2022; Talebian et al., 2014; Yuhanna et al., 2020). Importantly, Table IV and Table V represent complementary dimensions rather than the same dataset. Table IV describes ICT competence development in the pedagogical experiment, whereas Table 5 provides adopted evidence regarding learning participation and completion of theoretical and practical activities within an AI-supported distance-learning environment.

F. Integration of Cluster-Based, Inclusive, and AI-Supported Learning

The combined findings demonstrate complementary relationships among institutional organization, teacher competence, and digital learning technology. Figures 1 and 2 describe the pedagogical and organizational mechanisms supporting competence development. Figures 3-10 illustrate the implementation of structured digital interaction at the learner level. Tables III and IV describe the ICT competence framework and competence development. Table V presents participation within the interactive distance-learning environment.

Cluster-based education encourages institutional cooperation and connects theoretical and practical teacher training (Khimmatiev et al., 2025). AI-based systems can offer adaptive guidance, analytical support, and automated feedback (Karin et al., 2025; Mulyana et al., 2025). Assistive and adaptive technologies may be used to enable inclusive educational practices (Abdullayeva, 2024). Interactive navigation can help in organizing student progression across theoretical materials, assessments, and practical activities, covering several limitations identified in conventional online learning (Pikhart et al., 2023; Zaki, 2022; Stecula and Wolniak, 2022; Talebian et al., 2014; Yuhanna et al., 2020).

The integration of these components is particularly relevant to inclusive education because diverse learners may require different levels of technological, pedagogical, and accessibility support (Abdullayeva, 2024). Teacher ICT competence, adaptive technologies, AI-supported feedback, and institutional collaboration should therefore be considered interconnected elements of technology-enhanced education rather than isolated innovations.

G. Implications for Sustainable Development Goals

The proposed framework contributes primarily to SDG 4 (Quality Education) by supporting inclusive, equitable, and technology-enhanced learning. AI-driven information systems can expand the role of technology in higher education (Karin et al., 2025), while inclusive and adaptive technologies can support diverse educational requirements (Abdullayeva, 2024; Mulyana et al., 2025). Community-oriented AI frameworks further demonstrate the potential of digital technologies to support digital literacy, inclusion, and sustainable development beyond formal educational environments (Karmaker, 2027).

The improvement in ICT competence shown in Table IV and the learning-participation patterns presented in Table V represent two complementary dimensions of sustainable digital education: professional readiness of future teachers and effective participation of learners in technology-supported environments. Sustainable digital transformation therefore requires coordinated development of human competence, pedagogical practices, technological infrastructure, accessibility, and institutional collaboration.

Science and technology-based distance learning can be strengthened through the integration of cluster-based teacher development, ICT competence, AI-supported feedback, interactive navigation, and inclusive educational principles (Karin et al., 2025; Khimmataliev et al., 2025; Abdullayeva, 2024; Mulyana et al., 2025; Karmaker, 2027). This integration provides a broader framework for adaptive, inclusive, and sustainable higher education. This adds new information regarding AI for education as reported elsewhere (Irmayanti et al., 2026; Haristiani, 2019; Al Husaeni et al., 2022; Haristiani and Kusumawati, 2026).

CONCLUSION

The integration of cluster-based learning, ICT competence development, AI, interactive navigation, and inclusive educational principles provides a comprehensive framework for strengthening science and technology-based distance learning. The descriptive and comparative analysis revealed a shift in the experimental group to medium and high levels of ICT competence from lower levels, and the adopted distance-learning data showed higher participation in theoretical responses, assessment, and practical activities than in the control group. In general, the findings suggest that successful digital education requires coordinated technological, pedagogical, and institutional support. Cluster-based structures and adaptive technologies support teacher preparedness and inclusive practices in education. AI-enabled feedback and interactive navigation can improve the responsiveness of learning. Thus, the proposed framework contributes to adaptive, inclusive, and sustainable higher education and SDG 4 by linking the competence of educators, participation of learners, intelligent technologies, and institutional collaboration in an integrated educational environment.

REFERENCES

- Abdullayeva, G. S. (2024). Features of inclusive education with children with special educational needs in Uzbekistan. *Journal of Engineering Science and Technology (The Bioscan)*, 19(2), 827–830.
- Al Husaeni, D. F., Al Husaeni, D. N., Ragadhita, R., Bilad, M. R., Al-Obaidi, A. S. M., Abduh, A., & Nandiyanto, A. B. D. (2022). How language and technology can improve student learning quality in engineering? Definition, factors for enhancing students' comprehension, and computational bibliometric analysis. *International Journal of Language Education*, 6(4), 445–476.
- Ayinde, O. M., Salami, A. O., Ademola, M. A., Nnanna, O. M., & Anosike, C. O. (2026). Empowering information and communication technology (ICT) teachers through a behavioral approach to computer-aided design (CAD) for curriculum-oriented instruction: A community-based approach to pedagogical challenges. *ASEAN Journal of Community Service and Education*, 5(2), 121–136.
- Haristiani, N. (2019). Artificial intelligence (AI) chatbot as language learning medium: An inquiry. *Journal of Physics: Conference Series*, 1387(1), 012020.
- Haristiani, N., & Kusumawati, M. (2026). Integrating information and communication technology (ICT) and language in vocational education: A bibliometric and qualitative perspective toward workforce readiness and Sustainable Development Goals (SDGs). 19, 55–63.
- Ibrahim, A., Bolaji, H. O., & Abdulraheem, A. J. (2025). Accessibility and utilization of artificial intelligence (AI)-based intelligent tutoring systems (ITS) and information and communication technology (ICT) in enhancing biology education. *ASEAN Journal for Science Education*, 4(2), 93–104.
- Irmayanti, H., Iskandar, M. M., & Achilov, T. S. (2026). Designing a transparent AI system using SHAP and LIME. *Journal of Engineering Science and Technology*, 21(2), 81–88.
- Jadhav, P., Gaikwad, H., & Patil, K. S. (2022). Teaching and learning with technology: Effectiveness of ICT integration in schools. *ASEAN Journal for Science Education*, 1(1), 33–40.
- Karin, J., Dharmayanty, D., Luckyardi, S., Soegoto, E. S., Ximmataliyev, D., Yusof, M. K., Chochole, T., & Zangana, H. M. (2025). Evolution of artificial intelligence (AI)-driven information systems in higher education: A review. *ASEAN Journal of Educational Research and Technology*, 4(3), 523–530.
- Karmaker, R. (2027). Community-based artificial intelligence (AI) empowerment for rural girls: A framework for digital literacy, cybersecurity, and sustainable community development. *ASEAN Journal of Community Service and Education*, 6(2), 97–116.
- Khimmataliev, D. O., Salomova, R. N. V., Makhsumov, R. M., Khakimov, Z. O., Normurodova, A. K. Q., Togaev, B. E. U., Obidjanov, U. I., Omonova, N. P. Q., & Fitrilia, T. (2025). Enhancing ICT competence of future computer science teachers through cluster-based education models. *Journal of Engineering Science and Technology*, 20(4), 24–30.
- Mulyana, A., Djatna, T., Wahjuni, S., & Sucoko, H. (2025). Towards an adaptive edge computing framework for computation offloading: ABC-MDP approach. *NED University Journal of Research*, 22, 403–411.
- Nandiyanto, A. B. D. (2026). How to read and interpret FTIR spectra for materials: A master dataset with step-by-step guided peak-correlation analysis, representative examples, and a foundation for future artificial intelligence (AI)-assisted analysis. *ASEAN Journal for Science and Engineering in Materials*, 5(2), 323–356.
- Pikhart, M., Klimova, B., Cierniak-Emerych, A., & Dziuba, S. (2023). A comparative analysis of perceived advantages and disadvantages of online learning. *Behavioral Sciences*, 13, 262.
- Samiyeva, S. K., Olimov, S. S., Barnoeva, S. U. K., Ibragimov, U. M., Aslanova, N. K., Egamova, G. I. K., Mirzoeva, S. S. K., & Khusniddinova, Z. K. (n.d.). Advancing science and technology-based distance learning through artificial intelligence, interactive navigation, and Sustainable Development Goals (SDGs) integration [Manuscript accepted with revisions].
- Sanni, A. M. (2023). ICT tools for teaching the Arabic language. *ASEAN Journal of Religion, Education, and Society*, 2(2), 67–74.
- Stecula, K., & Wolniak, R. (2022). Advantages and disadvantages of e-learning innovations during the COVID-19 pandemic in higher education in Poland. *Journal of Open Innovation: Technology, Market, and Complexity*, 8, 159.
- Taleblian, S., Mohammadi, H. M., & Rezvanfar, A. (2014). Information and communication technology in higher education: Advantages, disadvantages, conveniences and limitations of applying e-learning to agricultural students in Iran. *Procedia - Social and Behavioral Sciences*, 152, 300–305.
- Usarov, J. E., Qahramonovna, R. M., Meyliyeva, M. S., Rustamov, B. K., & Allayorova, S. B. (2025). Development of inclusive learning of students with a social orientation in the environment of an educational cluster based on a competence-based approach. *ASEAN Journal of Community and Special Needs Education*, 4(1), 87–94.
- Yuhanna, I., Alexander, A., & Kachik, A. (2020). Advantages and disadvantages of online learning. *Journal Educational Verkenning*, 1(2), 13–19.
- Zaki, M. S. (2022). Advantages and disadvantages of online learning. *The Journal of International Social Research*, 15(92), 1.