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<https://doi.org/10.51889/2960-1649.2026.68.3.006>SHALABAY ALBINA^{1*}, CHILDIRBAYEV ZHUMADIL¹, SAPANOVA NURBANU¹¹Abai Kazakh National Pedagogical University (Almaty, Kazakhstan)

*Address of correspondence: Shalabay Albina, PhD student in the 1st year of the 8D01513 Biology educational program at the Faculty of Natural Sciences and Geography, Abai Kazakh National Pedagogical University, Almaty, Kazakhstan, <https://orcid.org/0009-0006-3284-1519>,
E-mail address: a.shalabai@abaiuniversity.edu.kz/Tel.: +7 776 606 8595

Forming Students' Ecological Culture Through Problem-Based Learning and a Virtual Laboratory

Abstract

Introduction. This study investigates the effectiveness of integrating problem-based learning and virtual laboratory technologies to develop ecological culture among university students. It aims to determine whether combining inquiry-based instructional strategies with digital simulation environments can enhance students' ecological knowledge, critical thinking skills, environmental responsibility, and practical engagement compared with traditional teaching methods. **Methodology and Methods.** A quasi-experimental design was applied involving undergraduate students in biology-related programs, divided into experimental and control groups. The experimental group was taught through problem-based learning activities supported by virtual laboratory platforms, while the control group received traditional instruction. Data were collected using diagnostic assessments, structured questionnaires, and performance-based evaluation tools to measure students' ecological knowledge, attitudes, and behavioral readiness. **Results.** The results indicate that students exposed to the integrated approach demonstrated higher levels of ecological understanding, improved analytical and problem-solving abilities, increased motivation, and greater participation in environmental learning activities than those in the control group. **Scientific novelty.** The study proves that combining problem-based learning with virtual laboratories produces a synergistic effect that strengthens both the cognitive and practical dimensions of ecological education. **Practical significance.** The developed integrated instructional model offers an effective approach to fostering ecological culture in higher education and supports the preparation of environmentally responsible, sustainability-oriented future professionals.

Keywords: ecological culture; problem-based learning (PBL); virtual laboratory; higher education; environmental education; educational technology; sustainable development education.

Introduction. In contemporary education, forming ecological knowledge and ecological culture has become a top priority because of growing global environmental challenges. Educational institutions are expected not only to transmit theoretical knowledge but also to develop students' critical thinking, problem-solving abilities, and environmental responsibility (Armstrong, 2011). Environmental education is a continuous process of learning and personal development aimed at forming ecological knowledge, values, and behaviors that promote responsible interaction with the environment and support human health.

Education for Sustainable Development (ESD) focuses on preparing individuals with ecological culture, systems thinking, and social responsibility. Such individuals can understand complex socio-environmental processes and make informed decisions at local and global levels to ensure a sustainable quality of life without compromising future generations (Wals & Blewitt, 2010).

A key component of modern sustainable pedagogy is developing ecological competence, which integrates knowledge, skills, and value-based attitudes that enable individuals to critically analyze and evaluate environmental

issues (Reen et al., 2025). Developing such competence is essential to building an environmentally responsible society capable of addressing contemporary ecological challenges (Mohan et al., 2024).

A comparative analysis of environmental education and ESD reveals several conceptual differences. First, ESD has a broader scope, focusing not only on environmental awareness but also on long-term behavioral and value-based transformation. Second, while environmental education often emphasizes the human–nature relationship from either an anthropocentric or ecocentric perspective, ESD promotes a more integrated and balanced approach. Third, ESD introduces a stronger ethical dimension, emphasizing responsibility toward future generations (Korotkova & Zakirova, 2020).

Furthermore, ESD promotes a subject–subject relationship between humans and nature, treating nature as an active partner rather than a passive object. It also emphasizes equal interaction between teacher and learner, fostering student-centered learning and intrinsic motivation (Wals & Blewitt, 2010). Modern research highlights that ESD relies on learner motivation supported by emotional engagement with nature and scientific understanding, which leads to responsible environmental behavior. In this context, education becomes a self-organizing system within a “learning society” (Korotkova & Zakirova, 2020).

Current studies emphasize that ESD is characterized by diverse content, interdisciplinary integration, and a combination of traditional and digital learning formats. It integrates natural sciences and humanities while maintaining a future-oriented perspective on global environmental issues (Wals & Blewitt, 2010). In addition, research on teacher education highlights the importance of innovative pedagogical technologies. Integrating digital tools enhances students’ digital literacy, critical thinking, and engagement in the learning process (Kerimbayeva et al., 2024; Meirbekov et al., 2024).

Recent studies also show that digital platforms and virtual learning environments can effectively develop ecological competence.

These tools improve students’ understanding of ecological processes and support the development of practical skills (Landa et al., 2023; Reen et al., 2025). Virtual laboratories boost students’ motivation and help them visualize complex biological systems (Asare et al., 2023; Brame, 2016).

Moreover, Problem-Based Learning (PBL) is widely recognized as an effective student-centered approach that enhances critical thinking, collaboration, and independent learning (Prince, 2004; Freeman et al., 2014). Through engagement with real-world problems, students develop the ability to analyze complex situations and propose evidence-based solutions (Sababha et al., 2016; Bagheri et al., 2013). Empirical studies confirm that PBL significantly improves student engagement and academic performance in higher education settings, while also promoting self-directed learning and higher-order thinking skills compared to traditional instructional methods (Ngereja et al., 2020; Bagheri et al., 2013).

In Kazakhstan, PBL implementation has shown positive outcomes in improving students’ creativity, engagement, and problem-solving abilities, although challenges related to methodological readiness and time constraints remain (Kerimkulova et al., 2016; Tungyshbay & Sainov, 2020). Overall, integrating innovative pedagogical approaches such as PBL and virtual laboratories represents a promising direction for enhancing ecological education and preparing future teachers with strong environmental competencies (Meirbekov et al., 2024).

This study aims to examine the effectiveness of integrating problem-based learning (PBL) and virtual laboratory technologies in enhancing university students’ ecological culture and to evaluate their impact on students’ ecological knowledge, attitudes, responsibility, and practical environmental engagement.

Materials and Methods. *Research Design.* This study used a mixed-methods quasi-experimental design to examine the effectiveness of integrating problem-based learning (PBL) and virtual laboratory technologies in developing students’ ecological culture. The research combined descriptive and inferential approaches

to provide both quantitative measurement and qualitative interpretation of learning outcomes. Pre-test and post-test measurements assessed changes in students' ecological culture.

Participants. The study included 120 third-year undergraduate students majoring in Biotechnology and Molecular Biology at Abai Kazakh National Pedagogical University. Participants were divided into an experimental group ($n = 60$) and a control group ($n = 60$). Both groups followed the same curriculum, while the instructional methods differed.

Instruments. We collected data using structured questionnaires, diagnostic tests, and academic performance assessments. The questionnaire used a five-point Likert scale (1 = strongly disagree, 5 = strongly agree) and measured four dimensions of ecological culture: ecological knowledge, ecological attitudes, ecological responsibility, and ecological action. In addition, the study included open-ended questions to explore students' perceptions of learning experiences with PBL and virtual laboratory environments.

Intervention. The experimental group was instructed through a combination of problem-based learning activities and virtual laboratory platforms, including PhET, CK-12, Labster, HHMI, and BioMan Biology. In contrast, the control group received traditional lecture-based instruction. The intervention included case-based ecological problem-solving tasks, collaborative group activities, and simulation-based laboratory exercises designed to promote active learning and practical engagement.

Ethical Consideration. The study followed the ethical principles of the Declaration of Helsinki and relevant national regulations on research involving human participants, as well as the Law of the Republic of Kazakhstan "On Personal Data and Their Protection" (No. 94-V of 21 May 2013). The research was carried out within the framework of regularly scheduled university courses, using instructional methods and freely available educational platforms already employed in higher education practice; it involved no medical, clinical, or biomedical procedures, no deception, and no collection of sensitive personal data. Under the institutional

regulations in force, studies of this type do not require review by a formal ethics committee. We observed all ethical safeguards described below throughout the study.

The administration of Abai Kazakh National Pedagogical University and the department responsible for the courses concerned granted permission to conduct the study. All participants were adult university students. Before the study began, they were informed of its aims, the procedures involved, the approximate time required for the questionnaires and tests, the voluntary nature of participation, and that the data would be used for research purposes only. All participants provided informed consent before the pre-test measurement.

Participants were informed that they could withdraw at any stage without giving reasons and that participation, refusal, or withdrawal would not affect whatsoever their course grades or their relationship with the teaching staff. To minimize perceived pressure arising from the status difference between instructor and student, participants completed the questionnaires anonymously, and the course instructor could not access responses in identifiable form. No incentives or rewards were offered for participation.

We paid particular attention to the equitable treatment of the two groups. The control group followed the full curriculum without any reduction in instructional content or contact hours, and no participant was disadvantaged by the group to which they were assigned. After the study, the materials and virtual laboratory resources used in the experimental condition were made available to the control group.

Questionnaire responses contained no names, student identification numbers, or other personal identifiers; individual records were coded numerically, and the codes linking pre-test and post-test responses were held separately and destroyed after the data were matched. We processed academic performance data in the same anonymized form. All data were stored on a password-protected device accessible only to the research team and are reported exclusively in aggregated form. Excerpts from the open-ended responses are presented without any

details that would permit the identification of individual participants.

We analyzed quantitative data using descriptive and inferential statistics. Independent-samples ANOVA was used to compare group differences, while ANCOVA controlled for pre-test scores. Spearman's correlation analysis examined relationships among variables. The researchers analyzed qualitative data from open-ended responses through thematic coding and identified key patterns such as problem-solving, critical thinking, collaboration, and learner engagement. Expert review established instrument validity, and Cronbach's alpha confirmed internal consistency. All statistical analyses were conducted at the $p < 0.05$ significance level.

Results. This study describes changes in the learning process of third-year students studying biotechnology and molecular biology at Abai Kazakh National Pedagogical University. During the study, the students' level of ecological

culture, their attitude toward the Problem-Based Learning (PBL) method, and the experience of using virtual laboratory platforms (PhET, CK-12, Labster, HHMI, BioMan Biology) were assessed in stages, along with the students' ecological culture levels, their attitudes toward problem-based learning (PBL), their experience using virtual laboratory platforms, and the effectiveness of integrating these two methods. A total of 120 students participated, and the analysis included only fully and qualitatively completed responses.

Initial level of ecological culture

At the beginning of the study, students' ecological culture was assessed according to four main components: ecological knowledge, critical thinking, practical ecological action, and ecological responsibility. The results obtained showed that although the students had a general understanding of environmental issues, their ability to conduct in-depth, systematic analysis was insufficient.

Table 1

Initial level of ecological culture

Component	Mean value	Description
Ecological knowledge	2.88	Average
Critical thinking	2.61	Slightly below average
Practical activity	2.45	Low
Environmental Responsibility	2.70	Average

These results indicate that students have a foundation in ecological knowledge, but their ability to apply it in real-life situations is weak. In particular, the low practical performance indicator demonstrates that students have little direct experience engaging with ecological issues.

Impact of Problem-Based Learning (PBL)

Table 2

Dynamics of the PBL impact

Indicator	Pre-test	Post-test	Growth
Ecological knowledge	2.88	3.52	+0.64
Critical thinking	2.61	3.44	+0.83
Proposing a solution	2.49	3.40	+0.91
Participation	2.45	3.36	+0.91

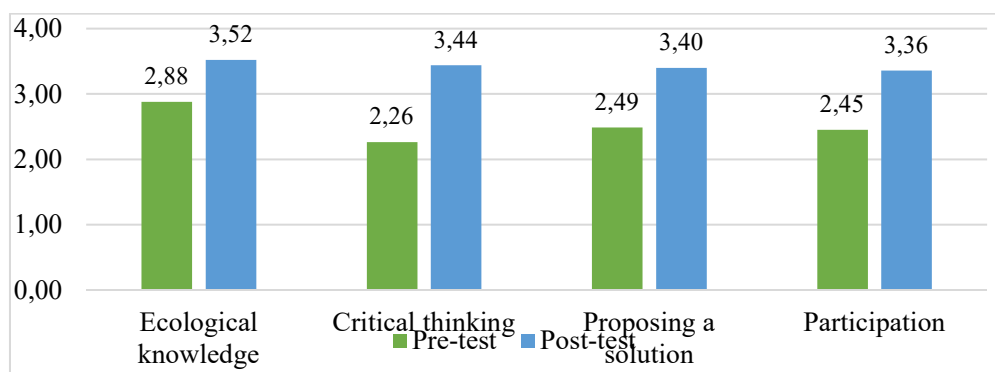
After introducing PBL, the greatest increases were in the ability to propose

After the introduction of PBL, students were presented with case studies based on real-world ecological problems (biotechnological waste, the impact of genetic modification on ecosystems, and bioremediation issues). During this phase, students' skills in analysis, argumentation, and solution proposal increased significantly.

solutions and in active participation in the learning process.

Figure 1

Dynamics of the PBL impact



This indicates that students shifted from passive listeners to active researchers and decision-makers.

Impact of Virtual Laboratory Tools

Virtual laboratories were used in the learning process to visualize and model complex biological and ecological processes. Each platform affected a specific cognitive level.

Table 3

Impact of virtual laboratory platforms

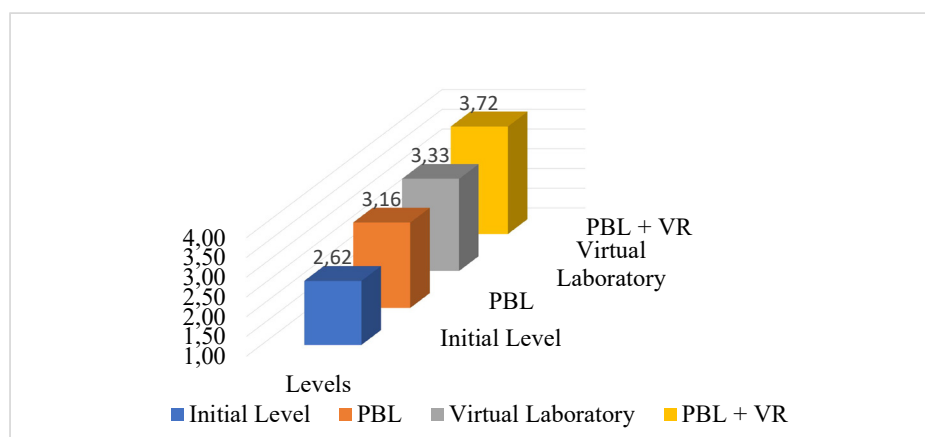
Platform	Main activity	Results
PhET	Main visualization	Understanding made easier
CK-12	Consolidation of theory	Knowledge organized
Labster	Scientific Modeling	Analytical thinking increased
HHMI	Biological Systems	Developed a deep understanding
BioMan Biology	Game elements	Motivation increased

These results show that virtual labs not only provide information but also increase student motivation and allow a hands-on understanding of complex biological processes. While the Labster and HHMI platforms strengthened scientific thinking and modeling skills, BioMan

Biology made the learning process engaging and interactive. The group that combined PBL with a virtual laboratory achieved the highest results. This model enabled students to simultaneously understand the theory, model it in a virtual environment, and propose a concrete solution.

Figure 2

Dynamics of the development of ecological culture



This chart shows that the greatest increase in students' ecological culture was observed in the combined method. The sharp increase in scores, especially when using PBL and VR,

demonstrates the synergistic effect of the two methods.

One-way ANOVA was used to determine differences among the groups.

Table 4

ANOVA results

Variable	F	p-value	Conclusion
Teaching method	15.21	<0.001	Significant effect
Group type	6.48	0.002	Significant
Interaction	5.91	0.004	Significant

The ANOVA results showed that the teaching method had a statistically significant effect on students' ecological culture. In particular, integrating PBL and the virtual laboratory

yielded significantly higher results compared to the individual methods.

ANCOVA analysis was conducted to control baseline differences.

Table 5

ANCOVA results

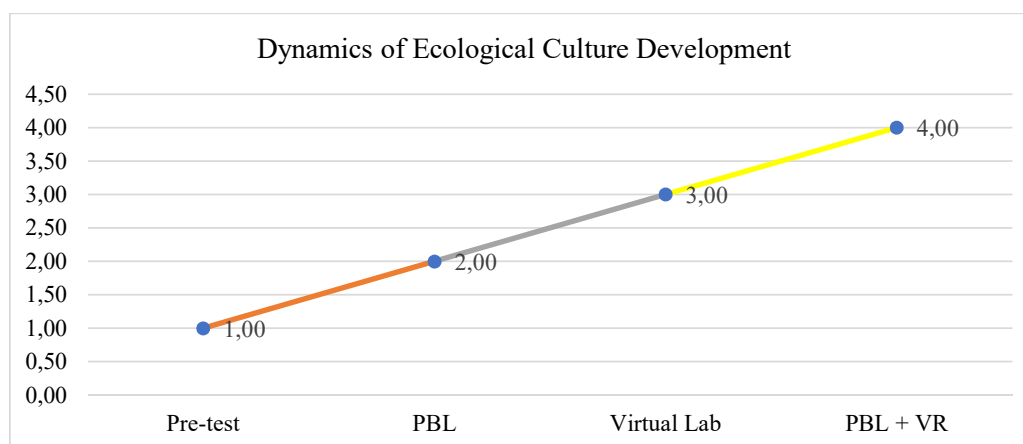
Measure	F	p-value
Pre-test (covariate)	9.12	0.001
Teaching method	17.34	<0.001

Although the pre-test effect was statistically significant, the teaching method's impact remained significant even after controlling for it. These results demonstrate that the effects of

PBL and the virtual laboratory are genuine and sustained. Summarizing the research results, the dynamics of changes in students' ecological culture were as follows:

Figure 3

Dynamics of changes in students' ecological culture



Pre-test → initial level (low-average)

PBL → increased critical thinking and participation

Virtual Lab → increased understanding and motivation

PBL+VR → highest level (integrated development)

Discussion. The findings indicate that integrating problem-based learning and virtual laboratory technologies positively affected students' ecological culture. Ecological knowledge, critical thinking, environmental responsibility, motivation, and practical engagement improved. These results are consistent with the principles of constructivist and student-centered learning. Both approaches emphasize active participation and constructing knowledge through experience (Wals & Blewitt, 2010). The findings suggest that combining problem-based learning and virtual laboratories can support both the cognitive and value-oriented aspects of ecological education.

These findings align with previous international studies reporting the positive effects of problem-based learning on students' academic achievement and higher-order thinking skills. Ngereja et al. (2020) found that project-based learning significantly improves students' critical thinking, collaboration, and active participation in higher education. Similarly, Bagheri et al. (2013) reported that students exposed to problem-based learning demonstrate stronger self-directed learning abilities than students taught through traditional instructional approaches. The current study confirms these findings and additionally demonstrates that PBL positively influences ecological responsibility and environmental awareness.

The study also showed that students became more actively engaged in identifying and solving ecological problems after participating in PBL activities. This result aligns with Hira and Anderson (2021), who emphasized that project-based and inquiry-based learning approaches increase students' intrinsic motivation and participation in online and collaborative learning environments. In contrast to traditional lecture-based instruction, PBL encourages learners to become active researchers and decision-makers, thereby strengthening independent analytical thinking and reflective learning skills. Furthermore, problem-based learning enabled students to approach ecological issues critically and analyze their cause-and-effect relationships in greater depth. Through group assignments and the analysis of real-life

environmental situations, students developed skills in substantiating their opinions with scientific evidence and making collaborative decisions. These changes indicate that PBL not only facilitates the acquisition of ecological knowledge but also enhances students' sense of responsibility, research engagement, and inclination toward sustainable environmental behavior.

Recent studies in science and environmental education also support the findings on virtual laboratory technologies. Asare et al. (2023) concluded that virtual laboratories improve student engagement, satisfaction, and conceptual understanding by allowing learners to visualize scientific processes interactively. Similarly, Landa et al. (2023) highlighted that innovative digital technologies enhance students' motivation and support deeper understanding of complex scientific concepts. The present study extends these findings by demonstrating that virtual laboratories are effective not only for improving conceptual understanding but also for strengthening ecological culture and environmentally responsible behavior. Digital learning environments also increase student engagement and improve learning outcomes by enabling interactive, flexible access to scientific content.

Virtual learning environments have been shown to significantly improve students' engagement and learning motivation by providing interactive and simulation-based experiences. These results align with the present study, where virtual laboratory platforms helped students better understand complex ecological processes and apply theoretical knowledge in practice. A key contribution of this study is identifying the synergistic effect of combining problem-based learning with virtual laboratory technologies (Makransky & Mayer, 2020). Students who used both approaches achieved higher results than those exposed to either method alone. This finding differs from some previous studies that examined PBL or virtual laboratories independently. The integrated model used in the present research allowed students to combine theoretical understanding with practical experimentation and collaborative

problem-solving. This suggests that integrating digital simulation technologies with inquiry-based pedagogy creates a more comprehensive learning environment for environmental education.

This finding indicates that combining inquiry-based pedagogy with immersive digital tools creates a more effective learning environment by supporting both conceptual understanding and active knowledge construction. Previous studies have also confirmed that integrated digital learning environments significantly enhance students' cognitive engagement, motivation, and conceptual understanding compared to single-method instruction.

The findings also support the principles of Education for Sustainable Development, which prioritize learner-centered approaches, critical thinking, and solving real-world problems. Participation in virtual ecological simulations and collaborative case analyses enhanced students' understanding of sustainability issues and increased their readiness to apply ecological knowledge in practical contexts. From this perspective, these instructional approaches effectively implement the core principles of Education for Sustainable Development within the learning process. In particular, these learning activities contribute to students' comprehensive understanding of ecological issues, their ability to evaluate them critically, and the development of responsible decision-making skills aligned with sustainable development goals.

From a pedagogical perspective, the findings emphasize the importance of integrating innovative technologies into higher education curricula. Contemporary environmental education requires more than theoretical instruction. Students also need opportunities to engage with authentic ecological problems. Integrating problem-based learning and virtual laboratories can support this process. It also contributes to the development of digital literacy, scientific reasoning, and sustainability-oriented thinking.

Despite the positive findings, several limitations should be acknowledged. The study was conducted in a single educational context and involved a relatively small sample, which

may limit the generalizability of the findings. In addition, some indicators, including motivation and engagement, were based on self-reported data and may contain subjective bias. Future studies should include larger, more diverse participant groups and examine the long-term impact of integrated digital and inquiry-based learning approaches on ecological culture development.

Overall, the findings suggest that integrating problem-based learning and virtual laboratory technologies can support the development of ecological culture in higher education. The study provides empirical evidence for combining inquiry-oriented pedagogy with digital learning tools in environmental education. These results may help further develop technology-enhanced approaches to ecological education.

Future research should expand the sample size, include multiple universities, and investigate long-term effects; additionally, the experimental design needs to be refined to clearly distinguish the individual effects of PBL and the virtual laboratory. A deeper analysis of qualitative data will allow for a better understanding of students' learning experiences.

Conclusion. This study comprehensively demonstrated the importance of Problem-Based Learning (PBL) and virtual laboratories in fostering students' ecological culture. The study results showed that although students' initial level was average, their ecological knowledge, critical thinking skills, practical abilities, and level of responsibility increased significantly through a specially organized learning process. Problem-based learning promotes students' active cognitive engagement. It supported the analysis of real-world ecological problems and independent decision-making. It also encouraged using scientific evidence in problem-solving. This method increased students' interest in learning and strengthened their independent learning skills. Virtual laboratories supported the visualization of complex biological and ecological processes. This helped students develop a deeper understanding of the subject matter. It also strengthened the connection between theoretical knowledge and practical application.

The study's main conclusion is that combining problem-based learning with virtual laboratories can effectively support the development of students' ecological culture. This integration improved ecological knowledge, environmental awareness, responsibility, and practical application skills. The findings indicate that the proposed approach supports both cognitive and value-oriented components of ecological education. It also provides students with opportunities to apply acquired knowledge in real-life environmental contexts. Furthermore,

the findings support the relevance of sustainable development principles in biology teacher education. They also highlight the importance of innovative pedagogical approaches in preparing future biology teachers. Integrating problem-based learning and virtual laboratories can support the development of ecological culture, critical thinking, and professional adaptability. These competencies are essential for responding to contemporary educational and environmental challenges.

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Information about the authors:

Shalabay Albina, Doctoral student (1st year), Abai Kazakh National Pedagogical University, ORCID ID: 0009-0006-3284-1519, email: a.shalabai@abaiuniversity.edu.kz

Childibayev Zhumadil, Abai Kazakh National Pedagogical University, ORCID ID: 0000-0002-6986-577X, email: zh.childibayaev@abaiuniversity.edu.kz

Sapanova Nurbanu, PhD, Abai Kazakh National Pedagogical University, ORCID ID: 0000-0003-3293-0985, email: n.sapanova@abaiuniversity.edu.kz