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# Modernizing geography teacher education through STEAM integration to enhance geoecological competence

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**ABSTRACT**

This study examines the effectiveness of integrating science, technology, engineering, arts, and mathematics (STEAM) into geography teacher education to enhance geoecological competence among prospective teachers. A mixed-methods pedagogical experiment was conducted with 178 undergraduate students from two pedagogical universities in Kazakhstan, including an experimental group (n=90) and a control group (n=88). The intervention involved the integration of interdisciplinary STEAM projects, digital modeling, geographic information systems (GIS), and practice-oriented tasks focused on regional geoecological problems. Data were collected through curriculum analysis, tests, questionnaires, project evaluation, reflective reports, and expert assessment. The results revealed statistically significant improvement in the experimental group across the cognitive, activity-based, value-motivational, and reflective components of geoecological competence compared with the control group ($p<0.05$). The findings indicate that STEAM integration strengthens interdisciplinary thinking, practical problem-solving, digital skills, and environmental awareness. The study contributes a validated model for modernizing geography teacher education in line with sustainable development and the digital transformation of education.



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## 1. INTRODUCTION

Contemporary developments in education require a substantial revision of the content and methods of teacher preparation. Against the backdrop of the competency-oriented paradigm and the ongoing digitalization of the pedagogical landscape, there is a growing emphasis on equipping educators to operate within multidisciplinary settings. This involves the strategic application of advanced instructional tools to enhance contemporary vocational practices [1]–[4]. In Kazakhstan, the modernization of higher pedagogical education is also associated with improving the quality of professional training, introducing innovative teaching approaches, and aligning educational outcomes with international standards [5], [6].

At the same time, the growing scale of global environmental challenges has strengthened the importance of environmental education. Climate change, natural resource degradation, increasing anthropogenic pressure, and ecological risks require the formation of environmental responsibility and sustainability-oriented thinking among younger generations [7], [8]. Geography education occupies a particularly important place in this process because it integrates knowledge about natural, socio-economic, and environmental systems [9], [10]. Accordingly, the development of geoecological competence among prospective geography teachers becomes a significant objective of teacher education. This competence includes knowledge of natural and anthropogenic processes, the ability to analyze environmental situations, decision-making skills related to sustainable resource use, and value orientations associated with environmental responsibility [11]–[13].

However, contemporary geography teacher education programs still often preserve a traditional disciplinary structure and remain largely oriented toward the transmission of theoretical knowledge. Such an approach limits the development of interdisciplinary, research-oriented, and practice-based competencies needed to address contemporary environmental challenges [14]. Within this framework, the science, technology, engineering, arts, and mathematics (STEAM) paradigm has gained traction as a pivotal strategy for renewing teacher preparation. By synthesizing scientific inquiry with technical and creative disciplines, this methodology cultivates a discovery-oriented mindset, fostering analytical reasoning and the practical execution of theoretical concepts in authentic scenarios [15], [16]. Recent studies have confirmed the educational potential of STEAM, but most of them focus either on school-level implementation or on selected aspects of science, technology, engineering, and mathematics (STEM) education rather than on the systematic redesign of teacher education programs [17], [18].

The present study contributes to this field by developing and experimentally validating a STEAM-based modernization model for geography teacher education aimed at strengthening geoecological competence among prospective teachers. The study combines curriculum content analysis, the design of a modernization model, and a pedagogical experiment to validate the efficacy of the suggested methodological framework [19]. Despite the growing interest in STEAM education, its systematic integration into geography teacher education and its impact on geoecological competence remain underexplored. Building on this, the current research investigates how a STEAM-integrated framework facilitates the growth of geoecological mastery in geography teacher training. The research question guiding the study is as: does the integration of STEAM technologies significantly improve geoecological competence in geography teacher education?

## 2. METHOD

### 2.1. Research design

By combining empirical measurements with interpretive techniques, this study adopted a multifaceted experimental approach within a pedagogical setting [20], [21]. The research design included three sequential stages: diagnostic, formative, and control. At the diagnostic stage, existing educational programs for prospective geography teachers were analyzed, and the baseline level of students' geoecological competence was assessed within each participant cluster, encompassing both experimental and control settings. The curriculum analysis focused on the structure of academic disciplines, the degree of interdisciplinary integration, the presence of practice-oriented and project-based learning. Furthermore, it examined the integration of software-driven investigative toolsets and analytical frameworks within the contemporary pedagogical landscape [14], [19].

At the formative stage, a STEAM-based model for modernizing the educational program was implemented [3], [16]. This stage involved revising course content, introducing interdisciplinary practical tasks, and integrating STEAM-oriented projects aimed at addressing geoecological problems. As highlighted within the framework of Figure 1, the formative intervention encompasses several interconnected steps that facilitate interdisciplinary learning. At the control stage, students' geoecological competence was reassessed using the same instruments applied at the diagnostic stage, which ensured comparability of the data collected before and after the intervention.

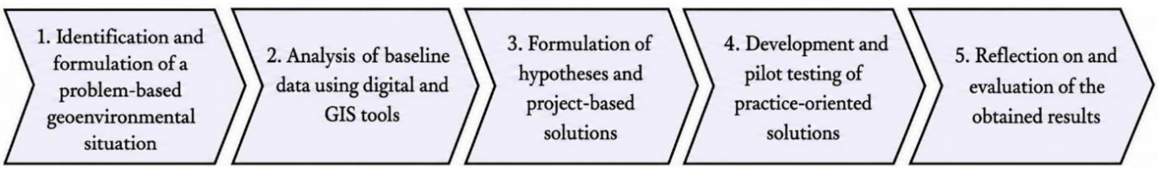


Figure 1. Methodological workflow for the formative intervention delivery

### 2.2. Participants

The empirical basis of the study included undergraduate programs in B014 Geography Teacher Education offered at Aktobe Regional University named after K. Zhubanov and Zhetysu University named after I. Zhansugurov. The research sample comprised 178 undergraduate students who engaged in the pedagogical experiment. The participants, ranging in age from 18 to 22 years, were enrolled across the second through fourth academic levels. The sample was formed using random selection to ensure comparability of learning conditions and the general level of professional preparation. The demographic and academic characteristics of the subjects are summarized in Table 1.

Table 1. Breakdown of the experimental sample across universities

| Higher education institution | Program of study | Sample size (n) | Year of study |
|---|---|---|---|
| Zhetysu University named after I.Zhansugurov | B014 “Training of Geography Teachers” | 61 | 2nd year (27)<br>3rd year (19)<br>4th year (15) |
| Aktobe Regional University named after K. Zhubanov | B014 “Training of Geography Teachers” | 117 | 2nd year (43)<br>3rd year (38)<br>4th year (36) |

## 2.3. Instruments

To ensure a comprehensive evaluation, the research utilized a set of synergistic tools tailored to the multi-dimensional nature of geoecological competence. These instruments were specifically designed to capture data across the cognitive, activity-oriented, axiological (value-motivational), and self-evaluative (reflective) domains [22], [23]. Measurement of the cognitive dimension involved a 40-question objective assessment. This tool aimed to evaluate the depth of students’ theoretical insights, their diagnostic skills, and their proficiency in addressing geoecological challenges. The assessment criteria were derived from the existing syllabus and the projected pedagogical goals within the geography program.

The value-motivational component was examined using a questionnaire focused on environmental responsibility, sustainable development, and attitudes toward the use of STEAM technologies in future professional practice. The activity-based component was assessed through case-based tasks and project work analysis. These instruments were used to evaluate students’ practical skills, interdisciplinary problem solving, and the use of digital and geospatial tools in addressing geoecological issues [23]–[25].

The reflective component was assessed through students’ reflective reports, which were used to identify changes in self-assessment, awareness of learning processes, and readiness for professional activity. Reflective analysis is widely recognized as an important element of competence-based education [22]. To strengthen validity, data from tests, questionnaires, expert evaluations, and project analysis were triangulated. Reliability was supported through repeated measurement at different stages of the experiment and through inter-expert agreement in the evaluation of project-based tasks. Participation in the study was voluntary, and the principles of confidentiality, anonymity, and responsible data use were observed throughout the research process.

## 2.4. Data analysis

To evaluate the research findings, the study employed a combination of descriptive metrics and Pearson’s Chi-square ($\chi^2$) analysis. These statistical tools were vital for identifying variations across the studied cohorts, with the threshold for statistical significance established at $p<0.05$. Quantitative data were processed to categorize student performance into three distinct tiers: advanced, intermediate, and elementary geoecological competence. This classification allowed for a clear comparison between the intervention and reference groups. Subsequently, the $\chi^2$ test served to validate the reliability of shifts observed during both the initial (diagnostic) and final (control) phases of the trial.

# 3. RESULTS AND DISCUSSION

The empirical data obtained from the evaluation of geography teacher training curricula are detailed in this section, alongside the practical implementation of the STEAM-based modernization model and its subsequent impact on the development of students’ geoecological competence.

## 3.1. Current state and gaps in geography teacher training

Understanding the structure and orientation of geography teacher education programs is essential for identifying limitations that hinder the development of geoecological competence. Particular attention was given to the balance between theoretical content and practice-oriented learning, the level of interdisciplinarity, and the extent to which digital technologies and research methods are integrated into the educational process.

### 3.1.1. Content orientation and identified limitations

The analysis of geography teacher education programs showed that both core and specialized disciplines provide fundamental subject knowledge. However, their contribution to the development of research, practical, and interdisciplinary skills remains limited. Most courses are characterized by a predominantly theoretical and descriptive orientation, with insufficient use of digital technologies, modeling, and project-based learning. Specifically, the curricula for courses such as fundamentals of cartography and topography, landscape science, and physical geography of continents and oceans primarily emphasize natural processes. However, the integration of spatial modeling and digital data analysis remains limited. A similar trend was observed in socio-economic geography, where territorial development studies rarely utilize contemporary analytical toolsets. Table 2 provides a detailed summary of these content analysis results.

Table 2. Content analysis of geography teacher education programs

| Block of disciplines | Discipline | Dominant focus of content | Identified limitations | The potential of STEAM integration | Geoecological competence components |
|---|---|---|---|---|---|
| Basic | Fundamentals of cartography and topography | Traditional mapping and topographic studies | Underutilization of geospatial software and digital processing tools | Spatial analysis, digital modeling | Cognitive, reflective |
| | Landscape science | Theoretical analysis of landscapes | Lack of project and research work | Modeling of landscape systems | Cognitive, reflective |
| | Physical geography of continents and oceans | Descriptive study of natural complexes | Weak research and digital component | Analysis of climatic and natural data | Cognitive |
| | Geology with the basics of geomorphology | Theory of geological processes | Lack of engineering-oriented tasks | Assessment of geo-environmental risks | Cognitive, reflective |
| | General geography | Systemic view of the Earth | Episodic interdisciplinarity | Integration of digital models | Cognitive |
| | Methods of teaching geography | Traditional pedagogical technologies | Insufficient STEAM orientation | Designing STEAM lessons | Cognitive, activity-based |
| | General economic geography | Economic and geographical analysis | Weak environmental context | Sustainable development analysis | Cognitive, value-motivational |
| Profile | Economic and social geography of Kazakhstan | Regional analysis | Lack of project activity | STEAM projects for regional development | Cognitive, activity-based |
| | Physical geography of Kazakhstan | Study of natural resources | Limited use of GIS and field data | Spatial analysis | Cognitive, activity-based |
| | Meteorology with the basics of climatology | Theory of atmospheric processes | Lack of mathematical modeling | Analysis of climate series | Cognitive |
| | Fundamentals of natural science | Integrative natural science knowledge | Limited practical focus | Interdisciplinary STEAM projects | Cognitive |
| | GIS in geography | Instrumental preparation | Non-systemic connection with geoecology | Modeling environmental risks | Activity-based |
| | Geoecology and rational nature management | Theory of sustainable development | Lack of field and engineering solutions | Environmental monitoring | All components |
| | Geoeconomics | Economic analysis of space | Insufficient environmental integration | Interdisciplinary analysis | Cognitive, value-motivational |
| | Country studies | Descriptive regional analysis | Fragmentary projectivity | Analysis of global issues | Cognitive |
| | Population geography | Demographic processes | Lack of digital and environmental analysis | Social and environmental modeling | Cognitive, value-motivational |

#### 3.1.2. Potential for STEAM-based modernization

The curriculum analysis further showed that the potential for STEAM integration is currently realized in a fragmented and unsystematic manner. This is reflected in the sporadic use of geographic information systems (GIS), the insufficient inclusion of environmental aspects in economic-geographical disciplines, and the limited methodological preparation of future geography teachers for designing interdisciplinary educational solutions. At the same time, the analysis revealed substantial opportunities for modernizing educational programs through the STEAM approach. The integration of digital technologies, engineering-oriented methods for analyzing natural processes, project-based learning, and creative forms of presenting geographic information can significantly strengthen the practice-oriented character of teacher education and support the comprehensive development of geoecological competence.

### 3.2. Conceptual framework and implementation of the STEAM-integration model

The identified limitations provided the basis for revising the content and methods of training prospective geography teachers. The modernization process was aimed at introducing interdisciplinary learning, digital technologies, project-based approaches, and engineering-oriented tasks across both core and specialized disciplines [3], [16], [25].

#### 3.2.1. Structural changes in core courses

Within the implementation of the proposed model in Figure 2, the content of core disciplines was revised to strengthen interdisciplinarity and incorporate digital tools into the learning process. Traditional descriptive and theoretical material was supplemented with elements of digital and mathematical modeling, empirical data analysis, and the visualization of spatial processes [2], [19]. Within the physical geography module, learners engaged in practical simulations of climatic processes and the statistical evaluation of meteorological datasets. These activities were supported by the integration of digital communication frameworks for result interpretation. Simultaneously, in fundamentals of cartography and topography, the instructional focus was redirected toward automated mapping techniques and advanced spatial informatics. These modifications expanded students' opportunities to work with geospatial data and to develop spatial thinking relevant to the study of geoecological processes [14], [25].

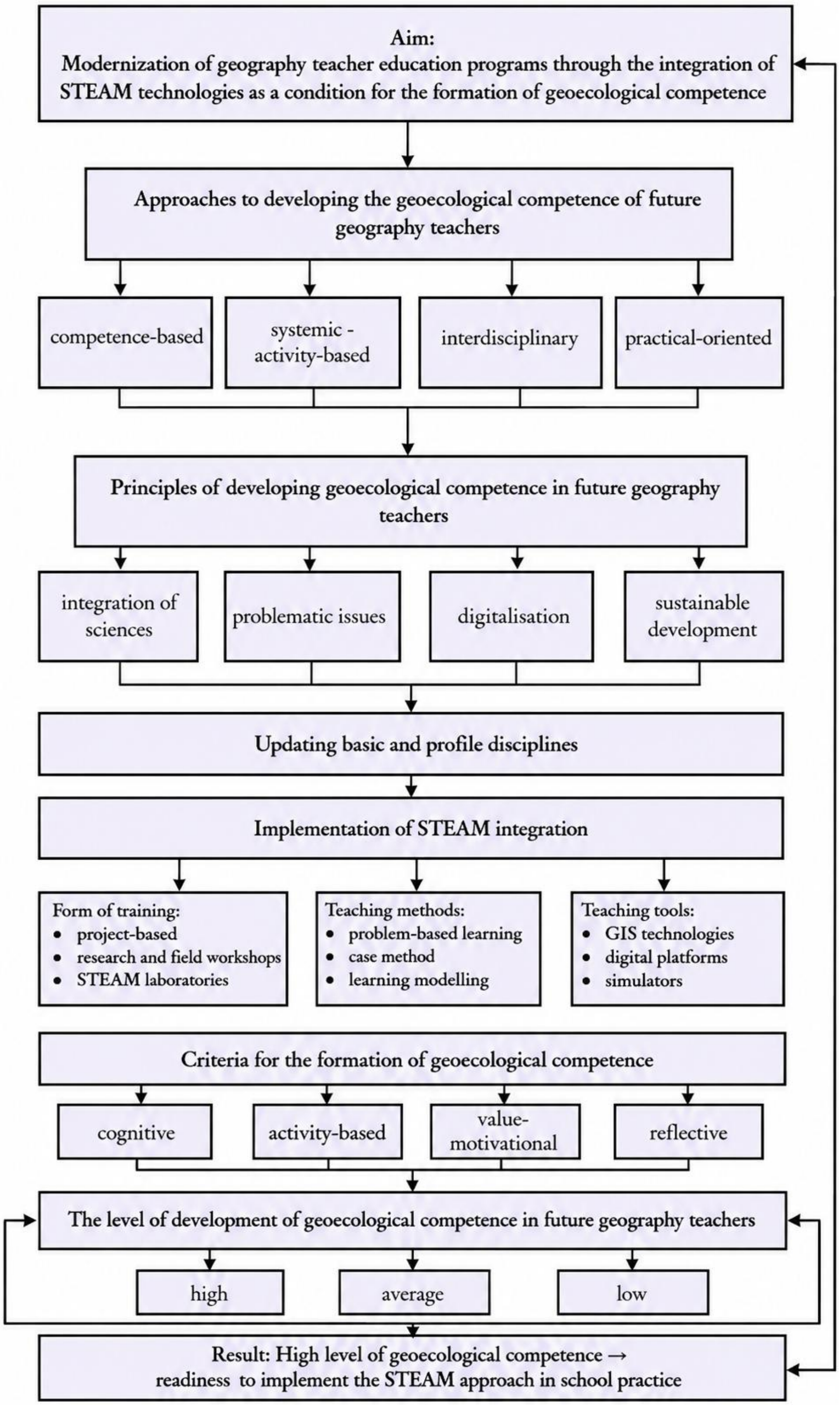


Figure 2. Model for the modernization of geography teacher education programs based on STEAM technologies as a condition for the development of geoecological competence

#### 3.2.2. Transformation of specialized disciplines

Significant changes were also introduced into specialized disciplines. In geoecology and rational nature management, the traditional study of sustainable development theory was supplemented by practice-oriented STEAM projects. Students completed assignments related to the analysis of environmental conditions, the assessment of anthropogenic pressure, and the development of proposals aimed at reducing environmental risks. GIS were used for the spatial analysis of environmental data and for modeling the effects of natural and anthropogenic processes [14], [19].

An important element of the STEAM approach was the integration of the "arts" pillar, aimed at developing the creative and humanistic dimensions of environmental education. Within project-based activities, students prepared pollution maps, infographics, multimedia presentations, and conceptual schemes reflecting the spatial distribution of pollutants, landscape transformation, and sustainable land-use solutions. Such integration of analytical and creative practices justifies the use of the term "STEAM" rather than solely "STEM" [3], [26].

### 3.3. Quantitative results of the pedagogical experiment

The effectiveness of the proposed model for modernizing educational programs was evaluated through a pedagogical experiment aimed at analyzing the dynamics of students' geoecological competence development. The quantitative analysis was designed to address the main research question, namely whether the systematic integration of STEAM technologies leads to a statistically significant improvement in the level of geoecological competence among prospective geography teachers.

#### 3.3.1. Baseline comparability of groups

The initial assessment revealed a high degree of homogeneity between the studied cohorts. Specifically, no notable disparities were detected in any geoecological competence domain ($p>0.05$), establishing a consistent baseline for the subsequent experiment, as seen in Table 3. Specifically, the experimental cohort displayed advanced proficiency in the cognitive and value-motivational domains (both at 21%), followed by the activity-based (19%) and reflective (14%) components. These figures were closely mirrored by the control group results, which stood at 22%, 20%, 18%, and 15%, respectively.

Table 3. Geoecological competence baseline (diagnostic stage)

| Competence component | Experimental group (n=90) | Control group (n=88) | p-value |
|---|---|---|---|
| Cognitive | High: 21%<br>Medium: 47%<br>Low: 32% | High: 22%<br>Medium: 46%<br>Low: 32% | >0.05 |
| Activity-based | High: 19%<br>Medium: 49%<br>Low: 32% | High: 18%<br>Medium: 50%<br>Low: 32% | >0.05 |
| Value-motivational | High: 21%<br>Medium: 48%<br>Low: 31% | High: 20%<br>Medium: 49%<br>Low: 31% | >0.05 |
| Reflective | High: 14%<br>Medium: 46%<br>Low: 40% | High: 15%<br>Medium: 45%<br>Low: 40% | >0.05 |

#### 3.3.2. Dynamics of geoecological competence development

Following the formative stage, the experimental group demonstrated marked improvement across all components of geoecological competence. The proportion of students with a high level of cognitive competence increased from 21% to 54%. For the activity-based component, the proportion increased from 19% to 49%. In the value-motivational component, the proportion increased from 21% to 45%, while in the reflective component it rose from 14% to 41%. By contrast, the control group showed no comparable positive dynamics. At the control stage, the proportion of students with a high level remained at 22% for the cognitive component, 19% for the activity-based component, 21% for the value-motivational component, and 14% for the reflective component.

#### 3.3.3. Statistical significance of differences

The differences between the experimental and control groups at the control stage were examined using Pearson's $\chi^2$ test, as seen in Table 4. Statistically significant differences were identified across all four components of geoecological competence ($p<0.001$). The $\chi^2$ values were 18.42 for the cognitive component, 20.15 for the activity-based component, 15.87 for the value-motivational component, and 22.31 for the reflective component.

Table 4. $\chi^2$ analysis of geoecological competence (control stage)

| Competence component | Experimental group (n=90) | Control group (n=88) | $\chi^2$ | p-value |
|---|---|---|---|---|
| Cognitive | High: 54%<br>Medium: 36%<br>Low: 10% | High: 22%<br>Medium: 50%<br>Low: 28% | 18.42 | <0.001 |
| Activity-based | High: 49%<br>Medium: 40%<br>Low: 11% | High: 19%<br>Medium: 52%<br>Low: 29% | 20.15 | <0.001 |
| Value-motivational | High: 45%<br>Medium: 42%<br>Low: 13% | High: 21%<br>Medium: 50%<br>Low: 29% | 15.87 | <0.001 |
| Reflective | High: 41%<br>Medium: 46%<br>Low: 13% | High: 14%<br>Medium: 48%<br>Low: 38% | 22.31 | <0.001 |

### 3.4. Qualitative results of the experiment

Qualitative assessment of the pedagogical trial results reinforces the statistical evidence, providing a more nuanced view of the advancement in students' geoecological aptitude. Specifically, learners within the treatment cohort manifested increased academic and vocational drive, coupled with more robust engagement with GIS-based and digital instruments. Moreover, they demonstrated a refined ability to evaluate regional environmental issues through a holistic lens, as shown in Table 5.

Table 5. Task performance indicators (experimental group)

| Type of work | Examples of assignments | Expert evaluation criteria | Average score (1–5) | Key achievements of students |
|---|---|---|---|---|
| Project work | Creating maps of water pollution in the region | Completeness of analysis, accuracy of GIS modeling, practical applicability | 4.6 | 85% of students created accurate maps and proposed measures to reduce pollution |
| Case study | Addressing environmental issues at school level | Soundness of decisions, interdisciplinarity, innovation | 4.2 | Students proposed comprehensive solutions with engineering, biological and social aspects |
| Reflective report | Analysis of own participation in project activities | Depth of reflection, awareness of personal role, readiness to apply | 4.0 | 78% of students noted an improvement in their independent analysis and project work skills |

The average expert scores ranged from 4.0 to 4.6 out of 5. In project work, 85% of students prepared accurate regional water pollution maps and proposed measures to reduce pollution. In case-based tasks, students developed solutions that integrated engineering, biological, and social dimensions. In reflective reports, 78% of students reported improvement in their independent analysis and project-work skills. Expert evaluation of the completed STEAM projects confirmed the high quality of students' work, their practical relevance, and their alignment with the requirements of school geography education.

### 3.5. Discussion of key findings

The research evidence suggests that embedding STEAM-oriented methodologies into the geography teacher training framework facilitates the multi-faceted growth of learners' geoecological proficiency. The most substantial improvements were observed in the cognitive and activity-based components, which suggests that the intervention was particularly effective in strengthening analytical performance, applied problem solving, and the use of geospatial tools in environmentally oriented tasks [27]. These observations corroborate prior scholarly works emphasizing the capacity of the STEAM paradigm to promote synergistic skillsets and environmental stewardship [28], [29]. Unlike prior studies focusing on school-level implementation, this study demonstrates the impact of STEAM at the level of teacher education, thereby extending existing literature.

The increase in the cognitive component from 21% to 54% indicates that the revised curriculum supported students' ability to analyze environmental processes and interpret geographical information more effectively. Similarly, the growth of the activity-based component from 19% to 49% confirms the value of project-based learning, GIS applications, and practice-oriented tasks in strengthening the applied dimension of geoecological competence. These findings are further consistent with studies emphasizing that STEAM promotes interdisciplinary integration, exploratory thinking, and the capacity to solve complex real-world problems [27]–[29]. In this respect, the present results suggest that the inclusion of digital tools, modeling, and project-based learning creates a learning environment in which future teachers develop not only disciplinary knowledge but also systems thinking and environmental literacy [28], [29].

The positive changes observed in the value-motivational and reflective components are also important. They suggest that STEAM integration influenced not only students' operational skills but also their environmental attitudes, professional responsibility, and capacity for self-assessment. This supports the competence-based view that teacher preparation should combine knowledge, action, values, and reflection within a unified educational framework. Additionally, the research offers a novel perspective by strategically embedding the "arts" facet within the STEAM-modernized curricula, thereby refining the professional training of geography educators. Within our framework, this component was realized through the artistic synthesis of environmental data and the design-oriented visualization of spatial processes. These practices strengthened not only analytical work but also environmental communication, thereby broadening the pedagogical value of the STEAM approach [30], [31]. Compared with earlier studies that considered STEAM mainly as a means of enhancing student engagement or improving school-level learning outcomes, the present results demonstrate its curriculum-level relevance for higher pedagogical education. This work expands the theoretical understanding of STEAM, positioning it as a holistic driver for program-wide reform in educator preparation, as opposed to a narrow pedagogical method.

At the same time, several limitations should be acknowledged. The geographic focus on two specific pedagogical universities in Kazakhstan might constrain the universal extrapolation of these outcomes. Moreover, the current study did not incorporate a multi-year longitudinal observation to track the vocational trajectories of the alumni and the sustained application of their geoecological skills in real-world classroom settings. Future research should therefore involve broader institutional samples, comparative designs, and longitudinal assessment of the sustainability of competence development. Overall, the results suggest that STEAM-based modernization of geography teacher education programs can be regarded as an effective mechanism for strengthening geoecological competence in the context of digital transformation and sustainable societal growth.

## 4. CONCLUSION

This empirical investigation confirms that the systematic integration of STEAM technologies into geography teacher education significantly enhances geoecological competence across cognitive, activity-based, value-motivational, and reflective dimensions. The proposed modernization model strengthens interdisciplinary learning, digital and geospatial skills, project-based problem solving, and environmental awareness among prospective teachers. The substantial progress recorded within the intervention cohort indicates that STEAM-driven curricular reforms provide a robust framework for refining teacher preparation. Such a model effectively aligns with the demands of ecological resilience and the pervasive digital evolution currently reshaping the educational landscape. Future scholarly inquiries should investigate longitudinal outcomes, the scaling of institutional adoption, and the synergy with high-tier technological instruments, such as immersive simulations, virtual field exploration, and AI-enhanced pedagogical systems.

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| Name of Author | C | M | So | Va | Fo | I | R | D | O | E | Vi | Su | P | Fu |
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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

## CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

**INFORMED CONSENT**

We have obtained informed consent from all individuals included in this study.

**ETHICAL APPROVAL**

The researchers followed institutional policies and it was approved by the ethical review committee of the University of Education.

**DATA AVAILABILITY**

The data that supports the findings of this study are available from the corresponding author, [MA], upon reasonable request.

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