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*TOLKYNBAYEVA AIGERIM[1], SAGYMBAY OKETAY[1], BAIKULOVA AIGERIM[2]**

[1]Al-Farabi Kazakh National University (Almaty, Kazakhstan)
[2]Kazakh National Women's Teacher Training University (Almaty, Kazakhstan)

*Address of correspondence: Baikulova Aigerim, Kazakh National Women's Teacher Training University, Almaty, Kazakhstan, https://orcid.org/0000-0001-9525-2048, E-mail address: aigerim.baikulova@mail.ru

Development of Students' Research Skills Through STEM Education (Survey Results)

Abstract

Introduction. The study examines the development of research competencies among students through the integration of innovative STEM-based pedagogical approaches in geography education. In response to societal demand for digitalization and preparation of learners for complex interdisciplinary problem solving, the research provides theoretical substantiation and experimental validation of STEM methodology effectiveness in fostering research skills among seventh-grade students during geography lessons. *Methodology and Methods.* A quasi-experimental design involved one hundred sixty-one respondents, including twenty-seven students from a secondary educational institution. Data collection employed a structured, closed-ended questionnaire containing five items that assessed frequency of research task implementation, student interest in technological approaches, preferences regarding project formats, and perceived didactic effectiveness of STEM integration. The survey followed bioethics principles with informed consent obtained from participants and guardians. Quantitative analysis included frequency distribution and correlation analysis of the respondents. *Results*. The results indicate limited systematic use of research tasks in current educational practice, while strong student interest in STEM integration in geography education is observed. Student responses demonstrate recognition of the positive influence of STEM-based approaches on the development of research competencies, improved comprehension, and stronger retention of learning material. STEM integration is associated with increased engagement in technology-enhanced learning and collaborative project-based activities. *Scientific Novelty*. Empirical evidence demonstrates that systematic application of STEM methodology provides an effective model for transforming geography instruction from knowledge transmission toward inquiry-oriented learning and strengthening research skill development among secondary students. *Practical significance.* Findings support implementation of STEM-enhanced geography curricula to strengthen research competencies among early adolescents and provide recommendations for expanding research-oriented tasks through interdisciplinary project design, technological tool integration, and structured mentoring of student investigations.

Keywords: STEM education, research skills, practice-oriented tasks, secondary school students.

Introduction. In the context of the rapid transformation of the global socio-economic and ecological landscape (Peter & Sprenger, 2022), accompanied by unprecedented contemporary challenges ranging from accelerating climate change and ecosystem degradation to imperatives of sustainable resource management and societal digitalization (Haefner & Sternberg, 2020) the development of research competencies has acquired the status of a significant educational objective (Mamirova, 2024). The capacity for systematic engagement with heterogeneous information arrays, formulation and verification of hypotheses, application of quantitative and qualitative data analysis methods, as well as the generation of innovative solutions to interdisciplinary problems, constitutes the core of a competency profile for graduates commensurate with the demands of a knowledge-based economy and the challenges of sustainable development. Geography as a scientific discipline possesses a unique epistemological status (Baerwald, 2010), functioning as an integrative platform for studying complex

spatially-organized territorial systems operating at the intersection of natural, social, and economic processes, thereby predetermining its exceptional potential for fostering research-based thinking. The dominant paradigm in contemporary geographical pedagogy maintains a reproductive-informational character, oriented primarily toward the transmission of descriptive knowledge and mechanical reproduction of factual material, which significantly constrains the development of students' independent research skills, critical evaluation of information, and analytical thinking (Feulner, 2014). The contradiction between the objective didactic potential of geography education and its actual implementation in the educational process underscores the necessity for seeking and implementing innovative pedagogical strategies, among which STEM-based approaches hold particular significance as an integrated methodology (English, 2016; Sutaphan & Yuenyong, 2019) that synthesizes natural science, technological, engineering, and mathematical knowledge in the context of addressing practice-oriented research tasks.

Research objective: To theoretically substantiate and experimentally verify the effectiveness of STEM-education methods for developing research skills among seventh-grade students in geography lessons. Within the framework of the present study, research skills of seventh-grade students are defined (Mamirova, 2024) as an integrated complex of developing cognitive abilities and operational competencies oriented toward independent or pedagogically-guided cognition of geographical reality objects and processes through identification of problematic situations, generation of research questions, and their systematic resolution. Skills constitute not a mechanical aggregate of discrete operations, but rather a holistic system of cognitive activity adequate to the cognitive capacities and psychophysiological characteristics of adolescence, distinguished by intensification of abstract-logical thinking, enhancement of intellectual autonomy, and formation of the foundations of scientific-theoretical cognitive style.

The structural organization of students' research skills is operationalized through a system of interconnected components (Meerah & Arsad, 2010). The first component represents the ability to generate hypotheses, consisting of the capacity, based on primary empirical observation and analysis of available information, to construct hypothetical, logically substantiated judgments concerning causal relationships between geographical objects and processes, as illustrated by formulations such as: with intensification of forest cutting on slope territories, an increase in the frequency of landslide phenomena is anticipated. The second component encompasses the ability to design research, including the development of an algorithmized sequence of actions for hypothesis verification through determination of target objectives, implementation stages, necessary instrumentation (cartographic materials, measuring instruments, statistical data), methods of information collection, and prediction of anticipated outcomes. The third component constitutes the ability to accumulate and document data, presupposing mastery of basic techniques for empirical information collection: implementation of systematic observations (meteorological parameters), work with existing information arrays (climatic, demographic databases), application of geoinformation technologies (GPS navigation, digital cartography), and accurate recording of obtained results in tabular, graphic, and schematic formats. The fourth component forms the ability to analyze and interpret data, expressed in the capacity to process collected information through procedures of comparison, classification, identification of patterns, trends, and deviations, which ensures transition from descriptive account of facts to their causal explanation through the establishment of correlations between various parameters (temperature regime, barometric pressure, and synoptic situation). The fifth component represents the ability to formulate conclusions, consisting of the capacity, on the basis of conducted analysis, to construct conclusions directly addressing the initial research question and confirming or refuting the original hypothesis, provided that conclusions are substantiated by empirical data and their conceptual generalization. The aforementioned

system of interconnected components, adapted to the substantive content of the seventh-grade geography curriculum (study of physico-geographical characteristics of continents and oceans, spatial patterns in population distribution and economic activity), serves as the object of diagnosis and purposeful development in the process of experimental implementation of a STEM-oriented pedagogical model.

The methodology of STEM-education constitutes an integrated pedagogical system (Oyana et al., 2015; Caldis & Kleeman, 2019) synthesizing the epistemological foundations and methodological apparatus of four interrelated knowledge domains: natural sciences (Science), technology (Technology), engineering (Engineering), and mathematics (Mathematics). The conceptual core of this methodology is revealed through a system of fundamental principles. The principle of integration presupposes overcoming the disciplinary fragmentation of traditional education and constructing a holistic cognitive model in which geographical knowledge is organically integrated with physical, chemical, and biological regularities, operationalized through mathematical modeling, and realized through application of contemporary technological tools. The principle of project-based activity determines the organization of the educational process around solving a complex interdisciplinary problem in the format of an integrated project, encompassing the complete research cycle from the identification of a problematic situation and the design of a solution to its materialization, testing, and presentation of results. The principle of practice-oriented problem-solving determines the substantive foundation of instruction through engagement with authentic contextualized problems possessing social and ecological significance (assessment of anthropogenic pollution levels in water bodies, design of water treatment systems, optimization of transportation routes considering geomorphological characteristics of the territory).

Geography, as a scientific discipline studying spatiotemporal systems in their complex interaction, possesses exceptional potential for realizing STEM methodology (Caldis & Kleeman, 2019). The synthetic nature of geographical knowledge manifests through multiple aspects of integration. The technological dimension is realized through the application of geoinformation systems for spatial analysis, the interpretation of remote sensing imagery for landscape transformation monitoring, the use of satellite navigation systems in field research, and the creation of interactive cartographic visualizations. The engineering dimension is actualized in the context of developing nature conservation solutions: design of anti-erosion structures, modeling of aquatic ecosystem rehabilitation systems, and construction of renewable energy installations accounting for regional physico-geographical factors. The mathematical dimension is represented through procedures of statistical data processing (calculation of demographic density, urbanization rates), construction and interpretation of graphic models (climatic diagrams), operations with cartographic scales, coordinate systems, and determination of metric and areal characteristics of territories.

The substantive content of the seventh-grade geography curriculum, focusing on the study of physico-geographical complexes of continents and oceans, provides significant opportunities for implementation of STEM methodology (Al Mamun et al., 2015). The thematic unit devoted to the atmosphere and Earth's climatic systems integrates natural scientific study of physicochemical mechanisms of precipitation formation and the greenhouse effect, technological application of digital meteorological stations and online platforms for meteorological data collection, engineering design of an automated greenhouse model adapted to a specific climatic zone, and mathematical construction and analysis of climatograms with calculation of mean daily and mean monthly temperature indicators. The thematic unit on the hydrosphere and World Ocean waters encompasses natural scientific investigation of physicochemical properties of water, mechanisms of oceanic current formation and hydrological cycle processes, technological analysis of satellite imagery to

track deglaciation dynamics and anthropogenic aquatic pollution, engineering construction of a filtration installation with assessment of its effectiveness, and mathematical calculations of salinity, river discharge, and current velocities. The thematic unit on natural zones presupposes natural scientific investigation of functional relationships in natural-territorial complexes (soil cover, vegetation, climatic conditions), technological application of geoinformation systems for mapping and analyzing transformation of natural zone boundaries, engineering development of projects for biological diversity conservation and desertification mitigation, and mathematical comparative statistical analysis of biodiversity indicators across various zones and quantification of anthropogenic impact area.

The integration of STEM methodology (Chattopadhyay & Biswas, 2024) into the seventh-grade geography curriculum ensures the transformation of descriptive material assimilation into active research and project-based activity purposefully oriented toward the development of subject-specific competencies and cross-disciplinary universal learning actions. The implementation of STEM methodology in school geographical education (Lindner et al., 2019) is operationalized through a system of pedagogical technologies and forms of educational activity purposefully oriented toward the development of structural components of research skills. About the seventh-grade geography curriculum, the following practice-oriented approaches are considered relevant.

The technology of working with geoinformation systems and remote sensing of Earth constitutes an instrumental framework for developing competencies in the accumulation, analysis, and interpretation of spatial data. In the course of educational projects, students conduct comparative analysis of multitemporal satellite imagery to identify dynamics of anthropogenic landscape transformation in Kazakhstan, including quantitative assessment of the contraction of the Aral Sea, desertification processes in the Ustyurt region, vegetation cover degradation in steppe ecosystems, or expansion of urbanized territories exemplified by the megacities of Almaty and Astana, requiring generation of hypotheses regarding causal factors of observed changes, data verification through multiple sources, and construction of substantiated conclusions, which constitutes the essential content of the research process.

Projects modeling climatic processes through the application of digital simulators and construction of simplified physical models (representation of the greenhouse effect) ensure the transformation of receptive assimilation of theoretical concepts into active experimentation. By manipulating variable parameters (carbon dioxide concentration, albedo of the underlying surface), students empirically establish causal relationships determining global climatic patterns, thereby developing skills in designing virtual experiments and analytical processing of their results.

Resolution of engineering tasks in the context of environmental management and sustainable resource use is realized through design and creation of functioning models of installations for water purification from anthropogenic pollutants, which integrates chemical knowledge of coagulation and adsorption processes, physical principles of filtration and biological mechanisms of biofiltration, actualizing the phases of planning and construction, presupposing quantification of the effectiveness of the proposed solution and its empirical testing, fostering development of systemic engineering thinking and competencies for practical resolution of multidisciplinary problems.

Organization of field research employing portable digital sensors for measuring physicochemical parameters of the environment (pH and turbidity indicators of water in local water bodies, temperature-humidity regime in various biotopes) transforms the traditional educational excursion into a full-fledged scientific investigation. Students accumulate empirical data in real time, perform their statistical processing, and interpret obtained results in the context of natural and anthropogenic factor impacts, thereby directly developing competencies in quantitative information collection and analysis. The presented system of STEM

practices ensures not fragmentary, but rather comprehensive engagement of students in the research process, where technological instrumentation, natural scientific knowledge, and mathematical apparatus function not as autonomous educational objectives, but as integrated means for solving relevant geographical tasks possessing cognitive and practical significance.

Materials and Methods. The subject of the research was the development of research skills among students through the means of integrating technological and engineering approaches (STEM-education) into the process of geography instruction. The objective of the survey was to identify the potential of STEM approaches in developing research competencies of students in geography education, as well as to determine the degree of students' readiness for participation in research activity and their motivational-value attitudes toward integration of technological methods into geography education.

Participants. The study involved 27 seventh-grade students (average age 13–14 years) enrolled in a general education institution. The selection of this age group was determined by the following factors: first, seventh grade corresponds to a transitional period in the development of educational-cognitive activity, when students are capable of complex forms of abstract thinking and prepared for independent investigations; second, the geography curriculum in seventh grade contains sufficient material allowing application of comprehensive STEM-approaches; third, this age period is characterized by high receptiveness to innovative teaching methods.

Criteria for participant selection included: enrollment in seventh grade at the time of the study, regular attendance at geography lessons, consent to participate in the survey, and availability of access to educational materials and resources for completing research assignments. For data collection, a closed-ended questionnaire consisting of five main questions was administered, aimed at identifying: frequency of completion of research assignments in geography study; degree of interest in using technological and engineering approaches; preferences regarding format of educational projects; assessment of didactic effectiveness of STEM-methods for understanding and retention of material; perception of the developmental potential of research assignments in forming cross-disciplinary competencies.

Data Collection Instrument. The questionnaire items were formulated taking into account the age-related characteristics of respondents, employing simple and clear terminology, with response options provided to enable students to adequately express their position. The completion time for the questionnaire was 10–15 minutes, which ensured minimization of fatigue and enhancement of answer quality.

Ethical Consideration. The conduct of the research was carried out in accordance with principles of bioethics and generally accepted standards of research activity. Before the survey, informed consent was obtained from students and their parents (legal guardians) regarding participation in the research, with detailed familiarization with the objectives, tasks, and data collection procedures. Complete confidentiality and anonymity of responses were guaranteed, with exclusion of any possibility of respondent identification. Data obtained in the course of the survey is used exclusively for scientific purposes and is not subject to transmission to third parties without the consent of participants.

Results and Discussion. Based on the survey conducted with 27 seventh-grade students within the framework of the research topic "Development of research skills among students through STEM-education in geography instruction", quantitative results were obtained (Figures 1–5), permitting identification of peculiarities in the integration of technological and engineering approaches into the educational process of geography at the level of basic general education.

Figure 1

Results of students' responses to the question "How often do you complete assignments in geography lessons that require not simply memorizing facts, but conducting a small-scale investigation (for example, analyzing data, formulating your own hypothesis, conducting an experiment, or creating a project)?"

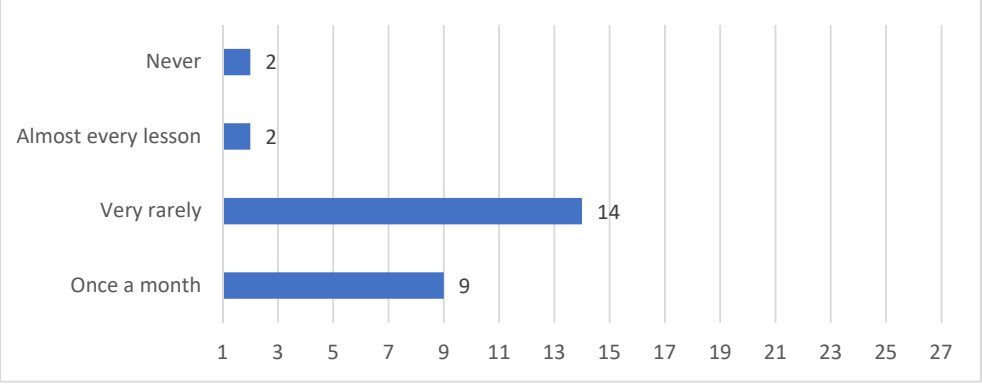


Figure 2

Results of students' responses to the question "Evaluate how interesting it is for you to complete assignments in geography lessons where you use technologies (for example, digital maps, satellite imagery, measurement sensors) or engineering approaches (for example, you create a model, design a solution to an environmental problem)?"

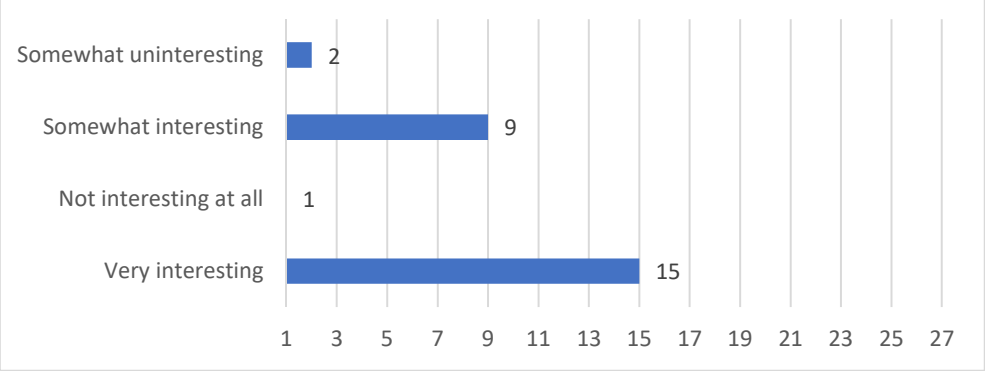


Figure 3

Results of students' responses to the question "If you were offered to choose a topic for an educational geography project to make it more interesting for you?"

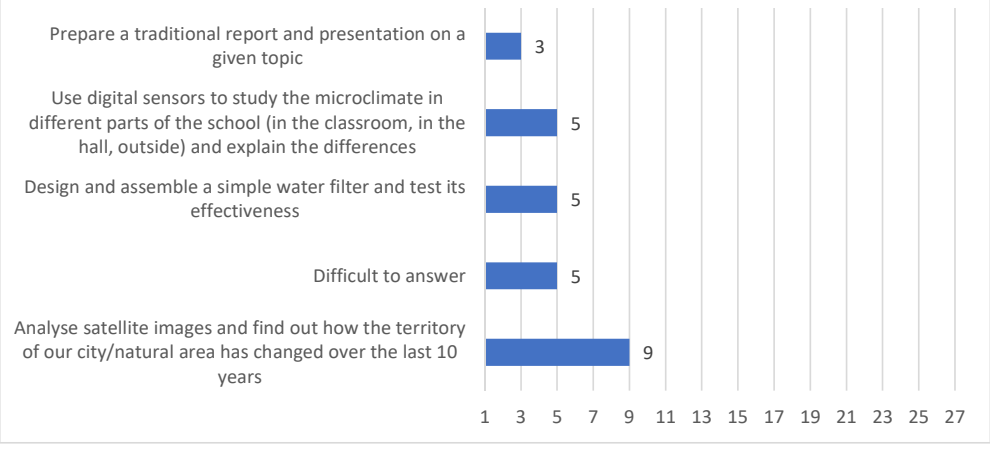


Figure 4

Results of students' responses to the question "In your opinion, do assignments where you need to work with data, technologies, and create something new help you better understand geography material?"

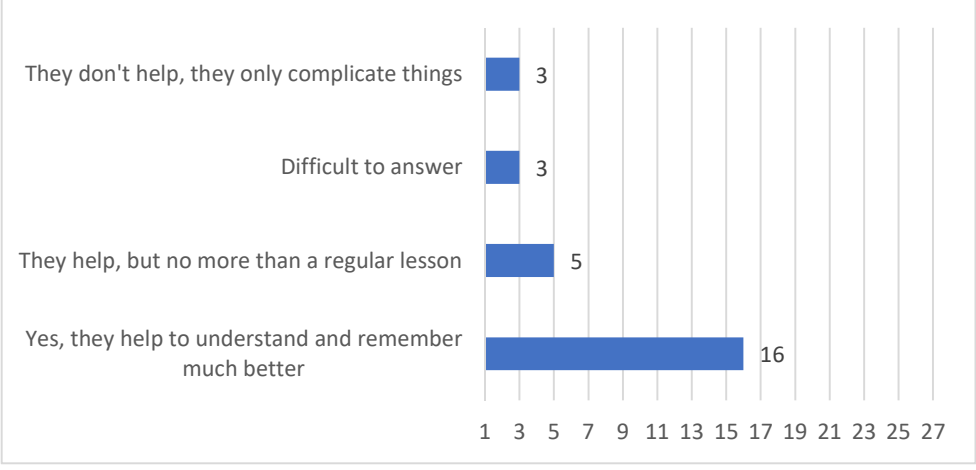
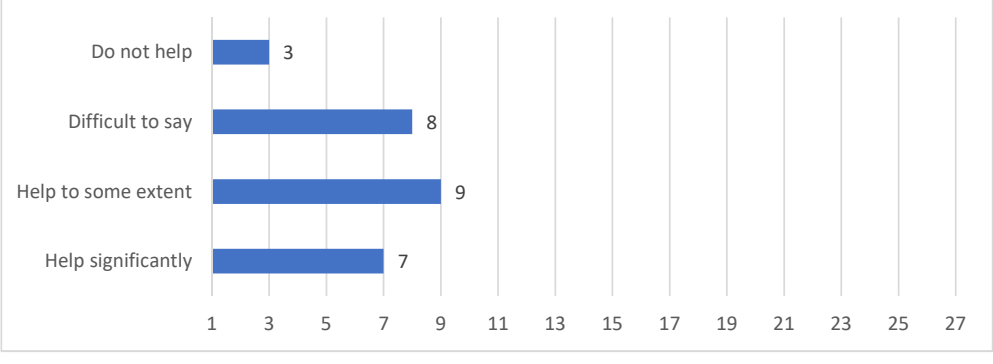


Figure 5

Results of students' responses to the question "Evaluate how many assignments you need to use knowledge from different subjects (for example, physics, technology, mathematics) to solve a practical task in geography help you develop skills in conducting research?"



Analysis of the frequency of research assignment completion revealed an absence of systematic application in educational practice. Only 2 respondents (7.4%) indicated regular completion of such activities in nearly every lesson. The majority of responses consisted of indicators of rare utilization of research assignments: 11 students (40.7%) reported frequency of completion once per month, while 12 students (44.4%) characterized such activity as occurring extremely rarely. Two students (7.4%) reported having no experience with research assignments, attesting to the existence of a category of students entirely excluded from this educational practice, indicating the necessity to increase the frequency and regularity of application of research methodologies in the process of geography instruction.

Nevertheless, high substantive recognition of the value of STEM approaches in geography education was identified. The overwhelming majority of respondents, 18 individuals (66.7%), evaluated the inclusion of technologies and engineering approaches in geography study as "very interesting." Additionally, 7 students (25.9%) selected the position "rather interesting." Thus, the aggregate indicator of positive attitude toward integration of STEM components into geography education comprises 25 respondents (92.6%). Negative assessments ("rather uninteresting" and "not interesting at all") were expressed exclusively by two students (7.4%), confirming the priority of this approach in motivational terms.

Analysis of student preferences regarding the thematic content of educational projects

revealed an uneven distribution of interests. The most attractive direction proved to be the analysis of satellite imagery for investigating territorial changes, which 11 individuals (40.7%) selected. Projects related to the design of water filtration systems and investigation of microclimate employing sensors interested respectively 5 (18.5%) and 6 (22.2%) students. Simultaneously, 5 respondents (18.5%) demonstrated adherence to traditional forms of knowledge presentation, selecting reports and presentations, reflecting the persistence of conservative educational preferences regarding result presentation methodology.

Assessment of the didactic effectiveness of research assignments relative to achieving understanding and retention of academic material proved positive. The majority of respondents - 17 students (63.0%) - are convinced that such assignments contribute to understanding and assimilation of material "significantly better" than traditional teaching methods. Five students (18.5%) acknowledged their usefulness, but not exceeding the effectiveness of conventional lessons. Three respondents (11.1%) found it difficult to provide a definite assessment, while two students (7.4%) indicated that research assignments "do not help, but only complicate" the educational process.

Regarding the cross-disciplinary aspect of research competency development, recognition of the developmental potential of STEM integration was identified. Eleven students (40.7%) indicated that such assignments "significantly" contribute to the development of research skills, while 9 individuals (33.3%) evaluated their influence as positive but partial. Thus, the aggregate indicator of positive perception of the developmental effect comprises 74% of respondents. Simultaneously, 4 respondents (14.8%) experienced difficulty in assessing the influence of STEM methods on the development of research competencies, and 3 students (11.1%) did not perceive a significant contribution to the formation of corresponding skills.

The quantitative analysis data provide grounds to establish that STEM approaches demonstrate pronounced potential in developing the research abilities of students in geography instruction. The obtained results are substantiated by positive assessments of students themselves regarding the motivational value, didactic effectiveness, and developmental influence of integration of technological and engineering approaches into geography education. Nevertheless, a key problem remains the unsystematic character of the application of research methodologies, which substantially constrains the possibilities of comprehensive and consistent formation of research competencies among students and requires purposeful correction of educational practice.

Conclusion. The conducted research demonstrates that integration of STEM methodology into geography instruction at the level of basic general education possesses pronounced developmental potential. Analysis of the obtained data revealed a substantial discrepancy between the proclaimed educational potential of research methodologies and their actual implementation in school practice. Despite the fact that the current application of research assignments is characterized as unsystematic (more than 45% of students rarely or extremely rarely complete such assignments), students demonstrate a high level of motivational readiness for their implementation. Empirical data indicate that STEM approaches in geography education facilitate the transformation of passive knowledge acquisition into active research activity, ensuring the development of all structural components of research skills: from the generation of hypotheses and design of investigations to accumulation, analysis, and interpretation of empirical data. The value of STEM integration lies in ensuring didactic effectiveness through the synthesis of natural scientific knowledge, technological instrumentation, and mathematical apparatus in addressing practice-oriented geographical tasks possessing social and ecological significance.

Nevertheless, the research identifies a key problem requiring correction: low systematicity of application of research methodologies substantially constrains the possibilities of comprehensive formation of research com-

petencies, indicating the necessity for purposeful changes in educational policy and methodological preparation of educators. It is recommended to increase the frequency and regularity of implementation of STEM practices in the process of geography instruction, ensuring a consistent and comprehensive character of their realization. Further research should be oriented toward the development of detailed methodological recommendations for structuring STEM-oriented geography curricula, the determination of criteria for assessing the formation of research competencies, and the identification of conditions optimizing the transfer of developed skills to addressing authentic geographical problems.

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Information about authors:

Tolkynbayeva Aigerim, PhD student of the Department of Geography, Land Management and Cadastre of Al-Farabi Kazakh National University, ORCID ID: 0009-0006-6865-0685, email: aigerim.tolkinbayeva@gmail.com

Sagymbay Oketay, Candidate of Geographical Sciences, Kazakh National University, Almaty, Kazakhstan, ORCID ID: 0000-0002-9262-9417, email: oketay.sagymbay@kaznu.kz

Baikulova Aigerim, PhD, Acting Professor, Kazakh National Women's Teacher Training University, Almaty, Kazakhstan, ORCID ID: 0000-0001-9525-2048, Scopus Author ID: 57190168487, email: aigerim.baikulova@mail.ru

