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Dulatkyzy D.[1], *Akbayeva G.N.[2]
[1,2]Karaganda Buketov University
[1,2] Kazakhstan, Karaganda
[1]*ORCID ID:* *https://orcid.org/0009-0003-8489-5015*
[2]*ORCID:* https://orcid.org/0000-0002-0314-0944
*rgul.ksu@mail.ru

COMPARATIVE ANALYSIS OF STEM EDUCATION PRACTICES: FOREIGN AND KAZAKHSTAN CASES

Annotation

In the context of digitalization and scientific-technological progress, the implementation of STEM education is becoming a priority in the modernization of educational systems. This article presents a comparative analysis of international practices in the implementation of the STEM approach, focusing on countries such as Finland, Singapore, and the United States. The analysis is based on five key criteria, which were developed based on the analysis of international studies and reports on the implementation of STEM education, in particular: OECD reports (for example, the PISA framework), UNESCO materials on STEM policy, analytical reviews of the National Science Foundation (NSF, USA), as well as practices recorded in the educational strategies of Singapore and Finland: the level of institutionalization of STEM, the scale and depth of its implementation, the degree of involvement of schools, teachers, and students, the role of government and the private sector, and the effectiveness of implementation measured by international assessments (such as PISA) and participation in academic digital transformation and rapid technological advancement, STEM education (Science, Technology, Engineering, and Mathematics) has become a key factor in preparing generations capable of thriving amid swift changes. The aim of the study is to identify effective STEM implementation models and define strategic directions for the further development of this field in Kazakhstan's education system. The findings reveal that each of the studied countries has established successful practices and mechanisms for implementing STEM education. The significance of the work lies in the possibility of using the identified models and recommendations for the successful implementation of STEM, which in turn contributes to the formation of competitive human capital and the adaptation of young people to the technological challenges of the 21st century.

Keywords: STEM education, comparative analysis, educational system, foreign models, international practices, project-based learning, curriculum integration

Introduction. In the modern world, characterized by digital transformation and rapid technological advancement, STEM education (Science, Technology, Engineering, and Mathematics) has become a key factor in preparing generations capable of thriving amid swift changes. International organizations such as UNESCO and OECD emphasize that developing competencies in STEM fosters critical thinking, creative skills, and innovation capabilities, which are essential for maintaining countries' competitiveness on the global stage [1].

Consequently, many countries are implementing national strategies to integrate STEM across all levels of education [2]. However, the effectiveness of these strategies largely depends on accounting for the cultural, pedagogical, and infrastructural specificities of each country [3].

Kazakhstan, aiming to modernize its education system, has begun to incorporate elements of STEM; however, this process remains fragmented and lacks a clearly defined national model [4]. At the same time, the experience of countries with successful STEM practices, such as Finland, Singapore, and the United States, is of significant interest and can serve as a guideline for the development of Kazakhstan's system [5].

This study is focused on a comparative analysis of STEM education models in the aforementioned countries with the aim of identifying key success factors and determining adaptable elements that can be effectively applied within Kazakhstan's national context. The relevance of the topic is driven both by the theoretical need to expand the comparative discourse on STEM education in post-Soviet countries and by the practical demand for recommendations to improve education quality.

The paper examines the main pedagogical approaches, structures, and implementation methods of STEM in various educational systems, as well as analyzes current initiatives in Kazakhstan. The research results will substantiate directions for improving STEM education considering the local context and contribute to forming a development strategy aligned with international standards and national particularities.

Over the past two decades, STEM education has become a focal point of academic discussion globally. Influential works by J.W. Bybee [2, p.45] and reports from the OECD [1, pp. 12-14; 3, p.78] emphasize STEM's role as a driver of innovation and economic progress. Theoretical approaches to STEM vary across contexts: from integrative models combining all four disciplines into cohesive project-based learning (United States, Finland) to top-down structured implementation led by national policy (Singapore).

Singapore’s model is rooted in outcome-based education and systematic teacher training [6]. Every aspect—from policy to classroom environment—is aligned to support STEM integration. In contrast, the U.S. model is highly decentralized, allowing diversity in programs and school-level autonomy, which fosters innovation but creates inconsistencies in quality [7].

The Finnish system, based on Sahlberg’s [8] research, emphasizes trust in teachers, minimal standardized testing, and the development of soft skills through interdisciplinary project work. In Kazakhstan, as reflected in national sources [4, p.31]. STEM is gaining traction, but the system faces challenges related to teacher preparation and the lack of localized methodological resources.

Despite the broad recognition of STEM's importance, several contradictions persist. First, although integrative approaches are widely advocated, there is no universal measure of success: strategies effective in Finland may not be transferable to Kazakhstan due to contextual differences in governance and culture. Second, while Kazakhstani literature mentions STEM adoption, it lacks in-depth empirical evaluations of its effectiveness in schools.

Additionally, a theoretical divergence is visible: some scholars focus on the technical aspect of STEM, while others highlight pedagogical design and creativity – central to the Finnish approach. In Kazakhstan, most frameworks appear eclectic and insufficiently adapted to the local school context, signaling a need for contextualized research and experimentation.

Given these disparities, the research employs a comparative analysis methodology and qualitative content analysis of key educational documents and academic literature. Singaporean and Finnish models are selected as reference points due to their documented success in international assessments [2, p.4; 5, p.2] and comprehensive teacher preparation strategies. Their contrast - centralized precision versus trust-based flexibility – offers valuable insights for adapting STEM education to Kazakhstan’s needs.

The term STEM first gained prominence in the U.S. in the late 1990s, aiming to equip students with skills for science and technology sectors. Since the early 2000s, the trend has shifted toward interdisciplinary learning. Finland officially embraced phenomenon-based learning in 2016, transitioning to holistic, real-world problem-solving approaches. In Kazakhstan, STEM initiatives emerged in 2017, particularly within Nazarbayev Intellectual Schools, but their nationwide implementation remains uneven and fragmented [6, p.2].

Since the beginning of the 21st century, STEM has become a priority approach in the national education policies of countries such as Canada, the United States, Singapore, China, Finland, and Japan. This approach enables the integration of STEM/STEAM education with trends like BYOD (Bring Your Own Device), flipped classrooms, and gamification, fosters interdisciplinary connections, and encourages the practical application of acquired knowledge through project-based and research-oriented activities. Countries that implement STEM at the policy level consistently rank among the leaders in international assessments such as TIMSS and PISA in mathematics and science, and demonstrate significant advancements in labor market competitiveness [9; 10].

An important feature of the American approach is the involvement of students through extracurricular activities and partnerships with industry, because in the United States one of the key initiatives was the introduction of Next Generation Science Standards, which focuses on research-based learning and equity in STEM education [7, p.11]. And the US system is focused on the development of critical thinking, project work. In addition, the United States has extensive extracurricular activities, summer camps, which seek to increase student engagement and expand participation in STEM fields.

STEM is actively developing in Kazakhstan, especially within the framework of the Digital Kazakhstan program [11], paying special attention to the integration of robotics, programming and 3D modeling, in particular in Nazarbayev Intellectual Schools, although a unified model is still being formed, but these efforts, in our opinion, mark significant progress towards modernizing its education system and meeting global trends.

In Singapore, the government is actively promoting STEM through the Applied learning program (ALP) [12]. Its main idea is to solve real problems, develop innovation skills. This model relies on close collaboration between educational institutions and industry to ensure that STEM education is relevant and effective [7, p.42].

Finland's approach to STEM education is characterized by the seamless integration of science, technology, engineering, and mathematics into project-based learning, with a low emphasis on standardized testing. A notable element of Finland's STEM ecosystem is the LUMA Centre Finland, a nationwide network that supports teacher training, student engagement, and research activities in natural sciences, mathematics, and ICT. LUMA serves as a hub for innovation and excellence, fostering a culture of scientific curiosity and collaboration fostering a culture of scientific curiosity and collaboration [13]. Compared to the systematic and thoughtful approach in countries such as Finland, Singapore and the United States, Kazakhstan's STEM model is still in its infancy. According to recent studies, the main problems remain the adaptation of methodologies to local conditions and insufficient training of teachers. This article examines international experience not only to show different ways of implementing STEM, but also to highlight elements that may be useful for Kazakhstan. Countries such as Finland, Singapore and the United States have achieved success thanks to government support for teacher training and the implementation of interdisciplinary teaching [14]. All this creates conditions for more successful development of STEM. By examining these cases, the research identifies not only best practices, but also potential pitfalls, emphasizing the importance of contextual adaptation rather than direct replication.

Methods and materials. In this study, the research is entirely based on secondary data from official sources. The diagnostic tools used including:

- Government reports and strategic plans [4, p. 31; 10, p. 4; 14, p. 16]
- Reports from international organizations [1, p. 25; 3, p. 7; 14, p. 3]
- Peer-reviewed academic articles [2, p. 12; 7, p. 42; 8, p. 25; 9, p. 47; 10, p. 4; 11, p. 110]
- PISA and TIMSS reports [5, p. 15; 14, p. 3]

Data collection was conducted through systematic selection and review of documents and scientific publications (2015–2024), using a content analysis method. Data processing included comparative tables and visual schemes created in Microsoft Excel 2021.

No direct participants were involved in the study, as the research is based on secondary data sources. Characteristics of students mentioned in the analyzed documents correspond to the target groups of PISA and TIMSS (15-16 years old for PISA, grades 4 and 8 for TIMSS).

The work used Microsoft Excel 2021, Mendeley Desktop 2.80 (Elsevier), and Canva online platform for data processing and visualization.

Results and discussion. According to the OECD's PISA 2018 results, Singapore and Finland consistently rank among the top countries in STEM competencies, while Kazakhstan and the United States demonstrate varying degrees of progress, as shown in Table 1.

Table 1. Level of student preparation in different countries according to the results of PISA 2018

Country	Science (PISA 2018 Score)	Mathematics (PISA 2018 Score)	Ranking (Science)	Ranking (Mathematics)
Singapore	551	569	1	1
Finland	522	507	6	17
United States	505	478	18	37

Country	Science (PISA 2018 Score)	Mathematics (PISA 2018 Score)	Ranking (Science)	Ranking (Mathematics)
Kazakhstan	441	448	53	48

Source: compiled by the authors based on the OECD report *(*PISA 2018 Results: Volume I*).*

PISA 2018 data shows how countries are coping with STEM education differently. Research shows that several things are important for the successful implementation of this approach: having a clear national strategy, including STEM subjects in the core school curriculum, continuous professional development of teachers, and ensuring equal conditions for all students. These points were used as a basis for analyzing how deeply STEM is embedded in the educational system of different countries. International experts also emphasize that it is the deep strategy, programs, and work with teachers that determine the sustainability and effectiveness of the STEM approach. Based on these frameworks, the current study focuses on institutionalization level as a primary criterion for comparative analysis, as presented in Table 2.

Table 2. Level of institutionalization of STEM education in different countries

Country	Presence of national STEM strategy	Level of integration in the education system	Comments
Kazakhstan	Partial	Medium	Within the framework of "Digital Kazakhstan" and Nazarbayev Intellectual Schools (NIS)
Singapore	Yes	High	Strong national focus with dedicated agencies and comprehensive curriculum integration
United States	Yes	High	"STEM for All" initiative, national standards, and diverse state-level programs
Finland	Yes	High	STEM is integrated into the general education system with emphasis on inquiry-based learning

Source: compiled by the authors based on the analysis of national strategies and data from OECD, World Bank, and Ministries of Education.

The data in Table 2 was collected through a comprehensive review of official government documents, educational policy reports, and academic literature on STEM education in each country. The comparison was conducted using a qualitative content analysis approach, focusing on three key criteria:

1. The existence and scope of a national STEM strategy or equivalent governmental program;
2. The degree to which STEM education is embedded in the formal education system;
3. Qualitative comments reflecting the specific features and contextual factors of each country’s STEM policies.

Singapore is important because of its highly institutionalized STEM model. Looking at the table, we can see that Kazakhstan has only partially implemented these approaches compared to the more advanced STEM models in Singapore and other countries. Thus, it is important to highlight that there are some gaps for improving STEM in Kazakhstan.

The following table 3 presents comparative data on the percentage of schools offering STEM programs and the extent of regional coverage in Kazakhstan, the United States, Finland, and Singapore — a country recognized for its exemplary and forward-looking STEM education system. This data highlights how national policies are translated into educational practice at the ground level.

Table 3. Level of implementation of STEM programs in different countries

Country	Schools with STEM programs (%)	Regional coverage (%)
Kazakhstan	~15%	40%
United States	65–70%	95%
Finland	90%	100%
Singapore	~85–90%	100%

Source: compiled by the authors using open statistical sources, reports by UNESCO, OECD, and national education programs.

This comparison demonstrates a significant disparity in implementation. For example, Kazakhstan, despite ongoing national efforts, shows relatively low coverage both in terms of school participation and geographic reach. On the other hand, countries like Singapore and Finland exhibit near-complete integration of STEM programs, reflecting not only strong institutional support but also consistent follow-through in school-level practice. These distinctions provide a clearer understanding of each country's capacity to implement STEM education at scale and ensure accessibility for all students.

The quality of STEM education implementation depends not only on national strategies and infrastructure but also on the active engagement of teachers and students. This includes professional development (PD) programs for educators, project-based learning for students, and the availability of extracurricular STEM activities.

The table 4 below compares key engagement indicators in Kazakhstan, the United States, Finland, and Singapore - countries at different stages of STEM education development.

Table 4. Teacher and student engagement in STEM activities

Indicator	Kazakhstan	USA	Finland	Singapore
% of teachers with STEM PD training	18%	75%	82%	88%
% of students involved in STEM projects	22%	65%	70%	85%
STEM clubs and extracurricular activities	Limited	Widespread	Well-developed	Highly developed

Source: compiled by the authors based on comparative analysis of national education reports, OECD data, and relevant academic studies on STEM engagement in schools

This data highlights significant differences in the depth of engagement. In Kazakhstan, limited teacher training and extracurricular offerings reflect early-stage development, while Singapore shows a mature ecosystem with high student participation and strong institutional support for teachers. This level of engagement is closely linked to student achievement and interest in STEM fields in later academic and professional stages.

Another important dimension of effective STEM implementation is the balance of public and private sector participation in funding and developing educational initiatives. Countries with dynamic private-sector involvement often see more innovation, while strong government support ensures equity and accessibility. As shown in Table 5**,** the role of public and private sectors in STEM funding significantly influences both the innovation capacity and the inclusiveness of STEM education systems.

Table 5. Role of government and private domains to support STEM education

Country	Public sector funding (%)	Private sector funding (%)	Key investors
Kazakhstan	80%	20%	NIS, Nazarbayev University, Samruk-Kazyna
USA	50%	50%	NSF, NASA, Google, Microsoft
Finland	90%	10%	Ministry of Education, municipalities
Singapore	60%	40%	Ministry of Education, Temasek Foundation, industry partners

Source: compiled by the authors using data from government reports, OECD sources, and information on public–private partnerships in STEM education.

The Singapore model shows how strategic collaborations between government and the private sector can foster innovation and scale up programs while maintaining quality. Although Kazakhstan is primarily publicly funded, it could benefit from private sector participation, as seen in the US and Singapore.

At the end, the success of STEM implementation is reflected in student performance indicators, such as PISA results and participation in international Olympiads. These results provide an opportunity to compare the effectiveness of different national systems, as we can see in the Table 6 below.

Table 6. STEM implementation results: academic performance according to PISA data and international comparisons

Measure	Kazakhstan	USA	Finland	Singapore
PISA 2022 – Science	397	502	531	551
PISA 2022 – Mathematics	382	478	507	569
International Olympiad Ranking (avg)	41st	4th	9th	2nd

Source: compiled by the authors based on PISA 2022 results published by OECD and average rankings from international science and mathematics Olympiads.

As can be seen from the table above, Singapore and Finland consistently show high results, which demonstrates the effectiveness of their well-organized and supported STEM systems, while Kazakhstan still encounter with some problems, like the need to improve qualifications of teachers and engage commercial fields.

The aim of the analysis was to identify key factors for the successful implementation of STEM and the possibility of adapting these main elements to the conditions of Kazakhstan education. The results showed that both centralized models (for example, in Singapore) and more flexible, trust-based approaches (as in Finland) ensure high levels of achievement if they are aligned with state priorities, the teacher training system and socio-cultural characteristics.

It is important to note, the analysis confirms that copying foreign models without taking into account the specifics of the national education system of Kazakhstan is impossible and inappropriate. It is necessary to adapt best practices taking into consideration conditions, traditions and resources. Our research highlights the importance of funding support for teacher training, STEM curriculum development, and school-business collaboration. As a result, research will inform culturally appropriate education system renewal.

As we have seen, it can be noted that there are many useful ideas in foreign cases, but nevertheless, the implementation of STEM education in Kazakhstan should be based on its own educational system. Without this, even the most effective foreign models may be inapplicable in our conditions in the educational system of Kazakhstan.

Conclusion. The purpose of our work lies in the studying international practices in STEM education and an analysis of the extent to which these practices can be implemented in Kazakhstan. Through a comparative analysis of the systems in Finland, Singapore, and the United States, five key dimensions were examined: the level of institutionalization, scale and depth of implementation, stakeholder involvement, the role of government and the private sector, and measurable outcomes through international assessments.

The analysis revealed that while each country follows a distinct path shaped by its national priorities and socio-cultural context, their success in STEM education is strongly tied to coherence between policy, teacher training, curriculum, and community engagement. Finland exemplifies a trust-based, flexible model, while Singapore represents a centralized, strategically driven approach. The U.S. demonstrates the value of grassroots innovation and community partnerships.

The findings demonstrate that Kazakhstan has made promising strides in initiating STEM reforms, particularly through targeted programs like those in Nazarbayev Intellectual Schools. However, systemic challenges remain, especially in areas such as teacher preparation, infrastructure, and the lack of localized instructional materials.

The study’s results align with its initial aim — to identify not models for replication, but models for informed adaptation. This confirms that it is impossible to fully implement foreign experience without taking into account the specifics of the Kazakhstan education system. When adapting foreign models, it is necessary to consider cultural values, traditions and available resources.

The importance of this study is that it is based on reforms that take into account the country's situation. It helps to develop a national STEM education policy based on global achievements. In addition, it emphasizes the importance of investing in teacher capacity, expanding cooperation between schools and industry, and supporting interdisciplinary learning.

However, the study has several limitations, namely, the analysis is based on documents, literature and existing data. The absence of empirical data from classroom implementation in Kazakhstan limits the scope of conclusions regarding actual impact. Future research should include longitudinal studies and field-based experiments to measure outcomes of adapted STEM practices in local schools.

Based on the findings, the following recommendations are proposed for future work:

- Expand empirical research on how STEM is currently implemented in Kazakhstani classrooms.
- Pilot localized STEM curricula that integrate international best practices.
- Invest in national teacher training initiatives focused on project-based, interdisciplinary learning.
- Strengthen public-private partnerships to ensure practical relevance and sustainability of STEM education.

In conclusion, Kazakhstan stands at a strategic point where it can benefit from the experience of world leaders in STEM education. However, only through careful adaptation, sustained investment, and systemic alignment can it build an effective and future-ready STEM education model.

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Дулаткызы Д.[1], *Акбаева Г.Н.[2]

[1, 2]Академик Е.А.Бөкетов атындағы Қарағанды университеті

[1,2] Қазақстан, Қарағанды

STEM БІЛІМ БЕРУ ТӘЖІРИБЕСІНІҢ САЛЫСТЫРМАЛЫ ТАЛДАУЫ: ШЕТЕЛДІК ЖӘНЕ ҚАЗАҚСТАНДЫҚ ЖАҒДАЙЛАР

Аңдатпа

Цифрландыру мен ғылыми-техникалық прогресс жағдайында STEM білім беру жүйелерін жаңғыртудың басым бағытына айналуда. Бұл мақалада STEM тәсілін жүзеге асырудағы халықаралық тәжірибелерге салыстырмалы талдау жасалып, Финляндия, Сингапур және АҚШ секілді елдерге баса назар аударылады. Анализ халықаралық зерттеулер мен есептерге негізделген бес негізгі критерий бойынша жүргізілді. Атап айтқанда: OECD (мысалы, PISA шеңбері) есептері, STEM саясатына қатысты ЮНЕСКО материалдары, АҚШ-тың Ұлттық ғылыми қорының (NSF) талдамалық шолулары, сондай-ақ Сингапур мен Финляндияның білім беру стратегияларындағы тәжірибелер. Бұл критерийлерге мыналар кіреді: STEM-нің институционалдану деңгейі, оны енгізудің ауқымы мен тереңдігі, мектептер, мұғалімдер мен оқушылардың қатысу дәрежесі, мемлекеттік және жеке сектордың рөлі, PISA сияқты халықаралық бағалаулар мен цифрлық трансформацияға қатысу арқылы өлшенетін іске асыру тиімділігі. Цифрлық және технологиялық дамудың жедел үдерісінде STEM (ғылым, технология, инженерия және математика) білім беру – өзгерістерге бейімделе алатын ұрпақты даярлаудың негізгі факторы болып отыр. Зерттеудің мақсаты – STEM-ді жүзеге асырудың тиімді модельдерін анықтап, Қазақстан білім беру жүйесінде бұл бағытты дамытуға арналған стратегиялық бағыттарды белгілеу. Зерттеу нәтижелері аталған елдердің тәжірибесінде STEM-ді тиімді енгізудің нақты құралдары мен тетіктері бар екенін көрсетті. Мақалада алынған нәтижелер негізінде, STEM білім беру жүйесін тиімді іске асыру елдің адами капиталын дамытуға, технологиялық өзгерістерге бейім ұрпақты тәрбиелеуге мүмкіндік беретіні көрсетілді.

Түйінді сөздер: STEM білім беру, салыстырмалы талдау, білім беру жүйесі, шетелдік үлгілер, халықаралық тәжірибе, жобалық оқыту, оқу бағдарламалары.

Дулаткызы Д.[1], *Акбаева Г.Н.[2]
[1, 2] *Карагандинский университет имени академика Е.А. Букетова*
[1,2] *Казахстан, Караганда*

СРАВНИТЕЛЬНЫЙ АНАЛИЗ ПРАКТИК STEM-ОБРАЗОВАНИЯ: ЗАРУБЕЖНЫЕ И КАЗАХСТАНСКИЕ КЕЙСЫ

Аннотация
В условиях цифровизации и научно-технологического прогресса внедрение STEM-образования становится приоритетом в модернизации образовательных систем. В данной статье представлен сравнительный анализ международных практик реализации STEM-подхода с акцентом на такие страны, как Финляндия, Сингапур и Соединённые Штаты Америки. Анализ проводится на основе пяти ключевых критериев, разработанных на базе изучения международных исследований и отчетов по внедрению STEM-образования, в частности: отчетов ОЭСР (например, рамка PISA), материалов ЮНЕСКО по STEM-политике, аналитических обзоров Национального научного фонда США (NSF), а также практик, зафиксированных в образовательных стратегиях Сингапура и Финляндии. Эти критерии включают: уровень институционализации STEM, масштаб и глубину внедрения, степень вовлеченности школ, учителей и учащихся, роль государства и частного сектора, эффективность реализации, измеряемую международными оценками (такими как PISA) и участием в академической цифровой трансформации. На фоне стремительного развития цифровых технологий STEM-образование (наука, технологии, инженерия и математика) становится ключевым фактором подготовки поколений, способных успешно адаптироваться к изменениям. Цель исследования – определить эффективные модели реализации STEM и обозначить стратегические направления для дальнейшего развития данного направления в системе образования Казахстана. Результаты показали, что в каждой из исследуемых стран существуют действенные механизмы, способствующие успешной реализации STEM-подхода. Значимость работы заключается в возможности использования выявленных моделей и рекомендаций для успешного внедрения STEM, которое, в свою очередь, способствует формированию конкурентоспособного человеческого капитала и адаптации молодежи к технологическим вызовам XXI века.

Ключевые слова: STEM-образование, сравнительный анализ, образовательная система, зарубежные модели, международная практика, проектное обучение, учебные программы.

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