

The Impact of STEM Programs on Academic Achievement, Motivation, Creativity, Problem-Solving Skills, and Other Educational Outcomes

Aina Balmukanova

Project Manager, Kazakhstan



Abstract

STEM education, which integrates science, technology, engineering, and mathematics, has evolved over the past two decades from a primarily policy-based educational initiative into an independent field of pedagogical research.

The purpose of this analytical review is to systematize and critically analyze the main areas of scientific literature on STEM education. It examines the evolution of the concept of STEM, the concept of interdisciplinary integration, and key pedagogical models, including problem-based learning, project-based learning, inquiry-based learning, and engineering design. It also examines evidence of the impact of STEM programs on academic achievement, motivation, creativity, problem-solving skills, and other educational outcomes.

Special attention is given to teacher training, the assessment of interdisciplinary outcomes, and issues of equal access to STEM education. A compelling body of evidence has now accumulated on the positive impact of STEM interventions, but the effect is uneven and depends significantly on the program content, the quality of pedagogical implementation, the duration of training, and the student's level of preparation. The main contradiction lies in the discrepancy between the declared interdisciplinary nature of STEM and the persistently subject-based nature of curricula and assessment. It is concluded that further development of STEM requires a transition from a simple unification of four disciplines to the targeted design of integrated educational tasks in which scientific research, mathematical modeling, technological tools and engineering design form a single cognitive system.

The scientific novelty of this article lies in its systematization and critical re-examination of current research on STEM education through the lens of the interrelationships between interdisciplinary integration, pedagogical mechanisms, and multi-level educational outcomes. Rather than a simple review of the effectiveness of STEM programs, this article proposes a generalized analytical model in which a real-world complex problem integrates scientific research, mathematical modeling, technological activity, and engineering

	design, and the outcome is examined simultaneously at the subject, interdisciplinary, cognitive, creative, social, motivational, and professional levels.
Keywords: STEM education, STEM learning, integrated learning, interdisciplinarity, engineering design, problem-based learning, project-based learning, STEM competencies, digital technologies, pedagogical models.	

Introduction

The development of STEM education has become one of the most significant areas of transformation in modern educational policy and pedagogical research. The term STEM encompasses four fields: science, technology, engineering, and mathematics, but its meaning has never been limited to a mechanical listing of the corresponding academic disciplines. Even at the early stage of the STEM approach's development, researchers noted the lack of a common understanding of what exactly constitutes STEM education and how the four disciplines should interact in the educational process [1].

The problem of defining STEM is fundamental. If STEM is understood as a collection of individual subjects, then the focus is primarily on improving the quality of teaching in science and mathematics. If STEM is viewed as an integrated educational model, however, establishing meaningful and actionable connections between disciplines becomes central. It is the latter approach that has gradually become one of the most influential in the scientific literature.

Integrated STEM education is not a single, fixed model, but a spectrum of educational practices with varying degrees of connection between disciplines. Key characteristics identified include goals, educational outcomes, the nature of integration, and implementation features [2]. This approach allowed for a shift from discussing STEM as a slogan for educational policy to an analysis of specific pedagogical mechanisms.

At the same time, empirical data has accumulated. By 2020–2021, systematic reviews and meta-analyses have emerged that have made it possible to assess the impact of STEM programs not just at the level of individual successful projects, but across studies. Therefore, it has become possible to conduct a more substantive analysis of which STEM elements are truly associated with improved educational outcomes, and which remain largely declarative.

The development of the concept of STEM education. Historically, school education was structured primarily around individual subject areas. Science, mathematics, technology, and engineering developed as relatively independent fields, and curricula replicated this structure. However, real-world professional and social challenges rarely correspond to the boundaries of individual disciplines.

Solving an engineering or environmental problem may simultaneously require scientific explanation, mathematical modeling, application of technology, and design of a practical solution. This contradiction became one of the foundations for the development of integrated STEM. The National Research Council viewed integration as a way to strengthen connections

between disciplines and create conditions in which students can apply knowledge from one field to solve problems arising in another [2].

However, the concept of STEM has long remained conceptually ambiguous. Breiner et al. have shown that even higher education teachers working directly in STEM disciplines may understand the concept differently. For some, STEM primarily refers to the combination of four disciplines, while for others, it refers to a specific type of interdisciplinary interaction [1]. Consequently, the presence of four components alone does not make an educational program an integrated STEM program.

Gradually, the scientific literature began to develop the idea of distinguishing between **multidisciplinary**, **interdisciplinary**, and **transdisciplinary** forms of integration. In a multidisciplinary approach, several disciplines are present within a single project but retain relatively independent content. The interdisciplinary model involves the interaction of concepts and methods from various fields.

The transdisciplinary approach goes further and focuses on a complex, real-world problem, in the solution of which the boundaries between disciplines become less significant. Thus, the evolution of STEM has progressed from the simple coordination of subjects to the search for mechanisms for their meaningful integration.

Interdisciplinary integration as a foundation for STEM. One of the most influential conceptual works is the Kelley and Knowles model, which links integrated STEM learning with scientific inquiry, engineering design, mathematical representation, and the use of technology [3].

The authors proceed from the fact that integration should be carried out not only at the level of the curriculum, but above all in the process of students solving specific problems. In this understanding, a STEM task has several interconnected components. First, a problem or practical need is formulated. Students then research the phenomenon, collect data, use mathematical methods, create or select technological solutions, and develop an engineering product or model. The resulting solution is tested and refined. This logic is fundamentally different from the situation where, after studying four separate subjects, a student is asked to formally complete a "STEM project." In the latter case, the integration may remain superficial. In a true STEM approach, the task itself must require the use of knowledge from multiple fields. The National Research Council identified potential outcomes of integrated STEM not only as improved academic achievement, but also as development of STEM literacy, the ability to transfer knowledge across disciplines, the formation of a STEM identity, and interest and readiness for further learning [2]. Consequently, the effectiveness of STEM cannot be assessed solely by traditional subject tests.

Main pedagogical models of STEM education. One of the most characteristic elements of STEM is learning through problem-solving and project-based learning. Unlike traditional imparting of pre-existing knowledge, students are placed in situations where they must independently define a problem, formulate possible solutions, test hypotheses, and evaluate the results.

The project-based approach is particularly well suited to the engineering nature of STEM. Students can design a structure, build a prototype, program a device, develop a model, or conduct an experiment. Knowledge of mathematics and natural sciences is used as tools to solve practical problems.

However, a project alone does not guarantee integration. If a project contains only a technological component or is a set of sequential tasks across different subjects, its STEM nature is limited. Therefore, the essential requirement is the existence of meaningful connections between disciplines.

Inquiry-based learning is based on asking questions, formulating hypotheses, collecting and analyzing data, and constructing explanations. Its connection to STEM is particularly evident when scientific inquiry transitions into engineering design. An important foundation for this approach was provided by the Framework for K–12 Science Education, published by the National Research Council in 2012. It views scientific practices and engineering design as central components of science education [4]. Students should not only learn established scientific facts but also gain experience in how knowledge is created, tested, and applied.

design has become one of the key mechanisms linking STEM disciplines. In a typical model, students are given a problem with specific constraints, develop possible solutions, select evaluation criteria, create a prototype, test it, and make modifications. Engineering design is important because it translates abstract knowledge into action. A mathematical formula becomes a calculation tool, a physical law becomes the basis for a design solution, and technology becomes the means of creating a product. It is the inclusion of engineering design that distinguishes many modern integrated STEM models from traditional science and mathematics instruction.

Digital technologies and robotics. By 2022, digital technologies had already become a significant component of STEM education. Computer modeling, programming, robotics, and computer-supported collaborative learning have enabled the creation of educational tasks that are difficult to implement using traditional means alone.

Of particular interest is a meta-analysis of computer-supported collaborative learning in STEM, which included 143 studies and 316 results. The authors found an overall effect size of approximately 0.51, indicating a moderate positive effect, with effectiveness dependent on student level, field of study, technology used, and pedagogical approach [5]. This allows for an important conclusion: **technology is not an independent source of educational effect** . The outcome is determined by the combination of technology and instructional design.

The Impact of STEM on Academic Outcomes. One of the central questions in the literature is the effectiveness of STEM compared to traditional forms of education. By 2022, the results of several meta-analytic studies had accumulated. Batdi, Talan, and Semerci analyzed 26 studies of STEM education and found a statistically significant positive effect on academic achievement; the overall effect size was approximately 0.655 [6]. However, this result should be interpreted with caution, as the included studies varied significantly in student age, subject content, duration, and intervention structure.

A more rigorous evidence base is provided by a meta-analysis by Lynch et al., which included 95 experimental and quasi-experimental studies of teacher professional development programs and STEM curricula. The mean weighted effect size was +0.21 standard deviations [7]. Moreover, more pronounced results were observed in programs that helped teachers use educational materials, deepened subject and pedagogical knowledge, and provided support for program implementation.

Thus, scientific evidence does not support the simplistic formula that "any STEM instruction automatically improves academic performance." Instead, effectiveness depends on the quality of pedagogical implementation. A separate meta-analysis of STEM programs aimed at mathematical achievement also found a positive, albeit relatively small, overall effect size of approximately 0.24 [8]. Differences between studies indicate significant heterogeneity in STEM interventions. Therefore, a more accurate conclusion is that **STEM has a potentially positive, but context-dependent, effect.**

STEM and the development of cognitive and creative abilities. Academic knowledge is only one part of the expected STEM outcomes. Problem-solving, critical thinking, creativity, the ability to process information, and the ability to apply knowledge to new situations also play an important role. From this perspective, the connection between STEM and creativity is particularly significant. A systematic review of STEM and STEAM research from 2010 to 2020 found empirical evidence for the positive impact of relevant educational interventions on students' creativity [9].

The inclusion of art in STEAM is seen by some authors as a way to expand the scope of creative activity and make design less focused solely on technical efficiency. However, the transition from STEM to STEAM should not be viewed as a one-size-fits-all solution. It is only effective if art truly serves a cognitive or design function, rather than being merely a formal addition to STEM.

An even more significant outcome of STEM is the development of the ability to transfer knowledge. In a real-world problem-solving situation, students must determine what knowledge from physics, mathematics, computer science, or other fields is necessary to solve the problem. This ability does not develop automatically when studying disciplines in isolation.

Motivation, engagement, and STEM identity. Another important area of research concerns motivational outcomes. The STEM approach involves using tasks that are practical and relevant to real-world situations. This potentially increases the subjective significance of learning. A study by De Loof et al. found that integrated STEM instruction can promote student engagement, but the effect depends on the specific organization of the learning process [10]. The mere use of STEM terminology does not guarantee increased interest.

In this context, it's important to distinguish between short-term engagement and long-term STEM identity. A fascinating project can boost interest in a particular activity, but developing a lasting intention to continue STEM education requires more sustained exposure, support from teachers, and positive learning experiences.

The National Academy of Engineering and the National Research Council included the development of STEM identity, interest, continued STEM education, and career orientation among the significant potential outcomes of integrated STEM [2].

Teacher training as a critical factor. One of the most persistent challenges in STEM is teacher training. Integrated learning requires teachers to possess competencies that extend beyond a single discipline. A math teacher must understand how their subject can be used in an engineering problem; a science teacher must understand how research results translate into design; and a technology teacher must understand how mathematical and scientific knowledge is used in product creation.

A systematic review of integrated STEM implementation challenges, based on an analysis of 17 studies, identified the teacher as the central challenge in STEM implementation [11]. This finding is consistent with the results of a meta-analysis by Lynch et al., which found that the characteristics of teacher professional development were associated with the magnitude of educational effects [7]. Consequently, the STEM challenge lies not only in the development of new teaching materials. Equally important are teacher professional development, collaborative planning, interdisciplinary collaboration among teachers, and the creation of professional communities.

The team-teaching model, in which several teachers collaborate to organize a STEM project, appears particularly promising. However, its large-scale implementation faces organizational limitations: the need for additional planning time, curriculum coordination, and schedule changes.

The problem of assessing STEM outcomes. The paradox of modern STEM pedagogy is that learning goals are becoming interdisciplinary, while the assessment system in many cases remains subject-specific. A systematic review by Gao et al. included 49 empirical studies of interdisciplinary STEM education. The authors found that most assessment procedures focused on monodisciplinary knowledge and affective outcomes, while interdisciplinary knowledge and practices were assessed significantly less frequently [12]. This is a fundamental methodological problem.

If a STEM program is designed to develop the ability to integrate knowledge of physics, mathematics, and engineering, but the final test only tests isolated facts about physics, the educational outcome is not fully assessed. Therefore, STEM assessment should consider not only the final product but also the process of its creation. Promising assessments include design solutions, engineering prototypes, research reports, argumentation, mathematical models, the ability to explain interdisciplinary connections, and the quality of collaboration. Thus, the development of STEM is inevitably associated with the transition from a predominantly test-based assessment to a multi-component assessment system.

Inclusiveness and the Social Dimension of STEM. STEM education is traditionally viewed as a tool for training specialists for the knowledge economy. However, its significance extends beyond the labor market. Modern society demands that citizens understand scientific

information, assess technological risks, and make decisions in the face of complex socio-technical problems.

At the same time, unequal participation across social groups remains a problem in STEM. A systematic review of Indigenous student support programs published in 2021 found that effective initiatives are more likely to utilize culturally relevant content and research practices [13]. This finding has broader implications: a universal STEM model is not necessarily equally effective for different student groups. Context, culture, access to resources, and family and institutional expectations can significantly influence outcomes.

Therefore, modern STEM education must simultaneously address two issues: improving the quality of STEM training and expanding access to it.

Key contradictions in STEM development. An analysis of the scientific literature reveals several systemic contradictions.

The first contradiction is between integration and the subject-based organization of education. STEM presupposes connections between disciplines, whereas school curricula, textbooks, teacher qualifications, and schedules are traditionally organized by subject [2].

The second is between the stated outcomes and the assessment system. Programs declare the development of interdisciplinary thinking, but assessment instruments often measure individual subject knowledge [12].

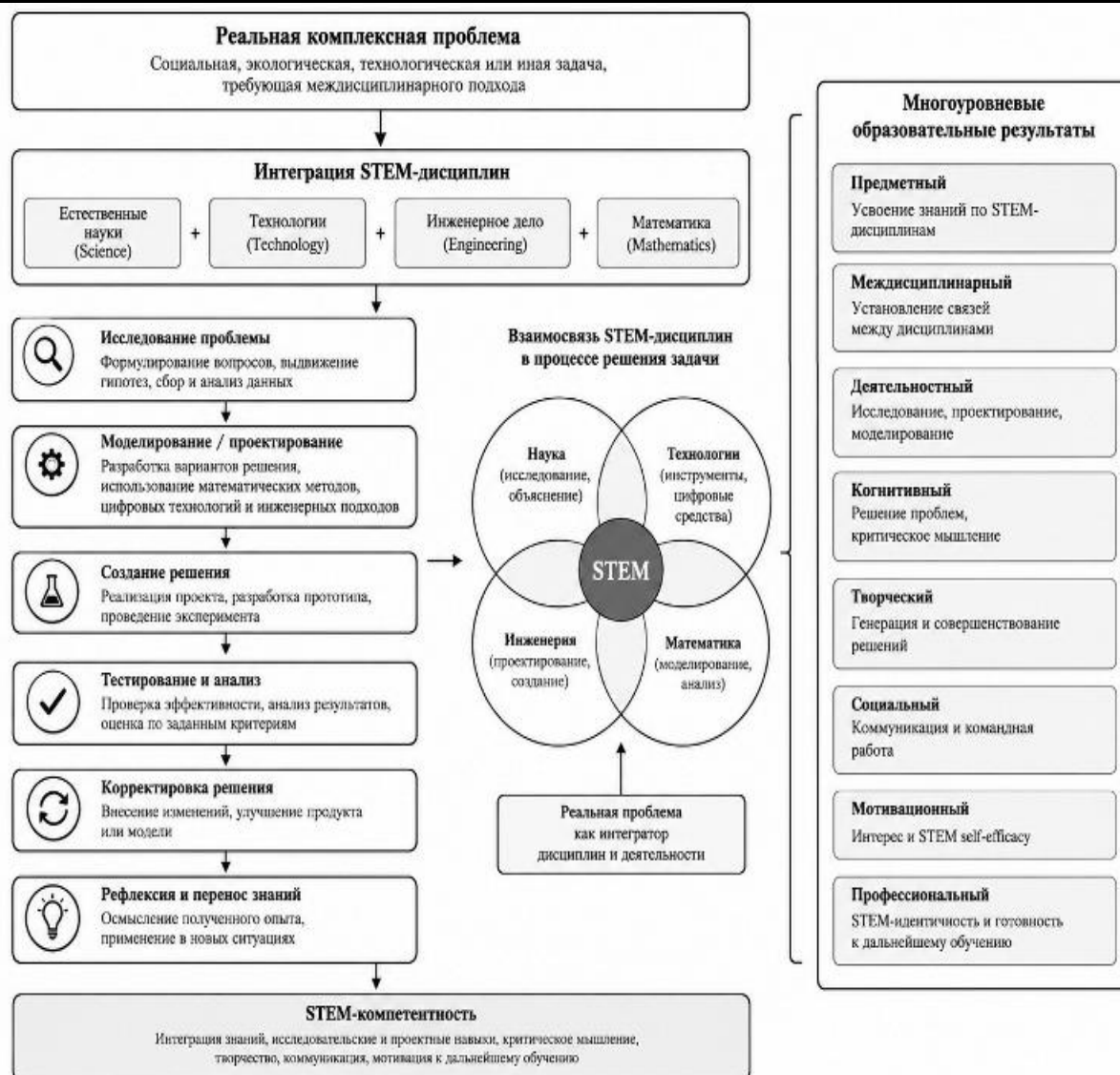
Third, there's a relationship between technological support and pedagogical effectiveness. The presence of robotics, software, or digital platforms does not guarantee educational outcomes. Research on computer-supported learning shows that effectiveness is determined by the interaction of technology and instructional design [5].

Fourth, there is a gap between high public expectations and the heterogeneity of the evidence base. Meta-analyses generally demonstrate positive effects of STEM, but the effect size varies, and the results depend on the age of the students, the subject area, the duration of the intervention, and the quality of implementation [6–8].

Fifth, there is a tension between STEM innovation and teacher readiness. Pedagogical competence remains one of the main limitations to the scaling of integrated programs [7, 11].

A generalized analytical model of STEM education.

Based on the literature reviewed, STEM education can be represented as a sequential system:



This model fundamentally distinguishes integrated STEM education from the simple combination of the four subjects. The central element becomes a problem that requires drawing on knowledge from various disciplines.

In this system, the educational outcome is also multi-level:

Level	Main result
Subject	Acquiring knowledge in STEM disciplines
Interdisciplinary	Establishing connections between disciplines
Activity-based	Research, design, modeling
Cognitive	Problem solving, critical thinking
Creative	Generation and improvement of solutions
Social	Communication and teamwork
Motivational	Interest and STEM self-efficacy
Professional	STEM identity and readiness for further education

It is precisely this multi-level nature of the results that explains why traditional subject tests are unable to fully assess the effect of STEM.

Conclusion

STEM education has undergone a significant evolution from a primarily political and economic concept of training personnel to a comprehensive pedagogical model focused on integrating knowledge and practices from science, technology, engineering, and mathematics.

An analysis of the scientific literature shows that the most consistent characteristics of STEM are a focus on real-world problems, interdisciplinary integration, research, engineering design, project work, and the use of technology. These characteristics are reflected in both conceptual models and systematic reviews of empirical research [2, 3].

Accumulated meta-analytic evidence generally indicates a positive impact of STEM programs on academic outcomes and the development of individual cognitive and motivational characteristics. However, the effect is not universal and depends on the quality of instructional design, teacher training, program duration, and the alignment of teaching methods with stated objectives [5–8].

The most significant unresolved problem remains the gap between the declared interdisciplinarity of STEM and the actual structure of the educational process. In particular, interdisciplinary results are significantly less often the subject of direct assessment than traditional subject knowledge [12].

Thus, the further development of STEM requires not so much expanding the number of STEM programs as improving the quality of their conceptual and pedagogical design. A promising model is one in which a real-world problem integrates scientific research, mathematical analysis, technological activity, and engineering design. In this case, STEM becomes not the sum of four disciplines, but a unique form of organizing students' cognitive and practical activities.

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