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L M Hrynevych[1], L L Khoruzha[2], N M Rudenko[3] and V V Proshkin[4]

[1] Department of management, Borys Grinchenko Kyiv University, 18/2 Bulvarno-Kudriavska St., Kyiv, Ukraine
[2] Department of theory and history of pedagogics, Borys Grinchenko Kyiv University, 18/2 Bulvarno-Kudriavska St., Kyiv, Ukraine
[3] Department of primary education, Borys Grinchenko Kyiv University, 18/2 Bulvarno-Kudriavska St., Kyiv, Ukraine
[4] Department of computer science and mathematics, Borys Grinchenko Kyiv University, 18/2 Bulvarno-Kudriavska St., Kyiv, Ukraine

E-mail: `l.hrynevych@kubg.edu.ua, l.khoruzha@kubg.edu.ua, n.rudenko@kubg.edu.ua, v.proshkin@kubg.edu.ua`

Abstract. The article considers the problem of STEM education in the context of improving the quality of science and mathematics literacy of pupils. The results of the monitoring study conducted by the "OsvitAnalityka" Analytical Center of Borys Grinchenko Kyiv University in cooperation with the Kyiv City Educational Agency and the Ukrainian Center for Educational Quality Assessment are presented. The state of formation of science and mathematical literacy of pupils as the ability to apply knowledge to solve practical problems for the implementation of STEM education has been established. Examples of practice-oriented integrated tasks in geography, chemistry, biology and physics that reveal the possibilities of STEM education are given. The success of the implementation of individual tasks, which involved subject integration and the use of knowledge in practice is analyzed. The most important factors influencing the quality of STEM education are highlighted: professional level of teachers, material and technical and educational-methodical support, motivation of pupils, practice-oriented content of education. As a result of the monitoring study, recommendations were prepared for general secondary education institutions for further implementation of STEM education.

1. Introduction

STEM education should play a key role in the education system, be a prerequisite for strengthening the competitiveness of the economy, human capital development and innovation. According to the Concept of Development of Natural and Mathematical Education (STEM education), "natural and mathematical education is a key direction in the development of education, part of public policy to strengthen economic competitiveness and human capital development, one of the main factors of innovative educational development, economy and the needs of society" [1]. In this context, one of the most important conditions for the implementation of such tasks of STEM education is the formation of pupils' science and mathematical literacy.

According to the methodology of the international comparative study PISA, "pupil mathematical literacy is defined as the ability to formulate, apply and interpret mathematics in

a variety of contexts. This includes mathematical reasoning and the application of mathematical concepts, procedures, facts and tools to describe explain and predict phenomena. Literacy helps to understand the role of mathematics in the world, to draw informed conclusions and to make the decisions people need as creative, active and conscious citizens. Science literacy is defined as the ability of a pupil as a conscious citizen to study and solve issues related to science and scientific ideas. A scientifically literate person is ready to argue about science and technology, which requires such competencies: to explain various phenomena from a scientific point of view, to evaluate and develop research, as well as to interpret data and evidence from a scientific point of view" [2].

So, in fact, it is about the ability of pupils to solve practice-oriented tasks. In other words, use the knowledge, skills and abilities acquired at school to overcome real life difficulties and challenges. This ability is a clear understanding of the role of natural and mathematical knowledge in the modern world, the ability to explain natural and scientific phenomena, draw sound conclusions about them, understand the impact of science and technology to improve the material, intellectual and cultural environment.

At the same time, the results of the international comparative study PISA, in which Ukrainian 15-year-old pupils took part for the first time in 2018, showed alarming trends in low academic achievement in science and mathematics. In particular, 36% of our pupils did not reach the basic level in mathematical literacy (OECD average is 23.9%), in science literacy is 26.4% (OECD average is 21%) [2]. According to the results, our pupils have special problems with the application of knowledge to solve practical and complex problems. Therefore, the study of the level of development of scientific and mathematical literacy of pupils as a guarantee of quality STEM education is on time.

As N. Morze points out, "the introduction of STEM education is changing the economy as a whole, making it more innovative and competitive. According to relevant studies, attracting only 1% of the population to STEM professions can increase the country's GDP to $ 50 billion. The need for STEM specialists is growing 2 times faster than in other professions, as STEM develops the ability to research and creative activities, experimentation; ability to work in a team on joint projects, including using ICT; promotes the formation of analytical, critical and innovative thinking. In addition, it is estimated that 75% of the professions that are currently emerging and developing will require STEM skills" [3]. Theoretical and methodological problems of STEM education are the subject of research of many scientists.

Thus, S. Cheryan, S.A. Ziegler, A.K. Montoya, L. Jiang [4], M.-T. Wang, J.L. Degol [5] investigated gender differences in performance in physics, chemistry, biology, geography and mathematics. M.-B. Ibáñez, C. Delgado-Kloos [6] revealed the importance of using digital technologies, including augmented reality, for the implementation of STEM education. S. Semerikov, S. Lytvynova and M. Mintii [7] described the process of introducing a course on the development of virtual and augmented reality software for future teachers of STEM disciplines. E.J. Sintema [8] presented the impact of COVID-19 on the implementation of STEM education, in particular, analyzed the impact of the pandemic on reducing the success rate of high school pupils in national exams. L.D. English [9] revealed the prospects of STEM education, the main approaches to integration of STEM, the spread of STEM on STEAM. K. Holmes, J. Gore, M. Smith, A. Lloyd [10] presented the influence of various factors on the quality of STEM education. M. Laforce, E. Noble, C. Blackwell [11] cited the impact of Problem-based learning and pupils' interest in STEM implementing. D.G. Hoeg, J.L. Bencze [12] based on the analysis of existing educational standards and programs in the United States cited the values of STEM education. R.B. Toma, I.M. Greca [13] revealed the possibilities of integrating academic disciplines in the implementation of STEM. V. Osadchyi [14] cited the peculiarities of the use of equipment for the implementation of STEM education. N. Kushnir [15] presented open educational resources for the organization of education in the context of STEM education.

STEM education in Ukrainian schools faces a number of problems, including declining levels of teaching sciences and mathematics, non-compliance of educational content with current requirements, teaching science and mathematics to teachers of other specialties, low quality textbooks, insufficient logistics of specialized classrooms, lack in some educational institutions appropriate conditions to provide pre-professional training and specialized training of natural and mathematical subjects, etc. In turn, the lack of knowledge does not allow school leavers to choose professions related to sciences and mathematics to continue their studies. In addition, the modern labor market offers more and more competitive vacancies every year, but the weak natural and mathematical training of young people makes it difficult to select candidates for vacancies.

These factors encourage the modernization and renewal of natural and mathematical training in school in accordance with the Concept of the New Ukrainian School [16], which among the key competencies necessary for successful self-realization in society, defines innovation, mathematical competence and competence in science, and technology. We also consider important the implementation of scientific education, which according to L. Hrynevych and N. Morze is a kind of pedagogical concept, the purpose of which is to promote and study science among pupils. Thus, the overarching idea of scientific education is the introduction of new methods of teaching sciences and mathematics and the formation of a scientific style of thinking, which, in turn, is the basis of human ability to innovate [17]. The outlined requirements are in line with the "Basic Standard of General Secondary Education", which defines the requirements for compulsory learning outcomes based on the competence approach [18].

The outlined problem acquires special significance for educational institutions of Kyiv, which usually serve as a reference point for the functioning and development of the education system for other regions of the country. Therefore, the analytical center "OsvitAnalityka" of Borys Grinchenko Kyiv University in cooperation with the municipal enterprise "Educational Agency of Kyiv" and the Ukrainian Center for Educational Quality Assessment organized and conducted a study of science and mathematical literacy of 15-year-old pupils in Kyiv. In most countries, it is at this age that pupils graduate from general school and face a choice of profession.

2. The aim of research

The purpose of the study is specified in the following tasks: 1) prove the feasibility of using the integration of disciplines as a condition for the implementation of STEM education; 2) identify problems in teachers' understanding of the essence of the integration process, the introduction of an integrated course in natural sciences; 3) prepare recommendations for general secondary education institutions for further implementation of STEM education.

3. Research methods

The following methods were used in the research process: analysis of scientific and pedagogical literature on highlighting the essence of STEM education, science and mathematics literacy; analysis of online resources on this problem, methodological literature on the development of practice-oriented integrated tasks in geography, physics, chemistry and biology; study and generalization of pedagogical experience on the factors influencing the quality of STEM education; monitoring research to study pupils' ability to solve STEM tasks; methods of mathematical statistics for the presentation of research results.

Respondents of the monitoring study on the quality of natural and mathematical education of pupils of schools in Kyiv were a representative sample: 3135 pupils, 976 teachers and 195 directors of schools in Kyiv. The tools of the research included test tasks for pupils, developed by the staff of the Ukrainian Center for Educational Quality Assessment, as well as questionnaires for pupils, teachers and directors of schools. The deadline for testing and interviewing is September 28, 2021.

This article presents some of the results of the monitoring study [19], which reveals the problem of the ability to solve practice-oriented problems as part of the formation of science and mathematical literacy of pupils to implement quality STEM education. A cluster with 6 integrated tasks was developed to demonstrate to pupils the possibilities of considering a certain phenomenon in the perspective of different disciplines (geography, chemistry, biology and physics). The cluster task was built around a cross-cutting theme. Limnological catastrophe, a rare natural phenomenon, was chosen as such a topic. The wording of the question involved consideration of the phenomenon from different angles. The subjects had to assess the importance of knowledge about the geographical laws of nature for human life, compare the hydrographic features of lakes, establish the relationship between physical quantities, analyze facts and explain them, apply theoretical knowledge in life. In addition, all test participants had to demonstrate a sufficient level of proficiency not only in science but also in mathematical literacy, as the tasks required the application of knowledge of mathematics.

4. Results and discussion

An integrated practice-oriented task was developed to determine the level of science and mathematics literacy of pupils as a guarantee of STEM education. The content of the task presents a rare natural phenomenon — Limnological catastrophe. Limnological catastrophe is a rare natural phenomenon caused by the release of carbon dioxide CO_2 from the lake water (limnology is lake science). The greatest limnological catastrophe of modern times, killing more than 1,700 people, occurred in 1986 on Lake Nios, at an altitude of 1,089 m above sea level in Cameroon. The water supersaturated with carbon dioxide rose from a depth of 150–200 meters to the surface of the lake, and the release of dissolved carbon dioxide (degassing) began. The erupted carbon dioxide spread in two streams up to 25 km from the lake, destroying all living things in its path. This condition includes two tasks in geography, two in chemistry, and one each in biology and physics. Appropriate levels of mathematical literacy are also required to solve problems. Consider the task of the test.

Task 1 (geography) If the carbon dioxide content of the two streams was lower, the consequences would not be so catastrophic. Under what conditions would the carbon dioxide erupted from the volcanic crater in which the lake formed be spread evenly in the adjacent territory within a radius of 25 km from the emission source?

A flat terrain

B temperate climate

C in windy weather

D sparse vegetation

Answer: A.

Task 2 (geography) On the tectonic map of the world, the territory of Cameroon and most of Ukraine is marked as areas of ancient platforms, within which there are faults. Why is carbon dioxide emitted by magma not saturated water in any of the 20,000 lakes in Ukraine?

A insufficient precipitation to form deep lakes

B the movement of water in freshwater lakes is impossible

C there are no lakes formed in the craters of volcanoes

D relict stagnant lakes have not been preserved

Answer: C.

Task 3 (chemistry) Carbon dioxide emitted from Lake Nios has accumulated near the earth's surface because it:

A lighter than air

B heavier than air

C is an acid oxide and reacts with water

D reacts with silica (IV) oxide in soil

Answer: B.

Task 4 (chemistry) It was found that during the Limnological catastrophe from the depths of Lake Nios erupted carbon dioxide with a volume of about 1.2 km^3 (NU). Calculate the mass (t) of this gas and indicate the closest to the correct answer among those given. For reference: 1 $km^3 = 10^{12}$ l, 1 $t = 10^6$ g.

A 2400000

B $0,0024$

C 1200000

D 1200000000

Answer: A.

Task 5 (biology) Read the text: "The limnological catastrophe caused carbon dioxide CO_2 to enter the blood because gas exchange occurs due to (1) and is associated with (2) partial pressure (3)". Instead of numbers in the text you need to enter the words in the line. Please indicate the correct answer.

A 1 – active transport, 2 – low, 3 – O_2

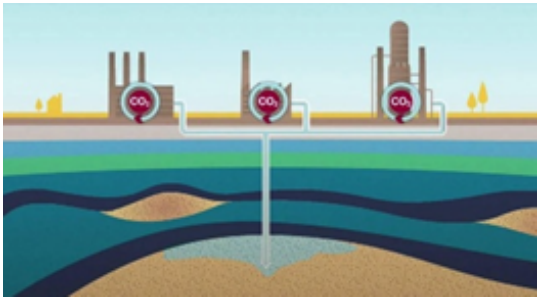
B 1 – active transport, 2 – high, 3 – CO_2

C 1 – diffusion, 2 – low, 3 – O_2

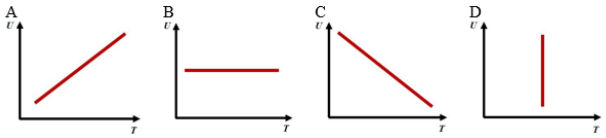
D 1 – diffusion, 2 – high, 3 – CO_2

Answer: D.

Task 6 (physics) Since the early 2000s, the technology of carbon capture and storage of man-made origin (Carbon Capture and Storage, CCS, see Figure) has been gaining popularity. According to it, this gas is buried in underground storage facilities deep underground. The



model of such a storage is a gas-filled closed vessel of constant volume. One of the arguments against the use of CCS technology is the danger of a man-made catastrophe. Which of the following graphs correctly illustrates the dependence of the internal energy U of carbon dioxide on the temperature T in the underground storage?



Answer: A.

The total number of points for the tasks is 20. According to the number of points and the complexity of the tasks there are four levels of pupils' ability to apply knowledge of sciences and mathematics to solve practical problems: primary (0–5 points), intermediate (6–10 points), sufficient (11–15 points), high (16–20 points). To describe the indicators of these levels, the approach to determining the levels of formation of natural and mathematical literacy in the PISA study is used [2]. A detailed description of the levels and indicators of pupils' ability to apply knowledge of sciences and mathematics to solve practical problems is given in the analytical report [19].

According to the results of the study, the state of formation of science and mathematical literacy of pupils as the ability to apply knowledge to solve practical problems for the implementation of STEM education:
6.3% of pupils from the total number of test participants reached a high level;
27.9% – sufficient;
42.2% – intermediate;
23.6% – primary.

According to the data, the majority of pupils (70.1%) reached the intermediate and sufficient levels, in addition, 23.6% of pupils did not reach the intermediate level. Comparing the obtained results with the normal distribution function, we note a pronounced left asymmetry, which indicates that pupils are not fully able to apply the acquired knowledge to solve practical problems and tasks for the implementation of quality STEM education (see figure 1).

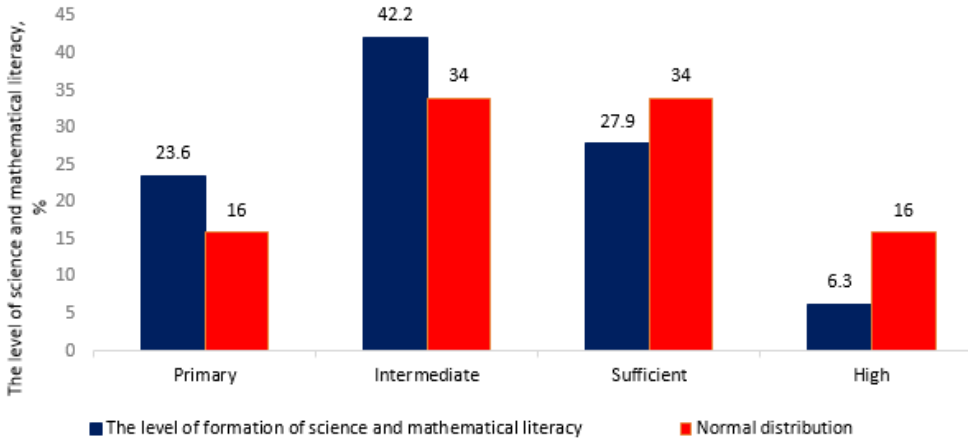


Figure 1. Comparison of the level of formation of science and mathematical literacy of pupils with the function of normal distribution.

Given that the monitoring study of the ability of Kyiv school pupils to apply knowledge of sciences and mathematics to solve practical problems was implemented for the first time, it is possible to partially evaluate its results by comparing them with the results of similar research. It should be noted that the results obtained are similar to the results of the assessment of knowledge of Ukrainian pupils in the international study of the quality of education PISA-2018. Thus, the basic (average) level of formation of science literacy was not reached by 26.4% of research participants, mathematical literacy – 36% of pupils. Only 3% of pupils became the best in the field of sciences, 5% in the field of mathematics [2]. We present the results of practice-oriented integrated tasks that demonstrate the possibilities of STEM education.

- 311 pupils (24.9% of the total) did not complete any task, only 14 pupils (1.1% of the total) completed all tasks.

- On average, 36.4% of participants gave the correct answer to each task, 41.2% – incorrect, 22.4% did not answer.

Thus, the results of practice-oriented tasks in STEM education can be assessed by the majority of respondents as quite low. In addition, the analytical report [19] states that comparing the obtained data with the finiteness of the normal distribution, we can see a pronounced left asymmetry. This indicates that pupils may not fully use the acquired knowledge to solve practical problems and tasks.

The success of each task is shown in figure 2.

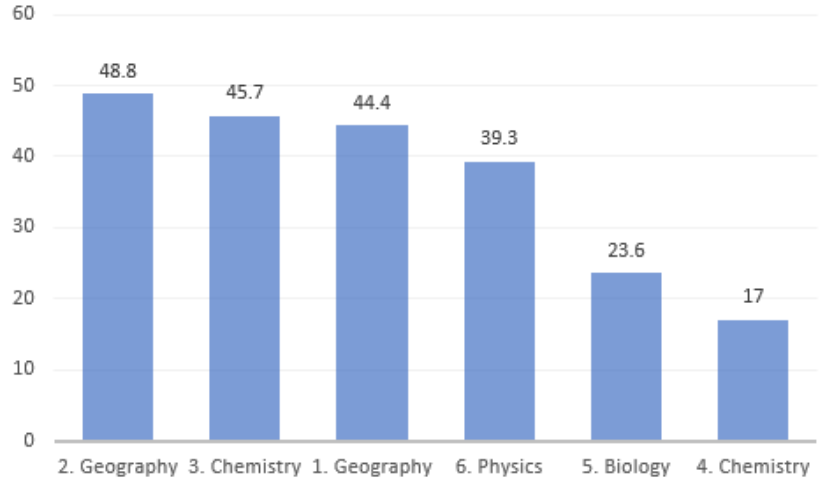


Figure 2. Percentage of pupils who gave the correct answer to individual test questions with practice-oriented integrated tasks.

As a result of the monitoring study it was established:

- Almost half of the test participants are able to assess the geographical patterns of nature of a particular area for human life; compare the hydrographic features of lakes; explain natural phenomena on the basis of chemical knowledge, the dependence of one physical quantity on another; read graphs; apply theoretical knowledge in everyday life.
- About a quarter of those tested are able to explain phenomena based on physical and biological knowledge, including the laws of biology and physics.
- The most difficult for the tested was task 4 (chemistry), it was completed by 17.0% of pupils, which indicates a rather low quality of mathematical literacy. The task tested the ability to apply mathematical methods to solve problems of chemical content, to perform certain calculations according to formulas and schemes of chemical transformation.
- The easiest task was 2 (geography), which was met by 48.8% of participants. They demonstrated the ability to establish the relationship between tectonic structure, topography and inland waters.

Analyze the success of individual tasks that involved subject integration. The pupils best coped with STEM tasks, which dealt with a natural phenomenon related to the following topics:

- "Inland waters: lakes, their types" (task 2, geography);
- "The amount of substance. Avogadro's law. Relative density" (task 3, chemistry).

With the help of these tasks the formation is checked:

- ability to compare hydrographic features of lakes (task 2);
- ability to explain phenomena on the basis of chemical knowledge and laws (task 3, chemistry).

It was found that almost half of the test participants are able to:

- to establish relationships between tectonic structure, relief and inland waters;
- to interpret phenomena on the basis of chemical knowledge and laws;
- to explain the dependence of one physical quantity on another.

According to the results of the study, the most difficult to perform were the tasks in which the described phenomenon concerned the following topics:

- "The amount of substance. Calculation of the mass of a substance by its quantity" (task 4);
- "Breath. Human respiratory system. Gas exchange processes in the lungs and tissues" (task 5).

These tasks tested:

- ability to apply mathematical methods for solving problems of chemical content, to use certain calculations according to formulas and schemes of chemical transformation (task 4);
- ability to analyze and explain facts (task 5).

Thus, according to the results of the study, the ability of pupils to solve practice-oriented integrated tasks as a condition for the implementation of STEM learning can be assessed as quite low. Therefore, the next step of the study was to find out the factors that affect the level of science and mathematics literacy of pupils. To do this, a survey of teachers and school directors identified a number of factors, the most important of which were the following:

- professional level of a teacher;
- material and technical and educational and methodological support;
- motivation of pupils;
- practice-oriented learning content.

The study [2] also proved that these factors affect the quality of STEM education. In particular, the relationship between these factors and the number of points obtained by different pupils as a result of testing. Analyze the factors that affect the quality of STEM education in more detail. First, we asked school directors to assess the qualifications of science and mathematics teachers. It was found that the vast majority of directors claim that the qualifications of teachers of sciences and mathematics in their educational institutions are sufficient to implement quality education. Respondents rate the qualifications of teachers of mathematics, geography and biology especially highly. This is confirmed in the answers of more than 75% of directors. Slightly lower they characterize the qualifications of teachers of chemistry (72.6%) and physics (66.7%), see table 1.

Next, it was important to determine whether teachers believe that their classrooms have modern equipment and the necessary materials for the quality implementation of STEM education. It was found that 20.6% of respondents agree with this, 38.7% rather agree, 27.9% rather disagree, and 12.12% strongly disagree. It should be noted that the obtained data correlate with the information from the directors of schools: 26.7% of people are satisfied with the availability of equipment and necessary materials for high-quality teaching of natural sciences and mathematics, 35.8% are rather satisfied. The next step of the study was to determine whether pupils have sufficient interest in academic disciplines as a guarantee of STEM education (see figure 3).

Table 1. Assessment of qualifications of teachers of educational institutions.

Subject teachers	%
teachers of mathematics	75.8
teachers of geography	75.7
teachers of biology	75.3
teachers of chemistry	72.6
teachers of physics	66.7

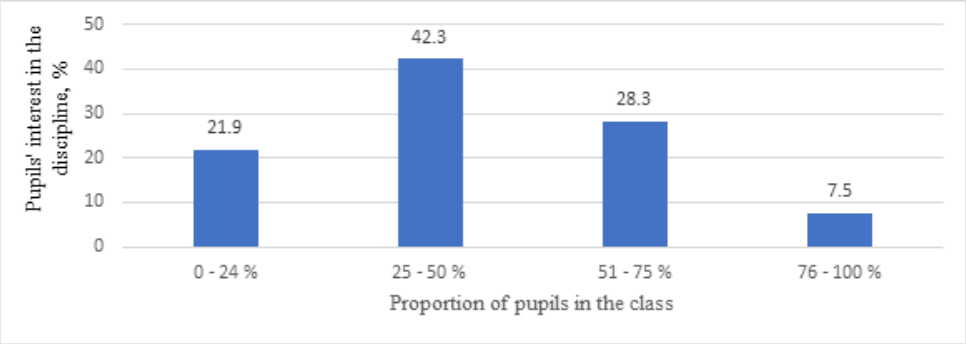


Figure 3. Pupils' interest in the discipline, %.

As a result, most teachers believe that between 25% and 50% of pupils in the class have an interest in the subjects they teach. One in three teachers (35.8%) believes that more than half of pupils are interested in its subject, one in five teachers (21.9%) say that less than a quarter of the class have a strong interest in the discipline. Fundamental in the context of our research was to establish the views of teachers on the ability of pupils to apply theoretical knowledge in practice to overcome various life challenges and problems. The obtained answers are given in figure 4.

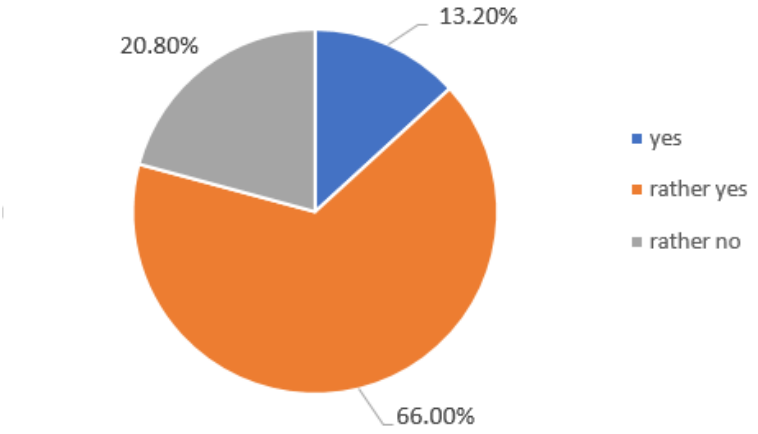


Figure 4. The ability of pupils to apply theoretical knowledge in practice.

It should be noted that only 13.2% of teachers answered yes to this question, the majority

are hesitant, choosing the alternative "rather yes" (66.0%). To understand the nature of these answers, it is advisable to identify the reasons that affect the ability of pupils to qualitatively apply theoretical knowledge in practice. The responses were ranked from more important to less important (see table 2). The reasons influencing the ability of pupils to apply theoretical knowledge in practice are identified (table 2).

Table 2. Reasons for the ability to apply theoretical knowledge in practice.

Rang	Reason	The answer "strongly influenced", %
1	lack of interest in learning	61.6
2	unsystematic attendance of lessons	47.3
3	passivity of pupils in lesson	38.2
4	detachment of the content of academic disciplines from the realities of today	24.9
5	inconsistency of pupils' homework	32.2
6	advantage in teaching theory over practice	15.7

It is established that the most important reasons influencing the ability of pupils to apply theoretical knowledge in practice are the following: lack of interest in learning; unsystematic attendance of lessons; passivity of pupils in lessons. The generalization of the obtained results allowed to state that the average percentage of correct answers to integrated tasks (in geography, chemistry, biology and physics) is from 17% to 48.8%. Almost half of the test participants are able to assess the geographical patterns of nature of a particular area for human life; compare the hydrographic features of lakes; explain natural phenomena on the basis of chemical knowledge, the dependence of one physical quantity on another; read graphs; apply theoretical knowledge in everyday life. About a quarter of those tested are able to explain phenomena based on biological and physical knowledge, the laws of biology and physics. The most difficult task for the test takers was to test the ability to apply mathematical methods to solve problems of chemical content, to perform calculations according to formulas and schemes of chemical transformation. The results show that almost half of the respondents can use only scientific knowledge at the intermediate level to solve problems related to everyday life, and use subject and procedural knowledge to implement quality STEM education. Mathematical literacy is formed at an even lower level, and therefore a much smaller number of pupils can: distinguish the mathematical content of the task, given in text or graphic form; apply mathematical methods to solve problems of applied content; interpret the results of calculations in the context of the task.

5. Conclusions and prospects for further research

1. The state of formation of science and mathematical literacy of pupils as the ability to apply knowledge to solve practical problems for the implementation of STEM education: 6.3% of students from the total number of test participants reached a high level, 27.9% – sufficient, 42.2% – intermediate, 23.6% – primary. The results are similar to the results of assessing the knowledge of Ukrainian pupils in the international study of educational quality PISA-2018, where the basic (average) level of science literacy did not reach 26.4% of participants, mathematical literacy – 36% of pupils. Only 3% of pupils became the best in the field of sciences, 5% in the field of mathematics [2].

2. As a result of the monitoring study, recommendations were prepared for general secondary education institutions for further implementation of STEM education:
   - in the context of further implementation of the reform "New Ukrainian School" in accordance with the requirements of the State Standard of Basic Secondary Education for teachers of sciences and mathematics of 5-9 classes on unlocking the competence potential of mathematics and sciences, in particular to pay attention to the competence paradigm practical, life problems that are relevant to pupils and motivate them to learn;
   - development of methods of teaching sciences and mathematics, including STEM laboratories, which allow the disclosure of the competence potential of mathematics and sciences in accordance with the requirements of the State Standard of Basic Secondary Education, ensure its integration;
   - preparation of methodological materials for the implementation of extracurricular activities (excursions, observations, experiments, etc.) aimed at developing the ability to use knowledge of natural and mathematical disciplines to solve life problems;
   - development of a system for assessing the ability of pupils to apply the acquired knowledge of STEM disciplines to solve practical problems, as well as tracking individual trajectories of pupil development;
   - introduction of interactive learning technologies, strengthening the role of learning activities in the team; use of digital tools for demonstrations, simulations of experiments, popularization of group work, electives to increase the level of interest of pupils in the study of sciences and mathematics;
   - active use in the learning process of interdisciplinary practice-oriented tasks; raising the status of mathematics in the integrative approach to the implementation of STEM education. We consider it promising in further research to clarify the feasibility and prerequisites for interdisciplinary integration in the implementation of STEM education, to justify and suggest ways to address other gaps in the formation of mathematical and scientific literacy.

ORCID iDs

L M Hrynevych https://orcid.org/0000-0002-5818-8259
L L Khoruzha https://orcid.org/0000-0003-4405-4847
N M Rudenko https://orcid.org/0000-0002-6274-9311
V V Proshkin https://orcid.org/0000-0002-9785-0612

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