Chapter 16

STEM-BASED TEACHING CHEMISTRY FOR SUSTAINABLE DEVELOPMENT GOALS IN LEARNING

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INTRODUCTION

The intersection of STEM education, chemistry teaching, and sustainable development represents one of the most promising frontiers in contemporary education. As global challenges become increasingly complex and interconnected, the need for innovative educational approaches that prepare students to address these challenges becomes paramount. There is examines the integration of STEM-based teaching methodologies in chemistry education, with a particular focus on their role in advancing sustainable development goals (SDGs).

The rapid advancement of technology and the growing emphasis on sustainable development have transformed the landscape of science education. Chemistry plays a crucial role in understanding and addressing many of the world's most pressing challenges, from climate change to resource management. However, traditional approaches to chemistry education often fall short in preparing students to apply their knowledge in real-world contexts and to understand the interconnections between scientific principles and global sustainability challenges.

STEM education has emerged as a powerful framework for addressing these limitations by integrating science, technology, engineering, and mathematics in ways that promote problem-solving, critical thinking, and practical application of knowledge. When applied to chemistry education, this approach offers opportunities to develop both scientific literacy and the competencies needed for addressing sustainable development challenges. The STEM approach enables students to engage with chemistry concepts through hands-on experimentation, technological integration, and real-world problem-solving, making the subject more accessible and relevant to their lives.

There is presents a comprehensive examination of STEM-based chemistry teaching as a tool for achieving sustainable development goals. Through three interconnected chapters, it explores the theoretical foundations of STEM education, practical methodologies for implementation in chemistry teaching, and the specific applications of these approaches to sustainable development education. The research draws upon both theoretical frameworks and practical experiences to demonstrate how STEM-based chemistry education can serve as a catalyst for developing environmentally conscious, scientifically literate citizens capable of contributing to global sustainability efforts.

The significance of this research lies in its potential to bridge the gap between theoretical knowledge and practical application in chemistry education while simultaneously addressing urgent global sustainability challenges. By examining the integration of STEM approaches with chemistry teaching and sustainable development goals, this work contributes to the broader discourse on educational innovation and the role of science education in preparing students for the challenges of the 21st century.

1. Theoretical Foundations of STEM Education

In today's world, characterized by rapid development of innovative technologies, education has become an integral factor in shaping citizens' competencies. It is crucial to provide students with quality education in the fields of natural sciences, mathematics, engineering, and programming. This is why STEM education (Science, Technology, Engineering, and Mathematics) has become a key direction in innovative education. Ukraine actively seeks to integrate into the European and global educational space, where the development of students' values and competencies is a priority[1,2].

The acronym "STEM" was introduced to denote an integrated approach to studying these subjects in educational programs to promote critical thinking, creativity, and problem-solving skills. STEM education is designed to prepare students for the modern technological world, where knowledge and skills in these areas are essential[3,4,5].

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[1] STEM-світ інноваційних можливостей : наук.-метод. посіб. / уклад.: О. О. Буряк та ін. Харків : Мадрид, 2019. 64 с.

[2] Yurchenko K. Закордонний досвід та перспективи розвитку STEM-освіти в українських школах. *Науковий вісник Ужгородського університету. Серія: Педагогіка. Соціальна робота*. 2022. № 1(50). С. 337–340. DOI: 10.24144/2524-0609.2022.50.337-340.

[3] Упровадження STEM-освіти в умовах інтеграції формальної і неформальної освіти обдарованих учнів : метод. рек. / Н. І. Поліхун та ін. Київ : Інститут обдарованої дитини НАПН України, 2019. 80 с.

[4] STEM-освіта / Інститут модернізації змісту освіти. URL: https://imzo.gov.ua/stem-osvita/ (дата звернення: 23.01.2025).

The main goal of STEM education lies in implementing state policy considering new requirements established by the Law of Ukraine "On Education"[6]; the Concept of State Policy Implementation in the Field of General Secondary Education Reform for the period until 2029 "New Ukrainian School", approved by the Cabinet of Ministers of Ukraine Order No. 988-r dated December 14, 2016[7]; the Concept of Natural and Mathematical Education Development (STEM Education), approved by the Cabinet of Ministers of Ukraine Order No. 960-r dated August 5, 2020, and other regulatory documents[8,9] that standardize STEM education development in general secondary and extracurricular education institutions.

Thus, STEM education encompasses such fields as science, technology, engineering, and mathematics. It provides a sequence of courses and programs that prepare students for successful employment and further education after completing general secondary education. This approach requires students to develop various skills, including technical and mathematical abilities, as well as the capacity to apply scientific concepts in practical activities. STEM education has become a necessity in the modern world, preparing the young generation for contemporary challenges and providing them with the knowledge and skills needed for participation in scientific and technological development[10,11].

It is important to note that STEM education is a relatively new concept in Ukrainian education. However, its relevance and importance are confirmed by numerous publications that have appeared in recent years. These publications address various aspects of STEM education implementation in

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[5] STEM-світ інноваційних можливостей : наук.-метод. посіб. / уклад.: О. О. Буряк та ін. Харків : Мадрид, 2019. 64 с.

[6] Про освіту : Закон України від 05.09.2017 р. № 2145-VIII. *Відомості Верховної Ради України*. 2017. № 38–39. Ст. 380.

[7] Концепція реалізації державної політики у сфері реформування загальної середньої освіти «Нова українська школа» на період до 2029 року : схвалено розпорядженням Кабінету Міністрів України від 14.12.2016 р. № 988-р. URL: https://zakon.rada.gov.ua/laws/show/988-2016-%D1%80#Text (дата звернення: 23.01.2025).

[8] План заходів щодо популяризації природничих наук та математики до 2025 року : затв. розпорядженням Кабінету Міністрів України від 14.04.2021 р. № 320-р. URL: https://zakon.rada.gov.ua/laws/show/320-2021-%D1%80#Text (дата звернення: 23.01.2025).

[9] План заходів щодо реалізації Концепції розвитку природничо-математичної освіти (STEM-освіти) до 2027 року : затв. розпорядженням Кабінету Міністрів України від 13.01.2021 р. № 131-р. URL: https://zakon.rada.gov.ua/laws/show/131-2021-%D1%80#Text (дата звернення: 23.01.2025).

[10] STEM-школа – 2021 : зб. матеріалів / уклад.: Н. І. Гущина та ін. Київ : Освіта, 2021. 155 с.

[11] Лебединець С. П., Бабенко О. М. STEM-освіта як компетентнісна модель навчання. *Актуальні проблеми дослідження довкілля* : матеріали X Міжнар. наук. конф., м. Суми-Тростянець, 25–27 трав. 2023 р. Суми, 2023. С. 306–307.

Ukraine, solving its challenges, and considering development prospects. The authors of these studies include such specialists as T. Andrushchenko, S. Buliha, I. Vasylashko, V. Velychko, S. Halchenko, L. Hloba, V. Kamyshyn, E. Klimova, N. Morze, L. Nikolenko, M. Popova, M. Rybalko, I. Sernytskyi, O. Stryzhak, V. Sharko, and many others[12,13].

The researched topic is also extensively covered in the works of foreign scientists such as J. Bouwma-Gearhart, N. Febrianti, S. R. Juwita, A. Luis August, J. Morrison, O. F. Nugroho, K. H. Perry, J. B. Presley, and others[14,15,16,17].

STEM education promotes creative thinking by encouraging students to think beyond the known and seek new ways of problem-solving. STEM education is important both for developing innovations and ensuring future success in science, technology, engineering, and mathematics fields.

Furthermore, STEM education stimulates the development of interdisciplinary connections and interdisciplinary thinking. Students learn to combine knowledge and approaches from different subjects to solve complex problems that rarely can be resolved using only one discipline[18].

The method of STEM education integration lies in combining various disciplines and approaches in learning to develop students' competencies in these areas. STEM integration creates favorable conditions for studying and applying knowledge, and develops the skills, abilities, and attitudes necessary for solving practical tasks.

The key competencies developed within STEM education include: mathematical competency, competencies in natural sciences, engineering and

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[12] STEM-школа – 2021 : зб. матеріалів / уклад.: Н. І. Гущина та ін. Київ : Освіта, 2021. 155 с.

[13] Stryzhak O. Y. et al. STEM-освіта: основні дефініції. *Information Technologies and Learning Tools*. 2017. Vol. 62, № 16. DOI: 10.33407/itlt.v62i6.1753.

[14] Bouwma-Gearhart J., Perry K. H., Presley J. B. Improving Postsecondary STEM Education: Strategies for Successful Interdisciplinary Collaborations and Brokering Engagement With Education Research and Theory. *Journal of College Science Teaching*. 2014. Vol. 44, № 1. P. 40–47.

[15] Luis August A. Integrating STEM Curriculum Across the Schools' Learning Environment to Reflect & Impact Life Practices. *KnE Social Sciences*. 2023. Vol. 8, № 20. P. 273–285. DOI: 10.18502/kss.v8i20.14608.

[16] Morrison J. TIES STEM Education Monograph Series: Attributes of STEM Education. Baltimore : TIES, 2006.

[17] Nugroho O. F., Juwita S. R., Febrianti N. STEM Education Planning Based on Contextual Issues Sustainable Development Goals (SDGs). *Pedagonal: Jurnal Ilmiah Pendidikan*. 2022. Vol. 6, № 2. P. 159–168. DOI: 10.55215/PEDAGONAL.V6I2.5554.

[18] Державний стандарт базової середньої освіти. URL: https://mon.gov.ua/osvita-2/zagalna-serednya-osvita/nova-ukrainska-shkola-2/derzhavniy-standart-bazovoi-serednoi-osviti (дата звернення: 23.01.2025).

technology, innovation, information and communication competency, lifelong learning, entrepreneurship, and financial literacy[19,20,21].

Competencies are complex capabilities that include not only skills and abilities but also deep understanding, readiness to interact in various situations, and flexibility in applying skills and abilities. STEM competency represents a dynamic system of knowledge, skills, abilities, ways of thinking, values, and personal qualities that form the capacity for innovative activity[22,23].

Thus, STEM education is a trend in modern education due to its ability to prepare youth for future challenges. It promotes the development of creative individuals who can understand, analyze, and solve complex problems in various spheres of life.

STEM education, from a competency-based approach perspective, emphasizes the importance of developing competencies that not only ensure successful academic careers but also help students better understand the world around them and become successful citizens. The ability to analyze information, ask questions, solve problems, and work in teams becomes key skills for students pursuing STEM education[24,25].

Consequently, STEM education involves the integration of natural sciences, technology, engineering, and mathematics to develop a holistic understanding of the world and promotes the development of various student competencies. STEM education within the competency-based approach becomes a key tool for student development in all aspects: from subject competencies to essential skills and value orientations necessary in modern

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[19] Пахомов Ю. Д., Єлізарова В. Г. Гендерночутливий STEM урок з використанням технології доповненої реальності. *Тенденції і проблеми розвитку сучасної хімічної освіти* : зб. наук. пр. I Всеукр. наук.-практ. конф. Івано-Франківськ, 2019. С. 35–38.

[20] Упровадження STEM-освіти в умовах інтеграції формальної і неформальної освіти обдарованих учнів : метод. рек. / Н. І. Поліхун та ін. Київ : Інститут обдарованої дитини НАПН України, 2019. 80 с.

[21] Що таке компетентнісний підхід у навчанні – відповідає Державна служба якості освіти. URL: http://surl.li/cvahx (дата звернення: 23.01.2025).

[22] Державний стандарт базової середньої освіти. URL: https://mon.gov.ua/osvita-2/zagalna-serednya-osvita/nova-ukrainska-shkola-2/derzhavniy-standart-bazovoi-serednoi-osviti (дата звернення: 23.01.2025).

[23] Про освіту : Закон України від 05.09.2017 р. № 2145-VIII. *Відомості Верховної Ради України*. 2017. № 38–39. Ст. 380.

[24] Фединяк О., Родзень С. Компетентнісний підхід у сучасній шкільній хімічний освіті. *Тенденції і проблеми розвитку сучасної хімічної освіти* : зб. наук. пр. I Всеукр. наук.-практ. конф., м. Івано-Франківськ, 23–24 трав. 2019 р. Івано-Франківськ, 2019. С. 16–19.

[25] STEM-світ інноваційних можливостей : наук.-метод. посіб. / уклад.: О. О. Буряк та ін. Харків : Мадрид, 2019. 64 с.

society. Research in STEM education from a competency-based approach perspective opens opportunities for further development of learners.

In many cases, the outcome of STEM activities is a specific product or project. STEM projects can lead to the creation of new technologies, inventions, scientific research, robots, software, material values, etc. These products can be not only material but also conceptual, reflecting new ideas and approaches to problem-solving.

When planning lesson outcomes, teachers anticipate student educational activity products based on the STEM concept. Here is a description of such products:

– S (Science): chemistry/biology/physics/ecology/computer science/health basics/etc. Activity product: observations, conducting experiments, revealing key lesson concepts and their components, understanding the value significance of knowledge and skills acquired during the lesson, developing attitudes, and developing specific values and vital knowledge and skills.

– T (Technology): developing independent research skills and improving information processing abilities. Product: creating videos, presentations, presenting own work, developing communication skills.

– E (Engineering): design, model design including virtual ones. Product: creating visual aids by hand, creating presentations, other research products, elements of engineering design, group work.

– M (Mathematics): improving measurement and calculation skills, abilities to read graphs, perform calculations, use quantitative and ordinal numbers. Product: understanding the qualitative and quantitative composition of chemical formulas, received information, analysis of "Final Diagnostic Work" results.

The general educational STEM approach promotes the development of skills and knowledge that can be useful throughout life and helps prevent the loss of these skills through practical and integrated learning.

The teacher's application of STEM activities, on one hand, stimulates individual student activity, forms positive motivation for learning, reduces passivity and student insecurity, ensures high learning effectiveness, forms certain personal qualities and competencies, and on the other hand, gives teachers themselves the opportunity to: self-improve, think and act differently, and renew their creative potential.

In life, students will need the ability to work with information, think logically, formulate questions, argue responses, make their own conclusions, and defend their opinions. STEM education enables optimal combination of theory and practice. It promotes the development of skills in working with various information sources. Educational process participants do not receive ready-made knowledge but learn to acquire it independently; decisions made in life situations are remembered more quickly than memorizing rules.

Therefore, STEM education is a trend in modern education due to its ability to prepare youth for future challenges. It promotes the development of creative individuals who can understand, analyze, and solve complex problems in various spheres of life. The implementation of STEM education is an important task in modern education that requires approaches different from traditional ones. We will examine these in the next chapter.

2. Methodology of STEM Education Implementation in Chemistry Teaching

A review of scientific publications dedicated to STEM-oriented chemistry teaching demonstrates the relevance of research aimed at improving education quality, developing students' chemical literacy, and forming 21st-century skills.

Rahmawatia Y., Andanswarib F. D., Ridwanc A., Gilliesd R., and Taylore P. Ch. investigated the opportunities and challenges of implementing a STEM approach based on Project-Based Learning (PBL) in teaching chemistry to 10th-grade students[26]. Their research demonstrates that participation in STEM projects improved conceptual understanding of chemistry, critical thinking, and collaboration skills, while stimulating interest in scientific concepts.

Fapriyan W. M. and Antuni W. emphasize the importance of developing chemical literacy among vocational education students through STEM-oriented learning[27]. Their research results indicate significant improvement in chemical literacy levels among the experimental group compared to the control group, confirming the effectiveness of the STEM approach in developing basic knowledge and practical skills.

Hidayatulloh R., Suyono S., and Azizah U. focused on developing STEM-oriented chemistry textbooks aimed at improving students' problem-solving skills. The results showed that the developed textbooks are valid and effective, providing significant improvement in students' academic performance and developing competencies for solving complex tasks[28].

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[26] Rahmawatia Y. et al. STEM Project-Based Learning in Chemistry: Opportunities and Challenges to Enhance Students' Chemical Literacy. *International Journal of Innovation, Creativity and Change*. 2020. Vol. 13, № 7. P. 1673–1694.

[27] Fapriyan W. M., Antuni W. STEM-based chemistry learning in a vocational context: A study of students' chemical literacy. *AIP Conference Proceedings*. 2023. Vol. 2556, № 1. P. 040026. DOI: 10.1063/5.0110399.

[28] Hidayatulloh R., Suyono S., Azizah U. Development of STEM-Based Chemistry Textbooks to Improve Students' Problem Solving Skills. *Jurnal Penelitian dan Pengkajian Ilmu Pendidikan: e-Saintika*. 2020. Vol. 4. P. 308–316. DOI: 10.36312/e-saintika.v4i3.306.

Rolanda V., Adlim M., and Syukri M. analyzed the knowledge level and readiness of future chemistry teachers to implement STEM methodologies in the educational process. Their research revealed an average level of proficiency in STEM domains and the need for further skill development in creativity, innovation, and planning[29].

Thus, the analysis of published research has demonstrated the significant potential of STEM approaches in chemistry teaching. They contribute not only to the development of chemical literacy but also to the formation of critical thinking, creativity, and collaboration skills necessary for adapting to modern world challenges.

Therefore, the goal of implementing STEM education in chemistry teaching is to create an integrated and practical approach to studying chemistry that promotes the development of students' competencies and skills necessary for successful socialization in the modern world.

The implementation of STEM education in the chemistry educational process fulfills several important objectives:

– increasing interest in chemistry through practical research and projects, as STEM demonstrates to students how chemistry is connected to real-life situations, which can enhance their interest in the subject;

– STEM education promotes the development of critical thinking skills, as it requires analysis, logic, and justification of decisions, which is particularly important in chemistry, where composition – structure – properties of substances – their application – occurrence in nature are connected by cause-and-effect relationships and require logic and understanding;

– STEM-oriented exercises present students with real tasks and allow them to solve practical problems, making chemistry learning more engaging and useful;

– STEM unifies natural sciences, technology, engineering, and mathematics, ensuring connections between different fields of knowledge and promoting understanding of their interrelationships;

– STEM education prepares students for work in modern technological society and for the labor market, where science and technology skills are required;

– in STEM projects, students often work in groups, developing communication and collaboration skills that are important in modern society and the labor market.

[29] Rolanda V., Adlim M., Syukri M. A Knowledge Analysis of the Implementation of STEM-Based Learning of Prospective Chemistry Teachers. *Scientiae Educatia*. 2020. Vol. 9. P. 203–215. DOI: 10.24235/sc.educatia.v9i2.6623.

The development and implementation of STEM-oriented lessons that actively engage students in practical research, experiments, and laboratory work is an important direction in the work of educational institutions of various forms of ownership. For chemistry teachers and their students, it is an element of creative activity and an opportunity to make their own discoveries or conduct their own research of chemical phenomena, compounds, etc.

The implementation of STEM-Based Teaching Chemistry in general secondary education institutions promotes the development of students' skills and strengthens their knowledge. The means of achieving success include various methods, approaches, and tools that contribute to the successful implementation of this technology. A question arises: which STEM activities should be chosen to achieve maximum effectiveness according to the set goals and objectives? Here are some of them:

– practical sessions and laboratory work – STEM learning, including chemistry, is typically based on practical sessions and laboratory work, helping students gain practical experience and skills that can be more easily retained for life;

– projects and research – STEM learning emphasizes projects and research, helping students develop analytical skills and solve real-world problems, which stimulates active application of knowledge and skills;

– knowledge integration – STEM education promotes the integration of knowledge and skills from various fields of science and technology, helping students see connections between different subjects and apply knowledge in various contexts;

– technology application – STEM learning incorporates the use of modern technologies and tools, which can maintain and enhance students' technological skills;

– support for critical thinking – STEM education promotes the development of critical thinking and the ability to analyze and solve complex problems, helping students develop analytical skills;

– engagement in creative thinking – STEM learning promotes creative approaches to problem-solving, developing creativity and independent problem-solving skills;

– continuous learning and self-development – STEM education can encourage students toward continuous learning and self-development as they learn to solve new problems and apply new technologies.

Let us summarize the main arguments regarding the importance of investigating STEM education implementation in the chemistry educational process:

– development of key skills: implementing STEM education in chemistry education promotes the development of key skills such as critical thinking, communication, and collaboration, which are essential in modern society and the labor market;

– preparedness for future challenges: STEM education helps prepare students to address global challenges such as climate change, energy efficiency, and medical discoveries by developing their research capabilities;

– increased interest in chemistry: using STEM education can make chemistry learning more engaging and practical for students, as it helps increase their interest and motivation to study this science;

– training qualified specialists: according to modern labor market needs, STEM education in chemistry can nurture a new generation of qualified specialists in science and technology, who are key to technological development;

– global competitiveness: countries actively developing STEM education typically have greater competitiveness on the world stage and can more easily cope with economic and technological challenges.

Supporting extracurricular STEM activities, field trips, and competitions expands students' opportunities in science and technology. Collaboration with industrial partners and scientific institutions, interaction with private companies and universities to provide students with opportunities to encounter real situations and problems in chemistry – this is timely!

The ability to safely and effectively handle chemical substances is an important part of chemical thinking but is not its only aspect. Chemical thinking includes understanding chemical processes, analysis and synthesis of chemical substances, predicting their behavior, experimental work, and making informed decisions based on chemical knowledge.

Handling chemical substances includes safety and precautionary measures when working with them. This is crucial for preventing possible negative consequences such as injuries or environmental contamination.

The proper and safe handling of chemical substances is a fundamental aspect of chemical thinking, but it represents only one component. Chemical thinking encompasses a comprehensive understanding of chemical processes and their properties, along with the ability to apply this knowledge for analysis, experimentation, and decision-making.

STEM education implementation in educational institutions occurs through STEM-oriented projects and subject-specific weeks integrated into chemistry education. STEM learning in secondary education should:

– focus on real-world challenges and problems;

– incorporate engineering design principles in lessons and extracurricular activities;

– immerse students in practical inquiry and open-ended investigation;
– facilitate productive collaborative work.

Successful STEM education implementation requires consideration of several critical factors[30]:

– integrated disciplines: STEM education employs an integrated approach, unifying various subjects into a cohesive educational process. Students simultaneously develop skills in natural sciences, mathematics, and technology, fostering deeper understanding of cross-disciplinary relationships.

– practical applications: STEM education emphasizes hands-on tasks and project-based learning, enabling students to apply theoretical knowledge in creating tangible solutions to real-world problems.

– complex thinking: a primary objective of STEM education is developing comprehensive analytical skills, enabling students to examine problems from multiple perspectives and formulate optimal solutions.

– practical implementation: STEM lessons provide immediate opportunities to apply theoretical knowledge, reinforcing learning through practical experience.

– active learning: STEM education promotes student engagement through active problem-solving and independent investigation.

– technical subject engagement: STEM makes technical sciences and engineering accessible and engaging for students.

– career preparation: students receiving STEM education develop valuable skills highly sought after in STEM-related fields.

– technological adaptability: STEM education prepares youth for rapid technological advancement in the modern world.

Within the competency-based framework, STEM education emphasizes developing skills that support both academic achievement and real-world success. Critical competencies include information analysis, inquiry skills, problem-solving abilities, and teamwork capabilities.

In STEM subjects like chemistry, students learn to apply scientific methodology to practical problems. They develop skills in hypothesis formulation, data collection and analysis, drawing conclusions, and evidence-based solution development. This approach enhances critical thinking and complex problem-solving abilities.

STEM education fosters creative thinking by encouraging students to explore beyond conventional boundaries and discover innovative problem-

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[30] Лебединець Н. І., Бабенко О. М., Лебединець С. П. STEM-освіта як важливий чинник компетентнісного навчання хімії. *Актуальні питання природничо-математичної освіти*. Суми, 2023. № 2(24). С. 84–89.

solving approaches. This creativity is crucial for advancing innovation in science, technology, engineering, and mathematics.

Furthermore, STEM education promotes interdisciplinary connections and integrated thinking. Students learn to synthesize knowledge and approaches from various disciplines to address complex challenges that rarely can be solved through single-subject approaches.

However, it is essential to establish specific indicators for evaluating the successful implementation of STEM education in developing both hard and soft skills. Let’s examine some key metrics:

– communication changes: assessment of shifts in student-to-student and student-teacher communication patterns, particularly in articulating thoughts, active listening, and conducting discussions;

– creativity growth: analysis of students’ enhanced capacity for idea generation and creative problem-solving;

– collaborative effectiveness: evaluation of joint project outcomes and improvements in student cooperation;

– problem-solving capability: analysis of problem identification and resolution skills development, specifically students’ ability to analyze complex tasks and devise solutions;

– self-organization and discipline: assessment of improvements in self-management skills and students’ project planning and execution abilities;

– critical thinking and analytical skill development: analysis of students’ enhanced capacity for critical information evaluation and data analysis;

– decisiveness and self-confidence growth: evaluation of students’ decision-making capabilities and confidence in their abilities.

Thus, STEM education within the competency-based approach becomes a fundamental tool for comprehensive student development, encompassing subject-specific and key competencies, essential skills, and value orientations necessary in modern society. The core competencies developed through STEM education include critical and creative thinking, complex problem-solving abilities, communication, teamwork, and proficiency in modern technology application.

3. STEM Education as a Tool for Implementing Sustainable Development Goals

STEM education is one of the essential approaches to achieving Sustainable Development Goals, as it ensures knowledge integration, critical thinking development, and real-world problem-solving skills. In the context of 21st-century global challenges, the integration of educational approaches with sustainable development principles becomes increasingly significant. STEM education, particularly in chemistry teaching, serves as a powerful tool for achieving the Sustainable Development Goals (SDGs) adopted by the United Nations[31]. This section analyzes the relationship between STEM education and SDG implementation, as well as practical aspects of implementing sustainable development principles through STEM-oriented chemistry education.

Researchers, particularly Fathurrohman I., Amri M.F., Septiyanto A., and Riandi R.[32], emphasize STEM education's role in enhancing educational quality through interdisciplinary approaches and active student engagement. Luis August A. emphasizes the importance of implementing STEM methods throughout the educational ecosystem to develop sustainable practices and impact quality of life[33].

Alali R., Alsoud K., and Athamna F. investigate STEM education's impact on achieving Sustainable Development Goals and confirm its effectiveness in promoting inclusive, quality education and expanding lifelong learning opportunities[34]. Nugroho O. F., Juwita S. R., Febrianti N. examine STEM educational program planning based on modern curriculum requirements and tasks related to global challenges[35].

The integration of STEM approaches in chemistry education creates opportunities for implementing multiple SDGs simultaneously. Let's examine them in detail.

STEM education plays a fundamental role in implementing Sustainable Development Goal *4 "Quality Education"*, creating an innovative educational paradigm that meets 21st-century challenges. Integrating STEM approaches into chemistry education not only improves educational quality but also ensures the development of key competencies necessary for sustainable societal development.

First, STEM education contributes to achieving sub-goal 4.1, which aims to ensure quality primary and secondary education. In the context of chemistry education, the STEM approach creates a solid foundation for

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[31] Sustainable Development Goals. URL: https://globalcompact.org.ua/en/17-sustainable-development-goals/ (date of access: 23.01.2025).

[32] Fathurrohman I. et al. Integrating STEM based Education for Sustainable Development (ESD) to Promote Quality Education: A Systematic Literature Review. *Jurnal Penelitian Pendidikan IPA*. 2023. Vol. 9, № 11. P. 1052–1059. DOI: 10.29303/jppipa.v9i11.4430.

[33] Luis August A. Integrating STEM Curriculum Across the Schools' Learning Environment to Reflect & Impact Life Practices. *KnE Social Sciences*. 2023. Vol. 8, № 20. P. 273–285. DOI: 10.18502/kss.v8i20.14608.

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understanding natural sciences through practical activities and experimentation. The integration of mathematics, technology, and engineering into studying chemical processes allows students to develop a comprehensive understanding of natural phenomena and their interrelationships.

The role of STEM education becomes particularly significant in implementing sub-goal 4.4, aimed at increasing the number of youth and adults who possess necessary skills for employment and entrepreneurship. STEM-oriented chemistry education develops critical thinking, analytical abilities, complex problem-solving skills, and innovative thinking. These competencies are key for successful professional activity in the context of the fourth industrial revolution.

In the context of sub-goal 4.7, which concerns ensuring knowledge and skills for sustainable development, STEM education creates opportunities for integrating sustainable development principles into the educational process. Through practical projects and research in chemistry, students understand the relationship between scientific discoveries, technological progress, and sustainable societal development.

STEM education also promotes gender equality in education (sub-goal 4.5), encouraging girls to study natural sciences and develop careers in STEM fields. Through innovative pedagogical approaches and practice-oriented learning, equal opportunities are created for all students, regardless of their gender, social status, or place of residence.

An important aspect is STEM education's role in preparing qualified teachers (sub-goal 4.c). Implementing STEM approaches requires educators to engage in continuous professional development, master new technologies, and learning methods. This contributes to improving teaching quality and forming a new generation of educators capable of effectively implementing innovative educational practices.

STEM education also plays a key role in developing students' digital literacy and technological competencies. In the era of digital transformation, these skills become an integral component of quality education. The integration of digital technologies into chemistry education through virtual laboratories, computer modeling, and online experiments expands educational opportunities and increases access to quality education.

Special attention should be paid to STEM education's role in developing students' research competencies. Through scientific research, experiments, and project activities, students not only acquire theoretical knowledge but also develop scientific thinking skills, learn to formulate hypotheses, plan experiments, and analyze results. This creates a solid foundation for future scientific and professional activities.

STEM education also promotes entrepreneurial competencies through practice-oriented projects and innovative product creation. Students learn to identify problems, generate solutions, assess risks and resources – crucial skills for future professional activities.

In the context of quality education, developing soft skills through STEM approaches is essential. Team project work, research presentation, communication with experts and stakeholders – all contribute to forming social skills necessary for successful professional activity.

STEM education creates opportunities for individualized learning and addressing students' special educational needs. The diversity of teaching forms and methods, choice of task complexity levels, and learning pace ensure educational process inclusivity and create conditions for each student's development according to their abilities and interests.

An important aspect is STEM education's role in forming motivation for lifelong learning. Through practical orientation and connection with real problems, students realize the value of education and the need for continuous knowledge and skill updates for successful professional activity.

STEM education plays a decisive role in implementing Sustainable Development Goal *6 "Clean Water and Sanitation"*, creating an educational environment where students study theoretical aspects of water resources and develop practical skills for solving water supply and treatment problems. Integrating STEM approaches into chemistry education ensures comprehensive understanding of water ecosystems and conservation technologies.

In achieving sub-goal 6.1 regarding universal access to safe drinking water, STEM education creates opportunities for studying chemical, physical, and biological aspects of water quality. Through laboratory research and practical projects, students master water analysis methods, study quality indicators, and investigate factors affecting water resource safety for human consumption.

STEM education's role becomes particularly significant in implementing sub-goal 6.3, aimed at improving water quality by reducing pollution and minimizing hazardous chemical discharge. Through interdisciplinary approaches, students investigate water pollution sources, study pollutant spread mechanisms in water ecosystems, and develop innovative water treatment methods using modern technologies.

STEM education also promotes technological competencies in water treatment and preparation. Students study filtration system principles, membrane technologies, water disinfection methods, and other modern approaches to ensuring water resource quality. Practical projects allow developing and testing original water treatment solutions using available materials and technologies.

In the context of sub-goal 6.4 regarding water use efficiency improvement, STEM education ensures understanding of rational water resource use importance. Through mathematical modeling and data analysis, students study water consumption patterns, calculate water footprints of various production processes, and develop water use optimization strategies.

An important aspect is STEM education's role in developing an ecosystem approach to water resource management (sub-goal 6.6). Students study relationships between water ecosystem components, investigate anthropogenic impacts on water resources, and develop projects for water ecosystem restoration and protection.

Special attention should be given to STEM education's role in developing research competencies in water chemistry. Students master qualitative and quantitative water analysis methods, study physicochemical water treatment processes, and investigate properties of new filtration and pollutant sorption materials.

STEM education also plays a vital role in developing technological solutions for sanitation (sub-goal 6.2). Students study wastewater treatment system principles, develop waste utilization projects, and explore alternative water source possibilities.

Digital technology integration in water resource studies is crucial. Using geographic information systems, virtual laboratories, and computer modeling allows students to analyze spatial water resource data, predict water quality changes, and develop water resource management scenarios.

STEM education promotes international cooperation in water resources (sub-goal 6.5). Through international project participation, data exchange, and joint research, students develop understanding of water resource problems' global nature and international cooperation importance.

In water ecosystem sustainability context, developing forecasting and modeling skills is important. Students study climate change impact assessment methods on water resources, develop water stress adaptation scenarios, and investigate water ecosystem resilience enhancement possibilities.

STEM education creates opportunities for developing entrepreneurial competencies in water technologies. Students develop innovative water treatment solutions, create water-saving technology prototypes, and study environmental innovation commercialization possibilities.

Communication skills development and water resource data handling ability are important aspects. Students learn to visualize water quality data, create informative presentations for various audiences, and effectively present their research results.

STEM education plays an important role in implementing Sustainable Development Goal *7 "Affordable and Clean Energy"*, creating an educational environment for understanding energy system principles and developing innovative renewable energy solutions. STEM approach integration in chemistry education ensures fundamental knowledge formation about energy transformations and competency development for clean energy technology implementation.

In achieving sub-goal 7.1 regarding universal access to reliable and modern energy supply, STEM education creates opportunities for studying various energy forms and transformation methods. Through laboratory research and practical projects, students study energy system operating principles, investigate different energy generation methods' efficiency, and develop solutions for increasing energy resource accessibility.

STEM education's role becomes particularly significant in implementing sub-goal 7.2, aimed at increasing renewable energy share. The interdisciplinary approach allows students to investigate chemical foundations of solar, wind, geothermal, and bioenergy. Through practical experiments, they study photovoltaic cell principles, investigate different solar panel types' efficiency, and develop innovative materials for renewable energy.

STEM education promotes technological competencies in energy efficiency (sub-goal 7.3). Students study energy audit methods, investigate material thermal properties, develop energy management systems, and create energy consumption optimization projects.

An important aspect is STEM education's role in energy storage technology development. Students research chemical principles of various battery types, study novel energy storage materials, and develop innovative solutions for increasing energy system efficiency.

In hydrogen energy technology development context, STEM education provides understanding of chemical processes for hydrogen production, storage, and use. Students investigate water electrolysis methods, study catalytic processes in fuel cells, and develop hydrogen technology implementation projects.

Special attention should focus on STEM education's role in bioenergy development. Through laboratory research, students study biological energy conversion processes, investigate different biofuel types' efficiency, and develop biomass energy production technologies.

STEM education promotes competencies in thermoelectric technologies. Students study thermal-to-electrical energy conversion principles, investigate thermoelectric material properties, and develop waste heat utilization systems.

STEM education also develops energy system mathematical modeling skills. Students master energy balance calculation methods, create energy network models, and forecast energy system development.

In energy social aspects context, STEM education promotes understanding of energy poverty and equitable energy resource access issues.

Digital technology integration in energy system studies is important. Using simulations and virtual laboratories allows students to analyze energy system operation, optimize parameters, and develop innovative solutions.

STEM education also creates opportunities for developing critical thinking about energy technologies. Students learn to assess different energy sources' environmental impact, analyze energy product life cycles, and make informed energy technology choices.

STEM education plays a decisive role in implementing Sustainable Development Goal *9 "Industry, Innovation and Infrastructure"*, creating an educational environment for developing innovative thinking and competencies in modern industrial technologies. STEM approach integration in chemistry education ensures preparation of specialists capable of developing and implementing innovative solutions for sustainable industrial development.

In achieving sub-goal 9.1 regarding quality infrastructure development, STEM education creates opportunities for studying chemical aspects of modern construction and structural materials. Through laboratory research and practical projects, students study new material properties, investigate durability enhancement methods, and develop innovative solutions for sustainable infrastructure.

STEM education's role becomes particularly significant in implementing sub-goal 9.4, aimed at industry modernization and environmental sustainability enhancement. The interdisciplinary approach allows students to investigate clean production processes, study industrial emission reduction methods, and develop resource-efficient production technologies.

STEM education promotes scientific research and innovation in industry (sub-goal 9.5). Students engage in research projects, study modern analysis and quality control methods, develop innovative technological solutions, and master scientific approaches to solving industrial problems.

An important aspect is STEM education's role in Industry 4.0 technology development. Students study production automation principles, investigate artificial intelligence and robotics applications in chemical industry.

STEM education also creates opportunities for studying additive technologies and 3D printing. Students investigate 3D printing material properties, study chemical aspects of various additive manufacturing methods, and develop innovative industrial applications.

In industrial biotechnology development context, STEM education provides understanding of biochemical production processes. Students study enzymatic technologies, investigate biocatalyst applications, and develop biotechnological solutions for sustainable production.

An important element is STEM education's role in energy-efficient industrial technology development. Students study energy consumption optimization methods and investigate renewable energy source applications in industry.

An important aspect is the integration of safety and occupational health principles into the study of industrial technologies. Students develop solutions to enhance the safety of production processes.

STEM education plays a fundamental role in implementing Sustainable Development Goal 12 *"Responsible Consumption and Production"* by creating an educational environment for understanding circular economy principles and developing competencies in sustainable production. The integration of STEM approaches in chemistry education ensures the formation of systematic understanding of product life cycles and the development of skills for implementing environmentally clean production technologies.

In the context of achieving target 12.1, which concerns the implementation of sustainable consumption and production programs, STEM education creates opportunities for studying the chemical foundations of production processes. Through laboratory research and practical projects, students investigate the impact of various technologies on the environment, study methods for assessing environmental footprints, and develop waste minimization strategies.

STEM education assumes particular significance in implementing target 12.2, aimed at sustainable management of natural resources. The interdisciplinary approach enables students to investigate resource efficiency, study alternative materials, and develop innovative methods for resource conservation in chemical processes.

STEM education promotes the principles of green chemistry (target 12.4). Students study methods for reducing toxic substance usage, investigate environmentally safe catalysts, and examine pollution prevention technologies.

A crucial aspect is STEM education's role in developing waste recycling and disposal technologies (target 12.5). Students investigate chemical methods for materials recycling, study biodegradable polymers, and create technologies for resource reuse.

STEM education also creates opportunities for studying product eco-design principles. Through project activities, students develop products considering their life cycle, investigate possibilities for using recycled materials, and create innovative solutions for extending product service life.

In the context of sustainable production development, STEM education provides an understanding of energy-efficient processes. Students study methods for optimizing energy consumption in production, investigate possibilities for renewable energy source utilization, and develop energy management systems.

In the context of responsible consumption, STEM education creates opportunities for developing critical thinking regarding consumer decisions. Students learn to analyze product composition, evaluate their environmental impact, and make informed decisions about sustainable consumption.

STEM education plays a critical role in implementing Sustainable Development Goal *13 "Climate Action"*, creating an educational environment where students develop comprehensive understanding of climate processes and acquire competencies for developing innovative solutions to combat climate change. The integration of STEM approaches in chemistry education ensures the formation of scientific understanding of global warming causes and consequences.

In the context of achieving target 13.1, which concerns increasing resilience and adaptive capacity to climate-related hazards, STEM education provides understanding of the chemical processes underlying climate change. Through laboratory research and experiments, students study the impact of greenhouse gases on the atmosphere, investigate their formation mechanisms, and propose emission reduction pathways.

STEM education's role assumes particular importance in implementing target 13.3, aimed at improving education and awareness regarding climate change mitigation. The interdisciplinary approach allows students to investigate the interconnections between industrial processes, energy consumption, and climate change, developing systems thinking and understanding of complex environmental interactions.

STEM education creates opportunities for developing technological competencies in climate change monitoring. Students study meteorological instrument principles, master methods for collecting and analyzing climate data, and utilize modern technologies for forecasting environmental consequences.

In the context of developing strategies for reducing greenhouse gas emissions, STEM education provides understanding of the chemical foundations of various technological processes. Students investigate methods for reducing carbon dioxide emissions, study renewable energy technologies, and develop energy efficiency enhancement projects.

A significant aspect is STEM education's role in developing research competencies for studying climate change. Students conduct experiments investigating the greenhouse effect, analyze atmospheric composition, study the impact of various factors on the climate system, and develop methods for carbon footprint assessment.

STEM education also promotes the development of innovative approaches to addressing climate change challenges. Through project activities, students develop green technologies, investigate possibilities for alternative energy source utilization, and create prototypes of environmentally friendly products.

In the context of international climate cooperation, STEM education promotes the development of global thinking and understanding of the necessity for collective action. Students participate in international climate research projects, exchange data and experience, and develop intercultural communication skills.

STEM education plays a key role in forming environmental consciousness and responsible attitudes toward climate change. Through practical research, students recognize the scale of the problem and the importance of individual actions for its resolution, develop environmental ethics, and practice responsible consumption.

A crucial aspect is the integration of digital technologies in studying climate change. The use of geographic information systems, satellite data, and computer modeling enables students to analyze global climate trends, visualize climate changes, and forecast their consequences.

In the context of climate change adaptation, STEM education provides understanding of natural ecosystem resilience mechanisms. Students study biochemical cycles, investigate natural carbon dioxide absorption systems, and develop strategies for enhancing ecological resilience.

An important element is the development of communication skills in climate education. Students learn to effectively present scientific data about climate change, develop information campaigns, and participate in public discussions of environmental problems.

STEM education also promotes critical thinking regarding climate change. Students learn to analyze scientific publications, evaluate the reliability of climate information, and counter environmental misinformation.

Overall, it should be noted that STEM education's effectiveness in achieving SDGs largely depends on the use of innovative pedagogical approaches. Project-based learning, problem-oriented learning, and research methods – all these enable students not only to acquire theoretical knowledge but also to develop practical skills necessary for implementing sustainable development principles. Digital technologies and virtual laboratories play a special role, allowing the modeling of complex chemical processes and their environmental impact.

Evaluating STEM education's effectiveness in the context of achieving SDGs requires developing special criteria and indicators. It is important to consider not only students' academic achievements but also the development of their environmental consciousness, capacity for innovation, and practical application of knowledge in solving sustainable development challenges.

Further development of STEM education as a tool for achieving SDGs requires ensuring a systematic approach to teacher training and appropriate educational material development.

Thus, STEM education in chemistry teaching serves as an effective tool for achieving Sustainable Development Goals. Through the formation of critical thinking, research skills, and capacity for innovation, it prepares a new generation of specialists capable of solving global problems and ensuring sustainable societal development. The continued development of STEM education and its integration with sustainable development principles remains an important task for pedagogical science and practice.

CONCLUSIONS

The comprehensive analysis demonstrates the transformative potential of STEM-based chemistry education in achieving both educational excellence and sustainable development goals. Through the systematic examination of theoretical foundations, practical methodologies, and sustainability applications, this research establishes STEM education as a crucial paradigm for modern chemistry instruction that addresses contemporary global challenges while fostering essential student competencies.

The theoretical framework established in the first chapter illuminates how STEM education serves as a cornerstone for developing critical thinking, creativity, and problem-solving capabilities within an interdisciplinary context. This foundation proves particularly significant for Ukraine's integration into the European and global educational space, as it aligns with international educational standards while promoting innovation and information-communication competencies. The emphasis on creating tangible products through the integration of science, technology, engineering, and mathematics demonstrates how theoretical knowledge can be transformed into practical applications, thereby enhancing student engagement and learning outcomes.

The methodological approaches detailed in the second chapter reveal the effectiveness of STEM-oriented teaching in developing chemical literacy and critical thinking skills. The implementation of STEM projects in chemistry education has shown remarkable success in increasing student engagement through practical applications and real-world connections. The research supports the assertion that this integrated approach not only enhances students' understanding of chemical concepts but also develops crucial skills such as safe laboratory practices, analytical thinking, and experimental competence. The emphasis on cross-disciplinary connections and the use of modern technologies in chemistry education prepares students for the complexities of contemporary scientific challenges.

The third chapter's focus on Sustainable Development Goals (SDGs) demonstrates how STEM-based chemistry education serves as an effective vehicle for addressing global sustainability challenges, particularly in relation to SDGs 4, 6, 7, 9, 12, and 13. This integration of sustainability principles with STEM education creates a powerful educational framework that enables students to understand and address real-world environmental and social challenges through the lens of chemistry. The research indicates that this approach not only enhances students' scientific knowledge but also develops their capacity to contribute to sustainable development solutions.

The main conclusion is that STEM-based chemistry education represents a vital educational approach that simultaneously addresses multiple educational objectives: the development of essential scientific competencies, the preparation of students for future careers in an increasingly technological world, and the cultivation of sustainability awareness and problem-solving capabilities. The research demonstrates that this integrated approach to chemistry education creates a learning environment that is both academically rigorous and practically relevant, preparing students to address the complex challenges of the 21st century while contributing to the achievement of global sustainability goals.

SUMMARY

The article addresses the critical challenge of integrating STEM-based approaches into chemistry education while simultaneously advancing sustainable development goals. The research examines how innovative STEM methodologies can transform traditional chemistry teaching to meet contemporary educational demands and global sustainability challenges. Through systematic analysis, the study demonstrates that STEM-based chemistry education significantly enhances students' critical thinking, problem-solving abilities, and practical application of scientific knowledge. The investigation reveals that implementing STEM projects in chemistry education creates meaningful connections between theoretical concepts and real-world applications, thereby increasing student engagement and comprehension of complex chemical principles. The research findings indicate that this integrated approach effectively develops students' chemical literacy while fostering crucial skills in laboratory safety, analytical thinking, and experimental competence. Moreover, the study establishes a clear correlation between STEM-based chemistry education and the advancement of multiple Sustainable Development Goals, particularly SDGs 4, 6, 7, 9, 12, and 13, highlighting the approach's effectiveness in preparing students to

address global environmental challenges. The findings demonstrate that this educational framework successfully integrates theoretical knowledge with practical applications, creating a learning environment that promotes both academic excellence and sustainability awareness. The research concludes that STEM-based chemistry teaching serves as an effective vehicle for developing environmentally conscious, scientifically literate individuals capable of contributing to sustainable development initiatives while meeting the demands of an increasingly technology-driven world.

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