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AI-Enhanced Digital STEM Language Learning in Technical Education

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Abstract

This article introduces a framework for scientific and professional language training tailored for STEM (Science, Technology, Engineering and Mathematics) specialists, emphasising the integration of digital technologies and artificial intelligence (AI) in language education. The framework aims to develop students' research communication skills and digital competencies, which are essential for effective participation in both national and international scientific discourse. The article discusses contemporary trends in STEM education, emphasising the importance of interdisciplinary approaches, project-based learning, and the utilisation of digital tools to boost language skills and scientific literacy. The article outlines the development and deployment of a digital platform aimed at supporting personalised and adaptive learning experiences, integrating various educational technologies and approaches. Empirical research conducted through a pedagogical experiment demonstrates the effectiveness of the framework, showing significant improvements in students' academic and linguistic competencies across multiple modules. The findings highlight the importance of combining language training with STEM education to equip future engineers for the challenges of a globalised and digitalised professional world. This work reports on the "Enhancing Scientific and Professional Language Learning for Engineering Students in Kazakhstan through Digital Technologies" project conducted at Saginov Technical University (STU) in Kazakhstan and funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP19678460). The research contributes to the ongoing discussion on improving language teaching in STEM fields, offering a framework that aligns with current educational demands and technological progress.

Keywords: STEM language; STEM discourse; framework; digital platform; AI integration; pedagogical experiment

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1. Introduction

The rapid integration of artificial intelligence (AI) and digital technologies into higher education has markedly transformed modern approaches to language learning and STEM education. Recent empirical and review studies show that AI-supported instructional tools, such as automated feedback systems, adaptive learning environments, and learning analytics, can improve learners' language achievement, motivation, and self-directed learning processes (Wei, 2023; Peña-Acuña & Corga Fernandes Durão, 2024). Meanwhile, research

in STEM education highlights that effective participation in scientific and professional communities requires not only disciplinary knowledge but also well-developed communicative skills, including academic writing, interpreting research data, and engaging with scientific discourse (Sinatra et al., 2015).

Despite these advances, the application of AI-enhanced language learning within STEM-oriented educational contexts remains fragmented. Existing research on AI in language education predominantly focuses on general English or second language learning, often without sufficient attention to disciplinary specificity or the communicative practices of STEM fields (Peña-Acuña & Corga Fernandes Durão, 2024; Dou et al., 2025). At the same time, studies in STEM education tend to prioritise technical knowledge acquisition and problem-solving skills, while language is frequently treated as a secondary or supportive skill rather than as a cognitive and epistemic tool central to scientific reasoning and professional identity formation (Sinatra et al., 2015). This separation reveals a clear research gap: there is a limited empirically grounded understanding of how AI-enhanced digital environments can systematically support the development of scientific and professional language competencies that are integral to STEM literacy.

Recent research further shows that STEM students often struggle to produce coherent scientific texts, communicate research findings, and follow suitable academic conventions, even when their technical skills are adequate (Xu & Ouyang, 2022; Tassilova et al., 2025). These results imply that traditional language teaching methods are not well aligned with the communication and research needs of STEM fields. Although AI technologies have great potential for personalised feedback, adaptive scaffolding, and automated analysis of student output, current educational research lacks validated pedagogical frameworks that effectively incorporate these technologies into STEM language education in a theoretically sound and methodologically solid way (Xu & Ouyang, 2022; Yan et al., 2025).

This gap is particularly evident in technical universities, where students are expected to engage in research-based learning activities, such as analysing scientific literature, formulating hypotheses, visualising experimental data, and presenting findings in multilingual academic and professional contexts. However, most AI-enhanced learning models address isolated language skills or technological functionalities, rather than supporting these complex communicative practices holistically within STEM-specific contexts (Dou et al., 2025; Tassilova et al., 2025). As a result, the pedagogical potential of AI to foster scientific language literacy in engineering and technical education remains insufficiently explored.

To address this research gap, the present study proposes and empirically evaluates an AI-enhanced digital framework for scientific and professional language training tailored to STEM students in technical higher education. The framework conceptualises scientific language as a core component of STEM literacy and positions AI technologies as pedagogical instruments that support research-oriented, interdisciplinary, and digitally mediated learning. Unlike prior studies that focus primarily on evaluating individual AI tools or general language outcomes, this research adopts a systemic educational perspective that integrates language learning, STEM content, and digital competencies within a unified instructional model (Xu & Ouyang, 2022; Yan et al., 2025).

The aim of this study is to examine the pedagogical effectiveness of an AI-enhanced digital framework for scientific and professional language learning in STEM education and to assess how its structured integration into a digital learning platform influences the development of scientific language literacy among technical university students.

To operationalise this aim and ensure theoretical and methodological coherence, the study is guided by the following research questions:

RQ1. How does the proposed AI-enhanced digital framework influence the development of scientific and professional language competencies of STEM students compared to traditional instructional approaches?

RQ2. How do students perceive the pedagogical value and usability of the AI-enhanced digital learning environment in supporting their research-oriented language activities?

Based on the theoretical assumptions of STEM literacy, AI-enhanced learning, and disciplinary language education, the following hypotheses are formulated:

H1. *Students who participate in AI-enhanced scientific and professional language training will demonstrate significantly higher levels of scientific language literacy than students receiving traditional instruction.*

H2. *Students exposed to the AI-enhanced digital framework will report higher perceived usefulness and instructional relevance of language learning activities compared to conventional learning formats.*

The paper outlines the theoretical and methodological foundations of the study and presents the proposed AI-enhanced digital framework for STEM-oriented language education. The subsequent analysis focuses on the empirical findings and their pedagogical implications, concluding with considerations for future research.

2. Literature Review

2.1. Framework for STEM Language Learning with Digital Technologies

The current stage of scientific and technological progress is characterised by the intensive integration of digital technologies, the globalisation of professional activities, and the growing importance of interdisciplinary skills. In these circumstances, engineers and STEM specialists must not only have a high level of professional knowledge but also master scientific discourse, the ability to convincingly present research outcomes, engage in international scientific exchanges, and effectively utilise digital tools for information presentation.

In this context, there is an increasing need to develop theoretically robust and practically relevant models of scientific and professional language training that promote the comprehensive development of research, communication, and digital skills in students specialising in technical fields. The framework outlined in this section draws on an analysis of contemporary scientific literature and synthesises best practices in STEM education, language teaching, and digital pedagogy.

The purpose of developing the framework is to establish a methodologically validated, digitally adaptable structure for scientific and professional language training of engineers, guaranteeing the development of a comprehensive system of knowledge, skills, and abilities in students necessary for participation in scientific and technical discourse at both national and international levels.

As a result of digitalisation, globalisation, and the development of interdisciplinary approaches to education, models focused on research activities, project-based learning, and the integration of digital tools into the educational environment are becoming increasingly significant (Hrynevych et al., 2023; Trubina, 2023).

In this context, integrating technology, an interdisciplinary approach, and research activities to develop competencies in the digital society highlights the crucial role of the digital environment, which promotes interaction, knowledge exchange, and the creation of learning networks (Bagiyan et al., 2021; Siemens, 2020; Le et al., 2023).

Several researchers are exploring current trends in digitalising education, focusing on integrating research-based teaching models and technology to develop students' professional and communicative skills in engineering fields (Ye, 2024; Pérez et al., 2025; Newton et al., 2025).

Based on the trends above, the theoretical and methodological foundation of the framework is rooted in the principles of an integrative approach, combining elements of interdisciplinarity, digitalisation, practical orientation, and inquiry-based learning. Within this framework, scientific language is regarded not only as a means of knowledge transfer but also as a tool for thinking, analysing, reasoning, and constructing professional meanings.

A key methodological basis of the framework is the integration of traditional didactic teaching principles with modern digital pedagogy methods, including artificial intelligence, interactive simulations, automated text analysis systems, and data visualisation. This approach ensures the alignment of the cognitive, communicative, and technological aspects of language training, fulfilling the current needs of engineering education and professional practice.

The framework of scientific and professional language training for STEM specialists is structured to serve several key functions.

(i) Cognitive, ensuring the formation of systemic knowledge about scientific language and its functional features;
(ii) Communicative, aimed at developing the ability to effectively interact in a professional environment;
(iii) Research, related to the development of skills in analysis, interpretation and presentation of scientific data;
(iv) Technological, ensuring the use of digital tools for organising and visualising scientific information;
(v) Evaluative, aimed at monitoring and self-evaluation of students' progress.

The framework is based on the understanding that professional language training in engineering education should not only teach linguistic norms but also foster research and critical thinking skills necessary for creating and analysing scientific texts, conducting experiments, and presenting research findings.

Unlike traditional methods, the proposed framework sees language learning as developing scientific literacy, which involves critically evaluating information, using language to explain phenomena, constructing evidence-based reasoning, and employing digital resources for analysis and communication. Therefore, scientific and professional language training is viewed as a holistic system that integrates linguistic, cognitive, digital, and research elements, designed to enhance students' ability to operate effectively in scientific and professional settings.

Modern approaches to STEM education focus on incorporating language skills as a vital part of engineers' professional training. This ensures that students build strong abilities in professional communication, critical data analysis, and digital literacy. According to researchers, integrating STEM and language training enables students not only to learn linguistic structures but also to grasp the principles of scientific discourse, the specifics of argumentation, and knowledge representation. In this context, language functions as a cognitive tool, shaping scientific thinking and the professional identity of future engineers.

In recent years, there has been a trend towards using interdisciplinary educational frameworks aimed at developing students' skills in project-based activities, research communication, and collaborative problem-solving. Such approaches are based on project- and problem-based learning methods, which ensure the contextual use of scientific language in real-world engineering situations (Jantassova et al., 2022). The main goal of employing interdisciplinary educational models is to cultivate skills in effectively using scientific

language to address professional problems, analyse technological processes, and present research findings through:

(i) Design thinking, which in turn encourages the development of research skills and an innovative scientific presentation style (Guaman-Quintanilla et al., 2023);
(ii) Interdisciplinarity, which integrates linguistic, technical, and research elements of STEM education, fostering a comprehensive understanding of scientific processes (Varianytsia et al., 2022);
(iii) A communicative approach to developing academic, research, and professional communication, along with cultivating a culture of scientific dialogue (Kreps, 2019);
(iv) A sociocultural approach focusing on intercultural competence and academic values essential for participation in the international scientific community (Cezar, 2020).

The combination of all these approaches ensures the systematic, adaptable, and practical nature of the framework, bringing the educational process as close as possible to real engineering practice conditions.

It is worth noting that significant focus is also being directed towards the digital transformation of language training. Modern educational platforms and digital ecosystems provide opportunities to organise personalised learning pathways, automatically analyse language errors, generate feedback, and develop customised recommendations. In this context, there are several reasons to utilise digital tools that not only eliminate traditional barriers to STEM learning but also open the door for more tailored and accessible STEM education.

2.2. Interactivity and Multimedia

The availability of interactive language resources has become a crucial element in creating engaging and effective learning experiences: from language apps and e-books to podcasts and multimedia content. With the rise of digital media tools, students can now access media content online via digital platforms, virtual learning environments, learning management systems, and podcasts. According to Parker and other scholars (Parker & Van Alstyne, 2016), a digital platform is designed to connect users and enable the exchange of goods, services, or social currency, thus creating value for all involved. Digital learning platforms now allow many people to experience the form, structure, and content of traditional education. One of the key features of digital educational platforms is their capacity to deliver interactive lessons. Using multimedia elements, virtual scenarios, and engaging activities, these platforms bring STEM language learning to life. Interactive lessons promote active participation, enabling students to practise language skills in real-world contexts and enhancing overall understanding and retention. Chinnery (2006), in his early research, emphasised the potential of examining mobile phones, personal digital assistants, and podcasting as distinct technologies. Nowadays, the features of these technologies, regarded as beneficial for STEM education, are integrated into devices like smartphones. As Altbach and Knight (2007) writes, information and communication technologies (ICTs) facilitate access to academic programmes through digital learning platforms known as e-learning. E-learning is an online ecosystem that connects multiple stakeholders through technologies and processes. The use of e-learning platforms has rapidly expanded worldwide because they provide people with a flexible, personalised way to learn and affordable, on-demand training.

Another example is the MOOC platform, which has emerged with the promise of enhancing educational opportunities globally. The term MOOC was coined by Dave Cormier in 2008 to describe a 12-week online course offered by the University of Manitoba (Canada). According to Parker and others (Chinnery, 2006), universities such as Harvard, Princeton, Stanford, and many others provide online versions of some of their most popular

courses through MOOC platforms. Digital learning platforms remove geographical barriers, providing accessibility and flexibility. As a result, digital platforms support learning by enabling students to interact in virtual spaces.

Podcasts play a crucial role in enhancing listening skills. These audio resources span a variety of topics, accents, and speech patterns, providing real-world context for STEM language learning. Podcasts enable students to get used to native speakers' speech, boosting their comprehension, pronunciation, and cultural awareness.

Furthermore, incorporating multimedia content such as videos, images, and infographics enriches STEM teaching by engaging visual learners. Visual stimuli improve understanding, aid memory retention, and provide context for applying STEM concepts. Multimedia content brings more energy to STEM teaching, delivering a more comprehensive and engaging learning experience.

A more advanced language tool today is virtual reality (VR), which elevates language immersion to new levels. VR language experiences mimic real-life situations, allowing learners to explore a virtual environment where the target language is used. This immersive method enhances language skills by offering a context-rich environment for practising and applying language.

Interactive and multimedia features in digital tools make learning more engaging for students, sparking their interest and motivating them to learn STEM concepts and language.

2.3. Accessibility and Personalised Learning

Digital technologies provide access to a broad range of resources, enabling students to study at their own pace and revisit complex ideas as needed, which is especially useful for language learning. Adaptive learning platforms can personalise content to suit individual student needs, providing tailored support for both STEM subjects and language skills, thereby improving learning outcomes. Multilingual content allows for the creation of personalised learning paths. Students can choose materials appropriate to their language skill level. This personalisation not only boosts engagement but also fosters a more effective and tailored STEM learning experience, aligned with individual needs and preferences.

Jonassen's (2003) work on personalised learning environments is based on the idea that technology should empower students to control their learning, think deeply, and solve real-world problems. His emphasis on constructivist approaches, cognitive tools, and problem-based learning has left a lasting impact on the development of personalised educational technologies and environments that support diverse students.

In a systematic literature review, (Sarker et al., 2019) examine in detail how personalised learning systems supported by digital technologies can be used to tailor to the needs of individual language learners. Their work highlights the potential of these systems to revolutionise language learning, making it more personalised, effective, and accessible, and also considers the challenges and factors necessary for successful implementation. Jamila Al Siyabi and others (Al Siyabi et al., 2022) discuss the future prospects for using assistive technology in language education. They believe that ongoing technological advances, combined with increased awareness and better teacher training, will probably lead to greater adoption of assistive technology in language classrooms.

2.4. Collaboration and Communication

Digital tools encourage student collaboration, enhancing communication skills necessary for discussing and presenting STEM ideas, and practising language in real-world settings. Online platforms enable students to connect with peers and experts globally, en-

riching their learning journey and exposing them to diverse perspectives in both language and STEM fields.

Language exchange communities harness digital communication to connect language learners and native speakers across distances. Through online platforms, individuals passionate about linguistic and cultural exchange come together in virtual spaces, forming a global network of learners. Cummins and Sayers (1995) recognised language exchange as the potential of worldwide connections to bridge cultural illiteracy.

As access to communication technologies grows, virtual exchanges in language education are becoming more visible. Unlike traditional STEM language learning methods, language exchange communities offer authentic, real-world language practice. This practice greatly boosts language proficiency. Digital platforms use technology to expand opportunities for language exchange. Features like instant messaging, voice calls, and video conferencing allow for smooth collaboration. Thanks to technological integration, language exchanges are free from communication barriers, enabling effective interaction.

Virtual exchange has been utilised in education for many decades (O'Dowd & O'Rourke, 2019), but interest in it is increasing rapidly. As this practice gains popularity, educators must review past experiences and better understand how virtual exchange has developed and how educators and researchers currently perceive it.

2.5. Real-World Application

Technologies like simulations and coding environments aid students in applying language skills in real-world STEM situations, bridging the gap between theory and practice.

Hrynevych et al. (2023) explored how digital tools can improve STEM education and language learning by fostering interactive and collaborative environments. Their work highlights the potential of digital tools to support both technical and linguistic growth, making STEM education more accessible and engaging for students. By integrating digital tools into STEM and language teaching, educators can craft more dynamic and inclusive learning experiences that cater to the diverse needs of students.

Chen et al. (2019) investigated how collaborative problem solving (CPS) in STEM education can be enhanced through learning analytics and examined the connections between students' learning behaviours, cognitive strategies, and awareness of CPS and its effectiveness. By analysing educational data, the research aims to identify factors that improve learning outcomes in STEM, providing educators with insights into how to better support students in collaborative problem-solving tasks within STEM fields.

Maspul (2024) argues that integrating technology and coding into project-based learning (PBL) can substantially enhance STEM education. He highlights the advantages of combining these elements, stressing how they can improve students' computational thinking, problem-solving skills, and creativity. By involving students in collaborative coding projects, this approach encourages interdisciplinary learning and fosters a deeper understanding of STEM concepts, ultimately equipping students to tackle real-world problems.

2.6. Different Learning Styles and Instant Feedback

Digital technology caters to different learning styles—visual, auditory, and kinaesthetic—allowing students to engage with content in their own way, which improves understanding and memory. Digital assessment tools provide instant feedback on language use and STEM comprehension, helping students identify areas for improvement and adapt their learning strategies accordingly. Digital platforms that include quizzes and feedback help students monitor their progress in both STEM knowledge and language skills. Davies (2002) believes that technology-enabled language evaluation offers significant opportunities to enhance language assessment and learning. While digital tools can increase the efficiency

and effectiveness of evaluations, it is essential to address issues of fairness, reliability, and safety to ensure these innovations benefit all learners. Technology supports personalised learning by adjusting content to meet the needs and circumstances of individual students. This tailoring helps address various literacy challenges and promotes more effective learning. Although these technologies offer numerous benefits, such as personalised learning and instant feedback, fully unlocking their potential requires overcoming challenges related to access, integration, and effectiveness (Biancarosa & Snow, 2006; McLaren, 2012).

Digital evaluation applications and platforms are currently transforming the way educators assess and support students, providing numerous benefits in terms of feedback, flexibility, and data analysis. Lorenzo Salas-Morero and Antonio Arauzo-Azofra examine the role and effectiveness of online quizzes in education, focusing on their use as a teaching and evaluation tool, and emphasise that online quizzes are a valuable resource for both teaching and assessment in educational organisations (Salas-Morero et al., 2012).

According to Robertson and Humphrey (Robertson et al., 2019), a review of technological tools for formative evaluation includes online quizzes, surveys, learning management systems, and interactive applications, highlighting significant benefits such as immediate feedback, increased engagement, and data analysis. These tools are used to support formative assessment by identifying areas where students need improvement and helping teachers tailor their teaching strategies.

Bahrani (2011) examines the use of technology in language assessment, highlighting how different digital tools can support and improve the evaluation process. The author recommends exploring new technologies, such as artificial intelligence and virtual reality, for their potential to enhance language assessment practices.

2.7. Digital Gamification

The integration of game elements and engaging content is transforming language learning, turning what was once seen as a difficult task into a fun and enjoyable experience. According to Groh (2012), gamification currently employs game elements to enhance user experience and boost engagement, especially in non-game settings. Anderson and Rainie (2012) define gamification as the creation of an interactive online system that uses people's competitive instincts and rewards to motivate players. Rewards can be virtual, such as payments, points, badges, or free gifts. According to McGonigal (2011), people worldwide spend 3 billion hours a week playing video and computer games.

Gamification introduces a game-like element into STEM learning, leveraging self-motivation associated with game dynamics. Many researchers have examined the relationship between gamification and student participation, motivation, and engagement. For example, a study (Thamvichai & Supanakorn-Davila, 2012) implemented a scoring system in an effort to combine game mechanics with an engineering curriculum. Using a quick questionnaire, the researchers assessed students' motivation to complete assignments.

In STEM language learning, gamification applies to specific skills, including vocabulary and grammar. Vocabulary games, word puzzles, and grammar quizzes make memorising and applying rules engaging. These games transform potentially boring aspects of STEM language learning into enjoyable activities, reinforcing skills through repetition and practice. Some researchers have incorporated gamification into e-learning systems. For example, Landers and Callan (2012) conducted a social experiment where college students took a short test, and based on their scores, they were ranked and given tokens that reflected their level of performance.

Educational apps, incorporating gamification and interactive content, are constantly updated to keep learners engaged. Regular updates, new challenges, and evolving content ensure the learning experience remains fresh and engaging. Games can offer interactive

and motivating learning experiences when carefully designed and implemented. K. Squire and J. Gobert focused on digital games, which have considerable potential to boost engagement and learning in STEM education. One reason for this is that educational games simulate real-world scenarios and problems, allowing students to explore and experiment in a controlled environment. This experiential learning approach helps students apply theoretical knowledge to practical situations (Squire, 2011; Gobert & Buckley, 2000).

According to Wang, L.H., game-based digital learning generally has a positive impact on student learning outcomes in STEM education, as the interactive and immersive nature of games helps keep students interested in STEM subjects, and students who use digital games as part of their STEM lessons often achieve higher academic results than those who do not use such games (Wang et al., 2022).

3. Materials and Methods

The methodological foundation of the study is based on contemporary pedagogical and linguo-didactic approaches tailored to the professional communication needs of modern technical specialists. The research adopts a systematic, research-oriented educational perspective, enabling a coherent analysis of scientific and professional language training within the context of digital transformation in higher technical education.

The study employs a comprehensive mixed-methods approach, combining scientific-theoretical and empirical research methods. The theoretical component includes the analysis, synthesis, generalisation, specification, and classification of linguistic, scientific, pedagogical, and methodological sources related to STEM language education, artificial intelligence-enhanced learning, and digital pedagogy. This theoretical analysis provides the conceptual basis for developing the instructional framework and the digital learning environment.

To develop a framework for scientific and professional language training tailored to technical specialists, a pedagogical process modelling method was applied. The framework was designed in accordance with key linguo-didactic principles of scientific and professional language education and implemented using an instructional systems design approach based on the ADDIE model (Analysis, Design, Development, Implementation, and Evaluation). This approach ensured the transparency, structure, and replicability of the framework development process.

Throughout the design and implementation stages, multimedia, interactive, and didactic instructional methods were incorporated into the digital learning environment to boost student engagement and facilitate research-focused language activities. The digital programme was created to ensure language learning tasks align with STEM-specific professional practices, such as academic writing, analysing scientific texts, and communicating research findings.

The empirical component of the study used a quasi-experimental research design. The participants included STEM students (N = 122) from Karaganda Saginov University, representing Mining Faculty. The study was carried out over one term, involving structured instructional sessions on scientific English and Russian integrated into the digital learning platform. The procedures included pre- and post-intervention assessments, guided language tasks, interactive exercises, and research-oriented assignments aligned with STEM-specific professional practices, such as academic writing, analysis of scientific texts, and communication of research results.

To assess the effectiveness of the proposed framework and the digital platform, quantitative data were analysed using SPSS, version 25 (Statistical Package for the Social Sciences). Statistical procedures were applied to compare learning outcomes before and after the intervention and to determine the significance and magnitude of observed changes in

students' scientific and professional language competencies. The use of statistical analysis ensured the objectivity and reliability of the empirical findings.

4. Framework of Scientific and Linguistic Training and Implementation of AI-Enhanced Digital Platform for STEM Language Learning

The literature review demonstrates that, despite significant advances in AI-enhanced language learning and STEM education, existing studies often address technological tools, language skills, or disciplinary content in isolation. Prior research highlights the importance of integrating scientific language development, STEM literacy, and digital pedagogy; however, it also reveals a lack of coherent, empirically grounded frameworks that systematically align these dimensions within technical higher education. In particular, the literature points to the need for pedagogical models that operationalise theoretical principles, such as disciplinary relevance, research-oriented learning, and adaptive feedback, through concrete instructional and technological solutions. Responding to these findings, the present study proposes a unified framework for scientific and linguistic training in STEM education that translates the key insights from the literature into an implementable digital learning system. The following section presents the conceptual structure of this framework and demonstrates how its guiding principles are realised through a digital platform and evaluated within a pedagogical experiment.

Digital tools can easily combine language learning with STEM education, promoting the development of critical thinking, problem-solving, and communication skills essential in today's connected world. As a result, the framework's development actively employs digital technologies to improve the effectiveness of STEM language literacy instruction, making it more engaging, tailored, and relevant to real-world contexts, ultimately equipping students for success in both language and STEM settings.

The digitalisation of education supports the shift from traditional teaching to a blended learning model, where online and face-to-face methods work together, and students become engaged learners. This aligns with the idea of participatory pedagogy, where scientific language teaching is grounded in collaboration, self-assessment, and critical thinking.

The use of artificial intelligence (AI) in language instruction is especially significant in the modern era. Research shows that AI allows for adaptive learning, whereby the system assesses a student's language proficiency and provides tailored exercises, texts, and feedback. This enhances the effectiveness of language learning and helps students develop their skills for meaningful interaction with digital data sources.

Moreover, current research emphasises the importance of developing scientific and engineering literacy in students, which includes the ability to use scientific language to interpret data, formulate hypotheses, describe experiments, and present research findings.

The STEM Language through Research concept involves teaching scientific language through research practice, where students develop linguistic skills while engaging with real engineering projects and scientific publications. This method encourages the growth of academic writing abilities, reading, and analysing scientific texts in the natural setting of professional activity (Jantassova & Damiyev, 2025). Therefore, an analysis of domestic and international research demonstrates that modern language training in engineering education should be founded on the following principles:

(i) Interdisciplinarity and integration of STEM disciplines;
(ii) Digitalisation and application of AI tools;
(iii) Research focus;
(iv) Contextual and activity-based approach;
(v) Adaptability of the educational environment.

The development and theoretical basis of a framework for scientific and professional language training for STEM specialists mark an important step in modernising the engineering education system within the context of digital transformation. The analysis identified key trends, patterns, and conceptual guidelines that influence the effectiveness of developing scientific and professional language competence in STEM fields.

The integration of five methodological approaches—design thinking, interdisciplinary, digital, communicative, and sociocultural—enables the principles of flexibility, adaptability, and contextual learning. Together, they foster a pedagogical environment where language becomes an essential part of professional and scientific thinking.

The digital component is especially crucial in the framework, facilitating the deployment of artificial intelligence technologies, virtual labs, text analysis, and data visualisation platforms. This not only enhances learning effectiveness but also prepares students for the digital engineering community.

The presented framework reflects contemporary requirements for training engineering personnel capable of independent research, professional communication, and the use of digital tools in scientific work. Its implementation aids students in developing a comprehensive set of skills necessary for successful integration into the global scientific and technical arena.

The framework for scientific and professional language training for STEM specialists is a multi-tiered system consisting of four interconnected blocks: conceptual, substantive, technological, and evaluation-and-performance. Each of these blocks reflects different aspects of the learning process and maintains the framework's integrity and consistency.

The model relies on the following fundamental linguo-didactic approaches:

(i) The principle of language functionality asserts that learning should focus on using language as a tool for thinking and professional activity, rather than as an end goal in itself. Language is viewed in its functional relationship with engineering tasks and scientific analysis.
(ii) The principle of integrating content and language (Content and Language Integrated Learning, CLIL) involves acquiring professional content alongside the development of language skills, enabling students to absorb terminology and concepts in engineering disciplines.
(iii) The principles of contextuality and situationality ensure that training revolves around real professional scenarios: analysing engineering projects, discussing scientific publications, and preparing reports and presentations.
(iv) The principle of cognitive activity promotes the development of analytical and critical thinking by using language as a means of scientific knowledge and argumentation.
(v) The principle of digital media literacy incorporates digital technologies into language learning, encouraging skills in handling electronic information sources, scientific databases, AI tools, and visualisation.
(vi) The principle of adaptability recognises the importance of considering individual student characteristics, language proficiency, and professional interests when selecting tasks and materials.

These principles illustrate the modern shift from traditional foreign language teaching to a comprehensive scientific and professional education, where language is not only an object of study but also a tool for design, research, and communication (Figure 1).

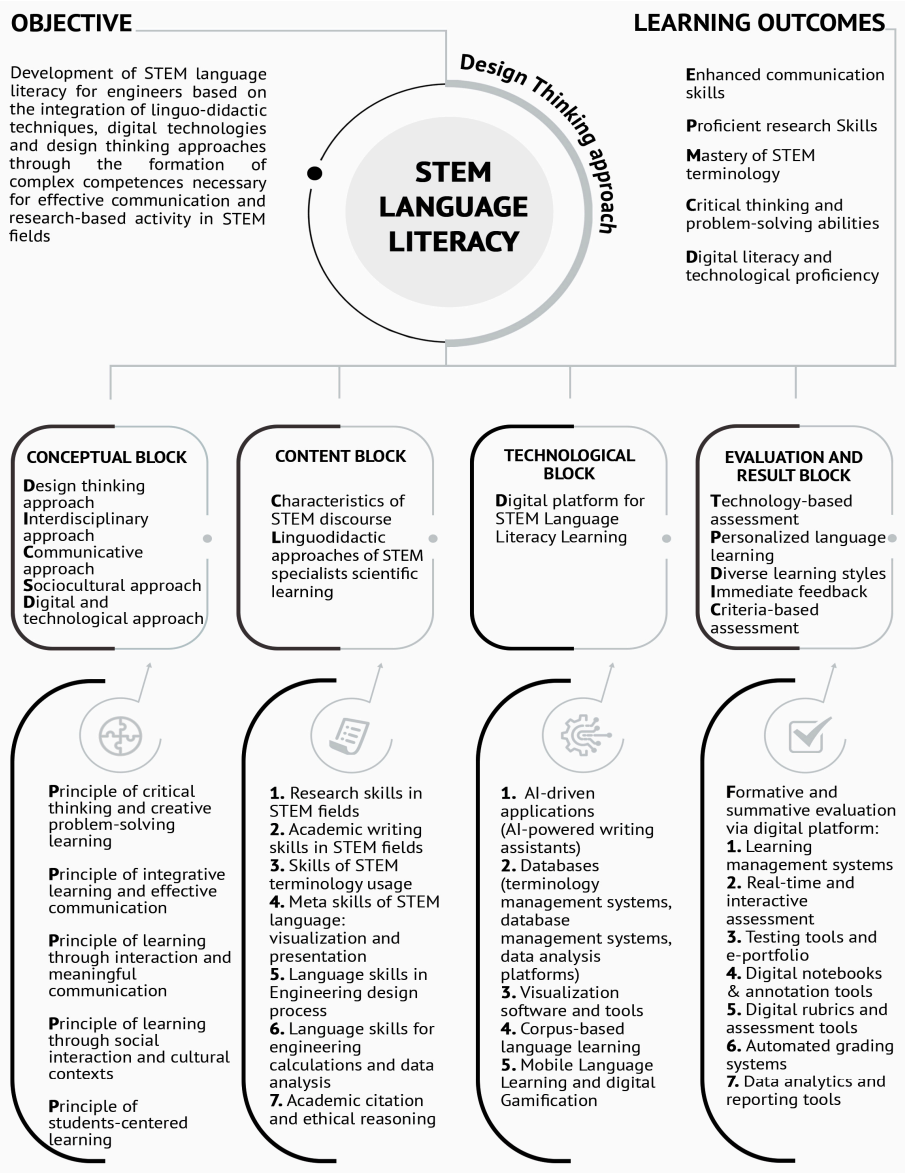

Figure 1. Framework of scientific and linguistic training in the field of STEM.

As shown in Figure 1, each block interacts with the others, forming feedback loops among goals, content, methods, and learning outcomes. This arrangement supports the continuity and flexibility of the educational process, which is especially important for engineering students, as competence develops alongside professional growth.

4.1. Conceptual Block

The methodological basis of the conceptual block is built on a synthesis of both classical and innovative approaches, including design thinking, communicative-activity, cognitive-linguistic, interdisciplinary, digital, and sociocultural approaches, which complement each other to form a holistic pedagogical system aimed at enhancing the cognitive development, communication skills, and digital literacy of engineering students.

The main aim of the conceptual block is to develop the ability to effectively use scientific language to solve professional problems, analyse technical processes, and present research results in oral and written forms.

4.1.1. Design Thinking Approach

This approach perceives learning as a process of designing and finding solutions, grounded in empathy, analysis, ideation, and testing hypotheses. When applied to engineers' language training, design thinking supports the development of students' research skills, their ability to understand task contexts, set communication goals, and tailor language to professional situations. The use of design thinking encourages creativity, critical thinking, and teamwork. During classes, students progress through identifying problems, gathering data, generating ideas, and implementing solutions through oral and written projects—from analytical reports to scientific posters. This fosters innovative scientific writing skills, using language as a means for constructing knowledge.

Introducing design thinking principles into language teaching helps make the educational process more like real engineering work, where language is closely connected to solving practical problems and presenting research results (Jantassova & Damiyev, 2025).

4.1.2. Interdisciplinary Approach

Interdisciplinarity is a fundamental principle of STEM education. The proposed model implements this by combining linguistic, technical, and research-based content. Education is centred on professional themes across engineering, physics, mathematics, environmental, and information sciences, with scientific language acting as a link between disciplines. An interdisciplinary approach enables students to develop a comprehensive understanding of scientific processes and the capacity to combine knowledge from different fields to solve complex engineering challenges. Language learning becomes an essential part of project and research activities, and linguistic training acts as a tool for professional socialisation. Furthermore, interdisciplinary learning boosts student motivation because the assignments are relevant to their future careers. For example, when studying engineering terminology, students examine real technical reports, thereby improving their language skills and developing their professional abilities.

4.1.3. Digital Approach

Contemporary linguo-didactics actively employs digital technologies to improve learning and boost interactivity. The digital approach to scientific and linguistic literacy in STEM aims to develop students' skills in working with electronic information sources, scientific databases, machine translation systems, and text visualisation and analysis tools.

The use of artificial intelligence (AI) opens new opportunities for personalised learning. AI-driven systems provide automatic checking of lexical and grammatical structures, style analysis, and feedback and suggestions to enhance written work. This approach is realised by creating a virtual educational environment that features gamification elements, interactive simulations, chats, and scientific interaction forums. This aims to boost student motivation and foster independent learning.

Digitalisation in language education broadens traditional learning and promotes the growth of a digital academic discourse where scholarly communication utilises modern media and AI tools.

4.1.4. Communicative Approach

The communicative approach remains important as a core principle of language teaching across any professional field. In engineering education, it specifically focuses on developing academic, research, and technical communication skills. Developing students' ability to use scientific language as a means of interpersonal and professional interaction is the main goal of this approach. The communicative component is carried out through

role-playing activities, simulated scientific conferences, and the preparation of reports, presentations, and debates.

Particular focus is given to developing skills in argumentation, clarifying terms, conducting scientific dialogue, and expressing disagreement correctly, which helps foster a culture of professional communication and critical thinking. Unlike traditional language education that focuses on linguistic forms, the communicative-professional approach sees language as a tool for reaching engineering objectives—from describing technical processes to engaging in interdisciplinary scientific projects.

4.1.5. Sociocultural Approach

The sociocultural approach is based on the idea that language is both a product and a tool of culture. For engineers, proficiency in scientific language involves understanding the norms of scientific communication, academic ethics, publication structure, and citation rules. Within the framework of the scientific and linguistic literacy model in STEM, this approach aims to develop students' intercultural communicative competence essential for participating in international scientific projects and conferences.

The sociocultural approach promotes academic values such as objectivity, openness, accuracy, and respect for intellectual property. It helps students understand that scientific communication is not just the exchange of knowledge but also interaction within a cultural and ethical framework. Therefore, the sociocultural approach enables students to see language not just as a standalone system of signs but as a way to connect with the wider scientific community. The integration of these five approaches guarantees the model's consistency and flexibility, enabling it to adapt to different engineering disciplines and students' language proficiency levels.

4.2. Content Block

The content block outlines the structure of educational materials and their organisational logic. It includes:

(i) Thematic modules based on seven characteristics of scientific and technical discourse, aligned with the main types of scientific activity performed by engineers (such as data analysis, design, modelling, and publication of results);
(ii) A system of language, speech, and communication skills developed within each module;
(iii) Forms and types of educational activities aimed at fostering research and analytical skills.

The content block highlights key aspects of language training, including academic writing, research skills, professional terminology, and data visualisation. It employs interdisciplinary teaching approaches that blend language training with STEM disciplines, thereby supporting students' ability to interpret, analyse, and produce scientific texts in line with academic standards. The essential educational elements that foster the development of scientific and professional language skills in engineering students—focusing on the linguistic and cognitive abilities needed to work effectively with technical and scientific information—are outlined within the framework of the content block.

Linguo-didactic approaches and their key features form the methodological foundation for this block, outlining approaches to teaching and the development of language skills through the adaptation of educational materials for teaching scientific and technical terminology to international standards. This includes training in scientific and technical communication using digital technologies such as online dictionaries, electronic glossaries, and databases; and employing interactive teaching technologies—like case studies and project-based learning—in real-world scientific and technical communication situations. An interdisciplinary approach to teaching scientific language is also adopted, focusing on the harmonisation and standardisation of terminology, along with modern technological

tools for teaching the language of research, thereby promoting scientific research and making it more accessible. These linguo-didactic approaches emphasise the systemic relationship between language, thought, and professional activity, highlighting the importance of functionality in learning. The process of developing linguistic competence is seen as a multi-level cognitive–communicative process, involving an understanding of how to construct scientific reasoning, argumentation, and the presentation of information.

These linguo-didactic approaches for the scientific and professional training of STEM students demonstrate the connection between theoretical and practical components of training and enable a balance among the substantive, cognitive, and technological aspects.

Together, they create a comprehensive framework for engineers' language training, ensuring the development of scientific, communicative, analytical, and research skills necessary for students to engage successfully in modern scientific and technical activities.

4.3. Technological Block

The technology block aims to integrate linguistic and technical components by leveraging modern educational technologies, defining the methods, forms, and digital tools that ensure the model's practical implementation.

Among digital tools, artificial intelligence (AI)-based platforms such as Grammarly Free, QuillBot, ChatGPT, and Perplexity hold a special place. They enable automatic checking of language structures, analysis of style and text organisation, and offer recommendations for enhancing writing and speaking skills.

The role of data visualisation systems (e.g., Tableau, Power BI) is significant, as students present the results of engineering experiments visually and describe them in report format. In this way, language becomes a tool for interpreting and explaining engineering phenomena.

The technology unit employs adaptive learning principles, where the content and difficulty of tasks change based on the student's level of preparedness. This encourages the personalisation of the learning journey and nurtures sustained motivation for self-study.

4.4. Evaluation and Performance Block

The evaluation and performance module focuses on monitoring, assessing, and analysing the effectiveness of training within the model. It encompasses both traditional and digital evaluation methods.

Traditional methods consist of testing, project defence, portfolio analysis, self-evaluation, and peer evaluation. Digital methods are carried out through online platforms and analytics systems that enable progress tracking, identify gaps, and offer personalised recommendations.

An important part of the evaluation module is the formative assessment system, which offers ongoing feedback between teacher and student. Special focus is given to developing students' self-reflection skills, which enhances their professional growth and awareness in the language learning process.

The programme's outcome is to develop a set of competencies in students that include mastery of scientific language, the ability to analyse and present data, use digital tools, and communicate effectively in a professional engineering environment. The developed framework can act as both a theoretical and practical foundation for designing digital training programmes focused on enhancing the scientific and professional language literacy of future engineers. Additionally, it can support empirical research to assess the effectiveness of the models implemented.

While the proposed framework establishes the conceptual and pedagogical principles underlying scientific and linguistic training in STEM education, its practical relevance

depends on how these principles are enacted within an instructional environment. To move from an abstract description to an operational model, the framework was embedded in an AI-enhanced digital learning platform that serves as the core medium for instructional delivery and learner interaction. The platform was designed specifically to translate each guiding principle of the framework into concrete learning activities, feedback mechanisms, and adaptive instructional features. The following subsection therefore focuses on the digital implementation of the framework, demonstrating how its theoretical assumptions are realised through the structure and functionality of the learning platform.

A digital platform for teaching scientific language in the STEM (science, technology, engineering, and mathematics) field was developed based on the framework of scientific and professional language training for STEM specialists. It aims to enhance the scientific and linguistic literacy of STEM professionals by integrating linguistic and methodological teaching methods, digital technologies, and design thinking approaches.

The digital platform is a contemporary educational platform designed to develop and improve students' competencies in scientific language for STEM disciplines. The platform responds to the needs of the digital transformation in higher education and emphasises the use of advanced technologies, including elements of artificial intelligence, adaptive learning algorithms, and multilingual interface support.

This platform is a versatile, multifunctional tool designed for undergraduate and postgraduate students, early-career scientists, and educators in technical fields. It offers access to interactive tasks, educational case studies, and adaptive feedback systems. The use of artificial intelligence technology guarantees personalised learning pathways and tracking of user progress.

The developed platform is hosted on the university server and offers a systematic approach to teaching scientific language through:

(i) Structured learning modules, including study texts, exercises, and tests of various formats (such as multiple-choice questions, KWL charts, matching terms and identification exercises, open-ended questions, true/false tests, essay writing tasks, and sentence reordering activities);
(ii) Personalised learning and automated feedback on completed tasks' results, considering syntax, grammar, and answer accuracy;
(iii) Integration with external systems and language models (LLMs) for intelligent support of the educational process;
(iv) The ability to generate reports and analytics on learning outcomes for teachers and administrators;
(v) Logging user actions and storing their work history, which enhances the transparency and manageability of the learning process.

The digital platform's architecture is designed as a hierarchical structure composed of units and modules, each hosting a set of exercises and tests. It relies on a relational database that includes tables for storing units, modules, assignments, student responses, and activity logs. All modifications are logged with a version history, enabling progress tracking and course content adjustments. The platform's interface is built to be responsive and available in multiple languages (Figure 2). The user interface follows the "single window" principle: students see a list of units, can navigate to modules, open texts for study, complete exercises, and receive automatic feedback (Figure 3). The administrator has access to a control panel for editing course content, adding new materials, and managing user accounts.

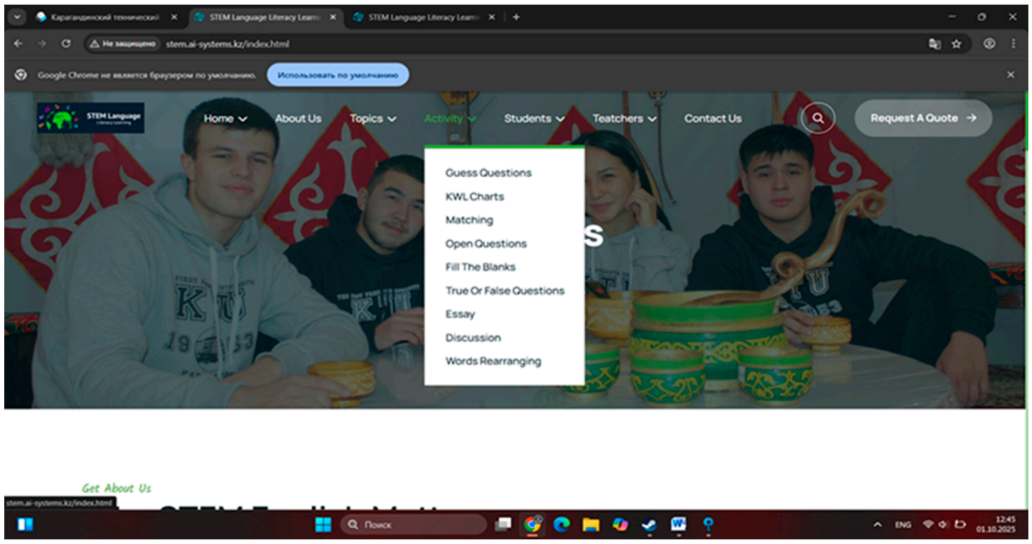

Figure 2. Interface of the digital platform.

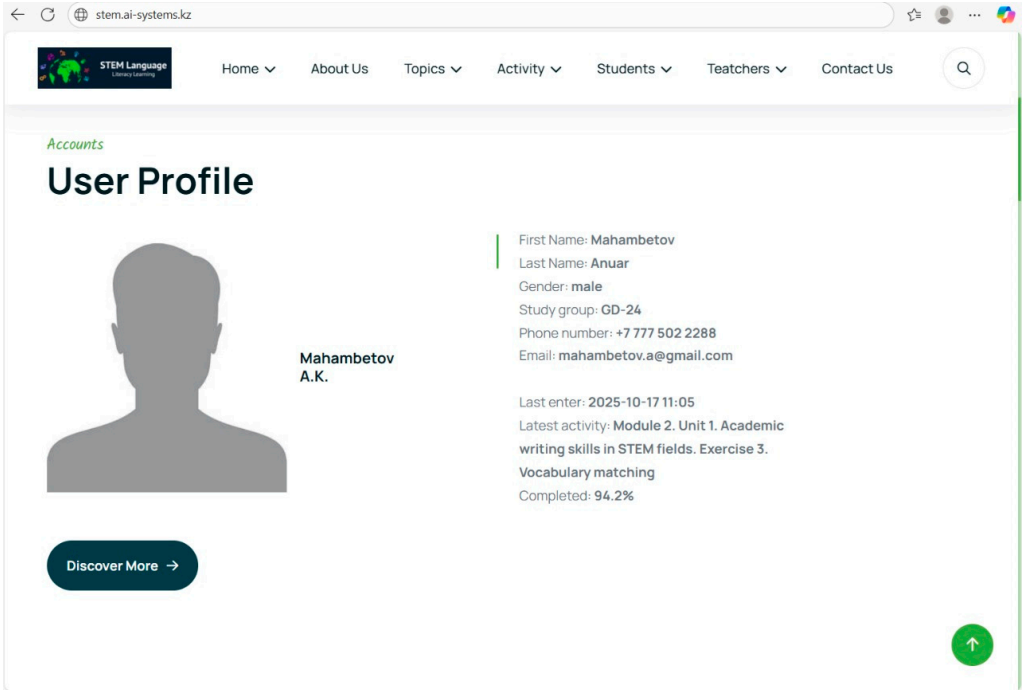

Figure 3. User interface.

The platform's interface is multilingual and adapted to various devices and browsers. Resolutions of 1024 × 600 pixels and higher are supported.

The most critical components of the digital platform structure are:

(i) Interactive training modules with texts and graphic support;
(ii) Various forms of exercises: guessing questions, KWL charts, matching terms, open and closed questions, essays, dialogues, restoring word order, etc.;
(iii) Flexible user interface with the ability to navigate between modules, forms and profiles;
(iv) An administrative module that allows you to edit content, manage users, and track actions in the system.

The digital platform supports the following key functions:

(i) Training exercises and testing;
(ii) Guessing questions activate prior knowledge;

(iii) KWL diagrams shape metacognition;
(iv) Comparison of terms develops the conceptual apparatus;
(v) Tests with gaps and open questions develop the accuracy of terminology use;
(vi) Essay and dialogue exercises develop productive written speech;
(vii) Adaptive feedback.

Each user's answer is automatically checked for grammatical correctness and factual accuracy, enabling effective progress tracking (Figure 4).

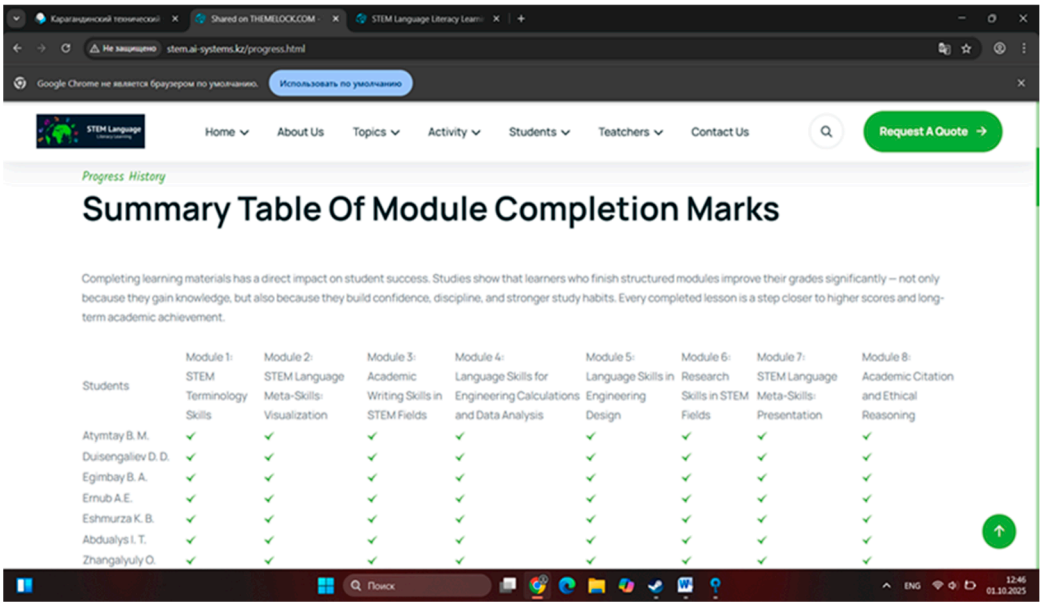

Figure 4. Criteria-based evaluation.

The digital platform integrated AI features. Integration with AI (based on large language models) offers feedback on user responses to open-ended questions that cannot be precisely matched with a correct answer. The feedback mainly addresses the presentation and factual accuracy and also points out grammatical errors, if present (Figure 5).

Users can view a history of their actions, including test attempts and completed tasks. The system logs key changes and interactions, ensuring full traceability.

The system is designed to support up to 500 simultaneous users, with a quick interface display (up to 5 s) and report rendering (up to 30 s). Security is maintained through role differentiation and safeguarding the administrative interface from unauthorised access. Integration with large language models (LLMs) hosted on external servers has been developed.

The digital platform's educational content includes eight modules focused on the features of scientific and technical discourse: research skills in STEM fields, academic writing skills in STEM, skills in using STEM terminology, STEM language meta-skills such as visualisation of technical information and presentation, language proficiency in the engineering design process, language proficiency for conducting engineering calculations and data analysis, academic citation, and ethical reasoning. These modules are:

(i) Module 1—Research Skills in STEM Fields (Searching, Collecting, and Analysing Information and Literature);
(ii) Module 2—Academic Writing Skills in STEM Fields (Scientific Writing);
(iii) Module 3—STEM Terminology Skills;
(iv) Module 4—STEM Language Meta-Skills: Visualizations;
(v) Module 5—STEM Meta-Skills: Presentation (Communicative Skills, Team Building);

(vi) Module 6—Language Proficiency in Engineering Design (Storytelling, Brainstorming, Digital Storytelling);
(vii) Module 7—Language Proficiency for Engineering Calculations and Data Analysis (Mathematical Language, Data Analysis);
(viii) Module 8—Academic Citations and Ethical Reasoning (Figures 6–8).

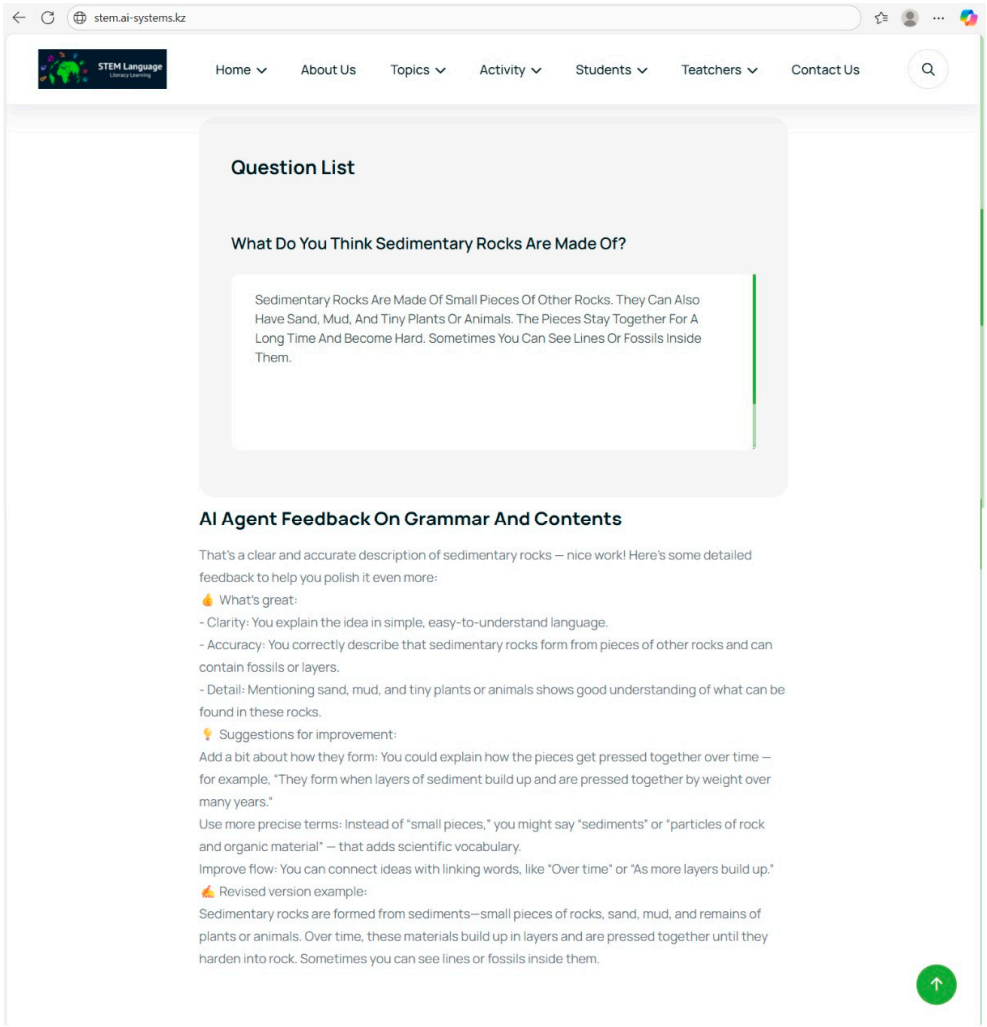

Figure 5. AI integration.

The digital platform for teaching scientific language in STEM education is unique and serves as a modern tool for integrating language training with technical disciplines. The programme emphasises interdisciplinary, interactive, and personalised learning. By incorporating artificial intelligence and analytics technologies, it creates the conditions for developing sustainable language competencies necessary for future specialists within the context of scientific and professional mobility.

The structural components of the digital platform and its curriculum for teaching STEM language in the scientific training of engineering and technical personnel represent a holistic framework aimed at the comprehensive development of students' linguistic, communicative, and professional skills. This framework considers the specifics of scientific and technical terminology, modern requirements for the digital transformation of education, and the needs of students specialising in engineering and technical fields in an environment of active integration into the international scientific and professional community.

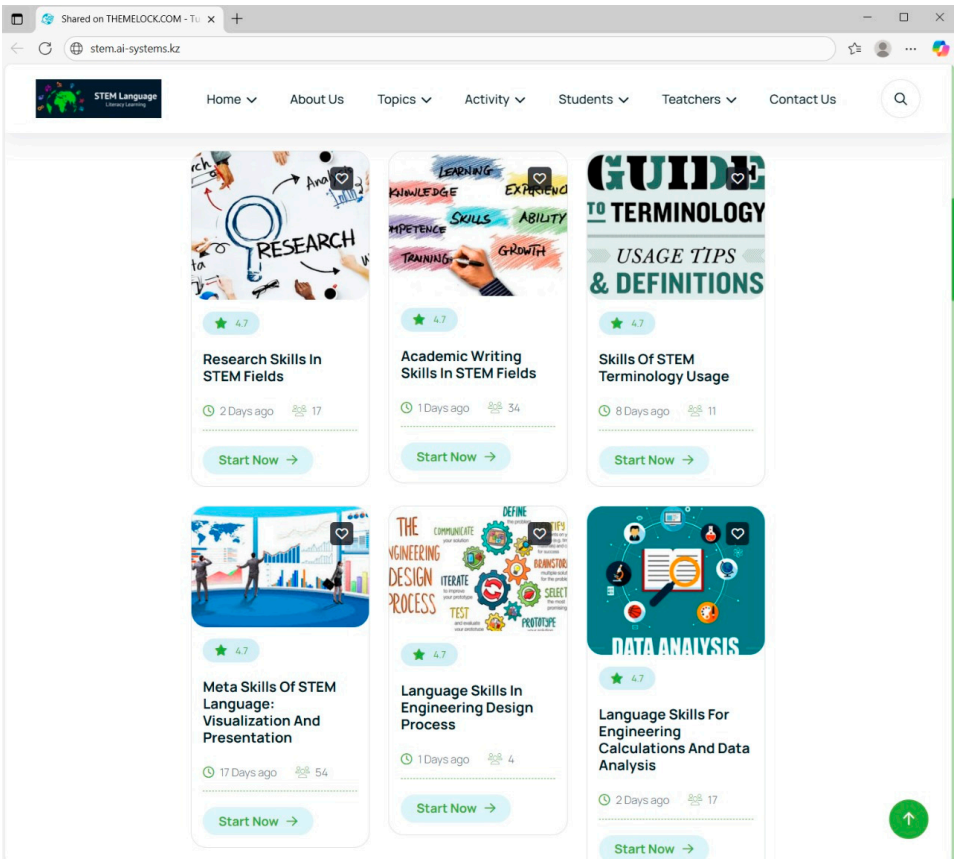

Figure 6. Interface of the Modules.

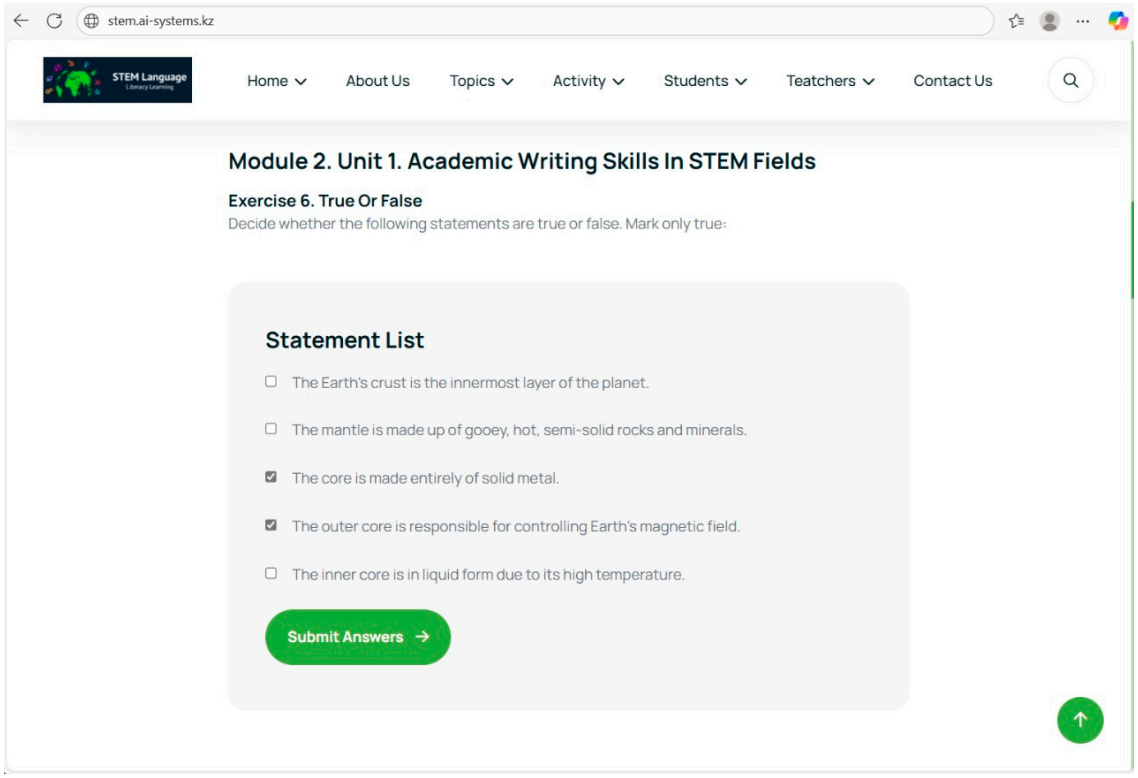

Figure 7. Module 2—Academic Writing Skills in STEM Fields.

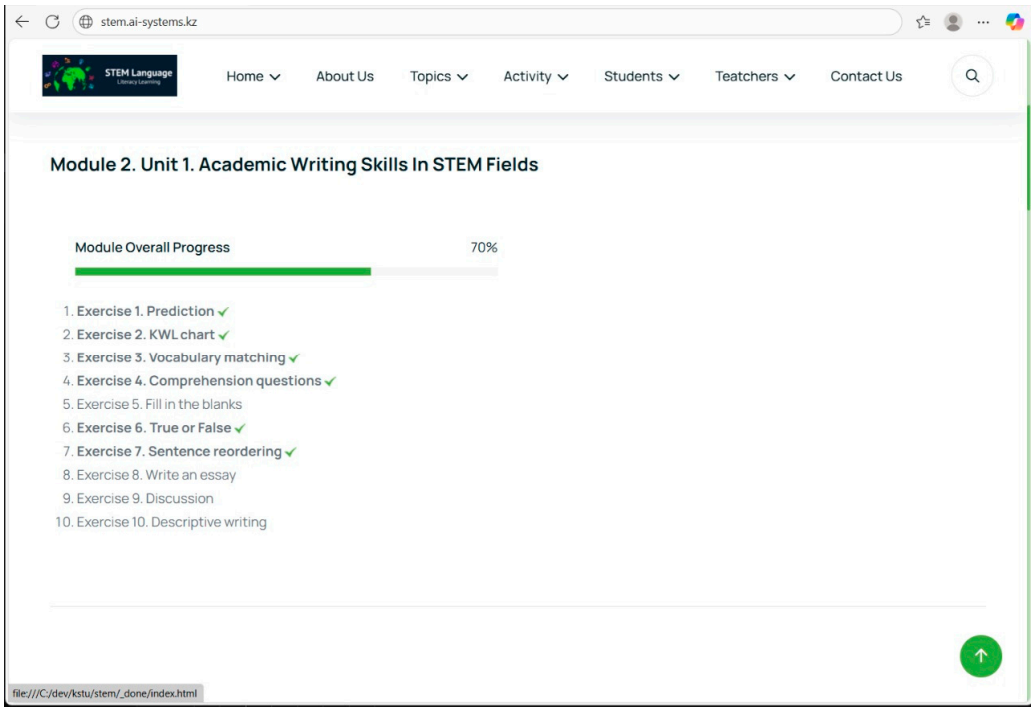

Figure 8. Assignments for Module 2.

A digital platform based on these structural components not only offers access to high-quality educational materials and interactive resources but also fosters conditions for adaptive, personalised, and interdisciplinary learning. By applying modern technologies, including elements of artificial intelligence and predictive analytics, this system boosts student motivation, enhances learning efficiency, and increases the practicality of language training.

The digital platform is scalable and can be adapted for use at other universities in the Republic of Kazakhstan, opening up prospects for further commercialisation within the framework of the national educational policy on digitalising higher education. According to the project's research schedule, this section presents a framework for scientific and professional language training for specialists in technical fields, defining its content, structure, and key components. A digital platform for teaching scientific and professional language was developed, and its modules were populated with educational content based on eight characteristics of scientific and technical discourse.

A comprehensive diagnostic tool developed as part of the study was used to evaluate the development of academic and linguistic STEM competencies. This tool comprised tasks spanning eight modules, reflecting the key components of scientific and technical discourse. Each module included both closed tasks, such as multiple-choice and matching, and open, productive tasks, such as text analysis, data interpretation, diagram description, and fragments of academic writing.

Eight instructional modules were structured to require approximately 10–12 h of dedicated student engagement. This per-module allocation contributed to a total of 80–96 h of platform-mediated instruction across the 15-week semester, comprising both in-class facilitated sessions and independent, self-paced study. Log data from the learning platform confirmed that participants in the experimental group spent an average of 42.7 h (SD = 6.1) actively interacting with the system.

Open-ended assignments were assessed using an analytical rubric that included the following criteria:

(i) Accuracy in the use of STEM terminology.
(ii) Logical and structured presentation;
(iii) Correct interpretation of data and visual materials;
(iv) Compliance with genre and academic conventions;
(v) Linguistic correctness (vocabulary, grammar and coherence).

Each criterion was assessed on a scale corresponding to CEFR levels (B1–C1).

To verify the reliability of the inter-expert assessment of open-ended tasks, a double-independent assessment approach (two-rater scoring) was employed. The assessors' agreement coefficient (Cohen's k/ICC) demonstrated high reliability ($\kappa > 0.80$), meeting accepted standards for pedagogical measurement.

Content validity was ensured by:

(i) Expert evaluation of the tool by teachers specialising in technical subjects;
(ii) Correlation of tasks with professional communication situations of STEM engineers;
(iii) Linking assessment criteria to CEFR descriptors and academic discourse.

Construct validity is confirmed by consistent results across interrelated modules and by the expected differences between the experimental and control groups after the intervention.

The results of this study indicate that students who engaged with the digital platform demonstrated statistically significant gains in scientific and technical language competencies across all eight modules. These findings are consistent with recent research on AI-enhanced language learning in STEM contexts, which suggests that adaptive and interactive digital environments can effectively improve terminology acquisition, academic writing, and professional communication skills. For example, Torkhani (2025) reported that AI-based interventions significantly enhanced EFL learners' grammar, vocabulary, and pronunciation through structured pre- and post-testing, while a study of Wei (2023) demonstrated that AI-supported learning environments increased both learning outcomes and student motivation compared with traditional instructional methods.

However, the observed improvements should be interpreted with caution due to several methodological limitations. The use of intact groups rather than randomised assignment may have introduced sample bias, and pre-existing differences between groups could partly explain the gains. Additionally, while module-based tests and analytic rubrics were used to measure competencies, the validity of these instruments has not been independently verified. The study's sample was also limited to one faculty at a single institution, which may reduce the generalisability of the findings.

Alternative explanations for the observed improvements include normal academic progression, heightened motivation due to participation in an intervention, and increased exposure to English through other courses. Specific features of the digital platform, such as multimedia content and interactive exercises, may also have increased student engagement rather than directly enhancing language competencies.

Future research should employ randomised controlled designs, validate assessment instruments with external benchmarks, and examine the impact of specific AI-supported features on learning. Comparative studies across different institutions and STEM disciplines would clarify the conditions under which digital and AI-enhanced environments most effectively support professional STEM language development.

The implementation algorithm for the scientific and professional language training framework for engineering and STEM specialists was developed considering the specifics of engineering and technical education. It aims to address the scientific and language needs of students majoring in STEM. The framework reflects the unique aspects of scientific communication in the technical field and emphasises the importance of developing strong scientific thinking skills, terminological literacy, and academic communication. These skills

are particularly important in the context of the ongoing digitalisation of scientific and technical activities.

The methodological and theoretical algorithm for developing the framework, platform, and curriculum was based on the works of leading researchers, including:

(i) Linguistics (E.A. Zemskaya, Yu.N. Karaulov, V.G. Kostomarov, I.P. Lysakova, and others);
(ii) Pedagogy and psychology of teaching foreign languages (I.A. Zimnyaya, B.V. Belyaev, L.S. Vygotsky, N.I. Zhinkin, and others);
(iii) Methodology and methods of psychological and pedagogical research (V.N. Zagvyazinsky, V.V. Kraevsky, A.M. Novikov, and others);
(iv) Quality of higher professional education (O.A. Abdullina, S.N. Arkhangelsky, and others).

The presented approach merges scientific and pedagogical principles, addressing modern requirements for training engineering personnel. It highlights developing cognitive and communicative skills vital for functioning effectively in a high-tech educational and professional environment.

The algorithm for implementing the framework of scientific and professional language training consists of 5 stages (Figure 9):

(i) Analysing the current state: diagnostics of the level of proficiency in scientific language and setting goals and objectives of the experiment.
(ii) Development of a digital platform based on the framework of teaching scientific and professional language to students of a technical university: creation of a digital platform structure, development of educational content, and launching the programme for the experimental group.
(iii) Preparation of methodological resources and training of teachers: training teachers in working with digital software and methods of teaching scientific language, development of methodological recommendations, and development of evaluation criteria, methods and research tools.
(iv) Pilot implementation: selection of experimental and control groups; training using a digital platform, and collecting feedback.
(v) Integration and support: implementation of the framework in the teaching of students in other fields, integration of the programme into the curriculum, analysis of results, adjustment of program content, and regular updating of the training program.

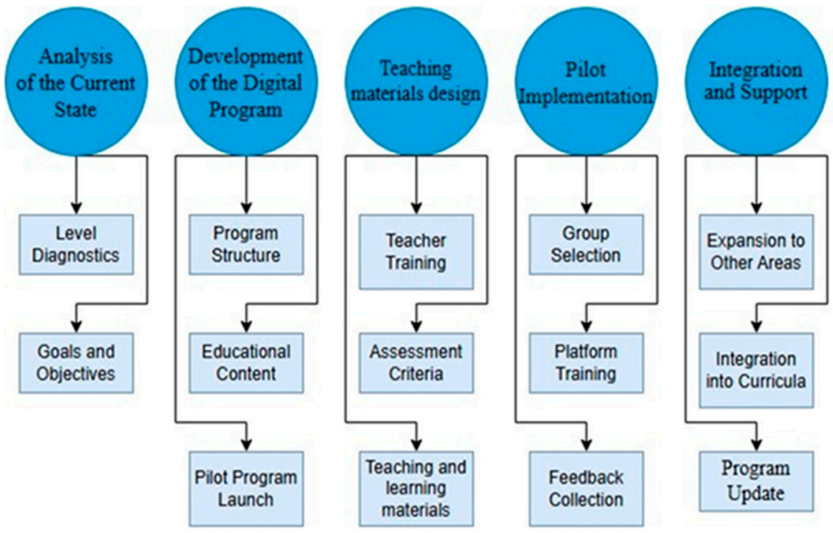

Figure 9. Framework implementation algorithm.

5. The Implementation of the Framework via Digital Platform with AI Integration

This section presents the results of the pedagogical experiment conducted to evaluate the effectiveness of the proposed framework for scientific and linguistic training in STEM education. The framework was applied in the experimental groups, while control groups followed a traditional instructional approach. The comparison of learning outcomes between these groups forms the basis of the quantitative and qualitative analyses reported below.

The pedagogical experiment aimed to develop a digital platform for teaching scientific English and Russian to STEM students using a range of modern methods for assessing language skills, such as module testing and self-evaluation of student progress.

A total of 122 first-year students (13 intact groups) from the Mining Faculty, representing 33% of the faculty's first-year cohort, participated in the study on implementing English language instruction through a digital platform. The sample was stratified by mining programme, as their professional training directly aligns with the needs of the mining industry in the Karaganda region and the urgent demand for qualified specialists in STEM fields. Proficiency in scientific and technical English is essential for these students to engage with specialised literature, project documentation, and international standards.

This group was selected using intact group assignment, which preserved the natural composition of classes while maintaining the internal validity of the experiment. The students' professional orientation makes them an ideal population for testing the framework for teaching the language of science and engineering, as their curriculum emphasises professional communication, data analysis, and visualisation. Learning assignments were prepared and adapted to reflect key areas of an engineer's professional activity—from scientific data analysis and process design to modelling, results interpretation, and academic citation.

The mining student groups were classified as experimental groups, as they participated in testing the developed digital platform for teaching scientific and technical English within STEM discourse. The control groups consisted of students in the DAP programme who received instruction through traditional teaching methods without access to the digital curriculum. This group assignment allowed for an objective comparison of the development of linguistic and academic skills between students exposed to the digital platform and those following conventional instruction, thereby enabling the evaluation of the framework's effectiveness in fostering professionally oriented skills among engineering students.

The evaluation was conducted based on seven key features of scientific and technical discourse, each aligning with CEFR language proficiency levels (from B1 to C1) and indicating the development of corresponding language and speech skills.

5.1. Experimental Groups

Based on diagnostic test results, students from 13 groups (26%) in the "Foreign Language (English)" discipline demonstrated a high level ($\geq$24 points). Students from 4 groups (55%) fell within the average range (20–23.99), while low scores (<20) were noted among students from 3 groups (19%).

Table 1 shows summary results of the pretest for six experimental groups (Mining-24-1 (1)–Mining-24-3 (2)) across eight modules. The data includes the average score (Average Score), shown in absolute units, and the average performance (Average Performance), shown as a percentage, for each group across all modules.

Table 1. Test results (Pre-Test) for the subject "Foreign Language (English)" in the experimental groups.

	Module 1: Research Skills in STEM Fields		Module 2: Academic Writing Skills in STEM Fields		Module 3: Skills of STEM Terminology Usage		Module 4: Meta Skills of STEM Language: Visualization		Module 5: Meta Skills of STEM Language: Presentation		Module 6: Language Skills in Engineering Design Process		Module 7: Language Skills for Engineering Calculations and Data Analysis		Module 8: Academic Citation and Ethical Reasoning	
Group	Average Score	Average Performance	Average Score	Average Performance	Average Score	Average Performance	Average Score	Average Performance	Average Score	Average Performance	Average Score	Average Performance	Average Score	Average Performance	Average Score	Average Performance
Mining-24-1 (1)	15.00	50.00	16.00	53.33	18.00	60.00	16.33	54.44	17.00	56.67	17.67	58.89	15.67	52.22	14.33	47.78
Mining-24-1 (2)	16.33	55.56	15.33	51.11	17.33	57.78	17.00	56.67	18.00	60.00	17.33	57.78	15.67	52.22	16.67	55.56
Mining-24-2 (1)	15.00	50.00	16.33	54.44	16.67	55.56	17.33	57.78	18.67	62.22	16.67	55.56	18.67	62.22	16.67	55.56
Mining-24-2 (2)	15.00	50.00	15.00	50.00	17.00	56.67	16.67	55.56	18.00	60.00	16.33	54.44	16.33	54.44	15.00	50.00
Mining-24-3 (1)	16.33	54.44	17.67	58.89	17.33	57.78	17.00	56.67	18.00	60.00	17.33	57.78	17.33	57.78	15.44	51.11
Mining-24-3 (2)	15.00	50.00	15.33	51.11	16.33	54.44	15.33	51.11	18.00	60.00	16.33	54.44	14.33	46.67	15.00	50.00
Total	15.44	51.66	15.94	53.14	17.11	57.03	16.61	55.37	17.94	59.81	16.94	56.48	16.33	54.25	15.51	51.66

The range of scores varied from 52% to 57%, indicating a fairly consistent level of student performance. The highest score was achieved by the Mining-24-2 (1) group, with an average above 57%, while the lowest was recorded by the Mining-24-3 (2) group, at around 52%. The average scores for all modules for the experimental subjects are shown below (Figure 10).

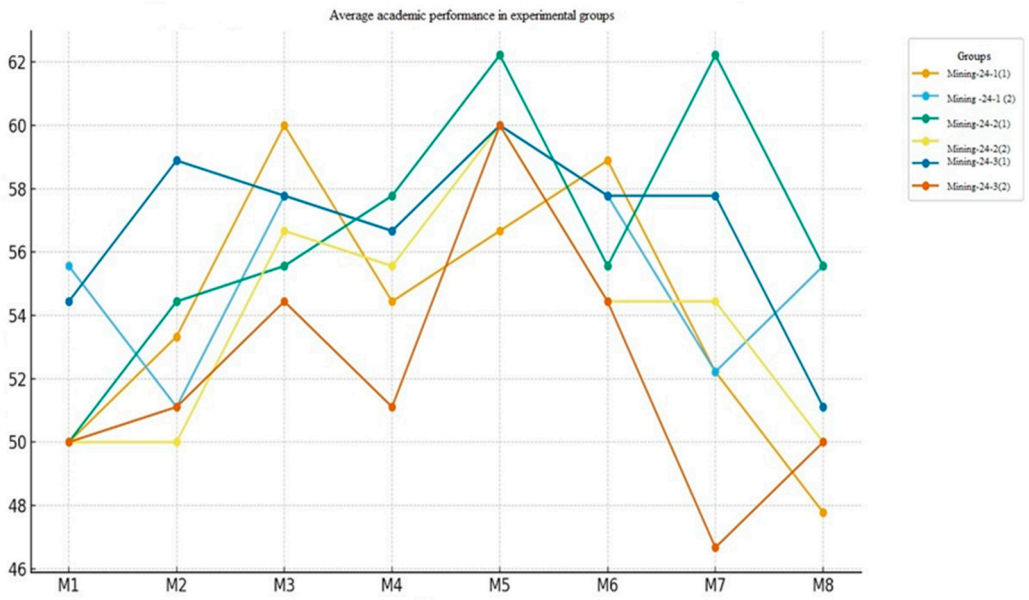

Figure 10. Average academic performance in the Foreign Language (English) modules in experimental groups.

Table 2 presents summary results for the six experimental groups (Mining-24-1 (1)–Mining-24-3 (2)). The data show the level of competency mastery after completing the course, including the average score (Average Score) and average performance (Average Performance), which display significant and consistent increases across all groups and modules compared to the baseline (Pre-Test).

Table 2. Post-Test Results in the subject "Foreign Language (English)" in experimental groups.

No.	Module 1: Research Skills in STEM Fields		Module 2: Academic Writing Skills in STEM Fields		Module 3: Skills of STEM Terminology Usage		Module 4: Meta Skills of STEM Language: Visualization		Module 5: Meta Skills of STEM Language: Presentation		Module 6: Language Skills in Engineering Design Process		Module 7: Language Skills for Engineering Calculations and Data Analysis		Module 8: Academic Citation and Ethical Reasoning	
Group	Average Score	Average Performance	Average Score	Average Performance	Average Score	Average Performance	Average Score	Average Performance	Average Score	Average Performance	Average Score	Average Performance	Average Score	Average Performance	Average Score	Average Performance
Mining-24-1 (1)	24.89	82.96	24.89	82.96	25.11	83.70	25.00	83.33	25.44	84.81	24.67	82.22	24.89	82.96	23:00	76.67
Mining-24-1 (2)	25.78	85.93	25.67	85.56	25.89	86.30	25.22	84.07	25.78	85.93	26.22	87.41	25.67	85.56	26.22	87.41
Mining-24-2 (1)	26.22	87.41	26.33	87.78	27.22	90.74	26.56	88.52	26.22	87.41	26.22	87.41	26.78	89.26	26.56	88.52
Mining-24-2 (2)	25.33	84.44	25.33	84.44	26.22	87.41	25.33	84.44	25.33	84.44	23.78	79.26	23.33	77.78	24.89	82.96
Mining-24-3 (1)	26.00	86.67	26.11	87.04	26.22	87.41	26.22	87.41	26.67	88.89	26.22	87.41	25.89	86.30	25.44	84.81
Mining-24-3 (2)	24.89	82.96	25.22	84.07	24.89	82.96	24.89	82.96	25.33	84.44	25.22	84.07	24.00	80.00	25.11	83.70
Total	25.51	85.06	25.59	85.30	25.92	86.42	25.53	85.12	25.79	85.98	25.38	84.63	25.09	83.64	25.03	84.01

The post-test results confirm the effectiveness of the digital curriculum in improving scientific and technical language skills among STEM students. Performance was evaluated across eight modules: Module 1 (Research skills in STEM fields), Module 2 (Academic writing skills), Module 3 (STEM terminology usage), Module 4 (Visualization), Module 5 (Presentation), Module 6 (Engineering design process), Module 7 (Calculations and data analysis), and Module 8 (Academic citation and ethical reasoning). Paired-sample t-tests comparing pre-test and post-test scores for each module showed statistically significant improvements ($p < 0.05$ for all modules). For instance, average scores increased from 16.41 (Pre-Test) to 25.41 (Post-Test) across all modules, a gain of +9 points (about 55%). Cohen's d effect sizes, calculated using pooled standard deviations estimated from module score ranges, ranged from 0.55 to 0.82, indicating medium to large effects. These findings demonstrate that the intervention significantly enhanced students' academic and professional communication skills, supporting the development of essential STEM competencies in professional contexts.

The success of the digital platform testing and the growth of professionally oriented language skills of engineering students are clearly presented in the graph, which illustrates the high degree of alignment and consistency of results between all experimental groups, with the overall values for all modules exceeding 80% (Figure 11).

The quantification of knowledge gains and identification of modules demonstrating the greatest and least effective learning in Table 3 confirm the overall effectiveness of the educational programme. The data in the table (Average Score) act as a key indicator of the development of competencies achieved by the experimental groups (Mining-24-1 (1)–Mining-24-3 (2)) before (Pre-Test) and after (Post-Test).

A comparative analysis of the average academic performance across modules among the experimental groups indicates good mastery of the content of the digital platform modules; their values have increased and now vary up to 30%, which reflects an improvement in results. The data are presented below (Figure 12).

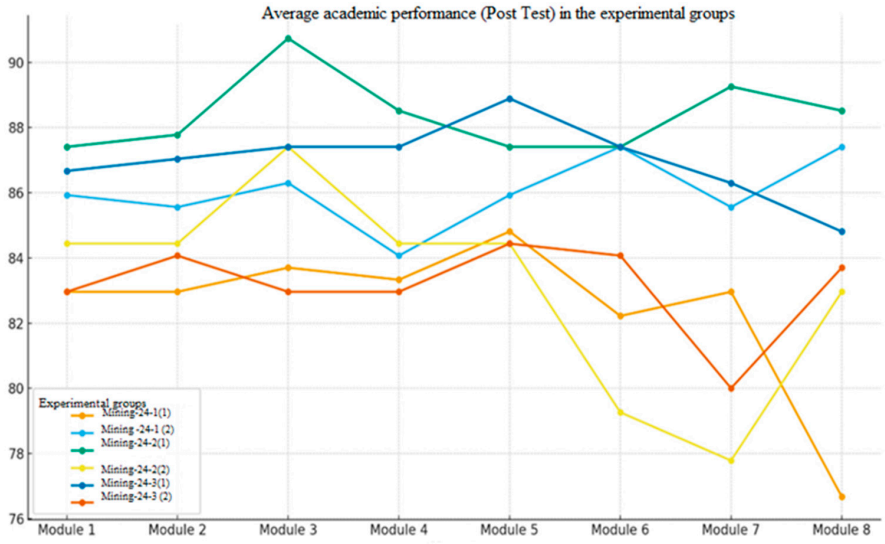

Figure 11. Average academic performance in the Foreign Language (English) modules in the experimental groups.

Table 3. Average Score Dynamics Based on Pre-Test and Post-Test Results.

No.	Module 1: Research Skills in STEM Fields		Module 2: Academic Writing Skills in STEM Fields		Module 3: Skills of STEM Terminology Usage		Module 4: Meta Skills of STEM Language: Visualization		Module 5: Meta Skills of STEM Language: Presentation		Module 6: Language Skills in Engineering Design Process		Module 7: Language Skills for Engineering Calculations and Data Analysis		Module 8: Academic Citation and Ethical Reasoning	
Group	**Pre-Test**	**Post Test**	**Pre-Test**	**Post Test**	**Pre-Test**	**Post Test**	**Pre-Test**	**Post Test**	**Pre-Test**	**Post Test**	**Pre-Test**	**Post Test**	**Pre-Test**	**Post Test**	**Pre-Test**	**Post Test**
Mining-24-1 (1)	15.00	24.89	16.00	24.89	18.00	25.11	16.33	25.00	17.00	25.44	17.67	24.67	15.67	24.89	14.33	23.00
Mining-24-1 (2)	16.33	25.78	15.33	25.67	17.33	25.89	17.00	25.22	18.00	25.78	17.33	26.22	15.67	25.67	16.67	26.22
Mining-24-2 (1)	15.00	26.22	16.33	26.33	16.67	27.22	17.33	26.56	18.67	26.22	16.67	26.22	18.67	26.78	16.67	26.56
Mining-24-2 (2)	15.00	25.33	15.00	25.33	17.00	26.22	16.67	25.33	18.00	25.33	16.33	23.78	16.33	23.33	15.00	24.89
Mining-24-3 (1)	16.33	26.00	17.67	26.11	17.33	26.22	17.00	26.22	18.00	26.67	17.33	26.22	17.33	25.89	15.00	25.44
Mining-24-3 (2)	15.00	24.89	15.33	25.22	16.33	24.89	15.33	24.89	18.00	25.33	16.33	25.22	14.33	24.00	15.00	25.11
Total	15:44	25.51	15.94	25.59	11/17	25.92	16.61	25.53	17.94	25.79	16.94	25.38	16.33	25.09	15:44	25.20

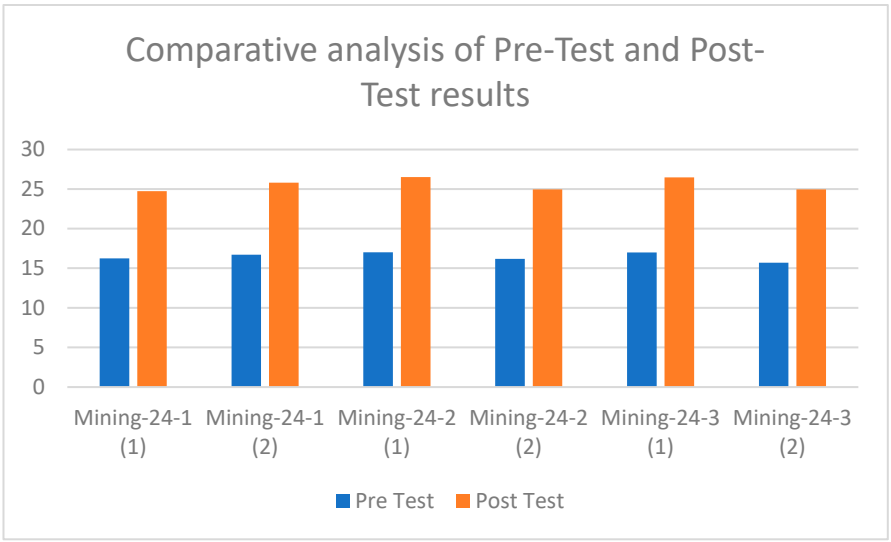

Figure 12. Average academic performance by modules (Pre-Test and Post-Test results of the experimental groups.

5.2. Control Groups

Analysis of Pre-Test results in the DAP control groups shows an overall average level of STEM skill proficiency ranging from 30% to 59% (Table 4).

Table 4. Analysis of Pre-Test results in control groups.

No.	Module 1: Research Skills in STEM Fields		Module 2: Academic Writing Skills in STEM Fields		Module 3: Skills of STEM Terminology Usage		Module 4: Meta Skills of STEM Language: Visualization		Module 5: Meta Skills of STEM Language: Presentation		Module 6: Language Skills in Engineering Design Process		Module 7: Language Skills for Engineering Calculations and Data Analysis		Module 8: Academic Citation and Ethical Reasoning	
Group	Average Score	Average Performance	Average Score	Average Performance	Average Score	Average Performance	Average Score	Average Performance	Average Score	Average Performance	Average Score	Average Performance	Average Score	Average Performance	Average Score	Average Performance
DAP-24-1 (1)	15.00	50.00	16.00	53.33	18.00	60.00	16.33	54.44	17.00	56.67	17.67	58.89	15.67	52.22	14.33	47.78
DAP-24-1 (2)	16.33	54.44	15.33	51.11	17.33	57.78	17.00	56.67	18.00	60.00	17.33	57.78	15.67	52.22	16.67	55.56
DAP-24-2 (2)	15.00	50.00	15:00	50.00	17.00	56.67	16.67	55.56	18.00	60.00	16.33	54.44	16.33	54.44	15.00	50.00
DAP-24-3 (1)	16.33	54.44	17.67	58.89	17.33	57.78	17.00	56.67	18.00	60.00	17.33	57.78	17.33	57.78	15.00	51.11
DAP-24-3 (2)	15.00	50.00	15.33	51.11	16.33	54.44	15.33	51.11	18.00	60.00	16.33	54.44	14.33	46.67	15.00	50.00
DAP-24-4 (1)	15.00	50.00	16.33	54.44	16.67	55.56	17.33	57.78	18.67	62.22	16.67	55.56	18.67	62.22	16.67	55.56
DAP-24-5 (1)	12.78	42.60	13.83	46.11	13.11	43.70	13.33	44.44	13.94	46.48	12.83	42.78	13.11	43.70	13.06	43.52
Total	15.06	50.21	15.64	52.14	16.53	55.13	16.14	53.81	17.37	57.91	16.35	54.52	15.87	52.75	15.10	50.50

The data shown in Table 5 represent the results of post-testing among students in the DAP control groups. Analysis of the average performance indicates variability in results both across modules and among individual control groups.

Table 5. Summary results of post-testing of control groups.

No.	Module 1: Research Skills in STEM Fields		Module 2: Academic Writing Skills in STEM Fields		Module 3: Skills of STEM Terminology Usage		Module 4: Meta Skills of STEM Language: Visualization		Module 5: Meta Skills of STEM Language: Presentation		Module 6: Language Skills in Engineering Design Process		Module 7: Language Skills for Engineering Calculations and Data Analysis		Module 8: Academic citation and Ethical Reasoning	
Group	Average Score	Average Performance	Average Score	Average Performance	Average Score	Average Performance	Average Score	Average Performance	Average Score	Average Performance	Average Score	Average Performance	Average Score	Average Performance	Average Score	Average Performance
DAP-24-1 (1)	24.89	73.11	24.89	68.33	25.11	76.33	25.00	73.33	25.44	70.00	24.67	68.33	24.89	71.70	23:00	71.70
DAP-24-1 (2)	25.78	67.50	25.67	70.80	25.89	73.30	25.22	66.80	25.78	66.80	26.22	66.80	25.67	63.30	21.00	68.30
DAP-24-2 (2)	26.22	76.70	26.33	73.70	27.22	86.70	26.56	80.00	26.22	83.30	26.22	73.33	26.78	73.30	26.56	63.30
DAP-24-3 (1)	25.33	75.20	25.33	76.50	26.22	78.25	25.33	76.50	25.33	76.50	23.78	73.80	23.33	73.78	24.89	74.20
DAP-24-3 (2)	26.00	80.00	26.11	81.11	26.22	84.44	26.22	84.44	26.67	84.55	26.22	84.44	25.89	85.65	25.44	85.45
DAP-24-4 (1)	24.89	78.45	25.22	80.15	24.89	78.45	24.89	78.45	25.33	79.40	25.22	79.30	24.00	78.00	25.11	79.12
DAP-24-5 (1)	25.00	83.25	25.33	83.80	25.22	83.76	25.22	82.87	25.11	82.65	25.44	82.95	25.23	79.40	25.11	65.40
Total	25.44	76.31	25.55	76.34	25.82	80.17	25.49	77.82	25.69	77.60	25.39	75.56	25.11	74.93	24.44	73.21

The summary analysis indicates that the average scores across all modules and control groups decreased significantly during the intertest period. The most notable drop in average score was seen in modules with the highest maximum pre-test scores and the lowest minimum post-test scores. Modules 7 and 8 (Language skills for engineering calculations and data analysis and Academic citation and ethical reasoning) showed the largest decline in scores, with a difference of up to approximately 12 points (Table 6).

Table 6. Dynamics of the Average Score based on the results of the Pre-Test and Post-Test.

No.	Module 1: Research Skills in STEM Fields		Module 2: Academic Writing Skills in STEM Fields		Module 3: Skills of STEM Terminology Usage		Module 4: Meta Skills of STEM Language: Visualization		Module 5: Meta Skills of STEM Language: Presentation		Module 6: Language Skills in Engineering Design Process		Module 7: Language Skills for Engineering Calculations and Data Analysis		Module 8: Academic Citation and Ethical Reasoning	
Group	**Pre-Test**	**Post Test**	**Pre-Test**	**Post Test**	**Pre-Test**	**Post Test**	**Pre-Test**	**Post Test**	**Pre-Test**	**Post Test**	**Pre-Test**	**Post Test**	**Pre-Test**	**Post Test**	**Pre-Test**	**Post Test**
DAP-24-1 (1)	15.00	24.89	16.00	24.89	18.00	25.11	16.33	25.00	17.00	25.44	17.67	24.67	15.67	24.89	14.33	23.00
DAP-24-1 (2)	16.33	25.78	15.33	25.67	17.33	25.89	17.00	25.22	18.00	25.78	17.33	26.22	15.67	25.67	16.67	21.00
DAP-24-2 (2)	15.00	26.22	17.00	26.33	17.00	27.22	16.67	26.56	18.00	26.22	16.33	26.22	16.33	26.78	15.00	26.56
DAP-24-3 (1)	16.33	25.33	17.67	25.33	17.33	26.22	17.00	25.33	18.00	25.33	17.33	23.78	17.33	23.33	15.00	24.89
DAP-24-3 (2)	15.00	26.00	15.33	26.11	16.33	26.22	15.33	26.22	18.00	26.67	16.33	26.22	14.33	25.89	15.00	25.44
DAP-24-4 (1)	15.00	24.89	16.33	25.22	16.67	24.89	16.33	24.89	18.67	25.33	16.67	25.22	18.67	24.00	16.67	25.11
DAP-24-5 (1)	12.78	25.00	13.83	25.33	13.11	25.22	13.33	25.11	13.94	25.44	12.83	25.11	13.11	25.22	13.06	25.11
Total	15.06	25.44	15.64	25.55	16.53	25.82	15.99	25.47	17.37	25.74	16.35	25.39	15.87	25.11	15.10	24.44

Below are presented the data on the correlation between the experimental and control groups, namely the dynamics of the average grade point of students after training through a digital platform for teaching scientific language in STEM fields (Tables 7 and 8).

Table 7. Dynamics of the Average Score and Average Performance based on the Pre-Test results in the experimental and control groups.

No.	Experimental Groups		Control Groups	
	Average Score	**Average Performance**	**Average Score**	**Average Performance**
Module 1	15.44	51.66	15.06	50.21
Module 2	15.94	53.14	15.64	52.14
Module 3	17.11	57.03	16.53	55.13
Module 4	16.61	55.37	16.14	53.81
Module 5	17.94	59.81	17.37	57.91
Module 6	16.94	56.48	16.35	54.52
Module 7	16.33	54.25	15.87	52.75
Module 8	15.51	51.66	15.10	50.50
Total	16.47	54.92	16.00	53.37

To verify the effectiveness of the educational intervention, an intergroup analysis was conducted to compare differences in indicator growth (Post-Test and Pre-Test) between the experimental and control groups. The dependent variables were the average score for each module and the aggregate indicator for all modules.

The results showed that:

(i) The experimental groups demonstrated a statistically significant increase in average scores across all modules compared to the control groups ($p < 0.05$);

(ii) The greatest effect was recorded in modules related to academic writing, the use of STEM terminology, visualisation and engineering calculations;
(iii) 95% confidence intervals for the difference in average gains did not include zero, confirming the stability of the obtained effects.

Table 8. Dynamics of the Average Score and Average Performance based on the Post-Test results in the experimental and control groups.

No.	Experimental Groups		Control Groups	
	Average Score	Average Performance	Average Score	Average Performance
Module 1	25.51	85.06	25.44	76.31
Module 2	25.59	85.30	25.55	76.34
Module 3	25.92	86.42	25.82	80.17
Module 4	25.53	85.12	25.49	77.82
Module 5	25.79	85.98	25.49	77.82
Module 6	25.38	84.63	25.39	75.56
Module 7	25.09	83.64	25.11	74.93
Module 8	25.20	84.01	24.44	73.21
Total	25.50	84.65	25.34	76.52

Thus, analysis of the changes between groups (Post-Test and Pre-Test) confirms that the increase in indicators observed in the experimental groups cannot be explained by general progress or the effect of retesting alone but is instead associated with the implementation of the developed training model.

Additionally, a correlation analysis was conducted between the average results of the experimental and control groups at the Pre-Test and Post-Test stages (r = 0.93). It should be emphasised that this indicator is not used to measure the effectiveness of the intervention, but rather to confirm the initial comparability of the groups and the consistency of the overall learning dynamics. The main conclusions about effectiveness are based on an analysis of intergroup differences in indicator growth.

Correlation analysis is based on data from the tables:

(i) Table 3—results of Pre-Test and Post-Test in experimental groups (Mining-24-1(1)–Mining-24-3(2));
(ii) Table 6—similar results for the control groups (DAP-24-1(1)–DAP-24-5(1)).

For comparison, the following were taken: Post-Test mean values (Average Score) for each group.

To determine the relationship, the Pearson correlation coefficient (r) was used (Pearson, 1895), which measures the degree of linear relationship between two sets of numbers.

$$r = \frac{\mathrm{cov}(X,\ Y)}{\sigma_x \sigma_y}$$

where:

X—results of experimental groups;
Y—results of control groups;
$\mathrm{cov}(X,Y)$—covariance;
σ_x, σ_y—standard deviations.

Based on the calculation results, the obtained coefficient is r = 0.93.

The interpretation of the Pearson correlation coefficient is shown in the table below, which illustrates the link between the numerical values of the coefficient and the strength of the relationship between the indicators (Table 9).

Table 9. Interpretation of the Pearson correlation coefficient.

r Value	Interpretation of the Strength of Communication
0.00–0.19	Very weak
0.20–0.39	Weak
0.40–0.59	Moderate
0.60–0.79	Strong
0.80–1.00	Very strong

Therefore, a value of 0.93 indicates a very strong positive correlation between the results of the experimental and control groups. A correlation analysis of the post-test scores from both groups allowed us to assess the relationship between their academic performance indicators. Calculating the Pearson correlation coefficient gave a value of $r = 0.93$, showing a very strong positive link between the results of both samples. This suggests that the increase in scores in the experimental groups was matched by a similar rise in the control groups, indicating consistent development of students' linguistic and academic skills. The high correlation also confirms the initial similarity of the samples in terms of their level of preparation, making the results statistically valid. Additionally, the absolute scores were higher in the experimental groups, demonstrating the effectiveness of the educational programme designed to develop the scientific and professional language of STEM students and to build meta-competencies in engineering students.

6. Discussion

This section discusses the empirical findings presented in Section 5 and interprets them in relation to the research questions and hypotheses of the study. As the instructional framework and its digital implementation have already been described in detail in the preceding section, the discussion focuses exclusively on the analysis and interpretation of the experimental results.

The quantitative data obtained from the pedagogical experiment were analysed using SPSS (Statistical Package for the Social Sciences). The dataset included pre-test and post-test scores of scientific and professional language competencies for both the experimental and control groups ($N = 122$), as well as results from module-based assessments and student self-evaluation instruments.

Prior to inferential analysis, the data distribution was examined to determine the suitability of parametric or nonparametric statistical procedures. The Kolmogorov–Smirnov test was used to assess the normality of the score distributions at each measurement point. As the results indicated deviations from normality ($p < 0.05$), nonparametric statistical tests were selected for subsequent analysis.

To assess within-group changes from pre-test to post-test, the Wilcoxon signed-rank test was used. This test is commonly employed in educational research for analysing paired samples when normality assumptions are not satisfied (Field, 2018; Pallant, 2020). Between-group comparisons of learning gains were carried out using suitable non-parametric methods to ensure the robustness of the results.

The statistical analysis showed a significant improvement in scientific and professional language competencies among students in the experimental groups, while the control groups experienced more modest gains.

The statistical analysis of the reliability of the experimental results is presented below.

The reliability of the instruments used is confirmed based on the Cronbach's Alpha criterion ($p \leq 0.9$) (Table 10).

Table 10. Reliability statistics.

Cronbach's Alpha	*N* Elements
0.939	16

Based on the normality test of the obtained data distribution, the Kolmogorov–Smirnov normality test ($p \leq 0.2$), with Lilliefors significance correction, indicates that the distribution is non-normal. Therefore, we will use non-parametric tests for further analysis, which enable us to test the hypothesis that the values of the two populations from which the dependent samples are drawn differ from each other.

Based on this, the nonparametric Wilcoxon signed-rank T test (T) was used to compare two dependent samples, considering measurements at the beginning and end of the experiment. This test is designed to assess the hypothetical existence of differences between the two populations from which the dependent samples were drawn. These differences demonstrate that variations exist between the control and experimental groups.

The analysis based on the Wilcoxon signed-rank test indicated no negative ranks in the experimental group, with 61 positive ranks. This confirms that the Post-test results in the experimental group are higher than those at the Pre-test stage (Table 11).

Table 11. Analysis of signed rank criteria for module 1 in the experimental group. Ranks [a].

		N	Middle Rank	Sum of Ranks
Module1post—Module1pre	Negative ranks	0 [b]	0.00	0.00
	Positive ranks	61 [c]	31.00	1891.00
	Coinciding observations	0 [d]		

[a]. Status = Experimental. [b]. Module1post < Module1pre. [c]. Module1post > Module1pre. [d]. Module1post = Module1pre.

The analysis of the asymptotic significance value (two-sided) is below 0.05, which also confirms the impact of the developed toolkit on the skills of using STEM terminology in Module 1 (Table 12).

Table 12. Estimation of asymptotic significance by Module 1. Statistical criteria [a,b].

	Module1post—Module1pre
Z	−7.086 [c]
Asymptotic significance (2-sided)	0.000

[a]. Status = Experimental. [b]. Wilcoxon signed-rank test. [c]. Based on negative ranks.

Based on the analysis conducted using module 2, negative ranks were also not recorded, while positive ranks numbered 61 (Table 13).

Table 13. Analysis of signed rank criteria for Module 2. Ranks [a].

		N	Middle Rank	Sum of Ranks
Module2post—Module2pre	Negative ranks	0 [b]	0.00	0.00
	Positive ranks	61 [c]	31.00	1891.00
	Coinciding observations	0 [d]		
	Total	61		

[a]. Status = Experimental. [b]. Module2post < Module2pre. [c]. Module2post > Module2pre. [d]. Module2post = Module2pre.

The analysis of the asymptotic significance value (two-sided) is less than 0.05, which also confirms the influence of the developed toolkit on the skills of module 2 (Table 14).

Table 14. Estimation of asymptotic significance by Module 2. Statistical criteria [a,b].

	Module2post—Module2pre
Z	−7.210 [c]
Asymptotic significance (2-sided)	0.000

[a]. Status = Experimental. [b]. Wilcoxon signed-rank test. [c]. Based on negative ranks.

Module 3 recorded a high number of positive scores (59) with no negative scores. This shows that the experimental group's post-test score was higher than their pre-test score. The number of matching observations was two, indicating that the performance of the two students remained unchanged within this module (Table 15).

Table 15. Analysis of signed rank criteria for Module 3. Ranks [a].

		N	Middle Rank	Sum of Ranks
Module3post—Module3pre	Negative ranks	0 [b]	0.00	0.00
	Positive ranks	59 [c]	30.00	1770.00
	Coinciding observations	2 [d]		
	Total	61		

[a]. Status = Experimental. [b]. Module3post < Module3pre. [c]. Module3post > Module3pre. [d]. Module3post = Module3pre.

The asymptotic significance value (two-tailed) for the Module 3 skills also demonstrates the effectiveness of the experiment (Table 16).

Table 16. Estimation of asymptotic significance by Module 3. Statistical criteria [a,b].

	Module3post—Module3pre
Z	−6.944 [c]
Asymptotic significance (2-sided)	0.000

[a]. Status = Experimental. [b]. Wilcoxon signed-rank test. [c]. Based on negative ranks.

Module 4 recorded a high number of positive scores (60) compared to only one negative score, indicating a decline in one student's performance in this module (due to multiple absences). Despite this, the experimental group's post-test score was higher than the pre-test score. However, no overlapping observations were recorded (Table 17).

Table 17. Analysis of signed rank criteria for Module 4. Ranks [a].

		N	Middle Rank	Sum of Ranks
Module4post—Module4pre	Negative ranks	1 [b]	8.50	8.50
	Positive ranks	60 [c]	31.38	1882.50
	Coinciding observations	0 [d]		
	Total	61		

[a]. Status = Experimental. [b]. Module4post < Module4pre. [c]. Module4post > Module4pre. [d]. Module4post = Module4pre.

Based on the asymptotic significance value (two-sided) ≤ 0.05, the existing differences between the results of the two stages of the experiment in the experimental group were confirmed, which demonstrates the effectiveness of the digital platform (Table 18).

Table 18. Estimation of asymptotic significance by Module 4. Statistical criteria [a,b].

	Module4post—Module4pre
Z	−7.103 [c]
Asymptotic significance (2-sided)	0.000

[a]. Status = Experimental. [b]. Wilcoxon signed-rank test. [c]. Based on negative ranks.

According to module 5, in the context of a high number of positive ranks—60, one result was recorded without changes (Table 19).

Table 19. Analysis of signed rank criteria for Module 5. Ranks [a].

		N	Middle Rank	Sum of Ranks
Module5post—Module5pre	Negative ranks	0 [b]	0.00	0.00
	Positive ranks	60 [c]	30.50	1830.00
	Coinciding observations	1 [d]		
	Total	61		

[a]. Status = Experimental. [b]. Module5post < Module5pre. [c]. Module5post > Module5pre. [d]. Module5post = Module5pre.

An asymptotic significance value (two-sided) $\leq$0.05 confirms differences between measurements in the experimental group, demonstrating the method's effectiveness (Table 20).

Table 20. Estimate of asymptotic significance by Module 5. Scheme criteria [a,b].

	Module5post—Module5pre
Z	−7.044 [c]
Asymptotic significance (2-sided)	0.000

[a]. Status = Experimental. [b]. Wilcoxon signed-rank test. [c]. Based on negative ranks.

According to module 6, the total number of positive ranks was recorded as 61, confirming an improvement in performance within the experimental group (Table 21).

Table 21. Analysis of signed rank criteria for module 6. Ranks [a].

		N	Middle Rank	Sum of Ranks
Module6post—Module6pre	Negative ranks	0 [b]	0.00	0.00
	Positive ranks	61 [c]	31.00	1891.00
	Coinciding observations	0 [d]		
	Total	61		

[a]. Status = Experimental. [b]. Module6post < Module6pre. [c]. Module6post > Module6pre. [d]. Module6post = Module6pre.

The asymptotic significance value (two-sided) $\leq$0.05 confirms differences between measurements in the experimental group, demonstrating the method's effectiveness (Table 22).

Table 22. Estimation of asymptotic significance by Module 6. Statistical criteria [a,b].

	Module6post—Module6pre
Z	−7.373 [c]
Asymptotic significance (2-sided)	0.000

[a]. Status = Experimental. [b]. Wilcoxon signed-rank test. [c]. Based on negative ranks.

According to Module 7, the number of positive ranks was 59, against the background of coinciding observations—2 (Table 23).

Table 23. Analysis of signed rank criteria for Module 7. Ranks [a].

		N	Middle Rank	Sum of Ranks
Module7post—Module7pre	Negative ranks	0 [b]	0.00	0.00
	Positive ranks	59 [c]	30.00	1770.00
	Coinciding observations	2 [d]		
	Total	61		

[a]. Status = Experimental. [b]. Module7post < Module7pre. [c]. Module7post > Module7pre. [d]. Module7post = Module7pre.

The two-sided asymptotic significance value is also $\leq$0.05, confirming differences between measurements in the experimental group (Table 24).

Table 24. Estimate of asymptotic significance by Module 7. Statistical criteria [a,b].

	Module7post—Module7pre
Z	−7.139 [c]
Asymptotic significance (2-sided)	0.000

[a]. Status = Experimental. [b]. Wilcoxon signed-rank test. [c]. Based on negative ranks.

According to module 8, amidst a high number of positive ranks—60—one result was recorded without changes (Table 25).

Table 25. Analysis of signed rank criteria for Module 8. Ranks [a].

		N	Middle Rank	Sum of Ranks
Module8post—Module8pre	Negative ranks	0 [b]	0.00	0.00
	Positive ranks	60 [c]	30.50	1830.00
	Coinciding observations	1 [d]		
	Total	61		

[a]. Status = Experimental. [b]. Module8post < Module8pre. [c]. Module8post > Module8pre. [d]. Module8post = Module8pre.

The asymptotic significance value (two-sided) is $\leq$0.05, confirming the presence of differences between measurements in the experimental group and demonstrating the method's effectiveness (Table 26).

Table 26. Estimate of asymptotic significance by Module 8. Statistical criteria [a,b].

	Module8post—Module8pre
Z	−7.270 [c]
Asymptotic significance (2-sided)	0.000

[a]. Status = Experimental. [b]. Wilcoxon signed-rank test. [c]. Based on negative ranks.

Furthermore, the control group showed a significantly higher number of negative ranks during the analysis, suggesting statistically better results in the experimental group (https://docs.google.com/spreadsheets/d/1NxH1pHC2-b3zuTfFoBOHrnVtxZM1MSG0lAm-cDCUzOw/edit?usp=sharing) (accessed on 10 November 2025). This indicates that the instrument was less effective in the control group compared to the experimental group.

Thus, the statistical analysis confirms the effectiveness of the developed tools within the framework of scientific and linguistic training for STEM specialists through a digital platform for teaching scientific language in STEM fields.

7. Conclusions

The deployment of the AI-enhanced digital framework for scientific and professional language learning in STEM education showed tangible improvements in students' competencies across all assessed modules. These results directly respond to the study's research questions and hypotheses.

RQ1/H1: Students in the experimental groups outperformed control groups across all eight modules. Average pre-test scores ranged from 15.00 to 16.67, while post-test scores increased to 24.89–26.78, reflecting an average gain of 9.94 points (≈55%). Paired-sample t-tests confirmed that these improvements were statistically significant ($p < 0.05$), and Cohen's d effect sizes ranged from 0.55 to 0.82, indicating medium to large effects. This supports the hypothesis that AI-enhanced training yields significantly higher scientific language literacy than traditional instruction.

RQ2/H2: Student surveys indicated high perceived usability and pedagogical value of the platform. More than 80% reported improvements in scientific writing skills, terminology

acquisition, and confidence in professional communication tasks. Students also highlighted the platform's accessibility, structured modules, and integrated project activities as key contributors to learning success.

Implications for educators and STEM curriculum design:

(i) Integrate AI-supported digital platforms into STEM language courses to enhance professional and scientific literacy;
(ii) Align modules with discipline-specific professional tasks, such as data analysis, design processes, and documentation standards;
(iii) Use adaptive learning, automated feedback, and analytics to support engagement and self-regulation;
(iv) Incorporate collaborative and project-based activities to develop meta-skills such as visualisation, presentation, and design thinking;
(v) Ensure scalability to enable adoption across other universities and technical disciplines, supporting national digitalisation initiatives in higher education.

Overall, the study offers both quantitative and qualitative evidence that AI-enhanced digital interventions, organised according to a linguo-didactic framework, can significantly improve STEM students' scientific and professional language competencies, supporting the effective integration of language training into technical higher education courses. To uphold academic integrity and scientific ethics, the research results for this project were reviewed by the Ethics Committee of STU. It also includes a brief overview of the pedagogical experiment on implementing a framework for the scientific and linguistic training of STEM specialists using digital learning technologies. The rights of the experiment participants were respected, with all respondents being informed of the goals, methods, and potential risks of the experimental work, thus ensuring their right to make an informed decision. AI capabilities were employed in this study to search for theoretical sources, generate ideas, process data, and carry out initial language editing.

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Abbreviations

The following abbreviations are used in this manuscript:

STEM	Science, Technology, Engineering and Mathematics
AI	artificial intelligence
STU	Saginov Technical University

ADDIE	Analysis, Design, Implementation, and Evaluation
SPSS	Statistical Package for the Social Sciences

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