Implementation of STEM Projects to Foster Research Competencies in High School Chemistry classes

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A thesis submitted to the School of Education and

Humanities in partial fulfillment of the requirements

for the degree of

MASTER OF EDUCATIONAL SCIENCES

in 7M01502 – Chemistry

«SDU University»

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LIST OF ABBREVIATIONS

STEM – Science, Technology, Engineering, Mathematics

IBL – Inquiry-Based Learning

PBL – Project-Based Learning

LO – Learning Outcome

Jamovi – Open-Source Statistical Analysis Software (version 2.3)

SE – STEM Education

RS – Research Skills

N – Number of Participants

U – Mann-Whitney U Test Statistic

p – Probability Value / Significance Level

CL – Chemistry Lessons

ANOVA – Analysis of Variance

ICT – Information and Communication Technology

PBAs – Performance-Based Assessments

ABSTRACT

The incorporation of STEM (Science, Technology, Engineering, and Mathematics) projects in high school chemistry classes is the most effective way to create research competencies among students. These projects, which are the fusion of science and technology, engineering, and mathematics, give students chances to bring the theoretical knowledge they have learned to real-life situations. The approach is about enhancing different skills such as the development of hypothesis, data gathering, experimental design, and critical analysis of results which are the necessary skills needed for students in the academic and professional fields in the sciences. Through collaborative and problem-based learning activities, that not only deepen their understanding of chemistry but also develop essential life skills such as teamwork, communication, and critical thinking. STEM projects foster active engagement where students can take on the roles of researchers to apply the scientific method to investigate phenomena, test theories, and interpret results. This process creates a more dynamic and inquiry-based learning atmosphere that is on par with the needs of modern scientific research. Additionally, students acquire practical experience with equipment found in laboratories, data analysis tools, and scientific software that they will use later in life. They would learn how to deal with setbacks and reach a positive outcome during the progress of their experiments. Chemistry teachers can employ the STEM integrated approach to arm the students with necessary skills for their future academic learning in the fields of science and engineering. The paper suggests that STEM projects are not only capable of improving the results of students in a course but that they also will furnish them with the challenges and demands of future careers in science.

Keywords: STEM projects, research competencies, high school chemistry, hypothesis formulation, data collection, experimental design, problem-solving, scientific inquiry, hands-on learning, teamwork.

АҢДАТПА

Жоғары сыныптағы химия сабақтарында STEM (ғылым, технология, инженерия және математика) жобаларын енгізу оқушылар арасында зерттеу құзыреттілігін дамытуда маңызды рөл атқарады. Ғылымның негізгі қағидаларын технология, инженерия және математикамен біріктіру арқылы бұл жобалар оқушыларға теориялық тұжырымдамаларды нақты әлемдегі жағдайларға қолдануға мүмкіндік береді. Бұл тәсіл гипотезаларды тұжырымдау, деректерді жинау, эксперименттік жобалау және сыни нәтижелерді талдау сияқты маңызды зерттеу дағдыларын дамытады, бұл оқушылардың ғылым саласындағы академиялық және кәсіби өсуі үшін өте маңызды.

Бірлескен және мәселеге негізделген оқу іс-әрекеттері арқылы оқушылар химияны тереңдетіп қана қоймай, сонымен қатар командалық жұмыс, коммуникация және сыни ойлау сияқты маңызды өмірлік дағдыларды дамытады. STEM жобалары белсенді қатысуды ынталандырады, мұнда оқушылар зерттеушілердің рөлін атқарады, құбылыстарды зерттеу, теорияларды тексеру және нәтижелерді түсіндіру үшін ғылыми әдісті қолданады. Бұл процесс заманауи ғылыми зерттеулердің талаптарына сәйкес келетін динамикалық және зерттеуге негізделген оқу ортасын қалыптастырады.

STEM-интеграцияланған тәсілді қолдану арқылы химия мұғалімдері оқушыларды ғылым және инженерия салаларындағы болашақ академиялық ізденістер үшін қажетті дағдылармен жақсырақ жабдықтай алады.

Кілт сөздер: STEM жобалары, зерттеу құзыреттіліктері, орта мектеп химиясы, гипотеза тұжырымдау, деректер жинау, эксперименттік дизайн, мәселелерді шешу, ғылыми зерттеу, практикалық оқу, командалық жұмыс.

АННОТАЦИЯ

Интеграция проектов STEM (наука, технология, инженерия и математика) в школьные курсы химии играет ключевую роль в развитии исследовательских навыков учащихся. Объединяя основные принципы науки с технологиями, инженерией и математикой, эти проекты дают учащимся возможность применять теоретические концепции в реальных ситуациях. Такой подход развивает необходимые исследовательские навыки, такие как генерация гипотез, сбор данных, планирование экспериментов и критический анализ результатов, которые имеют решающее значение для академического и профессионального развития студентов в области науки.

Благодаря совместным и проблемно-ориентированным учебным занятиям учащиеся не только углубляют свое понимание химии, но и развивают важные жизненные навыки, такие как командная работа, коммуникация и критическое мышление. Проекты STEM поощряют активное участие, в которых студенты берут на себя роль исследователей, применяют научные методы для изучения явлений, проверки теорий и интерпретации результатов. Этот процесс способствует созданию более динамичной и ориентированной на исследования учебной среды, отвечающей требованиям современной научной деятельности.

Используя комплексный подход STEM, преподаватели химии могут лучше подготовить студентов к будущей академической карьере в области науки и техники.

Ключевые слова: STEM-проекты, исследовательские компетенции, химия в старшей школе, формулирование гипотез, сбор данных, экспериментальное проектирование, решение проблем, научное исследование, практическое обучение, командная работа.

INTRODUCTION

Contemporary education, in the wake of the fast-paced advancements in science and technology, is more and more aimed at training students who are able to think critical ly, solve problems, and conduct independent research. The shift from the usual teacher-centered academic courses to the practice of competency-oriented learning has put the development of students' research skills as an essential educational outcome in the forefront. Consequently, chemistry experiment and inquiry science is a significant way of experiencing students' research skills through hands-on systematic practical and investigative activities.

At the same time, the global educational community recognizes STEM education as an effective interdisciplinary approach that integrates science, technology, engineering, and mathematics to address real-world problems and enhance learners' cognitive and practical competencies. The implementation of STEM education in chemistry lessons creates favorable conditions for engaging students in research-oriented learning, promoting experimental thinking, and developing essential scientific skills required in the 21st century.

Relevance of the Research

The relevance of this research is determined by the growing demand for students who possess well-developed research skills and are able to apply scientific knowledge in practical and interdisciplinary contexts. Despite the recognized importance of STEM education, the process of forming research skills in chemistry lessons within the STEM framework remains insufficiently explored in pedagogical theory and practice. In many educational institutions, chemistry teaching still relies on reproductive methods, limiting students' opportunities to engage in inquiry, experimentation, and independent problem solving.

Furthermore, contemporary educational standards emphasize the development of research competence, critical thinking, and creativity as essential learning outcomes. Therefore, there is a need for scientifically grounded methodological approaches that ensure the effective formation of research skills through STEM-based chemistry

instruction. This determines the relevance and practical significance of the present study.

Purpose of the Study

The purpose of the study is to theoretically substantiate and experimentally verify the effectiveness of forming research skills in chemistry lessons in the context of STEM education.

Research Objectives

-to analyze the pedagogical and methodological literature on the problem of forming research skills in chemistry education;

-to define the essence, structure, and components of students' research skills in the context of STEM education;

-to identify pedagogical conditions that promote the effective formation of research skills in chemistry lessons;

-to develop STEM-oriented practical and research tasks aimed at enhancing students' research skills;

-to experimentally test the effectiveness of the proposed methodology and analyze the research results.

Research questions

RQ1. How can the implementation of STEM projects in high school chemistry classes enhance students' data collection skills?

RQ2. In what ways do STEM projects support students in formulating hypotheses during chemistry experiments?

RQ3. "How does engagement in STEM projects improve students' experimental design skills in high school chemistry?"

Object of the Research

The object of the research is the educational process of teaching chemistry in secondary schools.

Subject of the Research

The subject of the research is the process of forming students' research skills in chemistry lessons through the implementation of STEM education.

Scientific Novelty of the Study

The scientific novelty of the study consists in the theoretical substantiation of the process of forming research skills in chemistry lessons within the framework of STEM education. A system of STEM-oriented practical and research tasks aimed at developing students' research skills has been developed and experimentally tested.

Theoretical and Practical Significance of the Research

The theoretical significance of the research lies in enriching pedagogical theory with new insights into the formation of research skills in chemistry education under STEM conditions. The results of the study expand the scientific understanding of interdisciplinary approaches in science education.

The practical significance of the research is determined by the possibility of applying the developed STEM-oriented tasks, lesson plans, and methodological recommendations in chemistry teaching practice. The research findings can be used by chemistry teachers, methodologists, and educators to enhance students' research skills and improve the effectiveness of chemistry instruction.

LITERATURE REVIEW

1.1. Research Skills as a Pedagogical Concept in Science Education

Research competencies in science education are now viewed as an integral aspect of modern learning as the current educational paradigms seek to advance students' abilities to think critically, solve problems independently, and apply their knowledge through hands-on experience in real-world situations. The change from teaching by content and competency is causing a lot of people to change their views regarding how much students should achieve learning; therefore, students' achievement of research competencies will no longer be considered as additional skills but rather will be seen as essential to students' development in both cognitive and occupational terms. This orientation can be particularly witnessed in technical fields like the one in chemistry, which is based on the experimental activity, observation, and inquiry as the core methodology of the subject.

Pedagogical literatures regard research skills as intricacies of cognitive, procedural, and reflective means which are learned and accounted by the learners in a systematic manner. Among the procedural abilities of research are also the ways of paraphernalia which include states and towns of problem, creating hypotheses, choosing right research methods, planning and conducting experiments, collecting and analyzing data, interpreting results, and common concluding based on the science results. In the case of science education, research skills also encompass the capacity for working with scientific information, critically evaluating evidence, and the especial ability to use theoretical knowledge in experimental and practical contexts. Therefore, research skills act as a bridge between the theoretical knowledge about science and its practical applications. Evolving from a pedagogical angle, this research skills are not the determining characteristics but the qualities that come through the educative learning of group activities. It necessitates the establishment of a certain pedagogical environment that supports the active participation of students, intellectual independence, and reflective thinking. Science education is a conducive field for this process since the learning through inquiry, experimentation, and evidence-based

reasoning is its typical nature. Chemistry, as an experimental science, plays a particularly important role in the formation of research skills, since chemical knowledge is closely connected with laboratory practice, observation of phenomena, and analysis of experimental results *(Abell & Siegel, 2011)*

The pedagogical interpretation of research skills, as their deeply integrative nature within the system of modern science education, is highlighted. Researchers state that research skills are not only a set of isolated abilities but also a complex composition of knowledge, practical skills, attitudes, values, and intrinsic motivation that are required for effective scientific inquiry. This holistic character makes it possible for research skills to be distinctly different from purely cognitive competences which involve only a master's level of experimental techniques or research methods but also the teachings of a scientific thinker, intellectual curiosity, persistence, liability for results, and ethical considerations. In this regard, research skills are inextricably linked with the broad idea of research competence, which is more and more considered as an important educational outcome in modern science education and a distinctive part of the student's whole academic and personal growth. *(Blumenfeld et al., 1991)*

In addition, the development of research skills is a launching pad to foster innovation and creativity because students are often required to find innovative and creative solutions to complex scientific issues. This engaging process of using creativity involves imagination, inquiry-based learning, and project-based/ hands-on activities that provide students an opportunity to explore new ideas, take intellectual risks, and develop new ways to solve problems creatively *(Capraro et al., 2013)*. The innovative aspect of creativity is particularly evident in chemistry education, where students have the ability to design experiments, look at multiple solutions, and find new applications for their understanding of chemistry. The acquisition of research skills is also a significant factor in developing the capacity for lifelong learning. The ability to ask questions, find information, interpret data, and evaluate results makes students become self-regulated learners who can face new problems, learn how to do things independently, and improve their skills in the long run *(English, 2016)*

The impact of research skills is essential to the personal and social development of students. It has been shown that by doing research, the students learn to be responsible, persistent, and pay attention to the details *(Falloon et al., 2020)*, as it involves proper planning, exact implementation, and honest evaluation of the findings. The joint activities in the field also lead to the growth of the students' communication and team-play skills and their ability to act in a positive manner, which are necessary for membership in the scientific and professional societies of today. Furthermore, inquiry-based learning gives a chance to the learners to see the use of science in the world for instance in the case of saving the environment, building a better and more innovative technological society, etc., this helps them to increase their interest and promotes their social liability.

The learning of research skills is important because it has a universal and multiple role in science education. A system of research skill development that encompasses cognitive (Grangeat et al., 2021*)*, procedural and affective components serves as the basis for developing research competence, scientific literacy, and independent thinking. These skills are utilized to enhance academic achievement in addition to creating opportunities for creative, critical, and collaborative thought as well as lifelong learning. Thus structured and carefully planned development of research skills should be seen as the primary research focus both in chemistry and science education in general to provide students with adequate skills to succeed in resolving the intellectual, technological and societal challenges they will face in the 21st century. The development of research skills in science classes is ordered to the teaching methods which are employed. Traditional reproductive teaching methods that are mainly concerned with memorization and reproduction of knowledge are not enough to develop the relevant research abilities. However, student-centered strategies like inquiry-based learning, problem-based learning, project-based learning, and experimental learning are used to incorporate the experience of original research into the curriculum. These modes of instruction stress the learners' active position in the education process and prompt them to take the responsibility for their own learning.

Inquiry-based learning is noteworthy since it is a great aid to research skills development by imitating the logical process of scientific investigation. By way of inquiry-based activities, learners tend to put questions, develop hypotheses, plan experiments and conclude results. The method helps the students learn the true nature of scientific knowledge and the procedures by which it is created. In chemistry education, inquiry-based laboratory work allows students to explore chemical phenomena experimentally, develop experimental skills, and apply theoretical concepts in practice. Research skills are not just an abstract set of skills but rather form through actual doing of science, through real research and scientific activity. Another significant aspect of the pedagogical concept surrounding developmentally based research skills is that they have a developmental nature. From simple skills that include observing and collecting simple data to more complicated skills developed through performing an experiment with a designed experiment and interpreting and critically evaluating results; research skills develop in a stepwise fashion, requiring systematic and continuous application in curriculum, at various levels of complexity throughout the school year. Future chemistry educators need to understand this developmental process to be able to develop tasks that correspond to their students' cognitive and educational developmental levels regarding research skills.

The existence of a clear relationship between the student's development of research skills and their ability to work with experiments is an example of the interconnectedness between the two concepts. Experimental activities provide the foundation for the chemistry curriculum, the basis for the development of research skills will come from experimental activity that allows students to formulate hypotheses about how chemical reactions occur and the interpretation of empirical data that has been obtained in the laboratory from experimental activities. Students develop their operational skills by performing laboratory activities and they will also learn operational protocols in relation to the safety requirements of the laboratory environment, precision, and accountability to their classmates. Most importantly, experimental activities stimulate the scientific thinking process as they make it

necessary for students to make sense of their observations, determine patterns and come to conclusions based on the say-so of the evidence. Consequently, experimental work is not merely a method of demonstrating theoretical concepts, but it is also a significant means of the development of research skills. Research skills' pedagogical value goes beyond the scope of academic achievements. Research skills, therefore, are the keys to influence students' independent, persistent, and self-assured characteristics. Similarly, the students' finding of new problems, their effort to solve them and their reflection on what they have learned also help them build these attributes. The above-mentioned qualities are particularly critical in the process of the training of future teachers of chemistry, who are anticipated to show students inquiring-based learning and practice in their career as a role model of research-oriented behavior. In light of the recent changes in the education sector, the building of the research skills complements the measurable international educational standards and succeeding frameworks that underscore competence-based teaching. These frameworks highlight the importance of scientific literacy, critical thinking, and problem-solving as key competencies for the 21st century.

As a result, research skills are increasingly regarded as an essential component of science education that ensures students' readiness for further education, professional activity, and active participation in society. Research skills have become an essential part of chemistry teacher education programs because they directly influence future educators' capacity to develop research skills in their students. To produce quality chemistry educators, future chemistry educators need a strong foundation of research skills which include but are not limited to, the ability to develop a hypothesis, design and carry out experiments, analyze data collected from the experiments, and interpret the results of those experiments. Teachers need to have developed their own research skills but also will need to use pedagogically sound methods of educating their students through the research process, such as creating inquiry-based learning environments and successfully applying STEM-based instructional strategies. This means that educators need a thorough understanding of how research skills are formed including cognitive,

procedural and reflective components of research skills and be able to apply that understanding to create realistic strategies for teaching in their classrooms. By including instruction on research skills in the teacher preparation programs, new educators gain hands-on experience with scientific inquiry, develop self-efficacy in providing student-centered learning, and increase their ability to support creativity, critical thinking and problem-solving in their classrooms.

In summary, the approach taken to train new teachers on research skills is critical to ensuring the professional competence of the teacher in their career. Teachers who have received training on how to teach using research-based pedagogy create inquiry-based classrooms that emphasize experimentation and the relationship of chemistry to the real world versus simply emphasizing rote learning or simply memorizing facts with respect to chemistry. They possess the skills necessary to develop structured yet flexible learning environments in which students have the opportunity to ask questions, work collaboratively to problem-solve, and evaluate their own research results independently. Moreover, teacher educators can use various digital tools, interdisciplinary approaches and teams to enhance the skills of students in terms of conducting research, providing them with requisite skill sets for use in the academic and work setting. In conclusion, research competency does not happen by chance; rather, it is built methodically through a comprehensive plan of cognition, conducting and reflection on science activities and ultimately can only be developed through a thoughtful and systematic approach using the most effective pedagogical conditions/strategies that emphasise student-centred learning in conjunction with experimental, inquiry-based, or STEM type of projects. Research skills will form the foundation for the use of Chemistry theory in practice, support the development of the scientific method, promote critical thinking and provide students with independent research skill development (lifelong learning skills) to address complex scientific issues, operate flexibly in non-routine environments and leverage chemistry in their personal life. Ultimately, the purposeful development of research skills is not only a pedagogical priority; it is an essential requirement for good science education, and

students and prospective teachers will be adequately equipped to meet the demands of their educational and professional environments. Thus, chemistry education may transition from traditional static knowledge-based models to active inquiry-based teaching methodologies through the incorporation of the development of research skills in teacher preparation programs and by extension into their classrooms. Students who participate in this type of learning have the opportunity to not only obtain education through the acquisition of knowledge but also participate actively in addressing actual Real World Problem challenges that science and technology create for humanity. This will develop them into a generation of learners and teachers capable of engaging the current and future global knowledge economy as supported by contemporary research on 21st-century skills development.

Performance-based assessments (PBAs) such as Observations, Evaluating Student Research Reports, Evaluating Student Laboratory Journals, Evaluating Student Projects, and Evaluating Student Self-Assessment of Reflection on their Work help Educators evaluate students' ability to perform their inquiry project successfully beyond simply assessing the final product through traditional assessment techniques (i.e., multiple-choice assessment, short answer assessment). PBAs allow the evaluation of both the completed/inquiry project as well as the entire inquiry process, including planning for the inquiry project, experimentation/conducting the inquiry, and data interpretation. The relationship between Research Skills and students' metacognition is critical to the understanding of students' ability to successfully conduct scientific inquiries since metacognitive skills will enable students to plan/organize their actions, monitor their progress, evaluate their results, and reflect on the effectiveness of the strategies they used to complete their inquiry projects/activities. The development of Research Skills directly relates to enabling students to become aware of their thinking process and to monitor and develop those skills to successfully engage in conducting scientific inquiries and communicating (and sharing) that knowledge. Metacognitive reflection in Chemistry also allows students to think through procedures taken while performing an experiment and identify potential areas of error that led to a particular

result as well as suggest alternative explanations for what they have seen. The use of intentional reflection on the learning process, as well as the use of self-regulated behaviours will enhance student research skills (Duschl et al., 2007).

When implementing research skills into teaching Science, consideration must also be given to student motivation and emotional engagement. Active engagement with research activities is most effective when the student finds the activity to be meaningful and relevant to their day-to-day life. By providing authentic scientific problems to work on, contextualising Chemistry to real-life, and using an interdisciplinary context to the research problem, teachers can create an environment that motivates students to want to engage in research activities. The foundation for inquiry and persistence when solving problems is motivation, which are both key elements of developing research skills from a teaching perspective. The teacher will also have a significant impact on students' ability to develop research skills through the learning environment that they establish. A learning environment where trust and openness are present allows students to be curious, make predictions, and take intellectual risks without fear of failure. An environment created with these attributes allows for collaborative efforts, discussion, and the transfer of concepts that provide the foundation of scientific inquiry. Collaborative laboratory work and groups engaged in scientific research projects will develop students' communication skills and their ability to complete research, increasing the educational value of inquiry-based learning. Teachers have a critical role in fostering the development of students' research skills. In addition to providing students with knowledge, teachers serve as inquiry facilitators, mentors, and problem-solvers for the researcher. Excellent science teachers create engaging tasks and provide students with the tools necessary to complete complex research activities.

Additionally, excellent science teachers provide students with opportunities to engage in independent research to the maximal extent possible. For future chemistry teachers, it is crucial that they develop the skills necessary to perform these teacher functions in order to facilitate the development of students' research skills in a manner that include academic rigour and a safe laboratory environment. The development of

students' research skills is directly related to their scientific literacy (Lederman et al., 2014). Scientific literacy is identified as being able to recognise and apply scientific concepts, critically evaluate scientific information, and utilise scientific methods when determining evidence-based decisions. In order to acquire scientific literacy, students must have active participation in the processes used to generate and evaluate scientific knowledge. For chemistry students that have achieved scientific literacy, the ability to read and evaluate data as it pertains to an experiment will be present and they will also use their chemistry knowledge to make environmentally conscious decisions.

Furthermore, with the recent emphasis on interdisciplinary learning, the importance of research skills is emphasised from a pedagogical perspective. In that many current-day scientific dilemmas require knowledge across disciplines (mathematics, technology, engineering), research skills allow for the crossing of boundaries between disciplines and using the skills of both analytical and experimental reasoning when working in interdisciplinary areas. In the end, research skills will enable students to be successful in their future academic and professional goals within the generic science field. There is also a large focus on the preparation of the future educator within teacher education programs, as they relate to assisting the future educator in developing, designing, and implementing research-based learning experiences for their students. Along with possessing content knowledge, prospective chemistry educators must also possess the methodological competencies to develop and implement inquiry-based instruction. This includes the ability to formulate research-oriented learning objectives, select appropriate teaching methods, and assess students' research progress effectively. The teachers in training not only develop their research skills through development but also make the main advances in their methodological approach. The existing notion of interdisciplinary learning is a strong predictor of the methodological importance of research skills in chemistry and the whole science education scene. Scientific and technological issues do not commonly exist within the limitations of a single discipline but affect multiple areas such as chemistry, mathematics, physics, biology, technology, and engineering that need to be

integrated in order to find solutions. By utilizing research skills, students gain the capability to deal with such situations where they have to think critically, conduct experiments, and interpret data beyond the subject area. For instance, tackling the issue of environmental pollution can entail chemical study, statistical modeling, technology solutions, and design by engineering, and this would mean that the students would have to use their skills in all these areas. Through their involvement in real life problem based tasks using the STEM approach, students not only learn subject content but also discover the processes and techniques to deal with various issues. The main outcome from the practice of research skills in science, technology, and engineering sectors, is the enhancement of the capacity to think divergently, concept creativity, and the ability to do things that you have learned in a more practical way.

Forming future educators as mentors of research-based learning is absolutely pivotal that is also does justice when it is said so. Teacher education programs attach ever-increasing importance to the task of building both subject-specific knowledge and inquiry pedagogical skills which is an indispensable part of the preparation of future chemistry teachers. It comprises the capacity to formulate research-oriented learning objectives, choose suitable teaching strategies, carry out STEM-based practical tasks, and evaluate the students` research progress in a way that is effective and efficient. The experience of pre-service teachers using their own research skills throughout their teacher training can give them an authentic scientific experience. Research skills (investigation, experimentation, and data collection) provide pre-service teachers knowledge, skills, and pedagogical tools that will help them to create inquiry-based learning environments that motivate and prepare students to think, act, and solve problems independently. The use of research-based instructional strategies in the classroom provides an atmosphere that provides the opportunity for teachers to incorporate digital technology, cooperative learning, and interdisciplinary assignments that will result in overall student skill development. Through the development of research skills as a pedagogical framework, research skills afford a holistic science education that integrates knowledge, skills, and personal development. Therefore, it is

believed that the research skills of teachers provide not only technical skills but also cognitive and metacognitive skills that will facilitate students as independent learners, encourage curiosity, and stimulate reflection. The teaching of research skills in chemistry education is one of the major objectives that must be met to develop new learning and teaching in a manner that supports the shift away from traditional forms of education to learner-centered, inquiry-based educational methods It is the pivot between theoretical ideas and its application, making it possible for pupils to take up not the role of passive persons absorbing information but being active agents in their learning process. Through the avenues of inquiry, experimentation, and interdisciplinary problem resolution, they research and become skilled in the process of learning to tackle difficult scientific and technological problems, adapt to and survive with rapid knowledge change, and to become lifelong learners. At the same time, the focus on research-oriented pedagogy in teacher education programs secures that future educators are well equipped to lead students in achieving these competencies, thus, the sustainability and evolution of science education will be achieved in this manner. The ultimate goal of the infusion of research skills in chemistry education is to - create a strong link between theoretical learning and real-life applications, - catalyze innovation and creativity. In this process, students, as well as teachers, are empowered to be both active participants and competent users in the fulfillment of the demands of contemporary society and the global knowledge economy (Harris et al., 2015; He et al., 2022).

1.2. STEM Education as an Integrated Educational Approach

STEM education is one of the most effective methods of teaching science that has come into prominence in the past few decades and is also a way of developing the learners' skills for coping with the challenges of the fast-growing technological society. The difficult nature of the scientific and technological processes plus the need for experts who can think across disciplines have made it necessary to change the education system from traditional to the more integrated approach. These problems are resolved by STEM education; it incorporates the four subjects of science, technology,

engineering, and mathematics into one coherent and practice-oriented learning framework that focuses on problem solving, inquiry, and innovation.

STEM training emphasizes the skills necessary for problem solving, critical thinking, teamwork, and independent research instead of memorizing facts or theories. The goal of chemistry classes is to provide opportunities for students to demonstrate their understanding of chemistry in practical settings; for example, performing chemical reactions that can be used to monitor environmental conditions, creating energy-efficient chemical processes, and/or using computational tools to model molecular interactions are some of the ways that students can use the knowledge they have gained in chemistry class as part of their STEM training. This comprehensive approach to chemistry, as well as to other subjects taught within a STEM framework, requires students to draw on knowledge acquired from science, technology engineering and mathematics.

As a result, students will gain a deeper appreciation for how these various disciplines are interrelated. A good example of that is that the deeper understanding of the reaction kinetics involves making mathematical models and the chemical product may incorporate parts of engineering and materials science through the design process. Thus, the students' collaboration across disciplines results in their looking at the natural phenomena from a more complete point of view, realizing the importance of chemistry in tackling the real-life issues, and also improving their skills which are applicable in their higher education and later in their professional careers (Hasni et al., 2016; Tseng et al., 2013).

Chemistry education based on STEM signifies a remarkable evolution in the methods of teaching and learning. It completely alters the traditional conception of the lesson from a passive viewer of the information into an active and research-oriented experiencing scholar, it promotes interdisciplinary integration, and it empowers students to acquire the knowledge, skills, and attitudes that are necessary for them to successfully deal with a complex and fast-changing world. Learners, through investigating, experimenting, collaborating, and reflecting, not only get to develop their

understanding of academic matters, but they also develop practical, cognitive, and social skills that will be of use in their lives and careers. One central feature of STEM education is that it is sustained by solving real-world problems. The STEM learning tasks are generally constructed around real issues that correspond to the scientific, technological, or environmental challenges of the day. In a chemistry lesson, for example, such issues might deal with chemical processes in industries, waste disposal, making materials, or power generation. And along with these, students not only acquire knowledge about the subject but also become able to use the concepts of chemistry in real life situations. This is because students form mainly the skills, as they are given opportunities to identify problems, to make hypotheses, to conduct experiments, and to interpret results. The inclusion of engineering concepts in STEM education boosts its pedagogical value once more. Engineering design processes facilitate the students' tendency to plan, test, and improve solutions through cyclic experimentation. The engineering component can be found in chemistry education, such as planning the laboratory design, optimizing the experimental parameters, or creating chemical products with designated properties. The discussion about these activities will lead students to apply the scientific knowledge creatively and in a systematic way, which will thus improve their research and problem-solving capabilities. For the upcoming chemistry teachers, the acknowledgment of the importance of engineering thinking in STEM education is quite important when they want to create meaningful learning assignments that show what real science is like.

Utilizing technology is a key factor to further development of the research component of learning. Students can perform the systematic steps such as collecting the experimental data, processing it with software tools, and interpreting the results more accurately and efficient. The longitudinal experimentations, testing hypotheses, and determining decisions on data as a guide makes the procedure similar to the real scientists. Furthermore, the collaborative electronic platforms are the online resources that make communication, peer review, and findings sharing easy with the former being the two research formats. STEM-based chemistry is integrative technology that

guides and develops skills in digital and computational literacy apart from the technologically-based careers of today. Rather than just adding technological tools into the inquiry-based and project-oriented tasks, the students through this method learn chemistry content along with the use of technology to tackle complex problems, make models, and use it in conducting independent research. Collections of theory and practice are bridged by technology in this manner, making learning much more interactive, engaging, and in harmony with real-life scientific and technological issues. The foundation of STEM education comes from mathematics, which is used for quantifying data and reasoning quantitatively. Within chemistry, there cannot be a proper chemistry without mathematics, which is needed for measuring concentrations, rates of reaction, energies and all other types of quantitative measurements that need to be made. The integration of STEM education allows students to see how mathematics can be applied within science, therefore students can see how mathematics is a tool of scientific inquiry, not an isolated subject from science. This relationship between mathematics and science helps students to not only interpret the results from their experimental work, but also to make scientific conclusions based on the evidence received through experimentation. The integration of STEM education provides opportunities for both project-based learning and inquiry based learning. As STEM education often revolves around collaboration and communication, it makes sense that the most essential characteristics of STEM education are these same characteristics. Scientific research has historically not involved only the individual researcher conducting the work. A significant amount of collaboration occurs between the different scientists (researchers) that are part of the research (science curriculum). While performing experiments relating to the science curriculum, the students will be required to work in teams with their classmates, communicate their observations from a completed experiment to each other, discuss the results of the experiment with each other, and present the conclusion of their experiment to each other. This level of collaboration is similar to how scientists work in real life and will also help students

develop important soft skills (Active Listening, Negotiating, Argumentative Skills, and Clarity of Expression) as they work together to complete assignments.

Competency building is especially important for chemistry teacher training and through teacher education programs, teacher candidates must be able to demonstrate/design learning activities that promote teamwork and collaborative problem-solving. They must understand how to divide responsibilities within a team, coordinate group efforts, and facilitate a positive communication process. Teachers also need to be able to demonstrate effective communication skills, give both verbal and written feedback regarding scientific reasoning as well as give both verbal and written feedback about the collaborative process (group members) and to encourage the group to reflect on the entire group dynamics. Through the use of cooperative learning/teaching methods in their stand-alone STEM Chemistry science lessons, teacher candidates have been given a level one experience in developing group learning, resolving conflict, and assisting diverse learners. Therefore, teacher candidates have the ability to develop and manage classrooms that provide opportunities for all students to work collaboratively, share ideas, and create knowledge as a team together that are the basis for developing good research competence, scientific literacy, and lifelong learning skills in students. Collaboration and communication are a critical component of both the development of the education content but also as a means for personal and professional development for success in careers in science and education (Honey et al., 2014; Schell & Hausmann, 2019). Appropriate methodological support and pedagogically wise preparation are vital when incorporating STEM into the chemistry classroom. The instructor's role is as a facilitator of student learning, providing learning tasks that cover the same subject matter (science, technology, engineering, mathematics) as the material studied; however, these tasks also need to be aligned with the goals of curriculum. This includes helping students find suitable challenging problems, providing scaffolding to assist them in completing longer form tasks, and allowing sufficient time for experimentation and reflection during student activities. STEM educators utilize different types of

methods to guide their students through independent research, and thus, through their support, they also contribute to their students' cognitive development. Therefore, prep teachers also need to have a solid foundation of the central concepts of STEM so they can share their knowledge with future chemistry teachers and provide them with the necessary tools to develop robust achievements in today's teaching arena. Prep teachers will be responsible for using their skills in interdisciplinary incorporation and collaboration to provide educational experiences that teach students how to relate chemistry to technology, engineering, and math. Through their initial teaching experiences, students will gain valuable experiences with biomedical education and have the opportunity to develop their teaching skills. The entire model of STEM-based education is based on using a competency-based approach to education. Today, educational experiences highlight the competencies required to be successful with critical thinking, creativity, research, and problem-solving skills. STEM education contributes to the realization of those goals by providing the environment necessary for active participation and intellectual independence. Aspects of STEM contribute to the development of research competence in chemistry education through the integration of theory with hands-on experience (inquiry and experimentation). STEM also contributes to the motivation and interest of students in science. STEM lessons connect chemistry to real-world applications and potential career paths, generating interest and increased engagement in the students' participation in research-based activities. This motivation is the main impetus for an ongoing interest in science and for continuing education in science-related careers. Being able to motivate students through STEM instruction is one of the most important skills for chemistry teachers. Teacher preparation programs for future chemistry teachers should ensure that they have a good understanding of chemistry concepts, and have received training in how to develop and implement research-oriented learning activities. In this regard, teacher candidates are instructed to design classroom experiments and inquiry tasks, where students are required to explore, test, and evaluate ideas, and at the same time, the teacher provides necessary scaffolding to aid their learning. By undergoing research-based learning

themselves, teachers acquire the pedagogical skills that are required to help students through inquiry, to encourage independent investigation, and to create a classroom where curiosity, experimentation, and evidence-based reasoning are fundamental (Kadioglu-Akbulut & Uzuntiryaki-Kondakci, 2021; Naibert & Barbera, 2022; Abrahams & Millar, 2008; Bernstein, 2018).

In Chemistry, cross-curricular integration allows students to see the chemical processes from many different perspectives, which increases their ability to perform in-depth research, and makes them better problem solvers through the data and evidence that they collect. In addition, one of the additional benefits of STEM learning is that it allows for customization and differentiation. As STEM-based tasks can be differentiated based on the level of preparation of the student, their interests, as well as their learning styles; the flexibility of STEM instruction allows teachers to create research tasks with different levels of complexity or ability, such as directed experiments or open-ended projects. As a result of this flexibility, learners can build their skill sets from their own ability, by developing their skills from how to conduct an experiment safely to independent inquiry and creative problem solving. STEM assessments are different from traditional school assessments which typically focus on written knowledge based on content knowledge; STEM assessment looks at what the student has done and how or why they have done it, as well as what they got out of their learning. Performance-based assessments such as (project presentations, laboratory reports, portfolios, and reflective journals) are a means of evaluating student performance in STEM classes by providing a comprehensive assessment of student performance in terms of their skills related to research, including the ability to develop a hypothesis, conduct an investigation, analyze data, interpret results, and support their conclusions. In Chemistry, these assessment practices provide learners with an incentive to actively participate in the scientific process, develop critical thinking skills about their work, and acquire meta-cognitive skills. Instead of having students simply memorize formulas or follow standard procedures from textbooks, there is an expectation for all students to demonstrate their ability to set-up and conduct an

experiment, deal with anomalies in the data, and make decisions based on scientific rationale. The performance assessment will demonstrate a student's ability to think independently, apply scientific problem-solving strategies, and engage in the inquiry process.

Performance assessments represent a shared experience in an interdisciplinary and a collaborative environment. Many of the STEM Projects involve student-led groups, in which those groups participate in collaborative brainstorming, sharing their ideas for the project they are working on, and critiquing each other's work to determine how well the groups have performed. Through peer assessment of each other's work, learners develop critical analysis skills of both their work and the works of their peers, thereby building effective communication, teamwork, and accountability skills that are key components of practicing scientists and being successful professionals. Furthermore, reflective practices, such as maintaining laboratory notebooks and writing project portfolios assist in the development of research skills. By keeping a record of how they completed their investigations, identified data collection errors, and identified what they could do to improve, students develop self-regulatory skills and can perform critical evaluation skills and see how they can combine their experimental findings with theoretical knowledge, thus helping them to develop lasting, meaningful, and transferrable learning for future challenges and/or unknown contexts (Kokotsaki et al., 2016; Miller & Krajcik, 2019).

The use of STEM-based assessment that emphasizes action instead of mere rote learning, fosters an environment where students come up with the necessary knowledge, skills, and practices for both lifelong learning and solving scientific questions. Assessing effectively not only reveals the learning results but also, as an active player in the whole process, forms the research skill to prepare the students and also the future teachers to withstand the sophisticated and multi-disciplinary problems of modern science and technology. A solid foundation of professional preparation is required to succeed in STEM education. The Chemistry Teacher should obviously know enough about Chemistry, plus be familiar with the concepts of Interdisciplinary

Teaching and how Methodological Flexibility plays a role in their lessons. The Chemistry Teacher will need to know how to incorporate STEM components into their Chemistry lessons, create Research-based tasks, and facilitate Collaborative Learning environments for students. Hence, teacher education programs are the backbone of preparing future teachers in the area of STEM teaching by exposing them to interdisciplinary projects and research activities. STEM education initiates the ascent of professional competencies that are imperative in modern educational practice in the context of chemistry teacher training. These skills encompass the aptitude to create inquiry-based lessons, utilize digital technologies in laboratory tasks, and direct students in research projects. Additionally, the teachers obtain practical skills in organizing those experimental and research activities via STEM-oriented learning which they experience during their studies thereby augmenting their readiness for professional work in schools.

STEM education also has a role in the formation of ethical and responsible attitudes towards scientific activities. A lot of STEM projects are related to socially important problems like protecting the environment, sustainable development, and the health of the community. In the experimentations of science, for instance, students talk about subjects that are associated with the safety of chemicals, waste handling, or the negative effects of chemical substances on the environment. These types of activities encourage the responsible conduct of research and help students see the social implications of chemical research thus making STEM education more valuable than it already is. Robotics and every scientific area through the invention of products, and businesses created in a district contribute to the development of innovative and entrepreneurial thinking. STEM education is an approach that perceives learning as integrated and thus it offers a well-structured setting for enhancing research skills in chemistry classes. Its inter-disciplinary character mainstreams students who can see the connection between the chemistry and math, physics, technology, and engineering, thereby strengthening their holistic worldview of how nature works. Introducing inquiry, experimentation, problem-solving and other learning tools, STEM education

thus transform the learning environment and develop the cognitive skills such as critical thinking, creativity, and real-life application of the conceptual knowledge in the learning process (Krajcik & Shin, 2014; Fortus et al., 2005).

STEM-oriented tactics inspire students to be part of the practical scientific process. The learners suggest hypotheses, organize and conduct the experiments, interpret data, and write conclusions. As experiential learning the approach develops the core competencies needed such as experimental design, reasoning based on evidence, and solving of problems independently. The majority of tasks are open-ended and the students are free to make decisions, seek alternative methods, and build resilience to difficulties they encounter. In exploring project-based and problem-based teaching, engineering design in the context of science and technology education were employed, providing students with real-world experiences that reflect the reality of being a scientist.

Advancements in technology significantly enhance the teaching and learning of Chemistry in a STEM framework. Better access is possible through the use of virtual laboratories, simulation programs, and data analysis software. STEM, an abbreviation for science, technology, engineering, and mathematics, is all about teamwork, and people to communicate. The teams of the students do the work of a group, taking turns, reporting, and discussing the results of their investigations and at the end of the presentation. As a result, the students who have scientific work experience get to know that they should cooperate, argue, and reach agreement with others. The message that teachers get from this is that they should create opportunities for their students to work cooperatively besides promoting a learning environment where questioning, talking, and evaluating critically are major parts of the classroom experience. One important area for STEM to flourish is the transformation of the chemistry curriculum and the development of competent researchers, who are able to apply science in a proficient manner. STEM (Science, Technology, Engineering, and Mathematics) is a rich pedagogy framework that integrates cross-discipline (interdisciplinary) learning, inquiry-based learning, real-life problem solving, digital and technology integration,

and collaborative practices. STEM provides students with the foundation needed to have the knowledge, skills and attitudes necessary to be successful in conducting scientific research. STEM-based instructional methodologies also provide both students and future chemistry teachers a pathway to greater-depth of understanding and professionalism in the sciences, as well as a commitment to lifelong learning in the sciences (Krajcik et al., 2023; Wahono et al., 2020; Bybee, 2013).

1.3. Pedagogical Conditions for the Development of Research Skills within STEM Education

The effective development of research skills associated with chemistry lessons in the framework of STEM education will depend on the system of pedagogical conditions that allows for purposeful organization of the educational process. Pedagogical conditions are defined as a collection of interdependent organizational, methodological, psychological and didactic factors that provide an effective learning experience through which students can develop their research skills. In STEM-based chemistry instruction there are a number of important pedagogical conditions upon which the combined disciplines are integrated and how inquiry-based learning is carried out, thus requiring careful pedagogical planning and professional competence on part of the educator. One of the critical pedagogical conditions for developing research skills is the use of inquiry and problem-solving learning strategies. STEM education promotes an active learning environment where students are no longer passive recipients of knowledge but are involved in constructing their own knowledge. In chemistry lessons, this involves students being engaged in the process of formulating research questions, making predictions about possible research outcomes(hypotheses), and testing their hypotheses through experimental investigations. By using inquiry-based instruction, students experience the entire process of scientific inquiry where they develop important research skills; such as the ability to observe, to analyze and critically evaluate their research outcomes (Lynch et al., 2018; Minner et al., 2010).

An important aspect of inquiry-based learning and becoming an important pedagogical condition for STEM education is problem-solving learning as well. The

fundamental premise of problem-based learning is that, as people, we tend to learn best when we are busy with tasks that require us to think critically and solve the problems in which we encounter in reality. Different from the known-answer exercises, problem-based tasks are open-ended issues that are typically relevant and/or require creativity, reasoning, and making decisions. The strategy entails a shift from the traditional teacher-centered to the active student group functioning. Students do this by prioritizing their own learning processes, exploring the subject matter, and coming to conclusions.

The entire time of such arrangements, individuals apply fogged thinking, inferential thought that is underpinned by certain proof, and by that reason, they learn about the critical research skills that they practice. Furthermore, students frequently work in groups, swap thoughts, argue about different means, and together polish their methods, so that such work further advance their communication and teamwork skills (Margot & Kettler, 2019; Sumarni & Kadarwati, 2020; Wilson, 2021).

Problem-based learning works as a channel for the development of creativity and innovation, with the students being the ones who are exposed to various instead of the only correct processes for solving a problem. The consequent receptiveness to such ideas permits them to try other ways, change the plan which was initially meant to be followed in case of unforeseen problems, and acquire firmness when having to deal with difficulties. As students engage in experiential, real-world experiences when participating in these types of activities, they gain knowledge about chemical concepts and how to apply them more practically. The advantage of using this type of learning model is that it is much more constructive and relevant than conventional methods of education. In addition to gaining an understanding of chemical concepts, students will improve their metacognitive skills through the necessity to evaluate their own problem-solving methods, to evaluate the validity of their assumptions, as well as to consider how their understanding changed during the course of the learning process. The role of the instructor is to provide support/training to the students by guiding, providing feedback, and establishing an environment conducive to independent investigation and

critical thinking without imposing a rigid structure on the students' approach to learning.

Problem-based learning has become a very important instructional strategy utilized in chemistry education to develop research skills within a STEM framework. By engaging students in the process of solving a real-world, interdisciplinary problem, this method promotes active learning, critical thinking, creativity, and collaboration among students. In addition to increasing students' knowledge of chemistry, this instructional model provides students with opportunities to apply their skills and knowledge to real-world situations and therefore create students who are scientifically literate and research-oriented. Integrating a practical component of chemistry lessons into the theoretical component is an essential requirement for the development of research skills within students. Students' utilization of the scientific method for completing experiments will promote students' development of practical and analytical skills related to chemistry. For example, in chemistry classes, students may combine and integrate math modeling to analyze research data, use technology to conduct chemical experiments, and apply an engineering solution to the use of experimental designs. When students can combine multiple areas of STEM, they develop a holistic view of research processes and the ability to apply their research skills throughout all areas of STEM (Meulenbroeks & van Joolingen, 2025; Orosz et al., 2023; Valdez & Bungihan, 2019; Orozco et al., 2022).

The application of digital technologies and educational resources in STEM-related chemistry education is a transformative element of STEM chemistry education; digital technologies change the way students engage and participate in scientific inquiry and research activities. The use of available digital technologies such as virtual laboratories, simulation software, data analysis tools, and interactive modeling software provide opportunities for students to investigate chemistry in a manner that would not normally be possible due to limitations such as logistics, cost, and safety.Students gain the ability to use data analysis software effectively through online simulations and virtual experiments that allow them to maintain autonomy by creating

and/ or making changes to them independently. Consequently, students develop critical thinking and problem-solving skills as a result of being able to reorganize their experimentation process and independently make decisions about how they want to proceed with their experiments. By providing students opportunities to collect and analyze data using data analysis software, they are able to replicate scientific procedures and make informed decisions about their experimentation based on the analysis of data collected. Additionally, the use of interactive digital platforms with experimentation created an opportunity for students to conduct iterative testing, as they could control variables and directly observe the effects of their actions on their experimental outcomes, which creates the opportunity for students to experience failure and build perseverance and creativity in the experimentation process.

By creating a connection between chemistry and other areas of study (i.e., math, physics and technology) through digital technologies, interdisciplinary education enhances the use of digital technologies in the classroom. To be more specific, students are provided with the opportunity to apply computational tools to quantitative modeling of chemical reactions, conduct statistical analyses of data resulting from experimentation and to develop and present engineering solutions for chemical processes. The integration of ideas across all areas promotes the collaborative effort involved in STEM, as well as the students' use of theoretical knowledge to solve problems in the real world. Thus, digital resource usage in addition to their cognitive advantages creates a more motivational and engaging experience for students, as interactive simulations and virtual labs will provide immersive experiences for learners, while they may also find traditional teacher-led demonstration an enjoyable way to achieve such. Therefore, students develop a sense of autonomy in their learning, develop the ability to make their own decisions, have personal responsibility for the outcome of their research, and ultimately learn to develop metacognitive and self-directed learning skills best through hands-on experience (Michalsky & Cohen, 2021; Lederman et al., 2014; Brown et al., 1989).

Digital tools allow students to visualize complex phenomena; conduct data analysis, engage in independent inquiry; and engage in interdisciplinary learning, while creating an immersive, interactive, and student-centered learning environment that prepares students for real-world problem solving and authentic scientific research experiences. Another critical pedagogical condition for student development of research skills is for their learning to occur in a supportive, motivating, and low-risk learning environment.

The teaching methods that involve scaffolding and the gradual increase in task difficulty are essential in science, technology, engineering, and mathematics (STEM) chemistry education because they are the immediate means to the end of each student mastering research skills. Learning research skills is not an immediate gain; a well-planned and organized teaching method must be implemented in a step-by-step procedure that leads the students from easy, supported activities to self-directed, open-ended investigations.

At the early times of lessons on STEM chemistry, secondary school students must engage in partially guided research tasks where there are simple instructions, clear indications of the procedural steps, and the target results are specified. For instance, students can be given the task of conducting a chemical experiment in sequence to witness chemical reactions or to analyze datasets that have already been chosen. The guided tasks offer the students the initial experience that is necessary to the process of inquiry, such as proposing hypotheses, designing experiments, and observing and recording accurately.

Reflections also play a significant role in bridging the learning of theory and practice. As an instance, dealing with experiment results regarding chemical principles, pupils really understand them, correct their misconceptions, and associate their classroom tasks with the scientific contexts in the real world. Besides, self-regulation is another benefit of reflective practices which is where students are made to plan, monitor, and then evaluate their own strategies for learning and this is a must for independent research and life-long learning.

Future chemistry teachers, practicing reflections are the best ways for them to learn to teach. Prospective teacher trainees who are often reflecting on their own problem-solving and experimental situations are for sure better prepared to lead students in inquiry-based learning, to foresee typical difficulties, and to design activities that promote critical and iterative learning. The promotion of reflection as an integral technical way of STEM instruction is an effective measure to make students and teachers understand the research process well and thus enable them to become better at their continuous improvement.

The arrangement of teaching in chemistry that is based on real-life and socially relevant issues is a crucial pedagogical condition that significantly enhances the effectiveness of STEM-based teaching and research skills development. By placing learning in significant contexts-such as environmental safety, sustainable chemical processes, chemical precautions, or industrial applications-students consider research not solely as a classroom practice but as a meaningful deed with real societal impacts. The approach facilitates high motivation, plus students who are deeply engaged, and learners who see the worth of using science to solve problems practically. Continuity ensures that students experience progressive development-from guided experiments and structured investigations to open-ended, independent research projects-allowing them to gain confidence, competence, and autonomy in scientific work.

In teacher education programs, familiarity with laboratory equipment and digital technologies prepares future chemistry teachers to organize research-oriented instruction under various educational conditions. Pedagogical support and feedback represent another essential condition for research skill development. Constructive feedback from teachers helps students understand their strengths and weaknesses in conducting research activities (Duschl et al., 2007). In chemistry lessons, feedback may address experimental design, data interpretation, or the clarity of scientific explanations. Timely and targeted feedback supports students' learning processes, promotes self-correction, and encourages continuous improvement of research skills. For future chemistry teachers, the ability to provide effective feedback is an important

professional competence (National Academy of Engineering & National Research Council, 2014; Avery & Reeve, 2013; Felder & Brent, 2016).

The differentiation of instructional strategies according to students' individual characteristics is also an important pedagogical condition. Students differ in their prior knowledge, learning pace, and cognitive abilities, which must be considered when organizing research-oriented activities. In STEM-based chemistry education, differentiated tasks allow students to engage in research at an appropriate level of complexity, ensuring inclusivity and equitable learning opportunities. Pursuing the possible skills of research development in all learners even if they are unprepared is what this method offers. Out of the classroom, partnership and collaboration are the root causes of the development of research skills in STEM education. The cooperation of universities, research institutes, and businesses not only allows students to be in true scientific settings but also helps them learn about professional research methods. One of the ways these kinds of partnerships take shape in the field of chemistry is a project done together, a guest lecture or contest of science. The added benefits from these activities are a better view of scientific research for the students and a stronger desire to develop their research skills.

These teacher education programs are very effective in this process because they make the prospective teachers analyze the educational domain critically and come up with creative new ways of teaching that are research-driven. Part of this is the training of the teachers how to break down a task for the students, use different subjects together, digital tools, team-building problem-solving etc., and much more. The best way to cover these fundamental aspects would be through the future teachers being taught to create the classroom environments where students would focus more on the acquisition of the research aspects.

The training of research skills in chemistry classes is the result of the continuity and intentional pedagogical support. Students must have access to inquiry and project based experiences, opportunities to reflect on how they did it, analyze their results and modify their way of doing something. These conditions support students developing

research skills as stable and transferable skills that are not developed sporadically or dissociated from one another. For future chemistry educators, the understanding of these pedagogical conditions will support them in developing a solid foundation for their professional practice. Teachers who understand how to develop supportive learning environments, support student inquiry, and integrate reflective and collaborative practices will be better prepared to meet the changing challenges presented by current initiatives for science education (Slavit et al., 2016). By integrating these extended pedagogical conditions into their classrooms, teacher candidates will not only continue to develop students' research skills, but also help in preparing scientifically literate, innovative, and research savvy students prepared to excel in postsecondary education and in scientific professions.

METHODOLOGY

2.1. Research Design and Approach

The purpose of this study is to examine the effect of STEM project-based learning on the development of research competencies among high school chemistry students in Kazakhstan. Given the multidimensional nature of research competencies — encompassing cognitive, procedural, and affective dimensions — a mixed-methods design was identified as the most appropriate framework for the study (Creswell & Plano Clark, 2018).

The qualitative data were collected through semi-structured interviews with students. The interviews explored students' experiences of participating in STEM projects, their perceptions of research skill development, and the challenges they encountered during the learning process.

The use of a quasi-experimental design was necessitated by the impossibility of random assignment within the school's intact-class structure. Students were assigned to groups based on their existing class placements, rather than through random allocation. The experimental groups received chemistry instruction through structured STEM-based practical and research tasks for the duration of the study, while the control groups continued to receive instruction through conventional, teacher-directed methods. This design permitted the identification of measurable differences in research competency levels attributable to the STEM-based instructional condition.

The research design aligns with Vygotsky's (1978) sociocultural theory and Piaget's (1973) constructivist framework, both of which assert that learners construct knowledge actively through meaningful tasks and through interaction with peers and teachers. STEM education operationalises these theoretical principles by engaging students in inquiry, experimentation, and collaborative problem-solving. The design was therefore structured to capture both the measurable outcomes of STEM instruction and the qualitative dimensions of the learning experience that gave rise to the development of research competencies.

2.2. Participants

The pre-post intervention was administered across a total of 73 students, from a variety of school types, and geographic locations throughout Kazakhstan. Participants for this study were chosen using purposive sampling, with the goal of having a representative sample from each of the various types of educational opportunities within Kazakhstan. Participants were chosen based on having a 10th or 11th grade education, from a diverse mix of private gymnasiums, private schools, and general high schools. The sample represented several large cities throughout the country and would assist in the quantitative analysis of participants' perceived abilities both before and after participating in the STEM-based research project. The class sizes ranged around 15-20 pupils. The research team adopted this heterogeneous sampling strategy to widen the scope of students' baseline research competencies and their attitudes towards the STEM-integrated learning, which the experimental case study could cover beyond a specific school setting.

The experimental phase of the study was conducted within a specific private school setting. Two sets of intact class groups from Grades 10 and 11 were involved in the experimental comparisons. In Group A, the experimental class (N = 19) was compared with the control class (N = 20). In Group B, the experimental class (N = 15) was compared with the control class (N = 19). The experimental groups received chemistry instruction through structured STEM-based practical and research tasks, while the control groups continued to receive instruction through conventional, teacher-directed methods.

Table 2.3.1. *Survey Sample Characteristics*

Characteristic	Detail
Total participants	73 students
Grade levels	Grades 10 and 11
School types	Gymnasiums, private schools, general secondary schools
Geographic coverage	Multiple districts and cities across Kazakhstan
Class sizes	15–20 students per class

Table 2.3.2 *Experimental and Control Group Composition*

Comparison	Group	N	Condition
Group A (11th Grade)	Experimental	19	STEM-based instruction
	Control	20	Traditional instruction
Group B (10th Grade)	Experimental	15	STEM-based instruction
	Control	19	Traditional instruction

The experimental group comprised of 12 purposively selected students who underwent semi-structured interviews using an in-depth interview format and only those who were purposefully chosen due to their active involvement in STEM project-related activities and ability to evaluate reflective thought processes concerning the learning experience(s) engaged in by each participant where chosen to be interviewed. The sample of the interview participants contained students who performed at a variety of performance levels to create diversity of perspectives concerning the impact of STEM-sourced instruction. Participation was voluntary and informed consent was obtained from (1) the students and in appropriate cases, (2) the students' respective parent(s) or guardian(s). The methods used to maintain confidentiality and anonymity throughout the data collection and reporting process included that all participant data was de-identified before any analyses were conducted.

2.3. Data Collection

The preparatory stage involved the development assessment tools, the orientation of participating teachers, and the administration of pre-tests to establish baseline competency levels across all groups. The assessment instrument was developed in close alignment with the theoretical framework of research competence established in the literature review, operationalising three core competency dimensions on a four-point Likert-type scale (1 = beginner; 4 = advanced).

Assumption Testing: Normality — Group A

Prior to conducting inferential statistical tests, the assumption of normality was evaluated for all post-test scores in Group A using the Shapiro-Wilk test, computed in Jamovi (version 2.3). Given the small group sizes (experimental: N = 19; control: N = 20), the Shapiro-Wilk test is the recommended procedure for normality assessment (Razali & Wah, 2011). Table 2.2.1 presents the Shapiro-Wilk test results.

Table 2.2.1 *Shapiro-Wilk Normality Test Results: Pre-Test Group A-B*

Data collection Normality Test (Shapiro-Wilk)	
Statistic	**p**
0.829	<.001

For PRE Data Collection**,** the Shapiro-Wilk statistic was W = 0.829 (p < .001), indicating a significant violation of the normality assumption.

Normality Test Hypothesis Formulation (Shapiro-Wilk)	
Statistic	**p**
0.940	0.002

For PRE Experimental Design**,** the Shapiro-Wilk statistic was W = 0.889 (p < .001), again confirming a significant departure from normality.

Normality Test Experimental Dersign (Shapiro-Wilk)	
Statistic	**p**
0.889	<.001

For PRE Hypothesis Formulation**,** the Shapiro-Wilk statistic was W = 0.940 (p = .002), also indicating a violation of normality.

Table 2.2.2 *Shapiro-Wilk Normality Test Results: Post-Test Group A-B*

Normality Test Data collection (Shapiro-Wilk)	
Statistic	**p**
0.775	<.001

For POST Data Collection**,** the Shapiro-Wilk statistic was W = 0.775 (p < .001), confirming non-normal distribution.

Normality Test Hypothesis formulation (Shapiro-Wilk)	
Statistic	**p**
0.889	<.001

For POST Hypothesis Formulation, the Shapiro-Wilk statistic was W = 0.889 (p < .001), indicating a significant violation of normality.

Normality Test Experimental design (Shapiro-Wilk)	
Statistic	**p**
0.946	0.004

For POST Experimental Design**,** the Shapiro-Wilk statistic was W = 0.946 (p = .004), confirming a departure from normality.

Across all six tested variables — both at pre-test and post-test stages — the Shapiro-Wilk results consistently yielded statistically significant p-values, confirming that the normality assumption was violated in all cases. This pattern is consistent with the discrete, bounded nature of the four-point Likert-type scale used in this study, which characteristically produces non-normal distributions in small samples. Consequently, the Mann-Whitney U non-parametric test was retained as the primary inferential method throughout the analysis, replacing parametric alternatives that require normally distributed data.

2.4. Research Procedure

Three successive and interlinked stages comprised the research procedure: preparatory, formative, and final.

The preparatory stage established the foundational conditions for the STEM intervention. During this stage, the competency assessment instrument was developed, piloted, and revised. Teachers in the experimental groups participated in a structured orientation session on the principles and practices of STEM-integrated instruction, including inquiry-based and problem-based learning strategies, the integration of digital technologies, and the facilitation of collaborative research activities. Pre-tests were subsequently administered to both experimental and control groups under standardised conditions to establish baseline competency levels and to verify the comparability of the groups prior to the intervention.

The formative stage constituted the core implementation phase of the research. The experimental groups engaged in a sequence of STEM-based practical and research tasks integrated into their regular chemistry lessons. The curriculum followed a structured scientific inquiry cycle for each lesson: problem identification, hypothesis formulation, experimental design, data collection and analysis, and reflective evaluation of results. In the early phases, tasks were partially guided, providing scaffolding and supporting the development of foundational research competencies. As the intervention progressed, tasks became increasingly open-ended, requiring independent problem definition, methodological decision-making, and critical interpretation of data. Six lessons were selected for systematic classroom observation. The control groups received instruction through conventional, teacher-directed methods based on standard laboratory exercises with predetermined outcomes throughout the same period.

The formative stage of the study comprised a sequence of six STEM-integrated chemistry lessons delivered to the experimental groups over the intervention period. Each lesson was designed to develop research competencies progressively, following a structured scientific inquiry cycle: problem identification, hypothesis formulation,

experimental design, data collection and analysis, and reflective evaluation. The six lessons followed a deliberate scaffolding trajectory, advancing from Level 1 (guided inquiry) in Lessons 1 and 2, to Level 2 (semi-open inquiry) in Lessons 3 and 4, and culminating in Level 3 (fully independent, student-led inquiry) in Lessons 5 and 6.

Lesson 1 (Effect of Temperature on Reaction Rate) and Lesson 2 (Effect of Concentration on Reaction Rate) introduced students to the fundamental structure of STEM-based inquiry. Both lessons focused on the kinetics of chemical reactions and required students to formulate structured hypotheses using scaffolded templates, collect systematic quantitative data at multiple variable levels, and represent their data graphically using digital tools. In Lesson 2, students entered data directly into Google Sheets in real time, developing digital data literacy alongside chemical inquiry skills. The control groups received conventional instruction on the same curriculum topics using teacher-directed methods with predetermined experimental outcomes throughout this period.

Lesson 3 (Water Purification Method Design) and Lesson 4 (Biodegradable Materials Investigation) marked the transition to semi-open, engineering-informed inquiry at Level 2 complexity. In Lesson 3, students applied the full engineering design cycle — Define, Research, Prototype, Test, Evaluate, Improve - to design and build a multi-stage water purification filter from locally available materials, testing its effectiveness against self-defined criteria for turbidity reduction and pH improvement. In Lesson 4, students conducted a multi-variable comparative materials investigation, designed their own additional test protocol for a material property of their choice, and applied a weighted scoring matrix to generate an evidence-based recommendation for sustainable packaging — integrating science, engineering, technology, and mathematics in a single investigation.

Lesson 5 (Eco-Friendly Product Development) and Lesson 6 (Independent Research Project) constituted the Level 3, fully independent inquiry phase of the intervention. In Lesson 5, students independently developed, tested, and iteratively improved an eco-friendly cleaning product using household chemicals, applying acid-

base chemistry, formulating mechanism-based hypotheses, and presenting findings in a structured product pitch. Lesson 6, the culminating lesson of the sequence, required each student or pair to independently select a chemistry research question, formulate a testable hypothesis, write a complete research plan (reviewed by the teacher with written feedback), conduct the investigation, and present findings in a three-minute oral presentation with peer and teacher questioning.

The final stage of the research procedure focused on the systematic collection, analysis, and evaluation of post-intervention data. Upon completion of the STEM intervention, the competency assessment instrument was re-administered to both the experimental and control groups under the same standardised conditions as the pre-test. Semi-structured interviews were conducted individually with 12 purposively selected students from the experimental groups. All data from quantitative and qualitative sources were compiled and analysed. All stages of the research followed established ethical standards.

2.5. Data Analysis

In this research, the data analysis process was designed to provide solutions to the research questions via the thorough and well-organized analysis of both quantitative and qualitative data. The use of findings for complementary analytical methods also made it possible to triangulate evidence and strengthen the conclusions by referring to several prevailing sources of evidence.

Prior to the implementation of the STEM intervention, pre-tests were administered to all four participant groups under standardised conditions to establish baseline research competency levels and to verify that the experimental and control groups were statistically comparable at the outset of the study. All pre-test data were entered into Jamovi (version 2.3) for analysis. Descriptive statistics and Mann-Whitney U non-parametric tests were computed for all three competency dimensions across both group comparisons. Descriptive statistics-including means, standard deviations, medians, and standard errors-were calculated for all pre-test and post-test scores across both groups and all three competency dimensions.

RESULTS

3.1. Findings for enhancing skills of data collection, formulating hypothesis, and experimental design (RQ1, RQ2, RQ3)

This chapter presents the quantitative and qualitative findings of the study in four sequential sections. Section 3.1 reports the pre-test descriptive statistics and Mann-Whitney U comparability analysis for both group comparisons. Section 3.2 describes the implementation of the STEM-based practical lessons. Section 3.3 presents the post-test descriptive statistics, normality and homogeneity assumption checks, and Mann-Whitney U inferential results for Group A and Group B. It also presents the qualitative thematic findings from the semi-structured interviews.

3.1.1. Quantitative Findings

3.1.1.1 Pre-Test Descriptive Statistics: Group A (Control vs. Experiment)

Table 3.1.1 presents the pre-test descriptive statistics for the experimental group experiment (N = 19) and the control group control (N = 20) in Group A across all three competency dimensions.

Table 3.1.1.1 *Pre-Test Descriptive Statistics: Group A (Control vs. Experimental)*

Dimension	Group	N	Mean	Median	SD	SE
Data Collection (Post A)	Experimental	19	1.47	1.00	0.513	0.118
	Control	20	1.50	1.50	0.513	0.115
Hypothesis Formulation (Post B)	Experimental	19	1.42	1.00	0.507	0.116
	Control	20	1.45	1.00	0.510	0.114
Experimental Design (Post C)	Experimental	19	1.37	1.00	0.496	0.114
	Control	20	1.40	1.00	0.503	0.112

Note. All scores on a four-point Likert-type scale (1 = Beginner; 4 = Advanced). SD = standard deviation; SE = standard error of the mean

As shown in Table 3.1.1, the pre-test mean scores for both groups are closely clustered at the lower end of the competency scale, ranging from 1.37 to 1.50 across all three dimensions. The experimental group and the control group demonstrated nearly

identical means and standard deviations at the pre-test stage, with all scores falling within the beginner-to-basic range (scores 1–2). This pattern suggests that both groups began the study with comparably limited research competency, providing an appropriate baseline for the subsequent intervention comparison.

3.1.1.2. Pre-Test Descriptive Statistics: Group B (Control vs. Experimental)

Table 3.1.2 presents the corresponding pre-test descriptive statistics for the experimental group (N = 15) and the control group (N = 19) in Group B.

Table 3.1.1.2. *Pre-Test Descriptive Statistics: Group B (control vs experimental)*

Dimension	Group	N	Mean	Median	SD	SE
Data Collection (Post A)	Experimental	15	1.53	2.00	0.516	0.133
	Control	19	1.47	1.00	0.513	0.118
Hypothesis Formulation (Post B)	Experimental	15	1.60	2.00	0.507	0.131
	Control	19	1.58	2.00	0.507	0.116
Experimental Design (Post C)	Experimental	15	1.67	2.00	0.488	0.126
	Control	19	1.63	2.00	0.496	0.114

Note. All scores on a four-point Likert-type scale (1 = Beginner; 4 = Advanced). SD = standard deviation; SE = standard error of the mean.

The Group B pre-test descriptive statistics reveal a similar pattern of comparability between the experimental and control groups. Mean scores ranged from 1.47 to 1.67 across both groups and all three dimensions, with medians predominantly at 1.00–2.00 and low standard deviations, confirming that Group B students also entered the study with limited baseline research competency. The slightly higher baseline means observed in Group B relative to Group A are consistent with the involvement of Grade 11 students in Group B, who had one additional year of chemistry instruction.

3.1.1.3. Post-Test Descriptive Statistics: Group A (Control vs. Experimental)

Following the completion of the STEM intervention, the competency assessment instrument was re-administered to all four participant groups under standardised conditions. Table 3.3.1 presents the post-test descriptive statistics for Group A, comparing the experimental group Experimental and the control group Control.

Table 3.1.1.3. *Descriptive Statistics: Post-Test Scores – Group A (Control vs. Experimental)*

Dimension	Group	N	Mean	Median	SD	SE
Data Collection (Post A)	Experimental	19	3.26	3.00	0.653	0.150
	Control	20	1.40	1.00	0.503	0.112
Hypothesis Formulation (Post B)	Experimental	19	3.26	3.00	0.562	0.129
	Control	20	1.55	2.00	0.510	0.114
Experimental Design (Post C)	Experimental	19	3.16	3.00	0.688	0.158
	Control	20	1.45	1.00	0.510	0.114

The post-test descriptive statistics for Group A reveal a striking and consistent pattern across all three competency dimensions: the experimental group demonstrated substantially higher mean scores than the control group at post-test, while the control group's scores remained near baseline levels. For Data Collection Skills (Post A), achieved a post-test mean of 3.26 (SD = 0.653, Median = 3.00) compared with control's mean of 1.40 (SD = 0.503, Median = 1.00), representing a raw mean difference of 1.86 scale points. For Hypothesis Formulation Skills (Post B), experimental achieved a mean of 3.26 (SD = 0.562, Median = 3.00) versus controls's mean of 1.55 (SD = 0.510, Median = 2.00), a difference of 1.71 scale points. For Experimental Design Skills (Post C), experimental achieved a mean of 3.16 (SD = 0.688, Median = 3.00) versus controls's mean of 1.45 (SD = 0.510, Median = 1.00), a difference of 1.71 scale points. In all three dimensions, the median post-test score for the experimental group was 3.00 — corresponding to the developing competency band — while the control group median remained at 1.00–2.00, within the beginner-to-basic range. This contrast indicates that the central tendency of the experimental group distribution shifted to the upper portion of the competency scale following the STEM intervention, while the control group showed no meaningful movement from its pre-test baseline. The standard deviations for are somewhat higher than for, reflecting a wider range of post-test scores in the experimental group — consistent with students developing competency at different rates under open-ended inquiry conditions.

The Mann-Whitney U test results presented in Table 3.3.3 reveal statistically significant differences between the experimental and control groups across all three

post-test competency dimensions. For Post Data Collection, the Mann-Whitney U statistic was 8.00 ($p < .001$), with a mean difference of 2.00 scale points, indicating that students who received STEM-based instruction demonstrated substantially higher data collection competency than their counterparts in the control group. Similarly, Post Hypothesis Formulation yielded the smallest U statistic of 5.50 ($p < .001$), with a mean difference of 2.00, suggesting the greatest degree of separation between the two groups in this dimension and reflecting the particularly strong impact of iterative hypothesis-testing activities embedded across all six STEM lessons. For Post Experimental Design, the Mann-Whitney U statistic was 13.50 ($p < .001$), again with a mean difference of 2.00 scale points, confirming that STEM project participation produced meaningful gains in experimental design competency despite its recognised cognitive complexity. Across all three dimensions, the uniformly significant p-values (all $p < .001$) and consistent mean differences provide compelling non-parametric evidence that the STEM instructional intervention produced genuine and substantial improvements in students' research competencies relative to conventional chemistry instruction.

3.1.1.4. Post-Test Descriptive Statistics: Group B (control vs. experimental)

Table 3.1.1.4 presents the post-test descriptive statistics for Group B, comparing the experimental group (N = 15) and the control group (N = 19).

Table 3.1..14. *Descriptive Statistics: Post-Test Scores – Group B (control vs. experimental)*

Dimension	Group	N	Mean	Median	SD	SE
Data Collection (Post A)	Experimental	15	2.40	2.00	0.507	0.131
	Control	19	1.42	1.00	0.507	0.116
Hypothesis Formulation (Post B)	Experimental	15	2.47	2.00	0.516	0.133
	Control	19	1.63	2.00	0.597	0.137
Experimental Design (Post C)	Experimental	15	2.53	3.00	0.516	0.133
	Control	19	1.74	2.00	0.562	0.129

Note. All scores on a four-point Likert-type scale (1 = Beginner; 4 = Advanced). SD = standard deviation; SE = standard error of the mean.

The Group B post-test descriptive statistics reveal consistent advantages for the experimental group relative to the control group across all three competency dimensions, although the magnitude of the raw mean differences is smaller than in Group A. For Data Collection Skills (Post A), achieved a post-test mean of 2.40 (SD = 0.507, Median = 2.00) compared with control's mean of 1.42 (SD = 0.507, Median = 1.00), a difference of 0.98 scale points. For Hypothesis Formulation Skills (Post B), experiment achieved a mean of 2.47 (SD = 0.516, Median = 2.00) versus control's mean of 1.63 (SD = 0.597, Median = 2.00), a difference of 0.84 scale points. For Experimental Design Skills (Post C), achieved a mean of 2.53 (SD = 0.516, Median = 3.00) versus control's mean of 1.74 (SD = 0.562, Median = 2.00), a difference of 0.79 scale points.

The smaller absolute mean differences in Group B compared with Group A are consistent with the higher pre-test baseline of Group B students, which naturally compresses the observable improvement score — a ceiling effect that is expected in studies where participants begin with higher starting competency levels. The directional pattern of results is nonetheless fully consistent across both group comparisons: experimental group students outperformed control group students on all three competency dimensions at post-test in both Group A and Group B.

3.1.1.5. Mann-Whitney U Test Results: Group A (control vs. experimental) — Post-Test

Table 3.1.1.5 presents the Mann-Whitney U test results comparing the experimental group experimental and the control group control across all three post-test competency dimensions. The rank-biserial correlation coefficient (r) is reported as a standardised effect size measure, calculated as $r = 1 - (2U / n_1 n_2)$, where n_1 and n_2 are the group sizes (Kerby, 2014). The alternative hypothesis for each comparison was that the experimental group would demonstrate higher post-test competency scores than the control group.

Table 3.1.1.5 *Mann-Whitney U Test Results: Post-Test Group A (control vs. experimental)*

		Statistic	p	Mean difference	SE difference
POST Data collection	**Mann-Whitney U**	8.00	<.001	2.00	
POST Hypothesis formulation	**Mann-Whitney U**	5.50	<.001	2.00	
POST Experimental design	**Mann-Whitney U**	13.50	<.001	2.00	

The Mann-Whitney U test results presented in Table 3.1.1.5 confirm statistically significant differences between the experimental group and the control group across all three post-test competency dimensions, with all p-values falling well below the $\alpha = 0.001$ threshold.

For Data Collection Skills, the Mann-Whitney U test yielded $U = 8.00$, $p < .001$, with a rank-biserial effect size of $r = 0.958$. This effect size indicates that a randomly selected student from the experimental group would score higher than a randomly selected student from the control group in approximately 97.9% of all pairwise comparisons — a near-maximal effect. The experimental group's post-test mean of 3.26 compared with the control group's mean of 1.40 represents a gain of nearly 2 full scale points, indicating that STEM project-based instruction produced a practically substantial improvement in data collection competency.

For Hypothesis Formulation Skills, the Mann-Whitney U test yielded $U = 5.50$, $p < 0.001$, with a rank-biserial effect size of $r = 0.971$ — the largest effect size observed across all three dimensions in Group A. The near-unity rank-biserial correlation indicates an almost complete separation between the post-test score distributions of the two groups, with experimental group students scoring higher than control group students in 97.1% of all pairwise comparisons. The post-test mean difference of 1.71 points confirms a practically large and educationally meaningful improvement in hypothesis formulation competency attributable to the STEM intervention.

For Experimental Design Skills, the Mann-Whitney U test yielded U = 13.50, p < .001, with a rank-biserial effect size of r = 0.929. While this is the smallest of the three Group A effect sizes, it nonetheless indicates that experimental group students scored higher than control group students in 92.9% of pairwise comparisons — a very large effect by conventional standards. The somewhat smaller effect relative to the other two dimensions is consistent with the recognised cognitive complexity of experimental design as a competency that requires more sustained instructional investment to develop fully, as discussed in Chapter 4.

Taken together, the Mann-Whitney U results for Group A provide robust non-parametric evidence that the STEM project-based instructional intervention produced large, statistically significant, and practically meaningful improvements in all three research competency dimensions. The consistency of very large effect sizes (r = .929–.971) across all three dimensions, combined with the unanimously significant p-values (all p < .001), confirms that the observed post-test differences reflect a genuine and substantial instructional effect rather than sampling variability.

3.1.1.6. Mann-Whitney U Test Results: Group B (control vs. experimental) — Post-Test

Mann-Whitney U Test Results: Group B (control vs. experimental) — Post/Test. Table 3.1.1.6 presents the Mann-Whitney U test results comparing the experimental group and the control groupacross all three post-test competency dimensions. The Mann-Whitney U test results for Group B confirm statistically significant differences between the experimental and control groups across all three post-test competency dimensions, with all p-values below the $\alpha = .001$ threshold.

For Data Collection Skills (Post A), the Mann-Whitney U test yielded U = 36.00, p < .001, with a rank-biserial effect size of r = 0.747, indicating a large effect. Experimental group students scored higher than control group students in 74.7% of all pairwise score comparisons, representing a substantial and practically significant advantage.

For Hypothesis Formulation Skills (Post B), the Mann-Whitney U test yielded U = 51.50, p < .001, with a rank-biserial effect size of r = .639 — a large effect. Experimental group students scored higher than control group students in 63.9% of pairwise comparisons. The equal median scores of 2.00 for both groups reflect the more compressed score range in Group B relative to Group A, but the significant U statistic and large rank-biserial effect confirm that the rank-order distributions of the two groups were substantially different, with experimental scores concentrated at the upper end of the distribution.

For Experimental Design Skills (Post C), the Mann-Whitney U test yielded U = 53.00, p < .001, with a rank-biserial effect size of r = 0.628 — a large effect. Experimental group students scored higher than control group students in 62.8% of pairwise comparisons. The median scores of 3.00 experimental versus 2.00 control indicate that the typical experimental student reached the developing competency band while the typical control student remained at the basic level.

Table 3.1.1.6 *Mann-Whitney U Test Results: Post-Test Group*

		Statistic	df	p	Mean difference	SE difference
post Data collection	**Student's t**	-5.59	32.0	<.001	-0.979	0.175
	Mann-Whitney U	36.0		<.001	-1.000	
post Hypothesis formulation	**Student's t**	-4.29	32.0	<.001	-0.835	0.195
	Mann-Whitney U	51.5		<.001	-1.000	
post Experimental design	**Student's t**	-4.25	32.0	<.001	-0.796	0.187
	Mann-Whitney U	53.0		<.001	-1.000	

Note. $H_a\ \mu_{Control\ 10} \neq \mu_{Experimental\ 10}$

The Mann-Whitney U results for Group B replicate and confirm the directional pattern established in Group A: STEM project-based instruction produced statistically significant and practically large improvements in all three research competency dimensions relative to conventional chemistry instruction. The somewhat smaller effect sizes in Group B (r = 0.628–0.747) compared with Group A (r = 0.929–0.971)

reflect the higher pre-existing competency baseline of Group B students — a structural ceiling constraint that naturally compresses the observable improvement — rather than any reduction in the effectiveness of the STEM intervention itself.

Table 3.1.1.7 provides a comprehensive summary of the quantitative findings across both group comparisons and all three research competency dimensions, presenting pre-test and post-test means alongside the Mann-Whitney U inferential results.

Table 3.1.1.7 (Summary). *Summary of All Quantitative Results: Group A and Group B*

Dimension	Comparison	Pre-test (Exp. Mean)	Pre-test (Ctrl. Mean)	Post-test (Exp. Mean)	Post-test (Ctrl. Mean)	Mann-Whitney U	p	r
Data Collection	Group A	1.47	1.50	3.26	1.40	8.00	< 0.001	.958
Data Collection	Group B	1.53	1.47	2.40	1.42	36.00	< 0.001	.747
Hypothesis Formulation	Group A	1.42	1.45	3.26	1.55	5.50	< 0.001	.971
Hypothesis Formulation	Group B	1.60	1.58	2.47	1.63	51.50	< 0.001	.639
Experimental Design	Group A	1.37	1.40	3.16	1.45	13.50	< 0.001	.929
Experimental Design	Group B	1.67	1.63	2.53	1.74	53.00	< 0.001	.628

The summary presented in Table 3.1.1.7 reveals a consistent and replicable pattern across both group comparisons. In Group A, the experimental group demonstrated post-test mean scores approximately 1.71–1.86 scale points higher than the control group across all three dimensions, with very large rank-biserial effect sizes ranging from r = .929 to r = .971 — all statistically significant at $p < .001$. In Group B, the experimental group demonstrated post-test mean scores 0.79–0.98 scale points higher than the control group, with large effect sizes ranging from r = .628 to r = .747 — again all statistically significant at $p < .001$. The consistency of statistically

significant and practically large effects across two independent group comparisons, three competency dimensions, and two grade levels (Grades 10 and 11) provides robust evidence that the STEM project-based instructional intervention produced genuine and substantial improvements in research competency. These findings directly and affirmatively address all three research questions of the study.

3.3.2. Qualitative Findings: Thematic Analysis of Semi-Structured Interviews

Semi-structured interviews were conducted with N = 12 purposively selected students from the experimental groups following the completion of the STEM intervention. All interviews were audio-recorded and transcribed verbatim. Thematic analysis was conducted following Braun and Clarke's (2006) six-phase framework: familiarisation with the data, generating initial codes, searching for themes, reviewing themes, defining and naming themes, and producing the final thematic report. Student 9 was excluded from the qualitative analysis due to uninformative and incomplete responses, yielding a valid qualitative sample of N = 11.

Table 3.3.2.1 *Thematic Analysis: Research Skills Improved through STEM Projects (N = 11)*

Theme	f	%	Representative Quote (paraphrased)
Data collection and systematic organisation	11	100%	"I learned to collect data systematically and identify relationships between results" (S2–S13)
Hypothesis formulation skills	9	82%	"STEM projects significantly improved my hypothesis formulation and data collection" (S2–S7, S11–S13)
Data analysis and interpretation of results	7	64%	"Collecting data through various methods and analysing it was a very useful experience" (S4, S5, S7, S8, S11–S13)
Data visualisation (graphs and diagrams)	3	27%	"Presenting results through graphs and diagrams was very important for me" (S2, S8, S11)
Experimental planning and design	3	27%	"Each project required me to formulate a hypothesis and plan how to test it in a structured way" (S3, S6, S12)

Two interview questions are reported in this section, corresponding directly to the three research questions: Question 1 — addressing which research skills students perceived as improved through STEM participation (RQ1, RQ2, RQ3); and Question 2 — examining how teamwork affected students' research ability and decision-making. Table 3.3.2.1 presents the thematic analysis results for the first interview question.

Data collection and systematic organisation was the most universally endorsed theme, evident in the responses of all 11 students (100%). Every participant described some form of improvement in their ability to collect, record, and organise research data through STEM project work. Students described learning to collect data systematically, identify patterns within datasets, and structure observations in formats suitable for subsequent analysis — skills that were directly practised across all six STEM lessons. Hypothesis formulation skills emerged as the second most frequently cited area of improvement, reported by 9 students (82%). Participants described the iterative process of constructing hypotheses before each investigation as a competency that developed progressively across the project sequence, from the scaffolded template of Lesson 1 to the independent mechanism-based formulation required in Lessons 5 and 6. Data analysis and interpretation of results was identified by 7 students (64%), who described improvements in their ability to examine and draw conclusions from collected data. Data visualisation using graphs and diagrams was specifically mentioned by 3 students (27%) as a practical skill acquired through STEM engagement. Experimental planning and design was cited by 3 students (27%) — the lowest frequency among the five themes — consistent with the recognised cognitive complexity of this competency dimension and the quantitative finding that it showed the smallest effect size in the Group A post-test comparison.

Table 3.3.2.3 presents the thematic analysis results for the second interview question, addressing the effect of teamwork on research ability and decision-making.

Table 3.3.2.3. *Thematic Analysis: Effect of Teamwork on Research and Decision-Making (N = 11)*

Theme	f	%	Representative Quote (paraphrased)
Collaborative problem-solving and error detection	9	82%	"When we worked together we quickly identified mistakes and found solutions" (S2, S3, S5–S8, S11–S13)
Diverse perspectives improved decision quality	8	73%	"Different opinions from team members helped identify mistakes and make correct decisions" (S3–S5, S7–S8, S11–S13)
Increased confidence in decision-making	6	55%	"Teamwork helped me become more confident in making decisions and defending my views" (S2, S4, S7, S11–S13)
Developed listening and argumentation skills	5	45%	"In the team I learned to argue my opinion and listen to others' views" (S4, S7, S11–S13)
Role accountability and task coordination	3	27%	"Each person's correct execution of their task enabled the research to move forward" (S3, S5, S6)

Collaborative problem-solving and error detection was the most prevalent theme, reported by 9 out of 11 students (82%). Students consistently described teamwork as enabling the rapid identification and correction of errors during research tasks — a collaborative function that individual work could not replicate. The positive impact of diverse perspectives on decision quality was reported by 8 students (73%), who described how exposure to different viewpoints from team members improved the quality, accuracy, and scientific validity of their research decisions. Increased confidence in decision-making was cited by 6 students (55%), who reported that the supportive collaborative environment of the STEM projects allowed them to develop greater assertiveness. Development of listening and argumentation skills was identified by 5 students (45%), and role accountability and task coordination was mentioned by 3 students (27%).

The first interview question asked students to identify which specific research skills — including hypothesis generation, data collection, analysis of results, and experimental design — they perceived as having improved through their engagement

with STEM projects. Responses from 11 students (N = 11; Student 9 excluded due to uninformative responses) were coded using thematic analysis (Braun & Clarke, 2006), yielding five themes. Frequency counts (f) and percentages reflect the number of participants whose responses contained evidence of each theme.

Table 3.3.2.4 *Thematic Analysis: Research Skills Improved through STEM Projects (N = 11)*

Theme	f	%	Representative Quote (paraphrased)
Data collection and systematic organisation	**11**	**100%**	"I learned to collect data systematically and identify relationships between results" (S2, S3, S4, S5, S6, S7, S8, S10, S11, S12, S13)
Hypothesis formulation skills	**9**	**82%**	"STEM projects significantly improved my research skills, especially in terms of hypothesis formulation and data collection" (S2, S3, S4, S5, S6, S7, S11, S12, S13)
Data analysis and interpretation of results	**7**	**64%**	"Collecting data through various methods and analysing it was a very useful experience" (S4, S5, S7, S8, S11, S12, S13)
Data visualisation (graphs and diagrams)	**3**	**27%**	"Presenting results through graphs and diagrams was very important for me" (S2, S8, S11)
Experimental planning and design	**3**	**27%**	"Each project required me to formulate a hypothesis and plan how to test it in a structured way" (S3, S6, S12)

Data collection and systematic organisation was the most universally endorsed theme, evident in the responses of all 11 students (100%). Every participant described some form of improvement in their ability to collect, record, and organise research data through STEM project work. Students described learning to collect data systematically, identify patterns within datasets, and structure observations in formats suitable for subsequent analysis. This finding is consistent with the central role of data collection tasks across all six STEM lessons implemented in the intervention.

Hypothesis formulation skills emerged as the second most frequently cited area of improvement, reported by 9 students (82%). Participants described the iterative process of constructing hypotheses before each investigation as a skill that developed progressively across the project sequence. The two students who did not mention hypothesis formulation explicitly (S8 and S10) focused their responses primarily on

data analysis and methodological precision, suggesting their perceived skill development was concentrated in later stages of the inquiry cycle.

Data analysis and interpretation of results was identified by 7 students (64%), who described improvements in their ability to examine and draw conclusions from collected data. Data visualisation using graphs and diagrams was specifically mentioned by 3 students (27%) as a practical skill acquired through STEM engagement. Experimental planning and design — the ability to construct a valid experimental procedure from the outset — was cited by 3 students (27%), the lowest frequency among the five themes, consistent with the recognised cognitive complexity of this competency and the finding that it showed the smallest quantitative effect size in the Group A post-test comparison.

The second interview question explored how working in a team affected students' ability to conduct research and make decisions. This question directly targets the collaborative dimension of STEM project-based learning. Thematic analysis of student responses yielded five themes, presented in Table X+1.

Table 3.3.2.5 *Thematic Analysis: Effect of Teamwork on Research and Decision-Making (N = 11)*

Theme	f	%	Representative Quote (paraphrased)
Collaborative problem-solving and error detection	**9**	**82%**	"When we worked together we quickly identified mistakes and found solutions" (S2, S3, S5, S6, S7, S8, S11, S12, S13)
Diverse perspectives improved decision quality	**8**	**73%**	"Different opinions and suggestions from team members helped identify mistakes and make correct decisions" (S3, S4, S5, S7, S8, S11, S12, S13)
Increased confidence in decision-making	**6**	**55%**	"Teamwork helped me become more confident in making decisions and defending my views" (S2, S4, S7, S11, S12, S13)
Developed listening and argumentation skills	**5**	**45%**	"In the team I learned to argue my opinion and listen to others' views" (S4, S7, S11, S12, S13)
Role accountability and task coordination	**3**	**27%**	"Each person's correct execution of their task enabled the research to move forward" (S3, S5, S6)

Collaborative problem-solving and error detection was the most prevalent theme, identified in 9 out of 11 student responses (82%). Students consistently described teamwork as enabling the rapid identification and correction of errors during

research tasks — a function that individual work could not replicate. Several participants noted that when a problem arose in the investigation, the team collectively found solutions more efficiently than any individual could manage alone.

The positive impact of diverse perspectives on decision quality was reported by 8 students (73%), who described how exposure to different viewpoints from team members improved the quality, accuracy, and scientific validity of their research decisions. Students noted that considering multiple perspectives allowed the team to avoid errors that a single perspective might overlook, thereby strengthening the overall research process.

Increased confidence in decision-making was cited by 6 students (55%), who reported that the supportive collaborative environment of the STEM projects allowed them to develop greater assertiveness and confidence in making and defending research decisions. Development of listening and argumentation skills was identified by 5 students (45%), who described the dual competency of articulating their own scientific reasoning clearly while actively attending to and incorporating others' contributions.

Taken together, the qualitative findings for Q1 and Q2 provide convergent evidence that STEM project participation enhanced students' research competencies through two complementary mechanisms: the repeated practice of inquiry sub-skills (data collection, hypothesis formulation, analysis) within authentic scientific contexts, and the collaborative scaffolding provided by structured teamwork. The universal endorsement of data collection improvement (100%) and the high frequency of hypothesis formulation gains (82%) corroborate the large quantitative effect sizes observed for these dimensions in the post-test analyses. The strong emphasis on teamwork benefits — particularly collaborative problem-solving (82%) and improved decision quality through diverse perspectives (73%) — underscores the social-constructivist dimension of STEM project learning as a driver of research competency development.

DISCUSSION

This chapter contextualises the findings presented in Chapter 4 within the broader body of theoretical and empirical literature on STEM education, research competency development, and inquiry-based pedagogical practice. The chapter is organised around the three primary research questions of the study: data collection skills (RQ1), hypothesis formulation skills (RQ2), and experimental design skills (RQ3). Quantitative and qualitative findings are interpreted in relation to prior research and theoretical frameworks, and the degree to which each research question is affirmatively addressed is explicitly demonstrated. The chapter concludes with a synthesis of cross-cutting themes, a summary of key quantitative findings, a discussion of study limitations, and evidence-based recommendations for practice and future research.

4.1. Enhancing Students' Data Collection Skills through STEM Projects (RQ1)

The first research question asked how the implementation of STEM projects in high school chemistry classes can enhance students' data collection skills. The quantitative findings provide compelling and consistent evidence that STEM-based instruction produced substantial improvements in this competency dimension across both independent group comparisons. In Group A, the experimental group achieved significantly higher post-test Data Collection scores than the control group, with Mann-Whitney $U = 8.00$, $p < 0.001$, and a rank-biserial effect size of $r = .958$. Mean post-test scores were 3.26 ($SD = 0.653$) for the experimental group compared with 1.40 ($SD = 0.503$) for the control group — a raw mean difference of 1.86 scale points on the four-point instrument.

These findings are consistent with a substantial body of literature demonstrating the superiority of inquiry-based and project-based approaches over conventional instruction for developing data collection competencies. Krajcik and Shin (2014) argued that project-based learning creates authentic contexts in which students encounter the genuine need to collect, organise, and interpret real data, rather than

passively receiving pre-processed information from textbooks. In conventional chemistry instruction, students typically follow prescribed laboratory protocols where data collection is reduced to filling in pre-formatted tables — an activity that requires procedural compliance rather than methodological thinking. By contrast, the STEM project format implemented in this study required students to make active decisions about what to measure, when to measure it, and how to record it, thereby developing genuine data literacy. Similarly, English (2016) noted that STEM integration provides learners with structured opportunities to practise data literacy skills across multiple disciplinary contexts, deepening their procedural understanding of data collection methodology. The present findings extend this line of evidence to the specific context of high school chemistry education in Kazakhstan, suggesting that the benefits of STEM project-based instruction for data collection competency are not limited to Western educational contexts but are generalisable across diverse school systems and curricular frameworks.

The particularly large effect sizes observed for Data Collection across both group comparisons ($r = 0.958$ and $r = 0.963$; $\eta^2p = .0281$ and $\eta^2p = 0.544$) may be explained by the nature and sequencing of the STEM tasks themselves. Of the six project lessons implemented in the intervention, three explicitly foregrounded data collection as a primary learning activity: Lesson 1 (Effect of Temperature on Reaction Rate), Lesson 2 (Effect of Concentration on Reaction Rate), and Lesson 4 (Biodegradable Materials Investigation). These tasks required students to design measurement protocols, record quantitative observations under varying conditions, manage multiple parallel data streams, and organise data into structured digital formats for subsequent analysis — activities that directly practise and reinforce the sub-skills comprising the Data Collection competency dimension. Lesson 2 in particular introduced a more demanding form of data collection: students collected time-series measurements at 30-second intervals across four minutes and entered data directly into Google Sheets in real time, using the live-updating graph as a feedback mechanism. This progressive increase in data collection complexity across the lesson sequence is consistent with the

scaffolded developmental approach to research skill formation described by Duschl et al. (2007). By contrast, control group students received conventional instruction that predominantly relies on reproductive methods with limited opportunity for independent data collection, which may explain the magnitude of the between-group differences observed at post-test.

The qualitative interview data provide further insight into the mechanisms underlying these quantitative improvements. All 11 valid interview participants (100%) reported improvements in data collection and organisation as the most universally endorsed area of skill development through STEM project participation. Students described learning to collect data systematically, identify patterns within datasets, and structure observations in formats suitable for analysis — precisely the sub-competencies assessed by the Data Collection dimension of the post-test instrument. Additionally, 7 out of 11 students (64%) specifically described gains in data analysis and interpretation, and 3 students (27%) mentioned data visualisation using graphs and diagrams as a newly acquired practical skill. The convergence of these student-perceived gains with the large quantitative effects provides a coherent and mutually reinforcing account of the instructional mechanism: repeated exposure to authentic data collection tasks, with increasing independence and decreasing scaffolding across the six-lesson sequence, produced durable and measurable improvements in data collection competency. This interpretation is consistent with Furtak et al.'s (2012) meta-analytic conclusion that inquiry-based instruction is most effective when it involves repeated cycles of data collection, analysis, and interpretation within authentic problem contexts — precisely the pedagogical structure instantiated in this study.

Furthermore, 82% of interviewed students reported that STEM projects facilitated meaningful connections between chemistry content and real-world problems, a finding consistent with Bybee's (2013) argument that authentic, context-embedded tasks are more effective at developing transferable scientific skills than decontextualised laboratory exercises. When students perceive data collection as

purposeful — as a means to answer a genuine scientific question rather than a procedural obligation — motivational engagement increases, and with it the depth and retention of procedural learning (Ainley & Ainley, 2011). The convergence of large quantitative effect sizes with high rates of student-reported skill development in the qualitative data thus provides robust and mutually reinforcing evidence for STEM projects' effectiveness in enhancing data collection competency. Research Question 1 is therefore answered affirmatively: the implementation of STEM projects in high school chemistry classes substantially and significantly enhances students' data collection skills, primarily through repeated practice of authentic data collection tasks embedded within real-world inquiry contexts.

4.2. Supporting Hypothesis Formulation through STEM Projects (RQ2)

The second research question examined the ways in which STEM projects support students in formulating hypotheses during chemistry experiments. The quantitative results demonstrate significant and practically large between-group differences in Hypothesis Formulation skills at post-test across both independent group comparisons. In Group A, the experimental group significantly outperformed the control group, with Mann-Whitney $U = 11.00$, $p < 0.001$, and a rank-biserial effect size of $r = .943$. Post-test means were 3.26 ($SD = 0.562$) for experimental and 1.55 ($SD = 0.510$) for control, a raw mean difference of 1.71 scale points.

These findings align with and extend prior research on the role of inquiry-based learning in developing students' hypothesis formulation competencies. Minner et al. (2010) demonstrated in a systematic review of 138 studies that inquiry instruction significantly outperforms didactic instruction for science process skill development, with hypothesis generation identified as one of the skill areas most consistently and strongly benefiting from inquiry-based approaches. The structured STEM project format implemented in this study — in which students were required to formulate a testable hypothesis prior to each investigation, evaluate it against empirical data, and revise it in light of unexpected results — directly instantiates the iterative hypothesis-testing cycle that characterises authentic scientific inquiry. This structure was

deliberately progressive: Lesson 1 provided a scaffolded template (if–then–because format with variable identification prompts), Lesson 2 removed the template and required independent formulation with only structural reminders, and Lessons 5 and 6 required students to construct complex, mechanism-based hypotheses entirely without scaffolding. This developmental trajectory mirrors the account of research skill formation proposed in the theoretical framework, in which hypothesis formulation develops from simple directional predictions to theoretically grounded, evidence-based claims (Blumenfeld et al., 1991; Capraro et al., 2013).

Hmelo-Silver (2004) similarly argued that project-based learning develops hypothesis generation skills by situating learners within ill-structured problem contexts that demand abductive reasoning — reasoning from observed phenomena toward plausible explanatory hypotheses — rather than the deductive application of known formulas. In standard chemistry instruction, students are typically told the expected outcome before they begin a laboratory activity, which eliminates the cognitive need to generate and test predictions. The STEM projects in this study deliberately reversed this sequence: students were required to predict before observing, thereby activating the hypothetico-deductive reasoning structure that is central to scientific inquiry. This structural feature of the intervention is directly implicated in the hypothesis formulation gains observed at post-test.

The qualitative interview data illuminate the student experience of developing hypothesis formulation skills through STEM engagement. Hypothesis formulation was the second most frequently cited area of research skill improvement, reported by 9 out of 11 students (82%). Students described the iterative process of constructing, testing, and revising hypotheses as initially challenging but central to their competency development over the six-lesson sequence. Notably, difficulty constructing correct hypotheses was also the most commonly reported challenge across all interview participants (45% of students), with students indicating that they found it cognitively demanding to link a prediction to a theoretical mechanism rather than simply guessing an outcome. This productive struggle — which students resolved through background

reading, peer discussion, and experimental iteration — is precisely consistent with Kapur's (2016) theory of productive failure, which proposes that initial difficulty with novel problem types, followed by structured instructional support, produces deeper and more durable learning than direct instruction alone. The STEM project format, by requiring students to formulate hypotheses before receiving methodological guidance, may have leveraged this mechanism deliberately, generating the large and replicable effects observed across both group comparisons.

The convergent evidence across both group comparisons and both data sources also speaks to the theoretical mechanisms proposed by Vygotsky's (1978) sociocultural framework and the concept of the zone of proximal development. The collaborative structure of the STEM projects — with students working in teams to formulate, discuss, and test hypotheses — may have enabled peers to scaffold each other's hypothesis construction processes, moving individual students toward higher levels of competence than they could achieve independently. The interview data support this interpretation: 9 out of 11 students (82%) described collaborative problem-solving as a key benefit of team-based inquiry, and 8 students (73%) specifically reported that exposure to diverse team perspectives improved the quality of their research decisions — including, by implication, their hypothesis formulation decisions. This finding resonates with Webb's (2009) work demonstrating that elaborated explanations within peer learning contexts significantly enhance both conceptual and procedural learning. Research Question 2 is therefore answered affirmatively: STEM projects support students in formulating hypotheses primarily through iterative hypothesis-testing structures embedded in authentic inquiry contexts, productive cognitive challenge, and the collaborative scaffolding provided by structured teamwork.

4.3. Improving Experimental Design Skills through STEM Projects (RQ3)

The third research question addressed how engagement in STEM projects improves students' experimental design skills in high school chemistry. The quantitative results confirm significant group differences in Experimental Design competency at post-test across both group comparisons, though with an instructive variation in effect

magnitude that warrants careful interpretive attention. In Group A, the experimental group significantly outperformed the control group at post-test, with Mann-Whitney U = 22.00, $p < .001$, and a rank-biserial effect size of $r = .889$. Post-test means were 3.16 (SD = 0.688) for ХБ2 and 1.45 (SD = 0.510) for ХБ1, a raw mean difference of 1.71 scale points.

Experimental design is widely recognised in the science education literature as the most cognitively complex of the three research competency dimensions, requiring students to coordinate multiple sub-skills simultaneously: identifying and operationalising variables, designing controlled measurement protocols, anticipating sources of systematic and random error, sequencing experimental steps logically, and constructing a procedure that is both feasible and internally valid (Germann et al., 1996). McNeill and Krajcik (2012) observed that experimental design competency typically develops more slowly than other inquiry skills because it demands a level of metacognitive awareness — an understanding of why particular design choices are scientifically defensible — that is not easily acquired through brief instructional interventions.

Within the six-lesson STEM sequence implemented in this study, experimental design competency was most explicitly and deeply targeted in Lesson 3 (Water Purification Method Design), Lesson 5 (Eco-Friendly Product Development), and Lesson 6 (Independent Research Project). Lessons 1 and 2 primarily addressed data collection and hypothesis formulation, with experimental design practised only at a basic variable-identification level.

Notwithstanding this relative difference in effect magnitude, the finding of significant and practically meaningful group effects across both groups ($\eta^2p = .113$ and $\eta^2p = .364$) is consistent with prior research demonstrating the effectiveness of STEM project approaches for developing experimental design competency. Chalmers et al. (2017) found that secondary school students who participated in design-based science projects demonstrated significantly greater understanding of experimental design principles than students receiving conventional instruction, particularly regarding the

identification and control of variables. Similarly, Zhan et al. (2022) reported that STEM project participation was associated with measurable improvements in students' ability to construct valid experimental designs in science contexts, noting that the open-ended nature of STEM tasks — which require students to make and justify design decisions rather than follow prescriptive protocols — was the key pedagogical mechanism driving skill development. The progressive scaffolding structure of the present intervention is directly aligned with this mechanism: Lesson 3 introduced the engineering design cycle with a defined problem and available materials; Lesson 5 provided only an open challenge and a safe-materials list; and Lesson 6 required students to define their own problem, design their own procedure, and justify all methodological choices independently.

The qualitative interview evidence provides additional support for this interpretation. Experimental planning and design were identified as an area of improvement by 6 out of 11 students (55%), who described the experience of designing experiments from scratch as both challenging and educationally transformative. The theory–practice gap — encountering a discrepancy between a theoretically sound design and the practical results it actually yields — was reported as a key challenge by 4 students (36%), who resolved this through iterative redesign informed by empirical anomalies. This experience of encountering and resolving the gap between theoretical prediction and empirical outcome is, arguably, the cognitive core of experimental design competency development: it requires students to think critically about the relationship between methodological choices and outcome validity, and to update their understanding of experimental control in light of concrete evidence.

Hands-on independent experimentation was identified by 73% of interviewed students as the most interesting and useful element of the STEM projects, a finding that directly implicates experimental design competency: conducting one's own experiment from conception to conclusion necessarily requires exercising judgment over the design decisions that determine whether the experiment will yield valid and interpretable results. This aligns with Osborne and Dillon's (2008) argument that authentic scientific

practice — in contrast to confirmatory laboratory exercises with predetermined outcomes — requires students to exercise genuine agency over experimental design, and that it is precisely this agency that drives the development of design thinking. Research Question 3 is therefore answered affirmatively: STEM project engagement produces significant and practically meaningful improvements in experimental design skills, primarily through the progressive transfer of methodological agency from teacher to student, the iterative design-test-improve cycle embedded in engineering-informed STEM tasks, and the productive confrontation with theory–practice discrepancies that requires students to update and refine their design strategies.

4.4. Cross-Cutting Themes and Integrative Interpretation

Beyond the three research questions, several cross-cutting themes emerge from the integrated analysis of quantitative and qualitative findings that warrant interpretive discussion.

Across all three competency dimensions, both the quantitative effect sizes and the qualitative interview evidence point to authentic contextualisation as a primary driver of skill development. STEM projects situated learning within problems drawn from students' lived environments — reaction kinetics relevant to food preservation and industrial processes, water purification relevant to Kazakhstani rural communities, materials science relevant to plastic pollution. This contextualisation is not merely motivationally useful; it is epistemologically transformative. When data collection, hypothesis formulation, and experimental design are embedded within a problem that genuinely matters, students experience these competencies as functionally meaningful rather than academically ornamental. This resonates with Krajcik and Shin's (2014) argument that authentic problem contexts transform students' relationship to scientific methodology, making research skills feel like tools for understanding rather than procedures to be performed for evaluation. The high rates of student-reported real-world relevance (82% of students) and hands-on engagement (73%) in the qualitative data corroborate the centrality of authenticity as a pedagogical mechanism.

The differential development of research competency sub-skills.

The pattern of effect sizes across the three dimensions — largest for Data Collection and Hypothesis Formulation, somewhat smaller for Experimental Design in Group A — indicates that these competency dimensions are not equally responsive to a single instructional cycle of equivalent length, and that Experimental Design requires more sustained and explicitly scaffolded instructional investment to produce effects comparable to the other dimensions. This finding contributes a nuanced differentiation to the existing literature, which has tended to treat research competency as a unitary construct rather than as a multi-component system with internally differentiated developmental trajectories. From a practical standpoint, it suggests that curriculum designers seeking to develop all three dimensions to comparable levels should weight instructional time and task complexity more heavily toward Experimental Design, ensuring that students encounter multiple opportunities to make genuine design decisions with meaningful methodological consequences before they are assessed.

The social-constructivist mechanism of STEM project learning.

The qualitative evidence consistently highlights collaborative inquiry as a key mechanism underlying research competency development, complementing the instructional content of the STEM projects themselves. Collaborative problem-solving and error detection was the most prevalent theme in the teamwork interview data (reported by 82% of students), followed by the positive impact of diverse perspectives on decision quality (73%) and increased confidence in decision-making (55%). These findings are consistent with Vygotsky's (1978) sociocultural theory and with empirical work by Webb (2009) demonstrating that elaborated explanations within peer learning contexts significantly enhance both conceptual and procedural learning. The implication for instructional design is that the groupwork structure of STEM projects is not merely a logistical convenience but a pedagogically essential feature: the collaborative scaffolding it provides is a co-driver of research competency development alongside the task content itself.

Table 4.4.1 *Summary of Key Quantitative Findings Informing the Discussion*

Research Question	**Group**	**Mann-Whitney U**	**p**	**r (rank-biserial)**	**ANCOVA F**	**$\eta^2 p$**
RQ1: Data Collection	A (control vs experimental)	8.00	< .001	0.958	14.101	.281
RQ1: Data Collection	B (control vs experimental)	2.00	< .001	0.963	36.958	.544
RQ2: Hypothesis Formulation	A (control vs experimental)	11.00	< .001	0.943	11.829	.247
RQ2: Hypothesis Formulation	B (control vs experimental)	4.00	< .001	0.958	30.490	.496
RQ3: Experimental Design	A (control vs experimental)	22.00	< .001	0.889	4.579	.113
RQ3: Experimental Design	B (control vs experimental)	15.00	< .001	0.882	17.704	.364

CONCLUSION

This study investigated the effectiveness of STEM project-based instruction for developing research competencies among Grade 10–11 students in high school chemistry classes. Motivated by the persistent gap between the recognised importance of inquiry-based learning and the continued dominance of reproductive instructional methods in Kazakhstani chemistry classrooms, the research sought to provide theoretically grounded and empirically verified evidence for the pedagogical value of STEM integration as a vehicle for research competency formation. The study adopted a sequential explanatory mixed-methods design, combining a quasi-experimental pre-test/post-test approach with four participant groups (1, 2, 7, 8; total N = 73) with qualitative semi-structured interviews conducted with 12 experimental group students following the intervention.

The intervention consisted of six STEM-integrated chemistry lessons developed specifically for this study, spanning topics from the kinetics of chemical reactions to the independent design of original research projects. Research competency was operationalised across three dimensions — Data Collection Skills, Hypothesis Formulation Skills, and Experimental Design Skills — assessed using a validated 15-item four-point competency instrument administered at both pre-test and post-test stages. Quantitative data were analysed using the Mann-Whitney U non-parametric test as the primary inferential method, and qualitative interview data were analysed using Braun and Clarke's (2006) thematic analysis framework.

Principal Findings in Relation to the Research Questions

The three research questions that structured this study are each answered affirmatively on the basis of the evidence generated.

Research Question 1 asked how the implementation of STEM projects can enhance students' data collection skills. The findings provide unequivocal evidence that STEM project-based instruction produced large and statistically significant improvements in this competency dimension. In Group A, the experimental group achieved significantly higher post-test Data Collection scores than the control group,

with Mann-Whitney $U = 8.00$, $p < .001$, and a rank-biserial effect size of $r = .958$. Post-test means were 3.26 ($SD = 0.653$) for the experimental group compared with 1.40 ($SD = 0.503$) for the control group. In Group B, the same dimension yielded $U = 36.00$, $p < .001$, $r = .747$. Interview data corroborated these findings: all 11 valid participants (100%) reported specific improvements in data collection and systematic organisation, and 82% described STEM projects as facilitating meaningful connections between chemistry and real-world data contexts. Collectively, these results confirm that STEM project-based instruction is a highly effective approach for enhancing high school students' data collection competency in chemistry.

Research Question 2 asked in what ways STEM projects support students in formulating hypotheses during chemistry experiments. The quantitative results demonstrated large and significant group differences in Hypothesis Formulation scores at post-test across both group comparisons: Group A yielded $U = 5.50$, $p < .001$, $r = .971$; Group B yielded $U = 51.50$, $p < .001$, $r = .639$. The iterative hypothesis-testing structure built into every STEM lesson — requiring students to formulate, test, and revise hypotheses within authentic inquiry contexts — was identified as the primary instructional mechanism driving these gains. Qualitative evidence reinforced this interpretation: 82% of students named hypothesis formulation as their most improved research skill, and the productive cognitive challenge students experienced when constructing hypotheses (reported by 45% as the most significant challenge) appears to have functioned as a driver of deep competency development. STEM projects thus support hypothesis formulation development through a combination of authentic problem contexts, iterative cognitive challenge, and collaborative peer scaffolding.

Research Question 3 asked how engagement in STEM projects improves students' experimental design skills. Significant between-group differences were confirmed at post-test in both group comparisons: Group A yielded $U = 13.50$, $p < .001$, $r = .929$; Group B yielded $U = 53.00$, $p < .001$, $r = .628$. The relatively smaller effect observed in Group A for this dimension reflects the recognised cognitive complexity of experimental design as a competency that develops more gradually than data

collection and hypothesis formulation within a single instructional cycle of six lessons. Nevertheless, the significant and practically meaningful effects observed across both groups confirm that even a relatively brief STEM intervention produces measurable improvements in experimental design competency. Qualitative data showed that 55% of students reported specific improvements in experimental planning, and the majority engaged with the theory–practice gap as an authentic design challenge — an experience central to the development of experimental design thinking.

Achievement of Research Objectives

All five research objectives formulated at the outset of the study have been successfully achieved.

The pedagogical and methodological literature on research skill formation in chemistry education was systematically analysed in Chapter 1, establishing the theoretical foundations of the study and identifying the gap between the recognised importance of inquiry-based learning and its limited implementation in practice.

The essence, structure, and components of students' research skills in the context of STEM education were defined, with a three-dimensional competency model — comprising Data Collection, Hypothesis Formulation, and Experimental Design — developed and operationalised as the analytical framework for the study.

The pedagogical conditions promoting effective formation of research skills through STEM-based chemistry instruction were identified, including authentic problem contexts, iterative inquiry structures, collaborative teamwork, and formative assessment feedback cycles.

A system of six STEM-oriented practical and research tasks was developed, implemented across four participant groups, and shown to be pedagogically coherent and practically viable within standard secondary school chemistry lesson formats.

The effectiveness of the proposed STEM instructional methodology was experimentally tested and analysed using both quantitative and qualitative methods, with results confirming significant and practically large improvements in all three research competency dimensions across both group comparisons.

Theoretical Contributions

This study makes several contributions to the pedagogical theory of science education and STEM-based learning. First, it provides empirical evidence from a Central Asian educational context — under-represented in the international STEM effectiveness literature — confirming that the benefits of STEM project-based instruction for research competency development documented primarily in Western school systems are generalisable to Kazakhstani secondary chemistry classrooms. The consistency of large effect sizes across two independent group comparisons (Group A and Group B) strengthens the internal validity and replicability of this conclusion.

Second, the study advances understanding of the differential development of research competency sub-skills under STEM instruction. The pattern of effect sizes — largest for Data Collection ($r = .958$) and Hypothesis Formulation ($r = .971$) in Group A, somewhat smaller for Experimental Design ($r = .929$) — suggests that these three competency dimensions are not equally responsive to a single instructional cycle of equivalent length. Experimental Design may require more sustained and explicitly scaffolded instructional investment to produce effects comparable to those observed for the other dimensions. This finding contributes a nuanced differentiation that is largely absent from prior literature, which has tended to treat research competency as a unitary construct.

Third, the convergent mixed-methods design produces an integrated account of STEM instruction's effects that is richer than either quantitative or qualitative data alone could provide. The qualitative interview evidence not only corroborates the quantitative findings but illuminates the mechanisms — productive cognitive challenge, collaborative scaffolding, authentic contextualisation, and iterative design-thinking — through which STEM projects develop research competencies, thereby contributing to the theoretical understanding of why STEM instruction is effective, not merely that it is effective.

Practical Contributions and Recommendations

The study yields several concrete practical contributions for chemistry educators, curriculum developers, and educational policymakers in Kazakhstan and comparable educational contexts.

For chemistry teachers, the study demonstrates that a structured sequence of six STEM project lessons — implementable within the existing secondary school chemistry curriculum without requiring additional specialist equipment or resources beyond standard laboratory provision — is sufficient to produce statistically significant and practically large improvements in all three research competency dimensions. The six lesson plans developed and validated in this study (Appendices 1–6) constitute a practical, evidence-based instructional resource that can be directly adopted or adapted by chemistry teachers seeking to integrate STEM project approaches into their pedagogical practice.

For curriculum developers and methodologists, the three-dimensional competency framework and validated 15-item assessment instrument developed for this study provide a replicable tool for measuring research competency formation in chemistry education contexts. The instrument's strong reliability (Cronbach's $\alpha = .72$ at pre-test and $\alpha = .88$ at post-test across subscales) and confirmed content validity (CVR = .80 across all items) support its use in future curriculum evaluation and educational research studies.

For educational policymakers, the study provides evidence-based justification for the systematic integration of STEM project-based approaches into chemistry curricula at the secondary level. Given that the current State Educational Standard of Kazakhstan explicitly identifies research competency as a key learning outcome, the findings support policy initiatives that encourage and resource the transition from reproductive to inquiry-based instructional models in science education.

Concluding Statement

The present study provides theoretically grounded and empirically robust evidence that the implementation of STEM project-based instruction in high school

chemistry classes significantly enhances students' research competencies across all three assessed dimensions: Data Collection, Hypothesis Formulation, and Experimental Design. Across two independent group comparisons involving 73 students, the experimental intervention consistently produced large effect sizes (rank-biserial r ranging from .628 to .971), statistically significant post-test differences (all $p < .001$), and student-reported perceptions of meaningful skill development that align coherently with the quantitative outcomes. The convergent mixed-methods evidence situates these improvements within a theoretically coherent account of the pedagogical mechanisms through which STEM project-based learning develops scientific inquiry competencies: authentic contextualisation, productive cognitive challenge, iterative hypothesis-testing, collaborative scaffolding, and autonomous experimental agency.

In a broader educational context, the findings speak to the urgent need to move beyond reproductive models of chemistry instruction that restrict students' engagement with the authentic practices of scientific inquiry. The 21st-century skills of data literacy, hypothesis-driven thinking, and experimental design are not peripheral add-ons to chemistry education — they are its epistemological core. STEM project-based instruction, as demonstrated by this study, provides a practical, evidence-based pathway for realising this core in secondary chemistry classrooms. The lesson plans, assessment instruments, and methodological framework developed and validated in this research represent a concrete contribution to the pedagogical resources available to chemistry teachers committed to fostering genuine research competency in their students — equipping them not merely to pass examinations, but to think, design, and investigate as scientists.

SHORTCOMING AND LIMITATION

The study, while providing valuable insights into the implementation of STEM projects in high school chemistry education, has several limitations that should be acknowledged:

«Sample Size and Generalizability: One of the primary limitations of this study is the relatively small sample size. The experimental phase was conducted with a total of 73 students (N = 73: Control A = 20, Experimental A = 19, Control B = 19, Experimental B = 15) from a single private school setting, while the broader baseline survey involved a separate sample of 73 students from multiple schools across Kazakhstan. The limited experimental sample size restricts the ability to generalize the findings to a broader population of high school students, especially in public schools or schools from different socio-economic backgrounds.

Limited Scope of Subjects: This research focused solely on high school chemistry classes, which means the results are specific to this subject area. The findings may not necessarily apply to other STEM fields, such as physics or biology, where students may have different experiences with hands-on learning and research skills development.

Time Constraints: The duration of the STEM projects was limited, with a relatively short implementation period in the context of the school year. As a result, the study was unable to fully assess the long-term impact of STEM projects on students' research skills and attitudes toward scientific inquiry.

Curriculum Constraints and Resource Limitations: Another limitation faced by the study was the limited resources available for the STEM projects. In many cases, the projects were constrained by the availability of materials, lab space, and technology. The lack of adequate resources may have hindered the students' ability to fully engage with the projects and experiment in an optimal learning environment.

All validity of per-post assessment tools and interview questions scores indicated that data was not valid but reliable for only post assessment tool.

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APPENDICES

Appendix.1

LESSON 1

Effect of Temperature on Reaction Rate

School	KursAnt Bilim Group (Private School)	**Date**	_____
Grade / Class	Grade 10 · Experimental group	**Duration**	45 min
Teacher	Aibek Kailarbek	**Complexity**	Level 1 – Guided Inquiry
STEM Focus	Science (Chemistry) + Mathematics	**Participants**	___ / ___
Curriculum link	10.2.1.3 – Investigate factors affecting the rate of chemical reactions; apply mathematical relationships to experimental data		

STEM COMPONENT INTEGRATION	
S – Science	Students investigate how temperature changes the rate of the reaction between sodium thiosulfate ($Na_2S_2O_3$) and hydrochloric acid (HCl). They observe the disappearance of a cross drawn on paper through the cloudy precipitate.
T – Technology	Students use a digital stopwatch / phone timer for precision timing. Optional: free online graphing tool (Desmos or Google Sheets) to plot time vs. temperature.
M – Mathematics	Students plot Temperature (°C) on the x-axis vs. Reaction Time (seconds) on the y-axis. They calculate the rate as 1/t (inverse of time) and construct a data table. They identify a mathematical trend (inverse relationship) and describe it in words.

LEARNING OBJECTIVES	
All students	Understand that temperature affects reaction rate and can formulate a simple, testable hypothesis.

Most students	Plan a controlled experiment, collect time measurements at four temperature levels, and record data in a structured table.
Some students	Calculate reaction rate (1/t), plot a rate–temperature graph, and explain the result using collision theory.
Special needs	Identify that hot reactions happen faster than cold ones and record one measurement.

LESSON FLOW

Stage	Time	Teacher and Student Activities	Resources
Opening & Motivation (Engagement)	5 min	Teacher shows two videos: ice melting slowly vs. a fast exothermic reaction. Asks: "Why do some reactions happen faster than others?" Students share ideas (Think-Pair-Share). Teacher writes student predictions on board. Introduces the lesson question: "How does temperature affect reaction rate?"	Video clips, whiteboard
Task 1 – Hypothesis Formulation (STEM: Science)	7 min	Students receive a partially completed hypothesis template: "If temperature increases, then the reaction rate will _____ because _____. I will measure _____ and change _____. I will keep _____ the same." Pairs complete the template. Teacher reviews selected examples with the class. Concept check: independent variable, dependent variable, controlled variable.	Hypothesis worksheet
Task 2 – Guided Experiment (STEM: Science + Math)	18 min	Students work in groups of 3–4. Procedure (provided step-by-step on worksheet): ①Place 50 ml $Na_2S_2O_3$ solution in a beaker over the cross mark on paper. ②Add 5 ml HCl. Start stopwatch. ③Stop when the cross disappears. Record time (t). ④Repeat at four temperatures: 20 °C, 30 °C, 40 °C, 50 °C (use water baths). ⑤Record all data in the table. Teacher circulates, checks safety, asks probing questions: "Which variable are you changing? Is anything else changing?" Students calculate rate = 1/t for each trial and complete the data table.	$Na_2S_2O_3$, HCl, beakers, thermometers, stopwatch, water baths, worksheet
Task 3 – Data Analysis (STEM: Mathematics)	10 min	Students plot their Temperature (x-axis) vs. Rate 1/t (y-axis) graph on graph paper or in Desmos. Groups compare their graphs with another group. Questions: "What trend do you see? Does it match your hypothesis? Can you explain this using the idea of particle collisions?"	Graph paper or Desmos, data tables
Reflection & Closure	5 min	Exit ticket: students complete three sentence starters on a sticky note: ★ "My hypothesis was correct / incorrect because…" ★ "The most important thing I learned today	Sticky notes, pens

		is…" ☆ "One wish: I still want to understand…" Teacher collects sticky notes for formative assessment.	

HOW STEM WAS APPLIED IN THIS LESSON
SCIENCE: Students conducted a real chemical experiment ($Na_2S_2O_3$ + HCl) and directly observed the effect of temperature on reaction rate through systematic measurement. MATHEMATICS: Students did not simply record time — they transformed their data mathematically by calculating rate = 1/t (inverse function), which is a standard scientific convention linking chemistry and mathematics. They then constructed a graph showing a mathematical trend (positive linear relationship between temperature and rate), connecting algebraic reasoning to experimental chemistry. This integration ensured that students experienced science and mathematics as inseparable tools of inquiry, not as separate school subjects.

RESEARCH SKILLS DEVELOPED
HYPOTHESIS FORMULATION (Post B): Students practised constructing structured, testable hypotheses using a scaffold (if–then–because template). They identified independent, dependent, and controlled variables — the foundational skill for all subsequent lessons. DATA COLLECTION (Post A): Students followed a controlled procedure to collect time measurements at four temperature levels. They learned to use a stopwatch accurately, record measurements in a structured table, and calculate derived quantities (1/t). SCIENTIFIC REASONING: Through the graphing activity, students practised interpreting data trends and connecting their empirical findings to theory (collision theory).

WHAT WAS DONE IN THE LESSON – SUMMARY
Students: (1) watched motivational videos and generated prior knowledge; (2) formulated a structured hypothesis using a scaffold template; (3) conducted a guided controlled experiment measuring reaction time at four temperatures; (4) calculated reaction rate (1/t) and plotted a rate–temperature graph; (5) compared results between groups; (6) evaluated their hypothesis against evidence in a written reflection. Teacher: facilitated group work, circulated to check safety and procedural accuracy, asked probing questions to deepen understanding, and collected exit tickets for formative assessment. Key outcome: all students successfully formulated a hypothesis and collected a complete data set; most students correctly identified the trend in their graphs.

Appendix.2

LESSON 2

Effect of Concentration on Reaction Rate

School	KursAnt Bilim Group (Private School)	**Date**	_____
Grade / Class	Grade 10 · Experimental group	**Duration**	45 min
Teacher	Aibek Kailarbek	**Complexity**	Level 1 – Guided Inquiry
STEM Focus	Science (Chemistry) + Technology (Digital data tools)	**Participants**	___ / ___
Curriculum link	10.2.1.3 – Investigate factors affecting the rate of chemical reactions; use digital tools for data collection and visualisation		

STEM COMPONENT INTEGRATION	
S – Science	Students investigate how the concentration of hydrochloric acid (HCl) affects the rate of its reaction with marble chips ($CaCO_3$). They measure the volume of CO_2 gas produced over time using a gas syringe or measuring cylinder inverted in water.
T – Technology	Students use a digital stopwatch for measurements and enter their data directly into Google Sheets (or a prepared Excel-compatible template) on shared tablets/computers. They use the built-in chart function to construct a Volume vs. Time graph and read off the initial gradient to estimate rate.
M – Mathematics	Students calculate the gradient (slope) of the initial portion of the Volume–Time graph as an estimate of reaction rate. They compare gradients across three concentration levels. They evaluate whether the relationship between concentration and rate is linear or non-linear.

LEARNING OBJECTIVES

All students	Understand that concentration is a factor affecting reaction rate and record experimental measurements in a digital table.
Most students	Use digital tools to enter, organise, and graph data; calculate the gradient of a Volume–Time graph to estimate rate at each concentration.
Some students	Evaluate the relationship between concentration and rate quantitatively; discuss sources of experimental error and suggest improvements.
Special needs	Identify which concentration (high/low) produces more gas and record measurements with support.

LESSON FLOW

Stage	Time	Teacher and Student Activities	Resources
Opening & Connection to Lesson 1 (5 min)	5 min	Teacher displays a student graph from Lesson 1 (anonymised). Asks: "What other factors affect reaction rate besides temperature?" Students brainstorm (surface area, concentration, catalyst, light). Teacher focuses on concentration: "Today we test concentration." Brief demo: two test tubes with different HCl concentrations reacting with marble chips — students observe visually which is faster.	Two test tubes, HCl (low + high conc.), marble chips
Task 1 – Hypothesis Formulation (Less scaffolded than Lesson 1)	6 min	Students independently write a hypothesis in their lab journals. Teacher reminds them of the if–then–because structure. Students identify: independent variable (HCl concentration: 0.5M, 1.0M, 2.0M); dependent variable (volume of CO_2); controlled variables (temperature, mass of marble chips, volume of acid, particle size). Groups share hypotheses — teacher highlights variation: some predict linear, some non-linear.	Lab journals
Task 2 – Guided Experiment with Digital Data Entry (STEM: Science + Technology)	20 min	Procedure (step-by-step on worksheet): ①Measure 20 ml of HCl (0.5 M) into a conical flask. ②Add 2 g marble chips. Start stopwatch. ③Record volume of CO_2 every 30 seconds for 4 minutes in Google Sheets table. ④Repeat with 1.0 M and 2.0 M HCl. Key Technology step: students enter data directly into pre-prepared Google Sheets template on shared tablets. The template auto-generates a line graph in real time. Teacher pauses after first concentration: "Look at your graph — what shape is emerging? Does it match your hypothesis so far?"	HCl (3 concentrations), marble chips, gas syringes, flasks, stopwatch, tablets / Google Sheets
Task 3 – Gradient Calculation & Graph	9 min	Students use their Volume–Time graphs to estimate the initial gradient (slope of the steepest part) for each	Google Sheets, lab journals

Analysis (STEM: Mathematics + Technology)		concentration: Gradient = ΔVolume / ΔTime They record three gradient values in a summary table. Groups compare: "Which concentration produced the steepest initial gradient? What does that tell us about rate?" Students write one paragraph in their lab journals connecting their gradient data to collision theory.	
Reflection & Peer Review	5 min	Each group reviews another group's graph on Google Sheets. They write one comment: "Your graph shows ___. We agree / disagree because ___." Whole-class share: what similarities and differences were found between groups? Teacher asks: "What could cause different groups to get different gradients even with the same concentration?"	Shared Google Sheets, lab journals

HOW STEM WAS APPLIED IN THIS LESSON

SCIENCE: Students conducted a quantitative chemical experiment measuring CO_2 gas production over time at three concentration levels. This is standard experimental chemistry connected to the curriculum topic of reaction kinetics. TECHNOLOGY: The central STEM integration in this lesson was the use of Google Sheets as a live scientific data tool. Students did not merely record data on paper — they entered measurements in real time into a digital spreadsheet, watched the graph update automatically, and used the digital tool to calculate gradients. This mirrors the practice of professional chemists and data scientists who use computational tools for data analysis. Students also learned that technology transforms raw numbers into visual patterns, a key skill for scientific literacy. MATHEMATICS: The calculation of the gradient (slope) of a Volume–Time graph is an application of linear mathematics ($\Delta y/\Delta x$) in a scientific context, demonstrating that mathematics is a language of measurement, not an abstract exercise.

RESEARCH SKILLS DEVELOPED

DATA COLLECTION (Post A): This lesson advanced students' data collection skills significantly compared to Lesson 1. Students collected time-series data (multiple measurements over 4 minutes at 30-second intervals) — a more demanding collection task — and did so using a digital tool, requiring accuracy and organisation. HYPOTHESIS FORMULATION (Post B): Students wrote their hypothesis with less scaffolding than in Lesson 1 (no template provided), building independence. They also compared group hypotheses, developing awareness of how the same question can generate different predictions. EXPERIMENTAL DESIGN (Post C): Students identified and explicitly recorded all controlled variables — a foundational experimental design skill. The peer review activity built critical evaluation of experimental evidence.

WHAT WAS DONE IN THE LESSON – SUMMARY

Students: (1) connected new learning to Lesson 1 by brainstorming factors affecting reaction rate; (2) independently formulated a hypothesis identifying variables; (3) conducted a guided three-condition experiment (0.5 M, 1.0 M, 2.0 M HCl) collecting time-series volume data directly into Google Sheets; (4) used digital graphs to calculate initial rate gradients mathematically; (5) compared results between groups in a structured peer review. Teacher: demonstrated setup, circulated to support accurate measurement and data entry, paused the class at a midpoint for real-time graph reflection, and facilitated the peer review discussion. Key outcome: students produced three complete Volume–Time graphs and calculated gradient-based rate

estimates for each concentration. Most students correctly identified the positive relationship between concentration and rate and connected it to particle collision frequency.

Appendix.3

LESSON 3

Water Purification Method Design

School	KursAnt Bilim Group (Private School)	**Date**	_____
Grade / Class	Grade 10 · Experimental group	**Duration**	45 min
Teacher	Aibek Kailarbek	**Complexity**	Level 2 – Semi-Open Inquiry
STEM Focus	Engineering Design + Science (Chemistry) + Technology	**Participants**	___ / ___
Curriculum link	10.3.1.1 – Understand properties of water and solutions; 10.3.2.2 – Evaluate methods for water purification and treatment		

STEM COMPONENT INTEGRATION	
S – Science	Students apply their knowledge of chemical and physical properties of water (solubility, pH, turbidity, filtration) to design and evaluate a simple multi-stage water purification system using locally available materials.
T – Technology	Students use pH indicator paper / digital pH meters and turbidity comparison charts (printed or on tablet). They record observations photographically (tablet/phone) and present findings digitally.
E – Engineering	Core STEM integration: students use the engineering design cycle — Define problem → Research → Brainstorm → Prototype → Test → Evaluate → Improve. They design and physically construct a filter column from available materials and test its effectiveness against criteria they set themselves.
M – Mathematics	Students measure pH before and after purification, calculate % improvement in turbidity using a simple formula, and compare results quantitatively across design iterations.

LEARNING OBJECTIVES

All students	Understand the concept of water purification and identify at least two chemical or physical methods for removing contaminants from water.
Most students	Design and build a two-stage water filter using provided materials; test its effectiveness against defined criteria (clarity, pH); record and interpret results.
Some students	Evaluate the limitations of their design using evidence; propose one specific improvement based on data; connect design to real industrial water treatment processes.
Special needs	Assemble a basic filter with guided support and describe what each layer does.

LESSON FLOW

Stage	Time	Teacher and Student Activities	Resources
Opening – Real-World Context (7 min)	7 min	Teacher shows images / short video of contaminated water sources in Kazakhstan (or globally). Poses the engineering challenge: "Your team has been hired to design a low-cost water filter to make this water safe for a rural community. You have 20 minutes and the materials on your table." Class discusses: what makes water unsafe? (turbidity, harmful chemicals, pH extremes, bacteria). Teacher introduces the engineering design cycle on the board (6 steps). Students copy the cycle into their lab journals.	Images/video, whiteboard, lab journals
Task 1 – Define, Research & Hypothesise (8 min)	8 min	Groups (3–4 students) receive: a sample of "contaminated" water (coffee + sand + food dye mixture), a materials kit (gravel, sand, activated carbon, cotton wool, plastic bottle, pH strips). Each group: (a) tests the starting water — measures pH and estimates turbidity (1–5 scale using a printed comparison chart); (b) writes a design hypothesis: "We predict our filter will reduce turbidity from ___ to ___ and improve pH from ___ to ___ because ___."	Contaminated water, materials kit, pH strips, turbidity comparison chart
Task 2 – Design, Build & Test (Engineering Design Cycle) (18 min)	18 min	Groups design their filter column by deciding on layer order and thickness, sketch their design, and build it (cut bottle top, layer materials: gravel → sand → activated carbon → cotton wool, or their own arrangement). Test 1: pour 100 ml contaminated water through filter. Collect filtered water. Measure pH and turbidity. Compare to starting values. Engineering reflection: did it meet your criteria? What failed? Groups make ONE specific change to their design (e.g. add more activated carbon, change layer order). Test	Filter materials, beakers, pH strips, turbidity chart, tablets

		2: re-run with the modified design. Record results. Photo-document both designs on tablet.	
Task 3 – Data Analysis & Comparison (STEM: Math + Engineering)	7 min	Students complete a results table: | Stage | pH | Turbidity | % Change turbidity | Formula: % improvement = (start – filtered) / start × 100 Groups share results on board. Class discusses: which design was most effective? Why? Teacher asks: "Real water treatment plants use similar stages — can you identify them? What stage did your filter not include that a real plant would?" (e.g. chlorination, biological treatment)	Results worksheet, whiteboard
Reflection – Engineering Design Review (5 min)	5 min	"Two Stars, One Wish" for engineering: ★ What worked well in your filter design? ★ What change made the biggest improvement? ☆ What would you do differently if you had more materials/time? Teacher highlights connection to careers: environmental engineer, water treatment scientist.	Lab journals, sticky notes

HOW STEM WAS APPLIED IN THIS LESSON

ENGINEERING (Core integration): This lesson marks the first time students explicitly used the engineering design cycle — a structured problem-solving framework from engineering. Rather than following prescribed steps, students had to define their own criteria, design a solution, test it, evaluate it against evidence, and improve it. This iterative design-test-improve process is the defining feature of engineering thinking and was made explicit at every stage. SCIENCE: Students applied their chemistry knowledge — understanding of pH, adsorption, particle size, and physical separation — directly in a practical context. The filter design required them to select materials based on chemical and physical properties. TECHNOLOGY: Digital pH meters (where available), photographic documentation, and tablet-based turbidity comparison introduced students to technology as a measurement and communication tool in engineering practice. MATHEMATICS: The % improvement formula (Δvalue / start × 100) applied mathematics to evaluate engineering effectiveness — a direct application of proportional reasoning in a scientific and engineering context.

RESEARCH SKILLS DEVELOPED

EXPERIMENTAL DESIGN (Post C): This was the first lesson that directly and deeply targeted experimental design skills. Students had to — without full teacher direction — define their problem, set criteria, design a two-stage system, decide on layer order and materials, test it, and improve it. This is authentic experimental design, not procedure-following. HYPOTHESIS FORMULATION (Post B): Students formulated a quantitative prediction (specific pH and turbidity targets) rather than a simple directional prediction, representing a significant advancement from Lessons 1–2. DATA COLLECTION (Post A): Students collected before/after measurements across two test iterations, learning to evaluate the effect of a design change through comparative data — a more sophisticated data collection task than the structured experiments in Lessons 1–2.

WHAT WAS DONE IN THE LESSON – SUMMARY

Students: (1) engaged with a real-world water contamination problem as the engineering challenge; (2) measured baseline water quality (pH + turbidity); (3) designed and built a multi-stage filter using gravel, sand, activated carbon, and cotton wool; (4) ran Test 1, recorded results, identified what failed; (5) made one specific evidence-based design improvement; (6) ran Test 2 and compared results quantitatively; (7) calculated %

improvement in turbidity; (8) compared results across groups and connected findings to real water treatment processes. Teacher: introduced the engineering design cycle explicitly; circulated as a facilitator (not instructor); prompted groups with questions rather than giving answers; connected student designs to professional environmental engineering. Key outcome: students experienced iterative engineering design — the process of improving a solution based on evidence — for the first time. Most groups achieved measurable improvement in turbidity after the design revision.

Appendix.4

LESSON 4

Biodegradable Materials Investigation

School	KursAnt Bilim Group (Private School)	**Date**	_____
Grade / Class	Grade 10 · Experimental group	**Duration**	45 min
Teacher	Aibek Kailarbek	**Complexity**	Level 2 – Semi-Open Inquiry
STEM Focus	Science + Engineering + Mathematics (Full STEM — all dimensions)	**Participants**	___ / ___
Curriculum link	10.2.2.23 – Properties and environmental applications of polymers and plastics; 10.3.2.3 – Evaluate environmental impact of materials		

STEM COMPONENT INTEGRATION	
S – Science	Students investigate the physical and chemical properties of three materials — a conventional plastic bag (polyethylene), a starch-based biodegradable bag, and a paper sample — through a series of comparative tests: water resistance, tensile strength (force to tear), mass loss in moist soil simulation, and reaction with iodine solution (starch test).
T – Technology	Students use a digital balance to measure initial and final mass (after 24-hour soil simulation — results provided by teacher from a pre-set sample). They optionally photograph samples before and after tests. Data tables and bar charts constructed in Google Sheets.
E – Engineering	Students design their own comparative test protocol for one additional property of their choice (e.g. oil resistance, flexibility under load). They must define their procedure, identify variables, and justify their design choice — applying engineering design thinking to materials testing.
M – Mathematics	Students calculate % mass change over time, compare tensile strength measurements across three materials, and construct a comparative bar chart. They use a weighted scoring matrix to evaluate materials against four criteria and calculate an overall sustainability score for each material.

LEARNING OBJECTIVES	
All students	Identify differences between biodegradable and non-biodegradable materials and explain the significance for environmental sustainability.
Most students	Conduct comparative material tests; measure and record physical properties; calculate % mass change; construct a bar chart comparing materials across three dimensions.
Some students	Design and justify an additional material test; apply a weighted scoring matrix to recommend the most environmentally appropriate material; evaluate the limitations of laboratory-scale testing.
Special needs	Describe what biodegradable means and identify which material in the test is most eco-friendly.

LESSON FLOW

Stage	Time	Teacher and Student Activities	Resources
Opening – Environmental Problem (5 min)	5 min	Teacher displays images of plastic waste in Kazakhstani rivers and the Pacific garbage patch. Asks: "Could chemistry help solve this problem? What alternatives to plastic do we have?" Introduces the three materials: conventional plastic bag, starch-based biodegradable bag, paper sample. Students make a quick prediction ranking: which will be most environmentally sustainable and why?	Images, three material samples per group
Task 1 – Hypothesis & Test Protocol Design (STEM: Engineering) (8 min)	8 min	Teacher hands out the four standard tests with procedures (water resistance, tensile strength, soil simulation mass loss, iodine test). Groups discuss and write one additional test of their own: "We will additionally test _____ because it is relevant to real packaging use because _____. Our procedure: _____. Variables: _____." Teacher approves or redirects each group's additional test. Key: students must justify their choice scientifically.	Standard test worksheet, lab journals
Task 2 – Conducting Standard Tests (STEM: Science + Math)	20 min	Groups conduct four standard tests in parallel: ①Water resistance test: submerge 5×5 cm sample in water for 3 minutes. Rate integrity 1–5. ②Tensile strength: hang masses from a strip until it tears. Record breaking mass (g). ③Mass change: use teacher-prepared pre-weighed samples buried in moist sand for 24 h. Weigh now vs. start. Calculate % mass change. ④Iodine test: apply iodine solution. Record colour	Material samples, water containers, masses, digital balance, iodine

		change (starch test — purple = starch = biodegradable indicator). ⑤Groups conduct their own additional test. All data entered into Google Sheets table. Teacher circulates, asking: "Are you controlling for sample size? Why is that important?"	solution, Google Sheets, sand + pre-prepared samples
Task 3 – Scoring Matrix & Recommendation (STEM: Mathematics + Engineering)	7 min	Groups receive a weighted scoring matrix: | Criterion | Weight | Plastic | Bioplastic | Paper | | Biodegradability | 30% | | | | | Water resistance | 25% | | | | | Strength | 25% | | | | | Group test | 20% | | | | Students score each material 1–4 on each criterion, multiply by weight, and sum to get a total sustainability score. Bar chart (Google Sheets): comparing total scores. Groups write one paragraph: "Based on our evidence, we recommend _____ for sustainable packaging because _____." Class shares recommendations. Teacher highlights: "Different groups may have different recommendations — why? What does that tell us about the complexity of sustainability decisions?"	Scoring matrix worksheet, Google Sheets
Reflection – Full Lesson Review (5 min)	5 min	Individual reflection in lab journal: ★ "The most surprising result from our tests was _____" ★ "I used mathematics to _____" ☆ "One limitation of our tests that could affect our recommendation is _____" Teacher closes: "Today you did what a materials scientist does: test, measure, evaluate, and recommend. That is research."	Lab journals

HOW STEM WAS APPLIED IN THIS LESSON

SCIENCE: Students applied chemistry knowledge (polymer properties, starch chemistry, biodegradation, water resistance) through hands-on material testing. All four standard tests were grounded in real analytical chemistry methods used in materials science. ENGINEERING: Students designed their own fifth test — choosing a property relevant to real-world packaging use, designing a procedure, identifying variables, and justifying the design. This is materials engineering methodology, not recipe following. MATHEMATICS: The weighted scoring matrix introduced multi-criteria decision analysis — a genuine mathematical tool used by engineers and scientists to make complex decisions where multiple factors must be balanced. Students calculated weighted scores and compared them across materials, experiencing mathematics as a decision-support tool. Full STEM integration: this was the first lesson in which all four STEM components were explicitly and approximately equally integrated, preparing students for the fully open inquiry of Lessons 5 and 6.

RESEARCH SKILLS DEVELOPED

ALL THREE DIMENSIONS: DATA COLLECTION (Post A): Most demanding data collection task to date — students collected five types of data simultaneously (water resistance score, breaking mass, % mass change, iodine result, group-designed test) across three materials. They had to manage multiple parallel data streams accurately. HYPOTHESIS FORMULATION (Post B): Students extended hypothesis-writing into justifying a novel test protocol — a more sophisticated form of predictive scientific reasoning, connecting purpose to design. EXPERIMENTAL DESIGN (Post C): The student-designed additional test was the most independent experimental design task so far. Students had to identify a gap in the standard protocol, fill it with a justified

procedure, and defend their choice to the teacher. The scoring matrix introduced the idea that experimental findings must be synthesised, not just listed, to support a recommendation.

WHAT WAS DONE IN THE LESSON – SUMMARY
Students: (1) engaged with the plastic pollution problem and predicted sustainability rankings; (2) wrote a justified additional test protocol (their own design); (3) conducted four standard material tests — water resistance, tensile strength, % mass change, iodine starch test; (4) conducted their own additional test; (5) entered all data into Google Sheets; (6) completed a weighted scoring matrix; (7) constructed a comparative bar chart; (8) wrote a justified recommendation for sustainable packaging. Teacher: introduced the challenge with environmental context; approved/redirected group test designs; circulated as a facilitator throughout; led the closing discussion on why different groups can reach different recommendations from the same data. Key outcome: all groups produced a quantitative comparison of three materials across multiple dimensions and used a weighted scoring tool to generate an evidence-based recommendation. This was the most data-intensive and analytically demanding lesson in the sequence.

Appendix.5

LESSON 5

Eco-Friendly Product Development

School	KursAnt Bilim Group (Private School)	**Date**	_____
Grade / Class	Grade 11 · Experimental group	**Duration**	45 min
Teacher	Aibek Kailarbek	**Complexity**	Level 3 – Open Inquiry
STEM Focus	Full STEM Integration: Science + Technology + Engineering + Mathematics	**Participants**	___ / ___
Curriculum link	11.1.2.1 – Properties and applications of chemical compounds; 11.2.1.5 – Evaluate environmental impact of chemical processes; cross-curricular: design, technology, mathematics		

STEM COMPONENT INTEGRATION	
S – Science	Students develop an eco-friendly household cleaning product (surface cleaner or stain remover) using only safe, commonly available household chemicals (vinegar/acetic acid, baking soda/sodium bicarbonate, lemon juice/citric acid, essential oils). They apply their knowledge of acid-base chemistry, surfactant action, pH, and antimicrobial properties.
T – Technology	Students use pH meters and litmus paper to monitor product chemistry, optionally use a virtual simulation to model the acid-base reaction before mixing, and document their development process with digital photographs and a shared Google Slides presentation.
E – Engineering	Students apply the full engineering design cycle: identify a need → research chemical options → design formulation → prototype and test → evaluate against criteria → improve formulation → present. The product must meet self-defined criteria including safety, effectiveness, cost, and environmental impact.
M – Mathematics	Students calculate the molar concentrations of key active ingredients in their formulation, compare pH across formulation iterations, calculate cost per 100 ml product, and plot a multi-criteria evaluation radar chart.

LEARNING OBJECTIVES	
All students	Apply knowledge of acid-base chemistry and pH to explain the cleaning action of household chemicals. Develop and test a formulation that meets at least two defined criteria.
Most students	Use the engineering design cycle to develop, test, and iteratively improve a cleaning product formulation. Collect and interpret pH data across iterations. Present findings in a structured format.
Some students	Calculate molar concentration of active ingredients; construct and interpret a multi-criteria radar chart; evaluate the environmental advantages of the product over conventional alternatives using evidence.
Special needs	Identify which chemical (acid/base) is in the product and explain why it might be safer for the environment than commercial cleaners.

LESSON FLOW

Stage	Time	Teacher and Student Activities	Resources
Opening – Product Challenge (5 min)	5 min	Teacher shows the labels of two commercial cleaning products and reads the list of chemical ingredients. Asks: "Could we make something equally effective using safe, natural chemicals? Could a high school student design a real cleaning product?" Introduces the open challenge: "Your group will develop and test an eco-friendly cleaning product. You will present your product at the end of this lesson." Groups have complete freedom to choose the type of product and formulation — within the constraint that all ingredients must be from the safe materials list provided.	Commercial product labels, safe materials list
Task 1 – Problem Definition & Research (Engineering Design: Define + Research) (8 min)	8 min	Groups define: (a) product type and intended use; (b) target customer; (c) three criteria the product must meet (e.g. "pH between 4–7", "removes grease from glass", "costs less than 100 tenge per 100 ml", "contains no synthetic chemicals"). They research the chemistry of their chosen ingredients using a one-page reference sheet provided by the teacher (no internet — challenge to use prior knowledge). They write a formulation hypothesis: "We predict our formulation will work because the [acid/base] will [mechanism]."	Chemical reference sheet, lab journals

Task 2 – Prototype, Test & Iterate (STEM: Science + Engineering) (20 min)	20 min	Groups design and mix Formulation v1. Measure pH. Test on standardised dirty surface (teacher-prepared tile with grease + food dye). Rate effectiveness 1–5. Evaluate against criteria. Engineering reflection: which criterion did v1 not meet? What one change will improve it? Groups modify the formulation (Formulation v2). Re-test. Compare results. Documentation: groups photograph both formulations and the test surfaces. Record all measurements in a data table including: ingredient amounts (ml/g), calculated concentration of key ingredient, pH v1 and v2, effectiveness rating v1 and v2, estimated cost per 100 ml.	Household chemicals (vinegar, baking soda, lemon juice, essential oils), measuring cylinders, pH meters, test tiles, beakers, tablets for photos
Task 3 – Quantitative Evaluation (STEM: Mathematics)	7 min	Students complete a radar chart with five axes: pH suitability, cleaning effectiveness, environmental safety, cost, ease of preparation. Each product (v1 and v2) plotted on the same chart. Calculate overall improvement score: sum of (v2 – v1) across all criteria. Answer: "Did our changes improve the product overall? Was there any trade-off?"	Radar chart template, calculators
Presentation + Reflection (5 min)	5 min	Each group gives a 60-second "product pitch" (verbally or from 2 Google Slides): product name, key chemistry, pH, main criteria met, one improvement made. Class votes: which product would they most want to use at home and why? Teacher connects to real industry: "Chemists in consumer goods companies do exactly what you did today — formulate, test, improve, and present."	Google Slides (optional), lab journals

HOW STEM WAS APPLIED IN THIS LESSON

SCIENCE: Students applied acid-base chemistry, pH control, and understanding of cleaning mechanisms (surfactant action, acid dissolution of grease) directly in a product development context. This was applied chemistry at its most authentic — not a demonstration, but a real formulation process. TECHNOLOGY: Digital pH meters, photographic documentation, and the Google Slides presentation integrated technology both as a measurement tool (pH quantification) and as a professional communication tool (product presentation). The optional PhET simulation allowed students to model acid-base reactions before committing to a formulation — mirroring how engineers use computational models before physical prototyping. ENGINEERING: The full engineering design cycle was applied independently for the first time, without teacher-defined steps. Students defined their own problem, set their own criteria, and made all formulation decisions autonomously. The iterate-and-improve cycle (v1 → v2) is the essence of engineering methodology. MATHEMATICS: Molar concentration calculations, cost per unit calculations, and the radar chart (multi-criteria quantitative evaluation) all integrated mathematics as tools for product development decision-making.

RESEARCH SKILLS DEVELOPED

ALL THREE DIMENSIONS AT LEVEL 3 COMPLEXITY: HYPOTHESIS FORMULATION (Post B): Students formulated a product development hypothesis that was simultaneously a scientific prediction (mechanism-based) and an engineering claim (criteria-based). This is the most complex form of hypothesis in the sequence — it required synthesising chemistry knowledge with design thinking. DATA COLLECTION

(Post A): Students collected multi-variable data across two design iterations: concentrations, pH values, effectiveness ratings, and cost figures. They had to manage this data collection themselves, without a teacher-provided table structure. EXPERIMENTAL DESIGN (Post C): This was the most independent experimental design task in the sequence. Students defined their own criteria, designed their own formulation procedure, chose their own test methodology, and decided independently how to improve v1 to produce v2. Teacher acted only as a facilitator.

WHAT WAS DONE IN THE LESSON – SUMMARY
Students: (1) accepted an open product development challenge with no fixed procedure; (2) defined product type, target user, and three measurable criteria; (3) formulated a hypothesis about the chemistry of their product; (4) mixed Formulation v1 and tested it against all criteria; (5) identified one specific failure and modified the formulation independently; (6) tested Formulation v2 and compared quantitatively; (7) completed a radar chart and calculated an improvement score; (8) presented their product in a 60-second pitch. Teacher: issued the challenge and materials; acted only as facilitator (safety monitor, question-asker); did not prescribe any procedure or ingredient choices; connected student work to professional chemistry careers. Key outcome: this lesson represented the transition to fully independent inquiry. Students experienced the full scientific and engineering process — from problem definition to product presentation — autonomously for the first time. Most groups successfully improved their product between v1 and v2.

Appendix.6

LESSON 6

Independent Research Project

School	KursAnt Bilim Group (Private School)	**Date**	_____
Grade / Class	Grade 11 · Experimental group	**Duration**	45 min + extended preparation time (1 week)
Teacher	Aibek Kailarbek	**Complexity**	Level 3 – Independent, Student-Led Inquiry
STEM Focus	Full STEM Integration: Student-directed, all four components	**Participants**	___ / ___
Curriculum link	Student-selected curriculum connections (11th grade chemistry topics); cross-curricular: research methodology, communication, mathematics		

STEM COMPONENT INTEGRATION	
S – Science	Students independently investigate a self-chosen chemistry question connected to a real-world problem. The investigation must include a testable hypothesis, a designed experimental procedure, quantitative data collection, statistical or graphical analysis, and a conclusion evaluated against the hypothesis.
T – Technology	Students choose their own digital tools: Google Sheets for data management and graphing; Desmos for mathematical modelling; PowerPoint/Google Slides for presentation; optional: virtual laboratory simulations (PhET, Labster) for the exploratory phase.
E – Engineering	The experimental design — including choice of variables, procedure, sample size, and iteration strategy — is entirely student-determined. Teacher acts only as a reviewer of the design (approval stage) and a facilitator during implementation.
M – Mathematics	Each project must include at least one quantitative analysis element: a graph with trend line, calculation of rate/percentage/concentration, or statistical comparison (mean, range, standard deviation if appropriate).

LEARNING OBJECTIVES	
All students	Independently conduct all phases of a scientific investigation: question, hypothesis, design, data collection, analysis, conclusion, and presentation.
Most students	Design a complete and controlled experimental procedure; collect and analyse quantitative data; evaluate the hypothesis against evidence; present findings in a structured scientific format (report + oral presentation).
Some students	Apply advanced analytical tools (trend line analysis, error discussion, comparison to published data); evaluate the quality and limitations of their own investigation; suggest specific, evidence-based future research directions.
Special needs	With support, conduct a simplified version of the investigation and present at least one key finding.

LESSON FLOW

Note: Lesson 6 spans two phases. Phase 1 (in-class, 45 min): research proposal approval, experimental work, and oral presentations. Phase 2 (at home, 1 week prior): preparation of research question, hypothesis, and preliminary plan.

Stage	Time	Teacher and Student Activities	Resources
PHASE 2 (Homework, 1 week before) Independent Preparation	1 week	Each student (or pair) independently: (1) selects a research question connected to chemistry and a real-world problem (topic list and forbidden topics provided); (2) formulates a structured hypothesis with predicted outcome and mechanism; (3) writes a one-page research plan: materials needed, procedure outline, variables identified, data collection plan, analysis method. Teacher reviews submitted plans before the lesson and provides written feedback on: hypothesis clarity, experimental control, feasibility, data collection method. Students revise based on feedback if needed. Example approved topics from this cohort: "How does salt concentration affect the conductivity of water?"; "Which household acid most effectively removes limescale?"; "How does surface area of zinc affect the rate of its reaction with HCl?"; "How does the age of an apple affect its antioxidant content (iodine clock method)?"	Topic list, hypothesis template, research plan template, teacher feedback

PHASE 1 – Lesson Day Final Experiments (20 min)	20 min	Students arrive with their approved plan and any pre-prepared materials. During the lesson they: conduct the final experimental runs (or the primary data collection phase); record all data in their structured table; calculate any derived quantities (rates, concentrations, %); construct their final graph. Teacher circulates as facilitator only — asking questions, not giving answers: "Why did you choose that control? What does that outlier data point tell you? How will you represent that in your graph?" Safety checks conducted by teacher for all experimental setups.	Student-supplied materials + school equipment; Google Sheets; lab journals
PHASE 1 – Oral Presentations (20 min)	20 min	Each student/pair delivers a 3-minute structured presentation: 1 Research question and hypothesis (30 sec) 2 Method summary — key decisions and why (45 sec) 3 Results — key graph and finding (60 sec) 4 Conclusion — hypothesis confirmed/rejected, with evidence (30 sec) 5 One limitation and one future research suggestion (15 sec) After each presentation: 1 peer question, 1 teacher question. Presenter must respond with reference to their data. Peer assessment: each student completes a short peer review form for two other presentations (clarity, evidence, one question, one strength).	Google Slides (optional), printed graph, peer review forms
Whole-Class Scientific Symposium & Reflection (5 min)	5 min	Teacher facilitates a 3-minute class discussion: "What was the most surprising finding across all our projects? Which investigation had the strongest evidence? Which had the most interesting limitation?" Final individual reflection: students complete the research competency self-assessment rubric (same instrument used as pre/post-test) — reflecting on how far they have come since Lesson 1. Teacher closing: "Six lessons ago, most of you had never designed your own experiment. Today you have all completed an independent scientific investigation. That is what research competency means — and you have it."	Self-assessment rubric (post-test instrument)

HOW STEM WAS APPLIED IN THIS LESSON
Full STEM Integration — student-directed: SCIENCE: The entire investigation was grounded in chemistry — students chose chemistry questions, applied chemical knowledge in their experimental design, and interpreted their results using chemistry theory. TECHNOLOGY: Students independently chose and applied digital tools appropriate to their investigation — no tools were prescribed. This independent technology selection reflects real scientific practice. ENGINEERING: The entire investigation was structured according to the engineering design cycle — question → hypothesis → design → test → evaluate — without any prescribed steps. Students experienced this as their own methodology, not a teacher-imposed framework. MATHEMATICS: Each project required at least one quantitative analysis tool — graph, trend line, concentration calculation, rate comparison, or statistical measure. Students chose the appropriate mathematical tool for their data, integrating mathematics as a research instrument. What made Lesson 6 the culmination of the STEM sequence: by this lesson, students were no longer experiencing STEM integration as a teacher-designed feature — it was simply how they approached a research problem. The integration had become internalised.

RESEARCH SKILLS DEVELOPED
ALL THREE DIMENSIONS AT MAXIMUM INDEPENDENT LEVEL: HYPOTHESIS FORMULATION (Post B — Score 4): Students independently formulated testable, evidence-grounded hypotheses with explicit mechanisms, without templates or scaffolds. This represents the highest competency level: independent, specific, and theoretically justified hypothesis construction. DATA COLLECTION (Post A — Score 4): Students independently designed their own data collection systems — choosing what to measure, how often, and how to record it — and executed them across multiple experimental trials. This is fully autonomous, systematic data collection. EXPERIMENTAL DESIGN (Post C — Score 4): Students designed complete, controlled experimental procedures; justified their design choices; managed their own iterative process; and evaluated their designs honestly in the limitations section. This is the highest level of experimental design competency assessed in the study.

WHAT WAS DONE IN THE LESSON – SUMMARY
PHASE 2 (preparatory week): Students independently selected a research question, formulated a hypothesis, and wrote a complete one-page research plan. Teacher reviewed and provided written feedback. Students revised plans accordingly. PHASE 1 (lesson day): Students: (1) conducted final experimental runs from their approved plans; (2) collected complete quantitative data sets; (3) constructed final graphs and calculated derived quantities; (4) delivered 3-minute oral presentations with visual support; (5) responded to peer and teacher questions with reference to their data; (6) completed peer review forms for two classmates; (7) completed the self-assessment research competency rubric. Teacher: reviewed and provided feedback on all plans before the lesson; acted exclusively as facilitator and safety monitor during experiments; managed the oral presentation schedule; facilitated the closing symposium discussion. Key outcome: the completion of Lesson 6 marked the successful conclusion of the six-lesson STEM sequence. Every student conducted an independent scientific investigation from hypothesis to conclusion — a task that was beyond the competence of the majority at the beginning of the sequence. The oral presentation and peer review components additionally developed communication, critical evaluation, and self-assessment skills not directly measured by the post-test instrument but central to full research competency.

Appendix.7

Interview questions for students

1) What research skills (eg, hypothesis generation, data collection, analysis of results- experimental design) have you improved while working on STEM projects?
2) How has working in a team affected your ability to conduct research and make decisions?

Appendix.8

Pre/Post-test (Structure of atoms)

Instruction: to choose one correct answer from the four answer choices you are given assignments are given.

Skill Assessed: Data Collection

Question 1: How do you collect information on a given topic? From which sources do you prefer to obtain information?

Options:

I find it difficult to collect information and get it from only one source.

I get information from one or two sources, but they are not reliable.

I collect information from several reliable sources, but it is not always effective.

I gather information from various sources (books, articles, the internet, experts) and compare them.

Skill Assessed: Hypothesis Formulation

Question 2: How do you formulate a hypothesis for a research topic?

Options:

Formulating a hypothesis is difficult for me; I can only state it as a question.

-I can create a main hypothesis related to the topic, but I do not rely on concrete evidence.

-I formulate a hypothesis based on the topic and support it with several logical explanations.

-I formulate multiple hypotheses based on the actual problem and provide evidence for each possibility.

Skill Assessed: Experiment Planning and Execution

Question 3: How do you plan and carry out a research experiment? What methods do you use?

Options:

Conducting an experiment is difficult for me; I can only perform it based on guesses.

I can perform simple experiments, but it is difficult to observe and interpret the results.

I plan experiments, record results, and try to evaluate their significance.

I carefully plan experiments, analyze the results comprehensively, and try to generate new question