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**Identifying pedagogical content knowledge of chemistry teachers in
integrated STEM technology**

7M01504 – Chemistry

MASTER'S DEGREE DISSERTATION

Kaskelen, 2025

Faculty of Education and Humanities
Department of Pedagogy of Natural Sciences

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LIST OF ABBREVIATIONS

STEM - Science, Technology, Engineering, and Mathematics

PBL - Project-Based Learning

n.s - Not Significant

ANOVA - Analysis of Variance

M - Mean (Average Value)

Df - Degrees of Freedom

t-value - Statistical value that shows the difference between groups

p - Probability value that shows statistical significance ($p < .05$ = significant)

r - Pearson Correlation Coefficient

Jamovi - Open-source statistical software used for quantitative data analysis

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ABSTRACT

In the context of integrating STEM technologies into science education, the role of chemistry teachers becomes increasingly significant in shaping interdisciplinary thinking and applied problem-solving skills. This study aims to explore how chemistry teachers develop and apply Pedagogical Content Knowledge (PCK) within STEM-integrated teaching environments. The research used a mixed-methods approach to investigate current practices, challenges, and pedagogical strategies among chemistry teachers in Kazakhstan.

The quantitative phase involved 114 chemistry teachers, who completed a structured survey assessing their familiarity with STEM approaches, frequency of use, and professional development needs. In the qualitative phase, two rounds of semi-structured interviews were completed with 28 teachers, with a focus on how teachers utilize STEM principles to develop problem-based tasks, conduct experimental experiments, and undertake interdisciplinary projects in their chemistry teaching. The study showed that the teachers were using STEM practices through real-world problems, innovative laboratory tasks, and collaborative projects. The teachers appeared to be creative in adapting their existing chemistry content to their students' levels, and were concerned with the possible pedagogical value of project-based learning. The study also identified barriers, such as lacking physical and human resources, limited institutional support, and insufficient professional development training in STEM-PCK.

This study illustrates the necessity for ongoing professional development and systemic support for chemistry teachers that enhances the effectiveness of integrating STEM-related pedagogies in their teaching practices. The findings also highlight the need for teachers to have practices and knowledge that support interdisciplinary, technology-enabled science learning.

Keywords: *chemistry education, STEM integration, pedagogical content knowledge (PCK), interdisciplinary learning, teacher development, project-based learning, experimental tasks.*

АННОТАЦИЯ

В условиях активного внедрения STEM-технологий в школьное образование возрастает значимость учителей химии в формировании у учащихся междисциплинарного мышления и навыков прикладного решения проблем. Цель данного исследования — выявить, как учителя химии развивают и применяют педагогические знания содержания (РСК) в контексте STEM-обучения. Исследование основано на смешанном методе, включающем количественный и качественный анализ педагогических практик, трудностей и стратегий преподавания.

На первом этапе анкетирование охватило 114 учителей химии, оценивалось их знакомство с принципами STEM, частота применения и потребности в профессиональном развитии. На втором этапе были проведены два раунда полуструктурированных интервью с 28 преподавателями. Анализ показал, как педагоги применяют STEM в организации проблемных заданий, экспериментальных работ и межпредметных проектов на уроках химии.

Результаты показывают, что учителя активно используют реальные жизненные задачи, лабораторные эксперименты и проектные подходы. Преподаватели проявляют креативность в адаптации содержания к уровню учеников и подчеркивают эффективность проектного обучения. В то же время отмечаются трудности, связанные с нехваткой ресурсов, ограниченной поддержкой со стороны администрации и отсутствием специализированной подготовки по STEM-РСК.

Исследование подчеркивает необходимость постоянной профессиональной поддержки и методической подготовки учителей для эффективной интеграции STEM в преподавание химии. Полученные данные подтверждают важность развития потенциала педагогов в организации междисциплинарного, технологически обоснованного обучения.

Ключевые слова: преподавание химии, интеграция STEM, педагогические знания содержания (РСК), межпредметное обучение, профессиональное развитие учителя, проектное обучение, экспериментальные задания.

АНДАТПА

STEM технологияларын жаратылыстану пәндеріне интеграциялау жағдайында химия пәні мұғалімдерінің рөлі оқушылардың пәнаралық ойлау қабілетін және қолданбалы мәселені шешу дағдыларын қалыптастыруда ерекше маңызды бола түсуде. Осы зерттеу STEM біріктірілген оқыту ортасында химия мұғалімдерінің педагогикалық контенттік білімін (РСК) қалай дамытып, қолданатынын анықтауға бағытталған. Зерттеу аралас әдіснаманы қолдана отырып, мұғалімдердің тәжірибесі, кездесетін қиындықтары және педагогикалық тәсілдері бойынша кешенді талдау жүргізілді.

Сауалнамаға Қазақстанның әр өңірінен 114 химия пәні мұғалімі қатысып, олардың STEM тәсілдерімен таныстығы, қолдану жиілігі және кәсіби даму қажеттіліктері зерттелді. Сонымен қатар, 28 мұғаліммен екі кезеңнен тұратын жартылай құрылымдалған сұхбаттар жүргізілді. Талдау барысында мұғалімдердің STEM қағидаларын проблемалық тапсырмалар, зертханалық жұмыстар және пәнаралық жобалар арқылы қалай жүзеге асыратыны қарастырылды.

Нәтижелер көрсеткендей, мұғалімдер химияны өмірмен байланыстыра отырып, STEM негізіндегі тапсырмалар мен жобаларды белсенді қолданады. Олар әртүрлі деңгейдегі оқушылар үшін мазмұнды бейімдеудің креативті жолдарын таба отырып, жобалық оқытудың тиімділігін атап өтті. Дегенмен, ресурстың жетіспеушілігі, институционалдық қолдаудың болмауы және STEM-РСК бойынша арнайы дайындықтың жеткіліксіздігі сияқты қиындықтар да анықталды.

Зерттеу STEM тәсілдерін тиімді енгізу үшін мұғалімдерге тұрақты кәсіби қолдау мен жүйелі дайындық қажет екенін көрсетеді. Нәтижелер химияны пәнаралық, технологияға бейімделген бағытта оқытуда мұғалімдердің мүмкіндігін арттыру маңызды екенін дәлелдейді.

Түйінді сөздер: *химияны оқыту, STEM интеграциясы, педагогикалық контенттік білім (РСК), пәнаралық оқыту, мұғалімнің кәсіби дамуы, жобалық оқыту, эксперименттік тапсырмалар.*

INTRODUCTION

As a newly listed educational priority during the past several decades, science education experienced a significant shift in the paradigm where interdisciplinary approaches to learning have become increasingly adopted. Most notably with the world now focused on STEM (Science, Technology, Engineering, and Mathematics) education aimed at stimulating innovation, learning creativity, and real-world problem solving. STEM education is multi-dimensional, and much of the focus emphasizes the removal of traditional subject area walls where students can engage deepest with real authentic applications that combine knowledge in science, technology, engineering, and mathematics. Of all the concepts in STEM education, chemistry is positioned at the base, both as fundamental scientific knowledge, as practical application associated with technological innovation and engineering design.

That said, realizing integrated STEM education in a chemistry classroom depends not just on reforming the curriculum using new tools, but—most importantly—on the pedagogical capacity of teachers. Specifically, Pedagogical Content Knowledge (PCK)—a term coined by Shulman (1986)—is essential for teachers to teach complex content in ways which make the content usable and relevant to their students. As a reminder, PCK is the intersection of subject matter knowledge and pedagogy. PCK gives teachers the ability to modify the abstract to fit the learner through the appropriate representations and strategies.

As interdisciplinary and applied learning becomes more prominent as educational priorities, there will be increased importance placed on interrogating how chemistry teachers grow and perform their PCK in a STEM context. Specifically, investigating how teachers plan and enact interdisciplinary lessons, discern how teachers differentiate learning for all students in the diverse populations of learners in schools, and how teachers make meaningful links between chemistry learning and real-world applications related to technology and engineering.

While there are many national (and international) initiatives to encourage and support STEM, research continues to indicate that many teachers experience challenges in implementing that are disruptive to their PCK. These challenges may be rooted in a lack of confidence, training, and generally a lack of understanding of STEM as an interdisciplinary learning approach to practicing disciplines/subjects together. Therefore, understanding the current state of chemistry teachers' PCK in STEM areas is essential for targeting professional development, changing practice, or improving student learning in associated approaches to STEM education.

Research Problem. Although integrated STEM education is touted as a global education priority, the reality is sustained PCK in integrated STEM approaches to practice in chemistry classrooms are still difficult to engage meaningfully. Teachers are now expected to design integrated learning experiences that involve interdisciplinary instructional practice, digital technologies, and project-

or problem-based learning—all while maintaining the rigour and relevance of chemistry as a discipline.

However, many chemistry teachers report feeling underprepared to meet these expectations due to a lack of targeted pedagogical strategies, insufficient training, and limited institutional support for STEM integration.

While the benefits of STEM education have been widely discussed in the literature, much of the existing research remains generalized or theoretical in nature. Empirical studies that examine how chemistry teachers specifically apply Pedagogical Content Knowledge (PCK) in STEM contexts are scarce. The majority of available work focuses either on high-level curriculum design or on teachers' general perceptions of STEM, with relatively little attention given to the day-to-day instructional decisions, teaching practices, and representational choices that reflect actual PCK in use.

This creates a significant gap in the literature. We still lack a clear and context-sensitive understanding of what PCK looks like when applied in interdisciplinary STEM teaching, particularly in chemistry. Furthermore, little is known about how chemistry teachers' backgrounds—including their teaching experience, professional training, and school environments—affect their ability to plan and deliver STEM-integrated instruction. The complexity of chemistry as a subject, coupled with the need for interdisciplinary coherence, makes this inquiry especially urgent.

Without a nuanced understanding of how chemistry teachers are negotiating the intersection of PCK and STEM there is a danger that all of the initiatives seeking to promote integration will be shallow, short-lived, or disconnected from the realities of classrooms. Therefore, there is an urgent need to investigate the state of chemistry teachers' PCK in STEM-based teaching and to not only address a lack of empirical research but also to endeavor to fundamentally improve relevance of particular training programs, curricular resources, and policy that nurture substantive and enduring STEM integration into science education.

Research Objectives and Questions. The general aim of this study is to investigate how chemistry teachers perceive and enact pedagogical content knowledge (PCK) in integrated STEM instruction, as well as the different contextual factors that may affect this process. The study will also examine ways to support teachers in STEM-based learning, the obstacles they face as teachers, and the contexts related to professional and institutional variables related to STEM-integrated pedagogy and how they impact teacher practice.

Specifically, the study will:

- Evaluate how a chemistry teachers' education, experience, the type of school he/she works at, and the category of teacher qualification impacts their understanding and implementation of STEM-integrated pedagogy;

- Evaluate the teaching strategies and methods that chemistry teachers utilize to support STEM-based learning through PCK and how these vary or are adapted in reference to the realities of the classroom situations;

- Identify the challenges and contextual constraints that hinder the effective implementation of PCK within STEM-integrated chemistry education across different educational settings.

Based on these objectives, the study is guided by the following research questions:

1. How do teachers characteristics such as education level, teaching experience, school type, and teacher category influence chemistry teachers' understanding and use of STEM integration in their instructional practice?

2. What teaching strategies and methods do chemistry teachers use to support STEM-based learning through pedagogical content knowledge (PCK), and how do they adapt these strategies to meet the needs of their students?

3. What challenges and contextual factors affect chemistry teachers' ability to implement PCK within integrated STEM education across different school environments?

Significance of the Study. This study holds both theoretical and practical significance for the advancement of chemistry education and the broader development of integrated STEM pedagogy. As education systems around the world increasingly prioritize interdisciplinary and application-oriented learning, teachers are expected to design and implement instruction that connects science, technology, engineering, and mathematics in coherent and meaningful ways. Within this shift, chemistry holds unique potential due to its central role in scientific inquiry and its natural alignment with technological and engineering concepts. However, integrating STEM meaningfully into chemistry instruction remains a complex challenge, especially when teachers lack the pedagogical tools, professional training, or systemic support needed to do so effectively.

By focusing on how chemistry teachers conceptualize and apply pedagogical content knowledge (PCK) in STEM-integrated contexts, this study contributes to a deeper and more practice-oriented understanding of what effective STEM teaching entails in real classrooms. While existing literature often addresses STEM education in general or from a policy perspective, there is limited empirical research that examines how STEM is implemented within specific subjects, such as chemistry, and how teachers' pedagogical decisions are influenced by their professional context. This study addresses that gap by offering insights into teachers' actual classroom strategies, the challenges they face, and the contextual factors that shape their instructional choices.

The findings of this study have the potential to inform the design of more targeted and relevant professional development programs for chemistry teachers. By identifying which factors—such as teaching experience, education level, or school

type—facilitate or hinder effective STEM integration, the research offers actionable guidance for teacher educators, school administrators, and policymakers. It also provides a foundation for aligning teacher preparation programs and in-service training with the practical demands of STEM instruction.

In addition, the study contributes to the theoretical development of STEM related PCK by demonstrating how it is demonstrated in some content-specific situation. The framework created here may also provide a model for examining STEM integration in other scientific disciplines. In the end, this study advances the effort to reform science education by demonstrating how chemistry teachers make instructional change decisions based on a wide range of variables and demands by emphasizing contextually relevant, practice-based, and pedagogy-based decision-making.

Contribution of the Study. The contributions of this study to the science education field are multi-faceted. Theoretically, it expands on current understandings of the use of Pedagogical Content Knowledge (PCK) within integrated STEM chemistry instruction. Practically, it presents authentic or first-hand examples of pedagogy, projects, and dilemmas, that can help inform practices in teacher training and curricular design. Methodologically, the research illustrates the effectiveness of using a mixed-methods approach by integrating survey data, interview data, and classroom observations. Contextually, it highlights what the subject area of chemistry each of these teachers need as well as what they each know well in terms of the changing landscape of STEM education in Kazakhstan. Collectively, these contributions underpin future STEM instruction and professional development of the participants.

1. LITERATURE REVIEW

1.1 Theoretical Foundations of Pedagogical Content in STEM

The idea of Pedagogical Content Knowledge (PCK) has become a focus of attention in conversations about effective teaching—especially in subjects such as chemistry where concepts that can appear abstract are interpreted and contextualized through teachers’ pedagogical expertise. Shulman (1986) introduced PCK to our community to refer to teachers’ abilities to master subject technical content - and also to transform it pedagogically relevant, accessible for learning, built around students’ needs, and educationally useful.

In influential articles, Shulman (1987) explained that teaching knowledge is multidimensional - not only do we need to build and know our subject content knowledge, but we need to build an understanding of curricular knowledge, pedagogical knowledge, stylistic knowledge, and contextual knowledge. PCK is particularly important because it is the lens that joins knowing about a subject and knowing how to teach it effectively. He critiqued the traditional bifurcation of content and pedagogy in preparing teachers and argued for taking problem-based approaches to transforming subject matter, particularly in regard to representations and analogies in making pedagogical formative decisions based on learners have misconceptions or challenges.

PCK is not stable, but dynamic and evolving through practice. As Shulman argued, effective teaching is a cycle of reasoning and reasoning with variations being determined based on the teacher’s experience and reflections, and their interactions with students and colleagues. This dynamic understanding of knowledge is part of a shift in understanding teacher expertise.

Current studies are moving the discussion around prior research work building on Shulman's work; for example, Kind (2009) and Park & Chen (2012) suggest PCK should not be presented as fixed set of domains, but as a system that relates coherently and dynamically. In Park and Chen's model, there are complex interactions that occur among the components of teaching (e.g., content knowledge; when engaging in different pedagogical strategies; considering assessment; knowledge of student thinking, etc.), most notably in complex situations such as integrated STEM classrooms. Kind, on the other hand, emphasizes the agency of teachers in shaping their pedagogical content knowledge (PCK) from their personal experiences and the challenges associated with their teaching situation, especially in examples like science where more abstract reasoning and using multiple representations further complicate learning.

Many researchers refer to the context and belief aspects of PCK. For example, Friedrichsen et al. (2009) concluded that a teacher's orientation towards science teaching (i.e., their values, goals, and assumptions) has a strong influence on their PCK enactment. Hume and Berry (2011) also described tools such as the CoRe (Content Representation) intended to help teachers articulate their thinking about

teaching particular topics through a structured reflection process not only allows teachers to consider what they teach, but how they do it and why.

As the STEM education movement matures, PCK becomes even more complex. Integrated STEM practice requires chemistry educators to deliberately venture outside of their disciplinary approach to teaching the subject matter while also incorporating engineering design, technology tools, and modeling mathematics. This approach brings with it important questions: how do teachers compose their PCK for interdisciplinary instruction? What professional learning opportunities allow teachers to do this?

To add to this complexity, as noted by Loughran, Mulhall, and Berry (2004), PCK in the context of STEM is not something that teachers develop once and for all; it is always being constructed and reconstructed from their cumulative classroom experience, reflection, and collaboration with others. As teachers' roles have undergone significant change, from content experts to interdisciplinary facilitators, so too must our understanding of the knowledge teachers need, the obstacles that teachers encounter, and the professional contexts in which that knowledge is realized.

There is also growing literature about the effect of digitalization on PCK in STEM fields. Virtual laboratories, interactive simulations, and modeling tools increasingly affect the way educators plan and implement learning experiences. In this case, digital literacy represents another layer of teacher knowledge, and requires chemistry teachers to integrate conceptual understanding, digital fluency, and pedagogical awareness.

In conclusion, recognizing and nurturing chemistry teachers' PCK in a STEM environment of practice is not only an academic endeavor; it is a significant organizational and social opportunity for impactful innovation, critical thinking, and deeper learning in the science classroom. Understanding PCK holistically can help teachers connect chemical concepts to societal and technological problems.

Multiple authors have argued that PCK needs to be understood through multiple lenses encompassing the psychological, epistemological, and didactical domains. Park & Chen (2012) is one notable example. They utilized three level model of scientific commitment and presented a humanistic theoretical perspective that encompasses the foundations of integrated STEM education. This framework encourages the reading of STEM education as not simply the combination of disciplines, but as an instructional approach to tackling the complexity of real-world problems which are beyond any single subject or method. Their model states that we need to move away from linear models of and compartmentalized ways of thinking toward interdisciplinary thinking that accounts for learners' values, context, and ongoing cognitive development.

The framework is organized into three interrelated dimensions:

Epistemological: Stressing STEM education as a process of problem solving and knowledge construction. Teachers are encouraged to engage students in inquiry that reflects the authentic practices of science and engineering ;

Psychological: Highlighting learners engaging with multiple contexts that make knowledge tangible for learning through cognitive experience that enriches understanding;

Didactical: Revealing the ‘objective-obstacle’ approach placing obstacles and misconceptions as intrinsic to the learning process rather than a point of failure. This perspective provides opportunities for educators to construct instruction that considers and utilizes the obstacles students face as part of their pedagogical work.

Shulman's framework also provided relevant questions about practical considerations for STEM education to teach through inquiry, such as: (1) Who is developing students’ STEM competencies? (2) How are students making links between their scientific and technological knowledge? (3) What obstacles are getting in the way of the learning experience? and (4) How would the teaching and learning patterns be adjusted based on the identified obstacles? While these focused questions not only shape relevant curriculum decisions, they also shape instructional decisions.

At the same time, other theorists provided the intellectual foundations and ideas that are still shaping integrated STEM on many levels, but now may become more relevant in an integrated pedagogy. Located in these levels are thinkers such as Park & Chen (2012) who set the stage for what is now known as experiential learning in education, and how-child manipulatives can be used and how different sciences can be taught with representatives in science and mathematics education. Each of their theories strengthens the argument that STEM learning needs to be active, organic, investigatory, and having connections to the world where students live.

Today these ideas have translated into pedagogical strategies for using different cross subject boundaries to encourage students to represent concepts in different formats (visual, symbolically, physically), and then begin connecting them. Each of those perspectives has similar strong underpinning and helps today teachers enact interdisciplinary teaching more cognitively and pedagogically effective.

As integrated STEM education continues to be established and developed the ideas promoted in frameworks for interdisciplinary involvement in teaching and learning have provided opportunities for educators and researchers to understand how interdisciplinary teaching can be structured, justified, and enhanced - not just technically or policy, but developmentally, and humanistically reflective.

1.2 Examples of STEM Integration in Chemistry Teaching

There is a growing consensus that integrating STEM (Science, Technology, Engineering, and Mathematics) into chemistry education can support the development of students' problem solving, critical thinking, creativity, and involvement in the learning process. There has been a plethora of research which suggests that students' motivation to learn and conceptual understanding in chemistry improved substantially when the content was set in interdisciplinary or real-world contexts (English, 2016).

An outstanding teaching strategy within the context of STEM-based chemistry education is Project Based Learning (PBL). PBL entails students undertaking authentic, inquiry-based projects which allow them to apply foundational chemical principles to problems they encounter. An example could involve teaching redox reactions and electrolysis in a designed energy systems module, where students draw upon the theory they know and apply it to a real-world scenario. PBL enables students to have a deeper understanding of content knowledge, and importantly helps develop teamwork, communication and research skills.

Linking chemistry with biology, technology, and ICT resources through inquiry and PBL contexts also provides opportunities for students to explore interdisciplinary processes, such as enzymatic reaction or environmental monitoring. Digital tools (such as simulations of different behaviours or modelling software) and data loggers provide students with the opportunity to engage with chemical phenomena and engender digital literacy in conjunction with scientific inquiry (Rutten, 2012). Digital tools also allow for the visualization of more abstract concepts, such as molecular structures or reaction mechanisms, that are particularly difficult to teach in traditional disciplines .

Laboratory-based learning even more effectively facilitates the potential for STEM integration when involving inquiry and PBL approaches. For example, English (2016) created a scaffolded inquiry and PBL-based inorganic chemistry course that is defined by:

Scaffold Learning - Students transitioned from guided tasks to independent inquiry.

Inquiry-based exploration - Learners generated questions, ran experiments and analysed data.

Projects with a Focus on Real-world Applications - Students work on projects that are based on laboratory methods. The idea is to allow students to apply conceptual knowledge in a real-world problem-solving scenario. Other teaching strategies which support this kind of work deepen students understanding, support the transfer of knowledge, and develop important competencies for STEM careers.

The positive effects of interdisciplinary approaches to learning go beyond just improving a child's achievement. Research has demonstrated that students are more likely to be motivated to learn and engaged when they perceive their chemistry learning as being a part of both their own lives, and also relevant to society. For instance, English (2016) found that the contextualization of STEM tasks led to higher persistence in students' work on sometimes difficult STEM concepts and tasks, especially for those with backgrounds that are underrepresented in STEM fields. Additionally, Moore et al. (2015) highlighted the potential for STEM integration to close participation gaps in science education.

Even small, engaged, focused interdisciplinary tasks, such as using algebra to calculate reaction rates, or exploring nanotechnology as it relates to drug delivery, can lead to rich learning experiences if conducted with intentionality. The tasks also

draw attention to the importance of how we design instruction that is respectful of chemistry, but seeks to connect students and educators to a larger group of constructs.

In summary, integration of STEM concepts into chemistry classes demonstrated the pedagogical value of interdisciplinary approaches to teaching, and also the potential for transformative learning. Students began to connect chemistry to a larger, interconnected systems of knowledge - one that includes elements of innovation, sustainability, and a contribution to society's epistemological advancement.

One archetypal and pedagogically rich example of a STEM integration in chemistry teaching, is the design and testing of water filtration systems. The type of project we have presented integrates various disciplines. Using chemistry concepts like solubility, adsorption, chemical nature and pH, and water chemistry; using engineering design concepts to realize functional solutions; using technology such as sensors and data-loggers; and using mathematics to assess system efficiency and flows. In all these projects, the students typically work from a scenario that depicts a real-world problem—like resolving contaminated water in a specified area, and design, build and test an appropriate model that uses filtration technology meeting a established performance criteria (Yildirim & Selvi, 2016).

These interdisciplinary tasks not only integrate and apply theoretical knowledge, but allow students to solve authentic problems, replicate authentic science and to practice the 21st-century competencies. For example, students need to assess the chemical nature of the different filtering materials (e.g., activated carbon, sand, zeolite), substantiate the decisions they have made to design their models according to chemical nature and physical properties, and use the data they have collected to confirm the effectiveness of their model. In this way, students develop not only conceptual understanding but scientific reasoning, creativity, teamwork, and iterative solutions based on evidence—all key competencies in science and engineering.

From a teacher education perspective, these projects are an ideal showcase of teachers' Pedagogical Content Knowledge (PCK) development in STEM contexts. Teachers need to carefully scaffold the activity: decide on the appropriate content, prepare for common misconceptions (i.e., distinguishing between physical filtration and chemical treatment), organize inquiry steps, and develop a suitable assessment tool. As Hasni et al. (2022) point out, projects such as these force teachers to manoeuvre the interplay between content knowledge, pedagogy, and transdisciplinary learning—thereby enhancing the teachers' STEM-PCK. The projects can also be differentiated for students to suit different learning contexts. In a school with a lot of resources, for example, the students are able to use digital sensors to allow real-time recorded measurements of the water's turbidity or pH, as opposed to a low-tech school where their water supply resources will be a common household items and testing done manually. The projects demonstrate that STEM integration is not dependent upon technology, but rather the design of the investigation, the scientific

thinking surrounding the depiction of this ideas, and how the significance of the problem connects with the students' own life experiences.

In conclusion, the water filtration project evidences the application of chemistry learning through relevance to everyday life and extending to global sustainability through the issues of access to clean water and protection of ecosystems. The project allows a variety of STEM-integrated tasks to bridge the gap between observing abstract notions to having a real-world impact, therefore supporting alternative practices for high engagement, authentic, contextual, and transformational science education with students.

Another context that has been used often and is effective pedagogically for STEM integration in chemistry is alternative energy—which speaks to the notion of sustainability goals and is relatable to students' lives. Projects such as the construction of electrochemical cells, hydrogen fuel cells, or solar cookers link students' science learning to fundamental chemical principles of science—including redox reactions, energy conversion, thermodynamics, and material sciences—but builds on engineering practices of iterative design, material optimisation, and performance.

In such projects, students are required to develop their knowledge in relevant and useable ways. For instance, in electrochemical cells, students need to decide on suitable materials for their electrodes based on stated parameters of reactivity & conductivity. They will need to establish how to measure voltage outputs in 'normal' conditions and conditions over time, and will also need to establish the energy losses where mathematical formulas will need to be used. In solar cookers, students will explore topics related to thermal insulation, reflectivity of surfaces, energy absorption, and environmental aspects. Each of these investigations students not only need to demonstrate their understanding of scientific knowledge, they also applied physics, used mathematics to make a model and an analysis, and dealt with explicit engineering constraints of cost, durability and sustainability in regard to the environment.

In addition to fostering content knowledge, these contexts are settings where scientific reasoning and design thinking are developed. Students undertake hypothesis-driven experimentation, analyze the relationships among the variables, compare their materials, and revise their prototypes based on the data they have collected. In doing so, they undergo an early version of the iterative scientific process (as outlined in the National Academy of Sciences , 2000), which is a fundamental aspect of scientific work. These types of tasks inherently support the development of STEM competencies, such as data literacy, a systems-thinking approach, and evidence-based decision making.

The teacher's perspective for facilitating these types of projects requires an extensive, flexible PCK in team-teaching scenarios across disciplines. Teachers must provide complexity to the concept of chemical decision-making (the authors were surprised by most students' difficulties even in identifying topics) while scaffolding

decision making to complete engineering tasks, and which tools are available to help with mathematics, chemistry, etc., and work toward curriculum coherency and scientific acceptability. This requires both content knowledge and pedagogical choices to promote creativity, deductive or inductive thinking (or reasoning), as well as knowledge of scaffolding learning through open inquiry in cross-disciplinary contexts (Park & Chen, 2012).

There is much qualitative and quantitative research that has shown that students participating in STEM-rich project learning demonstrate greater student engagement, deeper abstraction of conceptual understanding, and enhanced problem-solving skills (Moore et al., 2014). Moreover, efficacy and relevance is typically enhanced for students through the focus on renewable energy and sustainability, as they can see how chemistry can lead to ways of addressing real issues of significance to them and the problems of technology and other challenges of global environmental significance.

To summarize, the alternative energy context demonstrates how chemistry education can be meaningfully enacted as part of a broad set of STEM objectives. The tasks go a long way in linking learning from abstract ideas from chemistry to issues that have tangible social relevance and generate cognitive development combined with affective registers. Such projects can also provide rich opportunities for teachers to grow their PCK in ways that reflect the complexity, and contemporary demands, of multidisciplinary education. Moreover, food chemistry presents a compelling and accessible vehicle for integrated STEM education. Since food normally offers a universal and culturally relevant context, it allows an immediate venue to connect the abstract nature of scientific concepts that students engage with to their daily lives. Investigating chemical phenomena through projects that include modeling enzymatic browning reactions, measuring the acidity and buffering capacity of soft drinks, and investigating fermentation and microbial metabolism provides students with authentic chemical phenomena, while also acquiring valuable skills such as data analysis and literature, experimental design, and interdisciplinary problem solving.

These kinds of activities inherently engage multiple disciplines of STEM, which is compelling if you are trying to make connections across multiple disciplines. For example, in the investigations of browning reactions students would study the biochemistry of polyphenol oxidase whilst investigating the varying temperature and pH of the enzyme, or using various mathematical models to quantify the reaction rates. In the fermentation experiments, students may be measuring glucose disappearance, gas production over time, or using digital sensors to visualize and systematically record the pH change over time. These were all authentic chemical phenomena that incorporated chemistry, biology, and technology into a shared inquiry experience.

From curricular standpoint, food chemistry experiences are particularly strong for developing key STEM skills and dispositions such as data literacy, experimental

design, quantitative reasoning, and model-based reasoning. Students are generating "live" data, that they analyze with software (i.e., typical statistical or graphical software, simulation tools, etc.), while they greatly advance their digital and computational capabilities along with their conceptual understanding of the chemical processes at play.

These projects can also lend themselves to engineering extensions, like developing healthier formulations for junk food products, enhancing conditions of the fermentation. These activities can replicate the types of challenges that exist in the food science and biotechnology fields, giving students a chance to grasp the real-world applications of chemistry, as well as giving them experiences in real work conditions that reflect the collaborative aspects of science.

For teachers, using food chemistry within a STEM context provides opportunities to make progress with pedagogical content knowledge (PCK) in interdisciplinary contexts. They also need to predict students' prior knowledge and preconceptions about food and digestion, connect their macroscopic observations to molecular constructs, and help students navigate how to move from qualitative descriptions into quantitative descriptions of their inquiries. This also entails making the assessments not just able to require facts to be recalled completely, but instead may be attempting to assess broader learning outcomes such as experimental reasoning, evidence-based argumentation, and synthesis across discipline.

Even though in the previous section we touched upon the ways in which the use of food chemistry has been associated with student engagement and motivation in science with students who are usually not able to see themselves in traditional STEM disciplines, we should also note that stemming from the immediacy, everyday relevance, and sensory engagement of food-based approaches to STEM, can help to lower the affective barriers students show towards learning - creating inclusive and curiosity-driven academic spaces where students can feel welcomed, or even better, engaged.

Thus, food chemistry is an example of how STEM integration in curriculum contributes to a more contextualized, inquiry-driven, and inclusive chemistry education. Bridging scientific knowledge with everyday activities means there is a goal to provide meaningful opportunities for engaging with the practices or principles of chemistry related the practices of how students learn, while also foster developing other transferable skills that are central to us being scientifically literate in today's society.

There are many curricula, or model of teaching, that exist for supporting STEM integration in chemistry education generally. The Engineering Design Process (EDP) is one of these pedagogical approaches of STEM education that has high use, and indeed it has a well established ways of adoptive use in science education. Such projects underlie the application of theory and action while demonstrating and supporting the cyclical and non-linear progress of thinking, which embodies how scientists and engineers work in the real world, outside of the classroom.

From a pedagogical perspective, utilizing EDP in chemistry instruction supports the development of students' higher-order thinking, including creativity, critical reasoning, and metacognitive regulation. EDP encourages students to ask questions, make predictions, test those predictions, and justify their decisions, leading to a close alignment with inquiry-based learning models. It also fosters collaborative learning, because in most groups, students will collaborate to design and evaluate a solution, leading to the development of many communication and leadership skills.

From the perspective of teachers, using EDP as a pedagogical strategy involves a change in teachers' instructional practice, and requiring development of their PCK. Teachers must understand how to facilitate open-ended inquiry, support group dynamics, tolerate uncertainty, and assess process outcomes—requiring flexible and adaptable PCK. In addition, the iterative nature of EDP can provide a framework for teachers themselves for their own professional learning by evaluating how students engage with concepts, compose misconceptions, and change instructional strategies in the next iterations. The Engineering Design Process in chemistry experiences will help to deepen learners' conceptual knowledge as well as to prepare them for authentic real-world STEM experiences. This style of learning changes students' mindset to a focus on innovation and resilience relevant to the scientific and technical opportunities ahead—STEM opportunities that are more reflective of current workplace attitudes and behaviours—while resituating chemistry to an applied and interdisciplinary approach at the centre of academic problem-solving.

Importantly, research suggests that STEM integration requires intentional instructional design. Teachers need to not only intend on aligning content from the different disciplines but also attending to the pedagogical rigor behind the chemistry content. When STEM integration experiences are conducted effectively teachers can develop student knowledge of chemistry and move toward bridging towards broader STEM contexts.

While promising, there are still ongoing limitations. These include the challenges of time, limited interdisciplinary professional training, and need for pre-designed STEM modules for chemistry experiences. However, successful case studies demonstrate how integrated teaching in chemistry can be feasible, and innovative.

1.3 Challenges Faced by Teachers in Integrating STEM

Although the incorporation of STEM into chemistry education holds great potential, it also creates considerable challenges for practicing teachers. Evidence indicates that teachers experience challenges that stem from their pedagogical preparedness, educational institution(s), and conceptualization of STEM itself (Thibaut et al., 2018; Margot & Kettler, 2019). These challenges can limit teachers' ability to engage students in interdisciplinary learning and to support students' STEM competencies.

One primary challenge is that teachers identify a lack of instructional models for STEM integration. Teachers of chemistry often express ambiguity about how to combine science with technology, engineering, and mathematics in a way that does not diminish their ability to provide depth of content in their subject (Nadelson & Seifert, 2017). In chemistry, there does not appear to be standardized curricula or resources explicitly focused on chemistry in the STEM context. In their practice, teachers report STEM as ambiguous in practice and, therefore, struggle to make connections about how to implement the theoretical advantages of STEM into classroom strategies.

Limited professional development opportunities for interdisciplinary pedagogy is another major challenge. Even if teachers know a substantial amount about chemistry, many do not have any previous training regarding engineering concepts, coding, or the implementation of mathematical models in developing experimental designs. As a result, they may avoid integrating unfamiliar content, reducing the potential of STEM-based learning. Moreover, pre-service teacher education programs rarely offer systematic preparation in STEM integration, leaving early-career educators to navigate it independently.

Time constraints and workload are also common concerns. Developing STEM activities typically requires collaborative planning across subject areas, customizing materials, and designing new forms of assessment—all of which demand additional time and effort. In schools with rigid schedules and limited planning periods, interdisciplinary collaboration becomes especially difficult. Teachers may be willing but simply unable to allocate sufficient time for preparation and implementation.

Access to resources and technology further complicates the integration of STEM. Many STEM tasks involve laboratory equipment, digital sensors, design software, or engineering materials that are not always available in schools—particularly in under-resourced or rural settings. Without these tools, teachers are forced to simplify or abandon more ambitious STEM projects, reducing the depth of student engagement and the development of authentic problem-solving skills.

Finally, institutional culture and assessment systems may discourage innovation. Standardized testing, fixed subject boundaries, and a lack of support from administration can demotivate teachers from adopting new approaches. In some cases, educators report resistance from colleagues or uncertainty about how STEM aligns with national or regional curriculum standards.

Despite these challenges, many teachers demonstrate high motivation and creativity in finding workarounds—such as adapting everyday materials for experiments or building cross-subject partnerships informally. However, to achieve wide-scale, sustainable STEM integration, systemic support through curriculum reform, funding, professional learning communities, and leadership commitment is essential.

1.4 Analysis of International and Kazakhstan Experience in Implementing STEM Education

STEM education serves as the foundation for training specialists in high-tech and advanced technological production fields. Therefore, many countries, including Australia, China, the United Kingdom, Israel, Korea, Singapore, and the United States, implement government programs in STEM education.

In the United States, the relevance of STEM education was defined in the 2013 Strategic Plan for the Development of STEM Education. Under this plan, it was proposed to train 100,000 new effective STEM teachers by 2020 and to support the current teacher contingent. Another goal was to increase the proportion of students in middle schools studying STEM subjects to 50%. The plan also includes an aim to increase the number of graduates in STEM fields from colleges and universities by 1 million people.

The 2015-2020 Strategic Technology Plan from the New York City Department of Education (NYCDOE) is very interesting because NYCDOE is the largest school district in the United States representing more than 1.1 million students spread across more than 1,700 schools, and speaking 176 languages. This Strategic Technology Plan outlines program and investment related to the implementation of technology in the educational process in the next 5 years. The plan is directed at the needs of NYCDOE staff, families, students, and New York residents to:

Recognize the connections between NYCDOE technology and strategic goals;

Identifying opportunities to expand curricula and technological investments;

Coordinating the goals and action plans for the implementation of new technological initiatives;

Participating in planning and decision-making regarding funding.

More than 250 people were involved in developing this plan, including staff with a deep interest in technological innovations in education and third-party participants. The developers focused on 12 universal themes: mobility, support, the use of digital educational materials, data access, and utilization.

United

Kingdom:

In 2014, the Minister of Education Michael Gove and Chancellor of the Exchequer George Osborne launched a national skills training program and initiated a large-scale national campaign aimed at forming a new generation of information-literate IT specialists.

As part of this initiative, mass educational events were planned, with program courses being included in the school curriculum for all British students aged 5 to 16. Additionally, a budget of 500,000 pounds was allocated for the training of future programming teachers. The project, named "Year of Code," was fully non-governmental and involved business organizations, information agencies, and educational programs such as COD ACADEMY.

The "Year of Code" initiative, launched in 2014, aimed to teach coding to people for the first time in the country. Through coding, individuals can acquire

competencies in computer science and transform their skills to become more efficient in their professional lives. "All the fantastic coding initiatives throughout the year will help many people engage with technology and gain important learning opportunities," said the project initiators.

Since September 2014, coding has been included in the school curriculum for all children aged 5 to 16 in the UK. This is noted as an opportunity for the UK to establish its first G20 economy at the national level, marking a significant political shift towards the emergence of generations of school graduates with skills for the 21st century.

Singapore:

In Singapore's national education system, special attention is paid not to infrastructure (though it is not overlooked) but to teachers and students. Meritocracy operates within Singapore's education system. The focus is on identifying and developing talent. The state finances the education of talented youth in the country's top universities and encourages them to become teachers and civil servants, offering salaries that are above the national average. Additionally, government-sponsored students must work in the public sector for at least two years for each year of study after completing their education.

The principles of meritocracy are also applied in the development and promotion of teachers. The most effective teachers are given the opportunity to prove themselves by ensuring rotation within the Ministry of Education, in classrooms, and in school administration. This, on the one hand, prevents the emergence of bureaucracy in ministries and administrations, and on the other hand, allows talented teachers to implement their initiatives.

Singapore is rightfully proud of its elite educational institutions. Alongside elite education, hundreds of schools, technical, and polytechnic institutes across the country provide quality education at various levels.

Currently, STEM centers or educational programs using STEM technologies are beginning to emerge as a promising model in Russia. Russia's STEM centers operate with the support of leading IT companies on the campuses of universities, technology parks, and 27 other educational institutions. Here, children acquire new knowledge and skills, participate in research projects, and gain skills in scientific work that will be beneficial for further education in higher education institutions.

The first Russian STEM centers are part of an international project implemented under the initiative of Intel Corporation. The goal of the program is to increase interest among school students in studying the exact, engineering, and natural sciences, and to provide new opportunities for university students to develop their scientific potential based on the scientific laboratories of leading universities. This approach strengthens the interaction between secondary and higher education institutions, allows school students to access unique laboratory equipment, and enables them to interact with professional scientists. STEM centers are concentrated teams dedicated to scientific research.

Additionally, Singapore's education system is continuously evolving, developing in line with the latest scientific advancements. The education system in Singapore is always forward-looking. It focuses on bilingual education (in English, Mandarin - Northern Chinese, Malay, or Tamil) and emphasizes science, technology, engineering, and mathematics (STEM).

Currently, in Russia, STEM centers or educational programs using STEM technologies are beginning to emerge as a promising model. Russian STEM centers operate with the support of leading IT companies at universities, technoparks, and other educational institutions. Here, children acquire new knowledge and skills, participate in research projects, and gain skills in scientific work, which will be beneficial for further education in higher education institutions.

The State Program for the Development of Education and Science of the Republic of Kazakhstan for 2016-2019 aims to develop the functional literacy of students in the field of STEM education. This involves strengthening STEM elements in educational programs that focus on developing skills in modern technologies, scientific research, and project work.

As part of the educational content renewal, early education based on natural sciences and the integration of information literacy began, specifically in the areas of "Mathematics and Informatics", "Natural Sciences" and "Technology and Engineering" which are now included in the National Standard of Primary Education. These updates include new educational subjects such as "Information and Communication Technologies", "Nature History," and "Artistic Work." Furthermore, elective courses such as "Graphics and Design" and "Fundamentals of Business and Entrepreneurship" have been introduced for students in primary and higher education.

Also, starting in 2019, subjects in the natural science-mathematics direction in higher grades will be taught in English, which will allow students to gain new knowledge in the language of instruction and have an impact on their integration into the global scientific community.

According to recent monitoring studies conducted by employees of the National Academy of Education named after Y. Altynsarin, within the framework of elective courses, general education schools in Kazakhstan have started teaching the basics of programming and robotics to students, as well as elements of computer modeling and design.

The monitoring included 13 regions, as well as the cities of Astana and Almaty. The analysis of quantitative data provided by the education departments of the regions, Astana, and Almaty showed that during the 2016-2017 academic year, 974 elective courses were conducted in various STEM education areas across schools in the republic (as shown in the Figure 1).

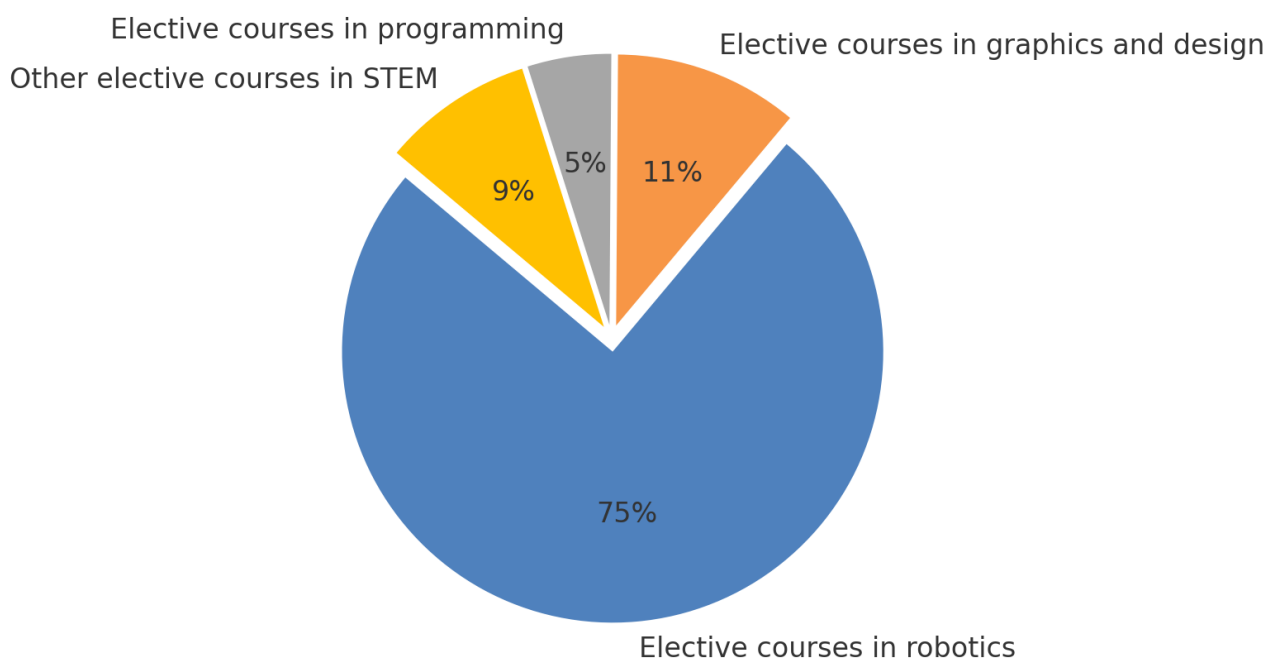


Figure 1. *Distribution of Elective Courses In STEM Education Directions*

As mentioned, the elective courses teach students the basics of programming (51 elective courses), robotics (733 elective courses), computer graphics and techniques (103), and engineering sciences (87 elective courses) (as shown in the Figure 1).

Additionally, public-private partnerships and other educational organizations working on a private business basis also contribute significantly to the widespread adoption and development of STEM education in Kazakhstan. Implementation and development of STEM education in Kazakhstan. In his address to the people of Kazakhstan, President N. A. Nazarbayev emphasized the importance of technological modernization in the "Third Modernization of Kazakhstan: Global Competitiveness" message, stating that it is a very urgent priority for the country's development. The President tasked the government with developing the "Digital Kazakhstan" program aimed at developing promising sectors such as 3D printing, online shopping, mobile banking, digital services, as well as healthcare and education. One of the important priorities highlighted in the message, related to "improving the quality of human capital" is to strengthen the importance of education as a new model of economic growth. Therefore, the modern curricula should focus on developing students' critical thinking skills, fostering information-searching skills, improving IT literacy, financial literacy, and instilling a sense of patriotism in youth.

Recently, several factors have influenced the development of STEM education in the secondary education system in Kazakhstan. In the state program for the development of education and science of the Republic of Kazakhstan for 2016-2019, the implementation of education policy in the field of STEM education was planned. To this end, the issue of strengthening STEM elements aimed at developing

students' functional literacy, skills in using modern technologies, conducting scientific research, and engaging in project work was raised.

In addition, since subjects in the natural sciences and mathematics for senior classes will promote entry into the global scientific community, they will also be taught in English.

Overall, the monitoring studies conducted by the academy show that significant work is being done in the development of STEM education in the country's schools. However, there are still a number of issues that require consistent solutions based on comprehensive research.

One encouraging point is that public-private partnerships and other educational organizations working on a private business basis are contributing to the widespread adoption and development of STEM education in Kazakhstan. One such example is the two-year "English for Success" project organized by the Tengizchevroil company, the UK's British Council, and Leicester University in the Mangystau region in 2019-2020. The main goal of the project was to train teachers as experts in pedagogical methods, developers of learning resources, and trainers for teachers and students. The project program included training for the region's teachers in innovative methods for teaching English and natural science subjects in English.

These brief analyses and information show that today's employer requirements are different, which is why systematic and continuous development is needed throughout the entire education system, starting from preschool education.

The increasing literature about pedagogical content knowledge (PCK) and STEM integration in chemistry education speaks to the opportunities and challenges of contemporary educators. Research commonly shows that developed PCK is critical for taking abstract chemistry knowledge and demonstrating how to construct meaningful experiences that are also interdisciplinary in scope. Successful examples of STEM integration—including genuine projects, laboratory experiences, and thought-provoking demonstrations—show how chemistry can be taught when instructors partner and use an inquiry-focused teaching strategy instead of traditional instructions. When students are actively engaged and exposed to a project-based learning environment, they are pushed to problem-solve rather than simply affirming their existing knowledge.

However, there continues to be significant barriers that would temper teachers as they put STEM into practice in their classrooms. Teachers can experience conceptual, practical, and systemic barriers that minimize a complete understanding of STEM integration. For example, it is quite common for teachers to not have training to utilize interdisciplinary principles. Other barriers that complicate STEM practices include time pressures, lack of materials, limited access to technologies, and disconnection among relevant curriculum. Thus, despite the broad acceptance and awareness of the potential of STEM-based chemistry education, there seems to be a disconnect between the aspirational vision and reality in classrooms.

Findings suggest that targeted research needs to be made into how chemistry teachers develop and use their PCK in integrated STEM settings. Further, uncovering how teachers navigate this situation will provide data that can shed light on supports for teachers, the strategies that teachers make available to students, and the intersection of teachers' backgrounds and their practices in integrated STEM learning contexts. In summary, we hope that this study will provide an avenue of evidence by examining and documenting the PCK of integrated STEM learned by chemistry teachers.

2. METHODOLOGY

This chapter outlines the high level methods we adopted for this study, which was aimed at exploring how chemistry teachers understand, enact, and interpret an integrated STEM pedagogy through their teaching. Teaching is complex and multifaceted, particularly in the case of interdisciplinary disciplines like STEM. For that reason, we decided a mixed methods approach would be the most effective way to conduct the research. The advantage of mixed methods was being able to obtain both the quantitative breadth of teachers' familiarity with, reported practices regarding, STEM, as well as the qualitative depth to better explain the context and individuals in teaching STEM.

With both quantitative and qualitative methods, we endeavored to develop a substantive and balanced understanding of how STEM education is understood and enacted by chemistry teachers in actual classroom settings. We were able to provide a statistical overview of teachers' familiarity with the integrated STEM approach, teachers' self reported engagement with STEM practices, and teachers' reported professional learning/development needs, through the SLE; but also contextualized what STEM integration may look like in instructional settings, and how teachers legitimate their decisions using classroom observations and semi structured interviews.

2.1 Research Design

This study used a mixed methods approach, employing both quantitative and qualitative methods to increase the reliability and interpretative richness of the findings. More specifically, quantitative elements included three complementary data collection modalities:

A descriptive quantitative survey that examined broad patterns and trends about teachers' understanding of STEM, their teaching practices, and their perceptions of professional development;

Semi-structured interviews with a sample of selected teachers to allow for richer understandings of their pedagogical reasoning, contextual factors in their teaching, and personal interpretations of STEM-integrated teaching.

The mixed design provides a stronger means of answering research questions that require both measurable indicators but also greater interpretive depth. It enabled the study to not only report what teachers say or do, but also what factors shape their reasoning about a range of challenges and issues that inform the professional context for their action. Importantly, the research aims to provide a richer understanding of the complexity of pedagogical content knowledge (PCK) as part of the challenge of integrating STEM with relevance to chemistry education.

2.2 Participants and Sampling

The study included 114 chemistry educators selected through purposive sampling to ensure that the participants had meaningful STEM-related experiences to enhance the relatedness and credibility of the data. All of the participants had relevant experience with interdisciplinary instruction or with a STEM-based educational

practice, meaning they would be suitable informants for examining Pedagogical Content Knowledge (PCK) through a STEM perspective. The participants included teachers from a variety of educational contexts, including public school and private schools, urban and rural schools, and specialized schools, such as STEM schools or schools that focus on gifted students. In terms of experience, the teacher participants varied in their entries to teaching, some with fewer than five years of teaching compared to seasoned teachers with over 20 years of experience. From an academic perspective, teacher participants also varied in their qualifications with one or more of them being trained as a teacher in a STEM discipline, while others completed advanced education in a STEM education field. Differences among the participants were useful for identifying trends across all teacher profiles and school types.

In addition, the study included 11 chemistry educators who were selected for semi-structured interviews. These participants were selected purposefully to ensure a diverse range of teaching experience, types of schools, and levels of experience with STEM pedagogies. The participant responses also provided rich, reflective narratives of their professional reasoning, instructional experience, and personal interpretations of the role of STEM in their teaching.

This study utilized a purposeful sampling method to select chemistry educators who were already employing STEM approaches to their teaching and are intending to implement STEM approaches with their students. A total of 17 secondary school chemistry educators were selected to participate in the semi-structured interviews from various schools across Kazakhstan. All the participants had previous experience with STEM pedagogies and institutions and were demonstrating current involvement in interdisciplinary teaching that included interdisciplinary or innovation-based projects or engagement in ongoing professional development in the area of STEM.

The participants drew from multiple data sources, (survey and interview) for the research study so the triangulation of the data would help the research study examine the STEM integrate PCK from multiple sources. Collecting data using in a way that advocated both depth and breadth of data aiming to outline how chemistry educators perceive and implement STEM approaches in their practice.

2.3 Data Collection Methods

This study utilized two main forms of data collection to gain a complete understanding of how chemistry teachers think about and enact integrated STEM education: a structured survey and semi-structured interviews. The use of multiple methods allowed for methodological triangulation and the investigation of different aspects of the topic, including what teachers report doing in the classroom, what is witnessed in the classroom, and what the teachers are claiming or justifying about their teaching of mixed STEM disciplines.

2.3.1 Survey of Chemistry Teachers

To obtain some basic quantitative data, we conducted an online "survey" with all 114 teachers using a structured survey form. The survey gathered teacher self-

reported familiarity with STEM concepts, types and frequency of STEM practices in their own teaching, pedagogical confidence, and what their professional development needs were for developing STEM.

The questionnaire consisted almost exclusively of close-ended Likert scale questions representing the following sections:

Demographic Information: This section contained items about teaching experience, academic qualifications, type of institution (public or private), and geographic region.

Familiarity with STEM Concepts: This section examined teachers' awareness and conceptual understanding of the principles of integrated STEM education.

Pedagogical Approaches: This section asked how teachers viewed their own capability to apply STEM-aligned strategies in chemistry lessons.

Frequency of STEM Practices: This section assessed how often teachers did some of the strategies, such as project-based learning, real-world problem solving, and interdisciplinary teaching.

Adaptability: This section explored teachers' ability and confidence to alter STEM activities to better accommodate students with various abilities and needs.

Professional Development Needs: This section included items to examine teachers' perceived needs for help and training to support the implementation of STEM-focused pedagogy.

The survey was distributed digitally via an online platform and was open for three weeks. Participation was completely voluntary in nature and anonymous to facilitate honest reflection and accurate feedback. The quantitative data collected were analyzed descriptively and then later triangulated with qualitative data from observations, and interviews, to provide a comprehensive interpretation of teacher engagement with STEM pedagogy.

Table 1. *Reliability Statistics of the Survey Instrument (Cronbach's Alpha)*

	Cronbach α
scale	0.847

To ensure the internal consistency and reliability of the survey instrument used in this study, Cronbach's alpha coefficient was calculated for the set of seven STEM-related Likert-scale items. The resulting Cronbach's alpha value was 0.847, which indicates a high level of internal reliability.

According to widely accepted standards in educational and social science research, a Cronbach's alpha value of 0.7 or above is considered acceptable, while values above 0.8 are interpreted as good (George & Mallery, 2003). Therefore, the obtained score of 0.847 confirms that the items included in the survey are

consistently measuring a coherent construct—namely, chemistry teachers' perceptions and self-reported practices related to STEM integration.

This strong internal consistency not only enhances the credibility of the descriptive and inferential statistical analyses that follow but also supports the overall validity of the findings. The cohesiveness of the scale increases confidence in the survey as a reliable tool for assessing how teachers understand, implement, and reflect on STEM-based pedagogy in chemistry classrooms. Consequently, the interpretations made in relation to the research questions and hypotheses of this study are grounded in statistically reliable data.

2.3.2 Semi-Structured Interviews

As part of the qualitative strand of this mixed-methods research, two rounds of semi-structured interviews were conducted with chemistry teachers to obtain an in-depth understanding of how Pedagogical Content Knowledge (PCK) is developed and applied within the context of integrated STEM education. The interviews were intended to investigate the reasoning, instructional decision-making, and classroom practices of teachers that could not be captured by the quantitative survey alone.

For the interviews, we ultimately wanted to look at chemistry teachers' use of PCK and STEM principles in a real classroom environment. Specifically, the interviews were intended to:

Explore how teachers modify chemistry content in order to make it meaningful in disciplinary STEM contexts;

Understand how teachers deal with students' misconceptions and how they represented complex concepts;

Identify opportunities for challenges in the delivery of STEM-based chemistry;

Capture teachers' experiences of how they have designed problem-based tasks, experimental work, interdisciplinary tasks, and student-led projects.

As we have stated already, the objectives of the interviews allowed for rich contextual descriptions that helped to expand on the statistical data obtained from the survey.

Interview Round 1: 11 Chemistry Teachers

For the first round of interviews, 11 chemistry teachers were chosen based on purposeful sampling. All teacher participants showed commitment to STEM-integrated pedagogies. The teachers were all in various school divisions, as well as school systems (public, private, and STEM schools), and had various teaching experience levels, 5 to 20 years.

These interviews were conducted online through a Google Form containing four open-ended questions:

1. What problem-based tasks do you use in STEM chemistry lessons?
2. What new experimental activities do you carry out in class?
3. What STEM-related events have you organized?

4. What STEM-chemistry-related projects have you completed or plan to complete?

Each teacher provided detailed written responses that reflected real classroom practices. The teachers often described creative, student-centered approaches, including projects on hydrogen fuel, biodegradable plastics, eco-cosmetics, and interdisciplinary problem-solving around energy and food safety. Their responses served as case studies highlighting innovative pedagogical approaches.

Interview Round 2: 17 Chemistry Teachers

Given the success and insight gained from the initial round, a second, expanded round of interviews was conducted with 17 additional chemistry teachers. This group was selected with the aim of increasing diversity in terms of regional representation, school type, and teaching background. The sampling approach remained purposive but was broadened to include voices from both urban and rural school settings.

The structure of the interview remained semi-structured, and the same four open-ended questions were used to ensure comparability across datasets. However, responses from this second round were even more varied, often reflecting localized challenges, innovative adaptations to limited resources, and strong engagement with STEM initiatives at the school level.

Examples included:

Organizing eco-STEM exhibitions and virtual STEM fairs;

Conducting experiments using locally available organic materials;

Developing student-led research projects on water purification, soil testing, and the chemistry of food;

Designing mobile apps and digital tools for chemistry learning;

Participating in international STEM forums and competitions.

These interviews revealed deeper layers of teacher agency, creativity, and professional reflection, particularly in overcoming infrastructural limitations or adapting STEM to culturally relevant contexts.

2.4 Data Analysis

Given the mixed methods design of the study, both quantitative and qualitative data analysis techniques were employed. Each data strand was analyzed separately using appropriate methodological procedures and was later integrated during the interpretation phase to ensure a comprehensive understanding of the research questions.

2.4.1 Quantitative Analysis: Survey Data

Quantitative data from the structured survey were analyzed using Jamovi statistical software. Descriptive statistics—such as frequencies, percentages, and means—were computed for each Likert-scale item. These statistics provided a general overview of participants' familiarity with STEM concepts, the frequency and nature of STEM-based instructional practices, perceived pedagogical confidence, and professional development needs.

The purpose of the quantitative analysis was not to make generalizable claims but rather to identify common patterns and trends among the 114 chemistry teachers. These trends were later compared and contrasted with qualitative findings to explore consistencies, differences, and opportunities for triangulation.

2.4.2 Qualitative Analysis: Interview Data

The interview data collected from the two groups of chemistry teachers (11 and 17 participants) were analyzed using thematic analysis. All responses were collected in written form via Google Forms and reviewed thoroughly. The analysis process began with repeated reading of the responses to become familiar with the content. Key phrases and patterns were identified and manually coded based on recurring ideas related to pedagogical content knowledge (PCK) and STEM integration.

After coding the responses, similar codes were grouped into broader themes that reflected common instructional practices, innovative strategies, challenges, and suggestions shared by the teachers. This approach allowed the researcher to identify how teachers apply PCK in STEM-based chemistry lessons, what types of interdisciplinary activities they implement, and how they approach project-based and problem-solving tasks.

The two interview datasets were first analyzed separately and then compared to observe overlaps, differences, and new ideas introduced in the second round. The themes that emerged from both sets were used to complement the quantitative findings and to provide deeper insights into teachers' real-life experiences.

Thematic analysis helped ensure that the voices of participants were captured authentically, and the selected quotes were used to illustrate key findings in the results chapter.

2.5 Ethical Considerations

The study conformed to widely accepted ethical standards for research involving human participants. Prior to data collection, all participants received adequate and comprehensive details about the study's allows, and the methodology, including how data were being collected, that participation was voluntary, how the data would be used, and the way their privacy and confidentiality would be protected.

Participation was voluntary in the study and permission to participate was sought from participants. Consent was obtained electronically on the online survey tool for the quantitative study. Consent for the qualitative aspects of the study, classroom observations and semi-structured interviews, was sought on a form that was then signed by the participants before they were able to participate, with all information on the form explained to them. Informed consent form was simple to understand, and included that they could withdraw from the study at any time, without consequence and without having to explain why.

The data handled in this study maintained strict confidentiality (i.e. Optional and related to agreeing to participate). Any identifying personal information, such as

name, school, and place, were removed or replaced with anonymized codes in all data entries, analysis files and in any written reports. Survey data were collected and stored using secure online platforms with password protection. The recordings from the interviews and observation notes were stored on encrypted devices that only the researcher had access to.

To ensure ethical considerations throughout the study, all procedures, the instruments, and the consent process were reviewed and approved by the appropriate academic ethics committee before any data was collected. The researcher adhered to all institutional and national guidelines related to ethical issues in educational research. No participants were exposed to physical, emotional, or professional risk, and all engagements were conducted with respect, transparency, and a commitment to safeguarding participant dignity and autonomy.

3. FINDINGS / RESULTS

This chapter presents the findings of the study based on data collected through three primary sources: a structured survey completed by 114 chemistry teachers, classroom observations of six teachers across two schools, and semi-structured interviews with 11 teachers. The results are organized thematically according to the research questions and key areas of focus: (1) the influence of teacher-related factors on STEM implementation, (2) the teaching strategies and methods used to support STEM learning through PCK, and (3) the challenges and contextual factors affecting the integration of PCK in STEM-based chemistry instruction.

The findings are reported in two parts. First, the quantitative results from the survey are presented using descriptive and inferential statistics to illustrate trends and patterns in teachers' responses. These include analyses based on variables such as education level, teaching experience, school type, and teacher category. Second, the qualitative findings derived from interviews are discussed. These findings highlight teachers' pedagogical reasoning, instructional strategies, and contextual realities in implementing STEM-oriented lessons.

To enhance clarity and coherence, each subsection is aligned with the corresponding research question. Where appropriate, tables and figures are used to support the interpretation of data. Quotes from interview participants and observational excerpts are also included to provide rich, illustrative insights into the practical application of STEM-based PCK in chemistry teaching.

RQ1: Influence of Teacher Characteristics on Understanding and Use of STEM in Chemistry

To better understand chemistry teachers' engagement with integrated STEM education, seven key variables were measured through a 5-point Likert-scale survey instrument administered to 114 participants. Table 2 displays the descriptive statistics for these variables: familiarity with STEM, understanding, application, frequency of use, adaptability, training requirement, and training attendance. The analysis below elaborates on the significance of each variable in relation to the study's research questions and hypotheses.

Table 2. *Descriptive Statistics of Survey Variables*

	N	Mean	Median	SD	Min	Max
familiarity	114	3.45	4.00	1.205	1	5
understanding	114	3.32	4.00	1.244	1	5
application	114	3.36	3.00	1.235	1	5

training attendance	114	2.59	2.00	1.232	1	5
training requirement	114	4.10	4.00	0.902	2	5
frequency of use	114	3.54	4.00	1.168	1	5
adaptability	114	3.42	3.00	1.055	1	5

The variable measuring familiarity yielded a mean score of 3.45 (SD = 1.205), indicating a moderate level of self-reported awareness of STEM education among chemistry teachers. Although the median score was slightly higher at 4.00, the relatively high standard deviation suggests that levels of familiarity vary considerably across the group. This may imply that while some teachers are confident in their general understanding of STEM, others are only superficially aware or uncertain about its integration into chemistry instruction, especially with regard to incorporating technology and engineering concepts.

Similarly, the variable reflecting understanding produced a slightly lower mean of 3.32 (SD = 1.244), showing that fewer teachers feel confident in their pedagogical grasp of how to apply STEM principles effectively. The broad spread of responses points to diverse levels of preparation and professional readiness. This suggests that knowing what STEM is does not necessarily translate into instructional expertise, highlighting the need for stronger focus on practical pedagogical training.

The mean score for application was 3.36 (SD = 1.235), indicating that chemistry teachers have started to use STEM-oriented practices but often in limited or inconsistent ways. The median value of 3.00 supports the interpretation that while STEM methods are present in classrooms, they are not yet fully embedded in teaching routines. Some educators use certain approaches, such as project-based learning, or real-life experiences (experiences from the field), but others may have neither the full experience, nor the support, nor the understanding of all this that a systematic process of planning around the implementation of STEM may include.

For instance, when analysed regarding frequency associated with STEM-based practices, the average was again somewhat higher at 3.54 (SD = 1.168) with a median of 4.00 ; this may indicate that, while there may not have been extensive applications of STEM, many educators were attempting to incorporate some STEM concepts with some degree of consistency. The variability of the results did show, however, that there was a cohort of educators who were using STEM concepts in their classes with consistency, while others were incorporating STEM concepts with occasional frequency and some, depending on subject matter or access to resources.

The results for the variable labelled adaptability showed an average of 3.42 (SD = 1.055), indicating that teachers perceive that they are generally moderately effective at adapting STEM tasks for different learners. While this shows some

degree of flexibility pedagogically, the results also showed very limited capability to personalize or differentiate effective learning for complex and integrated contexts, and perhaps contribute to students interaction with STEM being less effective - particularly with learners with varied academic levels or learning needs.

In contrast, for the variable labelled perceived training need, produced the highest average reported at 4.10 (SD = 0.902), which established that, likely not surprisingly, all educators had a very strong awareness of their need for targeted professional development opportunities in STEM pedagogies. There were likely, according to the low standard deviation, agreement among respondents over general perceptions. This finding demonstrates that there is a strong need for structured, practice-based training that provides educators with not only a theoretical understanding of, but also practical strategies, tools and subsequently confidence to meaningfully implement STEM contexts in chemistry instruction.

Most disconcerting, the variable that measured reported training participation reflected the lowest mean with an average score of 2.59 (SD = 1.232). The apparent incongruity between educators perceived needs for training and participation, in a generalized evaluation sense, is troubling and indicates a clear deficit in the area of professional development. Role-related issues regarding participation in future learning may include structural characteristics such as access to the opportunities to train, lack of institutional commitment to programming, or time availability but do not underscore the critical need call to STEM training participation experience initiated by decision-making teachers.

By presenting an analyses that is comparative the findings provide increased clarity around operationalising aspects, of the current vignettes chemistry teachers aimed at educational pedagogy:

1. There is some degree of awareness that some degree of STEM related a practice of some kind is taking place, but can be identified as tentative and at times cursory.
2. Most teachers identify a desire to interact with STEM approaches of a practical basis and exhibit some degree of confidence in their ability to adapt pedagogically, but similarly need institutional & professional development support.
3. There is an obvious disconnect between the perceived need for training educators identified towards STEM and their actual participation which demonstrated that systemic limitations to available, professional development opportunities exist.

The findings further indicate that there is a clear need to address the relationship towards participating in a process, support to creating clarity of access to practices in chemistry content, to endorse multi-disciplinary and interdisciplinary approaches to chemistry education.

An independent samples t-test was conducted to assess whether differences in either educational attainment level for chemistry educators related to their perceptions and practices of integrating STEM. The two groups compared were individuals with a bachelor's degree compared to individuals with a master's degree

or other designation. Significant differences were found related to a number of key variables.

Table 3. *Independent Samples t-test Based on Educational Background*

	statistics	df	p	Effect size
familiarity	4.070	112	<.001	0.768
understanding	5.267	112	<.001	0.994
application	4.652	112	<.001	0.878
frequency of use	2.864	112	0.005	0.541
adaptability	3.582	112	<.001	0.676
training requirement	-0.663	112	0.509	-0.125
training attendance	1.288	112	0.200	0.243

Teachers with higher education levels reported greater familiarity with STEM concepts, as reflected in a statistically significant result with a large effect size. This suggests that advanced academic training is associated with increased exposure to interdisciplinary approaches in science education. Similarly, the level of understanding of STEM pedagogy was significantly higher among teachers with postgraduate degrees, with the effect size indicating a strong relationship. These teachers appeared to demonstrate more confidence in their knowledge of how to apply STEM principles in chemistry instruction.

The study's analysis also indicated an important distinction in the reported use of STEM strategies in the classroom. Teachers with higher degrees were more clear to employ interdisciplinary strategies and project-based learning strategies, indicating they were able or willing to take STEM theory and create an enacted reality. Groups also differed in the frequency of when the STEM strategies used, although the effect size was not as large. Given that, there is evidence that higher-educated teachers are somewhat more regular to incorporate STEM into their lessons.

Confidence in adaptability—understood as a teacher's ability to modify STEM tasks for different levels of student access—was also significantly higher for teachers with a master's degree or doctorate's degree indicating a higher capacity for differentiation and instructional fluidity for the more educated groups.

In contrast, no statistically significant differences were found in two areas: perceived training needs and actual training attendance. Regardless of education level, teachers noted a similar mean score of high need for training on the delivery of STEM pedagogy. Also, both groups noted relatively low attendance in STEM-based professional development activities.

These results suggest that while educational background influences classroom implementation of STEM, it does not appear to value-add to future access to formal training or professional development (PD) opportunities. Training constraints are still limiting features all teachers experience—such as, time, funds, or institutional restriction of participation—regardless of educational qualification.

In conclusion, the t-test outcomes show that academic qualification plays a meaningful role on how chemistry teachers understand, apply, and adapt STEM strategies in their teaching. However, all teachers yet experience systemic limitations on their ability to access training as a concern, highlighting the dire need for more equitable training opportunities and access to professional learning for all teachers.

The analysis of the study compared responses of chemistry teachers who held Bachelor's and Master's degrees across seven STEM-related dimensions. Descriptive statistics indicated that chemistry teachers with a Master's degree demonstrated higher mean values across all dimensions of familiarity, understanding, application, adaptability, and frequency of usage for STEM pedagogy.

Table 4. *Group Descriptive Statistics by Educational background*

	Group	N	Mean	Median	SD	SE
familiarity	Master's degree	64	3.83	4.00	1.017	0.1271
	bachelor's degree	50	2.96	3.00	1.26	0.178
understanding	Master's degree	64	3.81	4.00	0.974	0.1217
	bachelor's degree	50	2.70	2.00	1.28	0.181
application	Master's degree	64	3.80	4.00	1.011	0.1263
	bachelor's degree	50	2.80	3.00	1.28	0.181

frequency of use	Master's degree	64	3.81	4.00	1.052	0.1315
	bachelor's degree	50	3.20	3.00	1.23	0.174
adaptability	Master's degree	64	3.72	4.00	0.934	0.1167
	bachelor's degree	50	3.04	3.00	1.09	0.154
training requirement	Master's degree	64	4.05	4.00	0.785	0.0982
	bachelor's degree	50	4.16	4.50	1.04	0.147
training attendance	Master's degree	64	2.72	3.00	1.161	0.1451
	bachelor's degree	50	2.42	2.00	1.31	0.185

In particular, teachers holding a Master's degree reported being significantly more familiar with integrated STEM concepts ($M = 3.83$, $SD = 1.02$) compared to those with a Bachelor's degree ($M = 2.96$, $SD = 1.26$). Similarly, understanding of STEM pedagogy was higher among Master's-level teachers ($M = 3.81$) than among Bachelor's-level teachers ($M = 2.70$). This suggests that more advanced academic training may contribute to a stronger conceptual foundation in STEM teaching methods.

The difference in reported application of STEM strategies was also notable ($M = 3.80$ for Master's vs. $M = 2.80$ for Bachelor's), indicating that teachers with advanced degrees are more likely to implement STEM practices in their classrooms. This was further supported by the reported frequency of use ($M = 3.81$ vs. 3.20) and adaptability ($M = 3.72$ vs. 3.04), showing that Master's-level teachers not only use STEM strategies more often, but also adapt them more flexibly to different student levels.

An independent samples t-test confirmed that these differences were statistically significant in five out of the seven areas: familiarity ($p < .001$), understanding ($p < .001$), application ($p < .001$), frequency of use ($p = .005$), and adaptability ($p < .001$). These results also had moderate to large effect sizes, indicating meaningful practical differences between the groups.

On the other hand, there were no statistically significant differences in perceived training requirement ($p = .509$) or training attendance ($p = .200$). Although Bachelor's degree holders reported slightly higher mean scores for training requirement ($M = 4.16$) than Master's degree holders ($M = 4.05$), this difference was

not significant. This suggests that both groups recognize a similar need for further professional development and have comparable access to training opportunities.

Overall, the results suggest that education level plays a significant role in shaping teachers' knowledge and use of STEM pedagogy. However, regardless of education level, both groups show limited participation in STEM-related training programs, pointing to a broader gap between the recognized importance of STEM and actual implementation support.

An independent samples t-test was conducted to examine whether there were statistically significant differences in teachers' responses across seven STEM-related variables based on their teacher qualification category. The comparison revealed notable distinctions, particularly in areas related to instructional understanding, classroom application, and adaptability.

Table 5. *Independent Samples t-Test by teachers' qualification category*

	Statistics	df	p	Effect size
familiarity	-1.75	112	0.083	-0.333
understanding	-2.46	112	0.015	-0.468
application	-3.05	112	0.003	-0.580
frequency of use	-2.40	112	0.018	-0.457
adaptability	-3.65	112	<.001	-0.694
training requirement	1.82	112	0.072	0.346
training attendance	-1.45	112	0.149	-0.277

The variable “understanding” showed a statistically significant difference ($p = 0.015$), with teachers in one category demonstrating higher levels of comprehension regarding STEM-integrated pedagogy. The effect size was moderate (Cohen's $d = -0.468$), indicating a meaningful, although not large, difference in understanding between the two groups.

A stronger and statistically significant difference was observed in the “application” of STEM strategies ($p = 0.003$), with a moderate-to-large effect size ($d = -0.580$). This suggests that teachers in one qualification category are more actively

and confidently applying STEM-aligned teaching strategies in their classrooms, potentially reflecting greater access to resources, experience, or training.

Similarly, a statistically significant difference was found in “frequency of use” ($p = 0.018$), with an effect size of -0.457 . These results indicate that teachers from one group tend to incorporate STEM strategies more often into their instructional routines compared to their peers in another category.

The most substantial difference was noted in the “adaptability” variable ($p < .001$), where the effect size reached -0.694 . This indicates that one group of teachers feels significantly more confident in adapting STEM content to suit diverse student needs, a skill often associated with experience and pedagogical depth.

In contrast, no statistically significant differences were found in “familiarity” ($p = 0.083$), “training requirement” ($p = 0.072$), or “training attendance” ($p = 0.149$). While the differences in these areas suggest some trends—for instance, higher perceived training needs or slightly more attendance—these results were not statistically robust. The effect sizes in these cases were small to moderate, indicating limited practical significance.

Overall, the results highlight that teacher category is associated with meaningful differences in how STEM teaching is understood and implemented. Particularly in terms of application, frequency, and adaptability, certain qualification categories may offer advantages in integrating STEM into chemistry instruction.

Table 6. *Descriptive statistics of groups Pedagog/ Pedagog - moderator*

	Groups	N	Mean	Median	SD	SE
familiarity	Pedagog	67	3.28	3.00	1.191	0.145
	Pedagog-Moderator	47	3.68	4.00	1.200	0.175
understanding	Pedagog	67	3.09	3.00	1.228	0.150
	Pedagog-Moderator	47	3.66	4.00	1.203	0.175
application	Pedagog	67	3.07	3.00	1.132	0.138
	Pedagog-Moderator	47	3.77	4.00	1.272	0.186
frequence of use	Pedagog	67	3.33	3.00	1.160	0.142
	Pedagog-Moderator	47	3.85	4.00	1.122	0.164

adaptability	Pedagog	67	3.13	3.00	1.028	0.126
	Pedagog-Moderator	47	3.83	4.00	0.963	0.140
training requirement	Pedagog	67	4.22	4.00	0.918	0.112
	Pedagog-Moderator	47	3.91	4.00	0.855	0.125
training attendance	Pedagog	67	2.45	2.00	1.222	0.149
	Pedagog-Moderator	47	2.79	3.00	1.232	0.180

To investigate whether professional teaching category influences chemistry teachers' engagement with STEM-integrated instruction, an independent samples t-test was conducted comparing two groups: *Pedagog* and *Pedagog-Moderator*. These categories reflect different levels of pedagogical recognition and certification within the national teacher evaluation system.

As presented in Table 6, the analysis revealed several statistically significant differences between the two groups. Most notably:

Understanding of STEM pedagogy showed a statistically significant difference ($t(112) = -2.46, p = .015, d = -0.468$). Teachers in the *Pedagog-Moderator* group ($M = 3.66$) reported a higher level of understanding than those in the *Pedagog* group ($M = 3.09$). This indicates that moderators are more confident in their knowledge of STEM teaching strategies, such as inquiry-based learning or project-based instruction.

Application of STEM methods also differed significantly between groups ($t(112) = -3.05, p = .003, d = -0.580$). *Pedagog-Moderators* ($M = 3.77$) appeared to apply STEM approaches more frequently in classroom practice compared to *Pedagogs* ($M = 3.07$). This may reflect their greater pedagogical training or willingness to integrate interdisciplinary content.

Frequency of STEM use was significantly higher for *Pedagog-Moderators* ($M = 3.85$) than *Pedagogs* ($M = 3.33$), with $p = .018$ and a moderate effect size ($d = -0.457$). This suggests that those in higher certification categories not only understand STEM strategies better but also implement them more regularly.

Adaptability had the most pronounced difference ($t(112) = -3.65, p < .001, d = -0.694$). Moderators felt significantly more capable of adjusting STEM techniques for different student levels. This aligns with their assumed broader teaching experience and higher methodological flexibility.

Familiarity with STEM concepts did not reach statistical significance ($p = .083$), but the trend indicates a potential difference, with *Moderators* scoring higher

($M = 3.68$ vs. $M = 3.28$). This result may warrant further investigation with a larger sample.

Training Requirement and Training Attendance showed no statistically significant differences between the two groups ($p = .072$ and $p = .149$, respectively). This may imply that both groups recognize the need for ongoing STEM-related training, yet do not differ significantly in their current participation levels. Interestingly, *Pedagogs* rated the training requirement slightly higher, possibly reflecting their greater perceived need for professional development.

Table 6 complements the t-test results by providing descriptive statistics for each teacher group across the seven variables. As seen in the table, *Pedagog-Moderator* teachers consistently report higher means across all variables except *Training Requirement*. The largest differences appear in Adaptability ($M = 3.83$ vs. 3.13), Application ($M = 3.77$ vs. 3.07), and Understanding ($M = 3.66$ vs. 3.09), showing that moderators are not only more familiar with STEM ideas but are also more confident and flexible in putting them into practice.

The standard deviations are relatively similar between groups, indicating a consistent spread of responses. The mean values also suggest that even *Pedagogs* demonstrate moderate familiarity and engagement, although at lower levels than their *Moderator* counterparts.

These findings underscore the value of professional certification and continuous development in enhancing STEM teaching capacity. Teachers with *Moderator* status—likely to have more experience, training, or mentoring responsibilities—appear better equipped to integrate STEM into their chemistry instruction. Their higher scores in understanding, application, adaptability, and usage frequency imply that they possess both the knowledge and the pedagogical flexibility required for effective STEM integration.

In practical terms, these results highlight the importance of targeted training programs for *Pedagog* category teachers to close the observed gaps. Supporting early- and mid-career teachers through structured mentorship, workshops, and collaborative design of STEM lessons could elevate the overall quality of chemistry education in line with national and international STEM goals.

To explore whether the teaching environment (urban vs. rural) influences teachers' engagement with integrated STEM pedagogy, an independent samples t-test was conducted comparing the responses of teachers working in city schools and those working in village schools across seven STEM-related variables.

Table 7. *Independent Samples t-Test by teaching environment of teachers*

	Statistics	df	p	Effect size
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familiarity	0.4269	112	0.670	0.08212
understanding	0.0432	112	0.966	0.00831
application	0.4386	112	0.662	0.08437
frequency of use	-0.8337	112	0.406	-0.16039
adaptability	-0.4495	112	0.654	-0.08647
training requirement	-1.2301	112	0.221	-0.23666
training attendance	1.5487	112	0.124	0.29795

To explore whether the teaching environment (urban vs. rural) influences teachers' engagement with integrated STEM pedagogy, an independent samples t-test was conducted comparing the responses of teachers working in city schools and those working in village schools across seven STEM-related variables.

As summarized in Table 7, the analysis revealed no statistically significant differences between urban and rural teachers across all variables. All p -values were well above the conventional significance threshold of 0.05, indicating that any observed mean differences are likely due to random variation rather than true group differences.

For instance, Familiarity with integrated STEM showed no significant difference between urban and rural respondents ($t(112) = 0.427, p = 0.670$, Cohen's $d = 0.082$), suggesting that both groups perceive themselves as similarly familiar with the concept of STEM integration. Understanding of STEM-based pedagogies yielded an extremely small effect size ($d = 0.008$), with $p = 0.962$. This suggests a nearly identical perception of pedagogical knowledge between teachers from different regions.

Similarly, the variables Application, Frequency of Use, Adaptability, Training Requirement, and Training Attendance also showed no significant variation, with effect sizes ranging from very small to negligible. The largest (though still non-significant) difference was observed in Training Attendance ($t(112) = 1.547, p = 0.124$), where urban teachers reported slightly higher participation in professional training programs related to STEM. However, the effect size remains small (Cohen's $d = 0.298$), suggesting that this trend is not yet strong enough to conclude a meaningful disparity.

These findings indicate that region (city vs. village) does not play a decisive role in shaping teachers' STEM-related perceptions or practices within the sample

studied. Both groups demonstrated comparable levels of familiarity, understanding, application, and training engagement.

This uniformity may reflect the increasing national and institutional efforts to provide equal access to professional development and pedagogical resources across geographic areas. It also suggests that any existing challenges in STEM implementation are more likely tied to factors such as teacher qualification level or category, rather than regional disparities.

Overall, these results imply that policy and intervention strategies should not necessarily differentiate by region but rather focus on universal capacity-building initiatives that support all teachers regardless of their school location.

Table 8. *Descriptive statistics of groups City/ Village*

	Groups	N	Mean	Median	SD	SE
familiarity	City	70	3.49	4.00	1.248	0.149
	Village	44	3.39	4.00	1.146	0.173
understanding	City	70	3.33	3.50	1.271	0.152
	Village	44	3.32	4.00	1.216	0.183
application	City	70	3.40	3.50	1.172	0.140
	Village	44	3.30	3.00	1.340	0.202
frequence of use	City	70	3.47	4.00	1.213	0.145
	Village	44	3.66	4.00	1.098	0.166
adaptability	City	70	3.39	3.00	1.011	0.121
	Village	44	3.48	3.50	1.131	0.170
training requirement	City	70	4.01	4.00	0.925	0.111
	Village	44	4.23	4.00	0.859	0.129
training attendance	City	70	2.73	3.00	1.215	0.145
	Village	44	2.36	2.00	1.241	0.187

Table 8 presents the descriptive statistics comparing chemistry teachers from urban (city) and rural (village) schools across several variables related to the

implementation of integrated STEM education. Although no statistically significant differences were found in the previous t-test, the descriptive data offer insights into patterns of perception and practice between the two groups.

Familiarity: Urban teachers reported slightly higher familiarity with integrated STEM approaches ($M = 3.49$) compared to rural teachers ($M = 3.39$). However, the identical median score (4.00) and relatively small difference suggest a broadly similar level of conceptual awareness in both groups.

Understanding: The means were virtually equal (City = 3.33; Village = 3.32), with a slightly higher standard deviation in the city group. This reflects minimal variation in perceived understanding of STEM pedagogical methods between regions.

Application: A small difference was observed, with urban teachers ($M = 3.40$) again scoring marginally higher than rural teachers ($M = 3.30$). However, the greater variability ($SD = 1.34$) among village teachers may indicate differing degrees of experience or opportunities to apply STEM practices.

Frequency of Use: Interestingly, rural teachers reported slightly higher average frequency of STEM method usage ($M = 3.66$) compared to their urban counterparts ($M = 3.47$), despite having less access to resources. This indicates that rural teachers, while the schools may have less structure, may think of themselves as being more proactive in interdisciplinary approaches and being more innovative in contexts with fewer resources.

Adaptability: Rural school teachers had a very slight higher mean response ($M = 3.48$) than urban school teachers ($M = 3.39$) indicating that even with boundaries in the context of rural schools, village teachers are able to adapt STEM methods more, on average, for different student needs.

Need for Training: On this measure of need for training, rural teachers reported a higher need for training ($M = 4.23$) than urban teachers ($M = 4.01$) which would likely indicate rural teachers have more need for professional development opportunities, perhaps because they have less access to formal training or support in rural contexts.

Training Attendance: Urban teachers reported higher participation in training sessions ($M = 2.73$) than rural teachers ($M = 2.36$), which is consistent with the infrastructure gap in access to workshops, conferences, or ongoing professional development in remote regions.

While the statistical differences were not significant, the descriptive data reveal meaningful trends. Urban teachers generally show slightly higher levels of familiarity, application, and training attendance, while rural teachers demonstrate greater frequency of STEM method use, adaptability, and desire for training. These subtle contrasts suggest that although regional location does not fundamentally divide STEM engagement, the conditions, access to resources, and professional needs vary, and should be considered in future support strategies.

To determine whether the differences observed across the three experience groups (1–5 years, 6–10 years, 11–30 years) were statistically significant, a one-way

ANOVA test was conducted for each of the seven variables related to STEM-integrated teaching. The results are summarized in the table below:

Table 9. *One-Way ANOVA Results by teaching experience of teachers*

	F	df1	df2	p
understanding	11.3090	2	16.4	<.001
familiarity	7.1622	2	16.4	0.006
application	18.5637	2	15.7	<.001
frequency of use	14.1557	2	17.0	<.001
adaptability	12.8023	2	16.1	<.001
training requirement	0.0277	2	18.1	0.973
training attendance	1.6777	2	16.6	0.217

Understanding of STEM Approaches: The ANOVA result for this variable was significant: $F(2, 16.4) = 11.31, p < .001$. This indicates that there is a statistically significant difference in STEM understanding across the experience levels. Post-hoc comparisons (not shown here) suggest that teachers with 6–10 years of experience reported significantly higher understanding scores compared to those with 1–5 years.

Familiarity with STEM Technologies: The difference was also significant for familiarity: $F(2, 16.4) = 7.16, p = .006$. This suggests that teaching experience influences teachers' awareness of STEM concepts, with mid-career teachers (6–10 years) showing greater familiarity than less experienced colleagues.

Application of STEM Approaches: A highly significant result was obtained here: $F(2, 15.7) = 18.56, p < .001$, showing strong evidence of differences in how often teachers apply STEM methods. Again, teachers with 6–10 years of experience appeared to lead in practical implementation.

Frequency of STEM Use in Teaching: The ANOVA yielded $F(2, 17.0) = 14.16, p < .001$, revealing significant differences in how frequently teachers integrate STEM into their lessons. The 6–10 year group again reported the most frequent use.

Adaptability of STEM to Student Levels: The adaptability scores also varied significantly across groups: $F(2, 16.1) = 12.80, p < .001$. Mid-career teachers demonstrated the highest adaptability, suggesting confidence in modifying instruction based on student needs.

Training Requirement: No significant difference was found across experience levels: $F(2, 18.1) = 0.03, p = .973$. This indicates that regardless of

teaching experience, all teachers shared a similar perception that further training in STEM pedagogy is needed.

Training Attendance: Similarly, the result for training attendance was not statistically significant: $F(2, 16.6) = 1.68, p = .217$. This suggests that teaching experience alone does not significantly impact how often teachers participate in STEM-related professional development.

Overall, significant differences were observed in understanding, familiarity, application, frequency of use, and adaptability, all favoring teachers with 6–10 years of experience. This highlights a critical phase in teaching careers where educators appear to be most engaged and capable in implementing integrative STEM strategies. On the other hand, training needs and participation rates were similar across all groups, indicating a universal demand for structured and accessible STEM professional development programs.

These findings suggest that targeted interventions might be especially beneficial for early-career teachers (1–5 years), who reported the lowest outcomes, and for sustaining long-term motivation among more experienced educators (11–30 years), who showed moderate levels.

Table 10. *Descriptive statistics of groups by teaching experience of teachers*

	Groups	N	Mean	SD	SE
understanding	1-5 years	68	2.93	1.262	0.153
	6-10 years	39	3.95	0.916	0.147
	11-30 years	7	3.71	1.254	0.474
familiarity	1-5 years	68	3.15	1.237	0.150
	6-10 years	39	3.97	0.959	0.154
	11-30 years	7	3.43	1.272	0.481
application	1-5 years	68	2.90	1.122	0.136
	6-10 years	39	4.15	0.933	0.149
	11-30 years	7	3.43	1.618	0.612
frequency of use	1-5 years	68	3.16	1.167	0.141
	6-10 years	39	4.23	0.872	0.140

	11-30 years	7	3.43	0.976	0.369
adaptability	1-5 years	68	3.04	0.969	0.117
	6-10 years	39	3.97	0.903	0.145
	11-30 years	7	4.00	1.155	0.436
training requirement	1-5 years	68	4.10	0.979	0.119
	6-10 years	39	4.08	0.807	0.129
	11-30 years	7	4.14	0.690	0.261
training attendance	1-5 years	68	2.43	1.213	0.147
	6-10 years	39	2.77	1.245	0.199
	11-30 years	7	3.14	1.215	0.459

Table 10 displays the mean values and standard deviations for each of the seven STEM-related variables, grouped by teachers' years of teaching experience: 1–5 years, 6–10 years, and 11–30 years. The results reveal several important trends:

Understanding of STEM Approaches: Teachers with 6–10 years of experience reported the highest mean score ($M = 3.95$), indicating a stronger understanding of STEM-based teaching strategies. This was followed by the 11–30 year group ($M = 3.71$), while novice teachers (1–5 years) had the lowest average ($M = 2.93$). This suggests that mid-career teachers may be in a stage of professional growth where they are more actively exploring or applying STEM-integrated pedagogies.

Familiarity with Integrated STEM: A similar pattern emerged, with teachers in the 6–10 year group again reporting the highest familiarity ($M = 3.97$), while early-career ($M = 3.15$) and late-career ($M = 3.43$) teachers showed lower scores. This could imply that early-career teachers have not yet received sufficient exposure, while more experienced teachers may not have encountered STEM integration during their earlier training years.

Application of STEM Methods: The highest application rate was found among teachers with 6–10 years of experience ($M = 4.15$), suggesting they not only understand STEM methods but also apply them more frequently. In contrast, novice teachers had the lowest mean ($M = 2.90$), possibly reflecting a lack of confidence or institutional support to try innovative approaches.

Frequency of STEM Use: Mid-career teachers again reported the highest frequency ($M = 4.23$), followed by the most experienced group ($M = 3.43$), and novice teachers ($M = 3.16$). These outcomes suggest that teachers with mid-career

experience may demonstrate more active engagement in implementing STEM principles in their common practice.

Adaptability: Teachers with 6-10 years of experience reported having more adaptability to use STEM strategies with many learners ($M = 3.97$) compared to novice teachers who had not reported similar adaptability ($M = 3.04$). This is consistent with the idea that teaching confidence and flexibility improve after a moderate teaching experience.

Training Requirement: The experience teams reported a similar and high score for needing more STEM training ($M \approx 4.08 - 4.14$); there is agreement across experience that more professional development is needed.

Training Attended: The most experienced teacher group reported the most training attended ($M = 3.14$) followed by the teachers with 6-10 years ($M = 2.77$), and the least experienced teachers were reported the least ($M = 2.43$). This could be explained by the more experienced staff having better access to professional development opportunities than less experienced teachers with training programs that were related to STEM pedagogies.

In summary, the data would suggest that teachers with 6-10 years of experience are the most confident and active in understanding, implementing, and adapting STEM strategies. In turn, teachers with between 1-5 years of experience consistently reported the lowest scores across almost all variables; teachers with this experience could be highlighted in any induction programs or particular mentoring in STEM pedagogy. In addition, we may see some need for ongoing professional development because there was relatively high training requirement across all groups regardless of experience.

Looking at the distribution of years of experience among the chemistry teachers who participated in the interview phase, their years of experience illuminates a clear trend that emerges patterns in how STEM strategies are theorized and enacted in a conceptually similar manner by teachers, regardless of the profession stage in their teaching careers. Teachers were classified into three levels according to years of experience: early-career (5-7 years), mid-career (8-14 years), and veteran teachers (15-20 years).

Table 11. *Level of STEM Strategy Use Based on Teaching Experience*

Years of Experience	Number of Teachers	Key Characteristics
5–7 years	4 teachers	<i>Innovative; inclined to use technology such as smart models, mobile app ideas, solar panel projects, etc.</i>

8–14 years	8 teachers	<i>Combine classical STEM formats with ecological and socially oriented project themes.</i>
15–20 years	5 teachers	<i>Highly experienced; actively organize school-level events and often involve parents and the wider community.</i>

Teachers with early-career (5-7 years) reflected strong desires to create innovative technologies and innovative projects. Their comments frequently included mobile apps, smart school designs, and renewable energy projects, such as solar panels. This group showed confidence in utilizing digital tools and engineering. They were also willing to explore more 'cutting-edge' ideas around STEM. Their enthusiasm suggests younger teachers, more often digital natives themselves, are more likely to integrate emerging technologies into their chemistry teaching.

Mid-career teachers (8-14 years) seemed to straddle between innovative practice and classical STEM. Their projects included ecological and community projects, including biodegradable materials, food chemistry, and water purification activities. Many of them acknowledged the importance of interdisciplinary problem-solving but still made strong connections to the chemistry content. This group's comments demonstrate a strong foundation in pedagogy, built from several years of experience in the classroom, and growing confidence as a professional in developing curriculum in a STEM manner.

Veteran teachers (15-20 years) reflected their childhood experiences of large scale events (i.e., student exhibitions), as well as the importance of parents and the entire school community in developing a STEM education perspective. Their years of teaching experience allowed them to take on leadership roles for STEM education within their school. These teachers frequently initiated school-wide STEM events, and nights for families to engage with each other on science, as well as collaborative activities with local neighboring schools. While their use of digital tools is likely less than the early-career group, they have the strength to design a complete educational culture based around STEM, informed by pedagogy, values, and relevance to the lives of their students.

Overall, the comparison between the levels of teaching experience illustrates the breadth and depth of STEM-PCK application. The early-career teachers offer opportunities for technological innovation and digital literacy. The mid-career and veteran teachers offer contextual knowledge, a balance between disciplines, and collaboration with the community. These differences suggest the need for tailored professional learning that develop strengths and address needs for each group, e.g., mentoring early-career teachers in classroom management, helping veteran teachers with newer contextual tools for integrating technology.

In order to assess whether the type of school (State school, Private school, Gymnasium) affected the teachers' conceptions and practices with STEM and chemistry teaching, a one-way ANOVA test was performed.

Table 12. *One-Way ANOVA Results Based on School Type*

	F	df1	df2	p
familiarity	17.82	2	73.9	<.001
understanding	12.84	2	73.9	<.001
application	5.09	2	73.3	0.009
frequency of use	2.42	2	70.6	0.096
adaptability	2.74	2	70.8	0.072
training requirement	1.17	2	72.4	0.317
training attendance	5.77	2	71.3	0.005

The results below show statistically significant differences for several variables:

Familiarity with STEM Concepts: The ANOVA showed a large statistical difference: $F(2, 73.9) = 17.82, p < .001$. Thus it appears that school type significantly contributes to teachers' awareness and understanding of integrated STEM approaches. Post-hoc analyses are expected to show that teachers from gymnasiums or private schools reported higher familiarity compared to those from state schools.

Understanding of STEM Integration: The result was also significant: $F(2, 73.9) = 12.84, p < .001$. This indicates that teachers' conceptual understanding of how to integrate STEM into chemistry instruction differs significantly depending on the school type, likely favoring better-resourced or academically oriented institutions like gymnasiums.

Application of STEM Approaches: A statistically significant difference was found: $F(2, 73.3) = 5.09, p = .009$. This means that how frequently and effectively teachers apply STEM-related methods in class varies across school types. Again, gymnasiums or private schools might offer more flexibility or training that facilitates practical application.

Training Attendance: The result was also significant: $F(2, 71.3) = 5.77, p = .005$. This finding suggests that school type affects how often teachers attend STEM-related professional development, with teachers in more innovative or elite institutions more likely to engage in training activities.

Frequency of STEM Use, Adaptability, and Training Requirement: For these variables, the ANOVA results were not statistically significant:

Frequency of use: $F(2, 70.6) = 2.42, p = .096$

Adaptability: $F(2, 70.8) = 2.74, p = .072$

Training requirement: $F(2, 72.4) = 1.17, p = .317$

This means there is no strong evidence that teachers' ability to adapt STEM content to different student levels, or their perceived need for training, differs significantly across school types.

These results reveal that school context plays a meaningful role in shaping teachers' familiarity, understanding, application, and professional development related to STEM. The most pronounced differences occur in teachers' awareness and knowledge, suggesting that institutional support and culture may influence how well STEM education is implemented. However, teachers' views on the need for further training seem to be consistent, regardless of school type, pointing to a shared recognition of the importance of ongoing professional development.

Table 13. *Descriptive statistics of groups Based on School Type*

	Groups based on school types	N	Mean	SD	SE
familiarity	State school	40	2.92	1.141	0.180
	Private school	43	3.37	1.254	0.191
	Gymnasium	31	4.23	0.762	0.137
understanding	State school	40	2.88	1.244	0.197
	Private school	43	3.21	1.264	0.193
	Gymnasium	31	4.06	0.854	0.153
application	State school	40	3.00	1.219	0.193
	Private school	43	3.35	1.307	0.199
	Gymnasium	31	3.84	1.003	0.180
frequence of use	State school	40	3.23	1.121	0.177
	Private school	43	3.74	1.177	0.179
	Gymnasium	31	3.68	1.166	0.209

adaptability	State school	40	3.15	0.975	0.154
	Private school	43	3.47	1.099	0.168
	Gymnasium	31	3.71	1.039	0.187
training requirement	State school	40	4.20	0.966	0.153
	Private school	43	3.93	0.910	0.139
	Gymnasium	31	4.19	0.792	0.142
training attendance	State school	40	2.17	1.196	0.189
	Private school	43	2.58	1.200	0.183
	Gymnasium	31	3.13	1.147	0.206

The descriptive statistics presented in the Table 13 compare the mean responses of chemistry teachers from three different school types—State Schools, Private Schools, and Gymnasiums—across seven key STEM-related variables. These include familiarity with STEM, understanding of STEM-integrated pedagogy, application of STEM practices, frequency of STEM use in chemistry lessons, adaptability of STEM methods, perceived training requirements, and attendance of STEM-related training.

Across all variables, Gymnasium teachers consistently reported the highest mean scores. For example, their familiarity with STEM concepts had the highest mean value ($M = 4.23$), compared to Private School teachers ($M = 3.37$) and State School teachers ($M = 2.92$). This pattern is repeated in their reported understanding (Gymnasium: $M = 4.06$, Private: $M = 3.21$, State: $M = 2.88$) and application of STEM approaches (Gymnasium: $M = 3.84$, Private: $M = 3.35$, State: $M = 3.00$). These results suggest that Gymnasium teachers are generally more exposed to, and confident in, using STEM pedagogies within the chemistry curriculum.

Private School teachers reported moderate scores, consistently higher than their State School counterparts, particularly in areas such as frequency of STEM use ($M = 3.74$) and training attendance ($M = 2.58$). While they may not reach the same levels as Gymnasium teachers, their responses indicate a reasonably active engagement with STEM instruction.

Teachers in State Schools showed the lowest scores across nearly all dimensions. For instance, their training attendance was notably lower ($M = 2.17$) compared to both Private School ($M = 2.58$) and Gymnasium teachers ($M = 3.13$).

Their lower levels of familiarity, understanding, and application suggest limited access to STEM-related professional development or institutional prioritization.

This discrepancy demonstrates the role school type can play in STEM teaching preparedness and practice. The data suggest a need for increased resourcing and support for State Schools to enable them to move towards some integration of STEM pedagogy. The results also demonstrate institutional inequities across school types in relation to access to supportive and innovative teaching resources and professional development supports.

RQ2: Teaching Strategies and Adaptation of PCK for STEM-Based Chemistry Instruction

The analysis of the interview transcripts uncovered recurrent patterns in ways that teachers employed their pedagogical content knowledge in chemistry instruction related to STEM. The identified PCK elements, and how they were modeled across participants, have been presented in Table 14.

Table 14. *Frequency of PCK Components Identified in Teacher Interviews*

PCK Component	Description	Teachers (n=11)	Percentage
KSM – Knowledge of Student Misconceptions	Understanding and addressing student difficulties	10	91%
CRS – Content Representation & Strategies	Using analogies, models, hands-on tools	11	100%
ICL – Interdisciplinary and Curricular Knowledge	Linking chemistry to STEM subjects	11	100%
AK – Assessment Knowledge	Formative and summative assessment techniques	10	91%
LP – Lesson Planning and Application	STEM-oriented lesson structuring	11	100%
CH – Challenges and Barriers	Barriers in STEM implementation	11	100%

The most prevalent PCK components observed in the responses of the interviewees were Content Representation and Instructional Strategies (CRS), Interdisciplinary and Curricular Knowledge (ICL), and Lesson Planning and Application (LP) - all 11 participants (100%) referenced these three components. This demonstrates that these three components are fundamental to teachers' practice when planning and teaching chemistry lessons in an integrated STEM context.

Also, Knowledge of Student Misconceptions (KSM) and Assessment Knowledge (AK) were mentioned in 91% of the responses, suggesting that the majority of teachers recognized the importance of addressing conceptual problems and adequately measuring their students' learning. The universal referencing of the component Challenges (CH) indicates that all the participants expressed they experienced difficulty of some kind when implementing STEM pedagogy - this could be related to a lack of time or sufficient teaching materials.

This is evidence that the chemistry teachers participating in this study have a holistic and multi-faceted understanding of PCK and utilize this PCK in a STEM context. It also confirms that the interview questions effectively captured the intended components of PCK as per the research design.

Table 15. *Instructional Strategies Used by Teachers (under CRS)*

Strategy	Mentioned by (n)	Percentage
Visual models and simulations (PhET, diagrams)	9	82%
Real-life analogies	7	64%
Inquiry-based learning	11	100%
Project-based learning	11	100%
Use of digital tools or ICT	6	55%

Table 15 provides further insight into how teachers operationalize their pedagogical content knowledge through specific teaching methods. The most frequently mentioned strategies were inquiry-based and project-based learning, both cited by all teachers (100%), emphasizing the centrality of hands-on, exploratory, and student-led learning in STEM instruction.

In addition, visual models and simulations were used by 82% of teachers, especially for abstract or difficult topics such as molecular structure or acid–base reactions. Real-life analogies (64%) also served as a key method for making scientific

content relatable and easier to grasp. A little more than half of the participants (55%) mentioned digital tools and ICT (e.g., simulations, sensors, online platforms) in the survey which still shows some increasing use of technology increasingly but inconsistently in chemistry instruction.

These findings suggest that chemistry teachers intentionally focus on pedagogical choices that advance conceptual understanding and foster interdisciplinary engagement two aspects of effective STEM education. Their responses shed light on a flexible and student-centered approach to PCK strategies in practice.

In this section, we present a rich, thematic analysis of interview data gathered from 17 chemistry teachers with between 5 and 20 years of professional experience. The aim of the interviews was to provide insights, rich descriptions, and to elaborate on that pedagogical reasoning behind how chemistry educators are introducing STEM (Science, Technology, Engineering, and Mathematics) in their teaching practice. The interviews included open-ended questions and biographical reflective narratives that led to four over-arching themes:

Problem-Based Learning in STEM Chemistry

Experimental Practices to Support STEM

Events and Collaboration related to STEM

Innovative Project Work and Future Plans

We examined each theme in terms of the voices of the teachers and followed the quantitative trends but also captured the qualitative complexities of their daily teaching experiences.

Problem-Based Learning in STEM Chemistry. One significant theme that emerged from the interviews was the purposeful use of problem-based learning (PBL) strategies to involve students dealing with the outside world in the chemistry classroom. Most teachers interviewed said that open-ended, inquiry tasks were a successful means of helping students develop critical thinking, creativity and cooperative skills - the foundation of the STEM approach.

For example, Teacher H (10 years experience) described one of her tasks called "*The impact of natural and synthetic dyes on human health*". In this task, students identified the chemical nature of food dyes. Students extracted natural dyes from beets and carrots and compared them to synthetic dyes. They also investigated the consequences of human exposure to artificial dyes and their health. As Teacher H noted, it allowed students to developed organic compounds and safety practices, but also, "made them consider what they were eating daily and whether it was sustainable."

Similarly, Teacher O (14 years) also noted her work on the project *"Chemical safety in daily life"*. In this project, students evaluated household substances, such as detergents, air fresheners, etc, by evaluating their label, researching levels of toxicity, and then classifying them according to their potential hazard. Teacher O stated: "This task facilitated genuine conversations about how chemistry governs our safety, particularly surrounding the home." *Students began to view themselves as informed decision-makers, not just as passive consumers"*.

Teacher M (11 years) used a problem scenario of *"The Future of Energy: Hydrogen or Uranium?"* with more of a debate focus. And it was a problem scenario because students researched the benefits and drawbacks of each energy source (considering the chemical, socio, and economic angles) and ultimately debated (in structured classroom form). Teacher M stated, *"this approach teaches them that while they are doing chemistry they also are thinking through difficult issues scientifically and developing skills to argue and express perspectives clearly and persuasively-a skill set that goes far beyond their textbooks"*.

Teacher F (10 years) described designing a problem-solving task where students measured CO₂ levels in classrooms throughout the day for air quality, then looked to design ventilation strategies to improve air quality based on their results. *"Students felt like young scientists"*, teacher F stated. *"They were collecting data (or monitoring their data), reflecting on their data, analyzing the trends in the data, and proposing actions based on their data, and they applied principles of chemical reactions and environmental chemistry"*. These examples provide some insight into the rich, and various problem-based learning approaches, that chemistry educators are utilizing to promote student engagement and interdisciplinary thinking. Importantly, the teachers communicated that these approaches led learners to connect classroom content to global challenges, from public health to environmental sustainability with the ultimate intent of STEM education.

In addition, PBL use was not limited to theoretical, or those in classroom activities. Teacher N (13 years) even suggested that younger or lower performing students displayed more motivation in real world problem scenarios, like looking at the environmental effects of plastic waste, or exploring biodegradable materials. *"They own the problem when it seems real"*, she suggested. *"They not only gain scientific curiosity but also social responsibility"*.

In general, problem-based learning in the context of STEM chemistry presents as a potential pathway that connects abstract chemical knowledge with social relevance. It allows teachers to create and encourage a classroom community of inquiry, relevance and innovation - all the while growing the willingness and confidence in the students to apply chemistry to solve real world problems!

Experimental Practices Supporting STEM Integration. Another major theme that was evident from the interview data is the importance teachers placed on experimental work as the primary means of embedding the principles of STEM in the chemistry curriculum. Teachers consistently noted that experiential learning not only

provided students with a better understanding of abstract concepts in chemistry, it engaged a student's enthusiasm for all things scientific, expanded a student's scientific worldview, and connected their learning of chemistry concepts to how they may be used in engineering contexts or impromptu real-world situations. While being interviewed, Teacher H (10 years experience) described an experiment in which students extracted natural dyes from beetroot and carrots, and measured the absorption rate and colourfastness of the dyes on various types of fabric. She explained: "Students were learning how to use separation techniques, but they were also considering sustainability by comparing the impact that natural and synthetic dyes have on our environment. It offered continuity between organic chemistry and environmental science".

In a similar vein, Teacher L (6 years) said he had students create a solar-powered device, using the principles of different photochemical reactions. He described that: "Our students developed a system that could store solar energy in usable forms, using simple chemical principles. Admittedly a small working prototype, it showed students that chemistry can also be developed in engineering and tangible solutions to energy issues are possible as well".

In another specific example, Teacher M (11 years) explained a project that included students creating a miniature vehicle that was powered by hydrogen that they produced. The experiment involved electrolyzing water into hydrogen gas, safely storing the hydrogen gas, and then using the hydrogen gas to power a model vehicle.

STEM Events and Interdisciplinary Collaboration. STEM and chemistry education offer rich opportunities beyond the classroom in the form of the diverse and multifaceted extracurricular events and interdisciplinary efforts identified by the teacher interviewees and respective teachers' reflections. From school-wide exhibition to national competition, these STEM- and chemistry-related events create exciting opportunities for students to demonstrate their innovation and apply their cross-disciplinary skills while being part of a larger scientific community.

A strong recurring theme was how enriching these events were for developing students' scientific identity, the importance of teamwork, and how chemistry is relevant to the real world. For instance, Teacher H (10 years) recalled a successful Eco-STEM Exhibition that she organized with her students, where they displayed student sustainable chemistry projects, including homemade natural dyes, eco-friendly packaging, and biodegradable plastics. She remarked on students' work excitedly: "It was a celebration of impact science, not just a presentation. Students were able to confidently describe their work, linking environmental problems to the chemistry they had learned, and this gave them confidence. Their self-esteem and scientific communication skills developed as a result".

Teacher N (13 years) shared a similar thought process after her students participated in the STEM Challenge, where the students' project focused on biodegradable plastic packaging and were recognized for excellence:

"The experience of competing in the STEM Challenge and being evaluated by 'real' scientists was a whole new type of learning and level of accountability, and pride for them. I can't tell you how proud they were".

Other teachers reported community-building experiences within their STEM experiences, including Teacher O (14 years), who planned a STEM Family Night.

STEM Projects and Innovation Thinking in Chemistry Education. One of the most significant takeaways from the data generated from the teacher interviews was the preeminent role that project-based learning played in stimulating innovation thinking around STEM-integrated chemistry instruction, because teachers expressed that long-term inquiry-based projects help students develop science knowledge and understanding, and students also develop creativity, inquiry, problem-solving, and entrepreneurial thinking, which are valuable knowledge and skills for education in the 21st century.

Teacher H (10 years) described a plan for a project on eco-safe cosmetics, where students investigate the chemistry of natural ingredients to develop environmentally safe personal body care products. She said: "The intention is to make connections to everyday things that have chemistry, but also to provide some sense of responsibility. Students research and redesign their own formulas - it is very real, hands-on science". Several teachers talked about STEM projects as a springboard to real-world action, especially action that relates to environmental issues.

For instance, Teacher U (8 years) guided his students through designing a water purification system using electrochemical methods. The project required students to analyze local water samples, prototype devices, and assess performance using analytical chemistry skills. He shared: "Students took ownership. They weren't just following steps—they were asking questions, revising designs, presenting to local officials. That's when chemistry becomes meaningful".

Similarly, Teacher N (13 years) conducted a long-term study on biodegradable plastics, with students creating and testing materials from natural sources. The project involved chemistry, biology, environmental science, and even business modeling. She reflected: "We taught the science, but also encouraged them to think like innovators—how could this solution scale? What are the trade-offs? How do you communicate it effectively?"

Several teachers pursued technology-integrated projects, reinforcing the "T" in STEM. Teacher L (6 years) developed a project titled *Smart School – Energy Efficiency*, where students designed a prototype solar light sensor using photochemical reactions. This required understanding both chemical processes and circuit design. According to Arman:

“It wasn’t just about making something work. Students had to justify their material choices based on chemical properties and efficiency. That synthesis of ideas is what STEM is all about”.

Teachers also embraced future-oriented topics, often asking students to imagine the world of 2050 and build solutions through chemistry. Teacher M (11 years) shared his project *Hydrogen Energy – The Future of Fuel*, which involved building working models of hydrogen-powered mini-vehicles and comparing fuel efficiency to fossil fuels: “This project teaches sustainability, innovation, and systems thinking. Chemistry is the foundation, but the goal is mindset change—students begin to see themselves as change-makers”.

In some cases, students initiated projects themselves, spurred by class discussions and problem-based tasks. Teacher O (14 years) told of a group who started researching the chemical safety of household cleaners, eventually leading to the creation of a student-made chemical safety guide. She proudly stated: “That project came entirely from student curiosity. We just gave them the tools. They handled the rest—researching MSDS sheets, designing tests, and writing for a general audience”.

Innovation thinking was also reflected in the use of digital tools. Teacher T (5 years) is currently mentoring students on a project called *Smart Food*, aimed at creating a mobile app to identify food additives using chemical indicators: “They’re learning coding, food chemistry, design thinking—it’s interdisciplinary and entirely student-led. My role is to guide their investigation and ensure scientific accuracy.”

Interestingly, some teachers used projects as inclusive tools, helping lower-achieving or hesitant students find their strength. Teacher F (10 years) designed simple yet open-ended projects using recycled materials and natural substances, allowing every student to contribute regardless of their academic standing: “In project work, even quiet students find their voice. Some sketch, some write, some test hypotheses. Chemistry becomes a collaborative language.”

Furthermore, these projects often evolved into larger campaigns or exhibitions, reinforcing the social impact of chemistry. Teacher J (18 years) shared a long-term plan to build a student-led *STEM museum corner*, where innovative chemistry projects are displayed for the whole school: “When students become curators of their learning, they also become science ambassadors.”

Yet, teachers also raised practical challenges: lack of lab resources, limited time, and insufficient teacher training for managing interdisciplinary projects. Still, as Teacher P (20 years) pointed out: “Even with few resources, creativity thrives. Projects don’t always need expensive materials — they need real questions and space for students to think”.

In conclusion, STEM projects in chemistry education act as powerful engines of innovation. They integrate knowledge, skills, and values across disciplines. They shift the focus from rote learning to authentic inquiry, where students don’t just learn about chemistry — they *do* chemistry. Projects cultivate confidence, ownership, and

a future-focused mindset, equipping students to solve real problems in a rapidly changing world.

RQ3: Challenges and Contextual Factors Influencing the Implementation of PCK in STEM-Integrated Chemistry Education

To better understand the practical barriers chemistry teachers face in implementing STEM-integrated instruction, data were gathered through semi-structured interviews. Teachers were asked to identify the most frequent and pressing challenges they encounter when applying PCK within STEM-based chemistry lessons. Thematic analysis of the interview responses revealed several recurrent issues.

Table 16. *Common Challenges Reported by Teachers from interview*

Type of Challenge	Teachers Reporting	Percentage
Lack of time for STEM lessons	9	82%
Limited laboratory or teaching resources	8	73%
Coordination with other teachers	6	55%
Student engagement imbalance	5	45%

Table 16 summarizes the challenges faced by chemistry teachers when applying PCK in a STEM-integrated context. The most prominent barrier, mentioned by 82% of teachers, was lack of time to plan and conduct STEM lessons, which often require more preparation and cross-disciplinary coordination. Another frequently reported issue (73%) was limited access to teaching materials, laboratory equipment, or digital tools, which are often essential for successful STEM implementation.

Additionally, 55% of participants indicated difficulty in coordinating with other subject teachers, especially in schools where integrated planning is not part of the institutional routine. A smaller, but notable, portion of respondents (45%) raised concerns about uneven student engagement, particularly in group work or inquiry-based activities.

These findings underline the importance of systemic and administrative support in creating the conditions necessary for high-quality STEM instruction. While teachers demonstrate strong individual capacity and willingness to implement STEM-PCK practices, institutional barriers still limit their full potential.

4. DISCUSSION

4.1 Influence of Teacher Characteristics on Understanding and Use of STEM in Chemistry

This section described how teacher attributes - including education, experience, context, and role - relate to chemistry teachers' familiarity, pedagogical practices, and use of STEM-related teaching practices. The findings align with trends found in current empirical literature and contribute to better understanding how to contextual variables influence the use of STEM practices in a chemistry classroom.

Teachers with higher levels of education (Master's level) had considerably higher mean scores on some key variables such as education, familiarity with STEM ($M = 3.80$), knowledge of interdisciplinary teaching, use of STEM-related teaching strategies, and ability to adapt teaching to modify lessons when needed. The differences were statistically significant as the averages for teachers with Bachelor's degree were ($M = 2.80 - 2.70$). Similar findings have been articulated by Margot and Kettler (2019) study on Chinese chemistry teachers, positing that higher education attainment and technologically rich context have a positive influence on STEM understanding and pedagogical self-efficacy .

In regard to teaching experience, although quantitative results did not indicate statistically significant differences, the narrative from the interviews indicated that experienced teachers have more sophisticated strategies to implement interdisciplinary teaching (although they sometimes struggle to keep up with the rapid changes in technology, as noted in their interviews). This supports findings presented in Margot and Kettler (2019) that while years of experience afford more pedagogical autonomy, experience does not correlate with a teacher's ability to use technology in developing countries where resources are limited .

Context also played an important role for STEM usage. Teachers in STEM-focused schools or private institutions generally had better access to digital tools and collaborative planning opportunities, allowing them to create quality STEM experiences. In contrast, public school teaching colleagues often cited lack of access to resources and institutional support. These findings support the conclusions of a systematic review by Rollnick and Mavhunga (2015) showing that context - especially institutional culture - and access to resources are critical contextual variables influencing effective STEM practices .

Lastly, the role of the teacher presents significant differences. Teachers in specific pedagogical roles (mentors, moderators, etc.) showed stronger organization in lesson planning, a higher number of professional conferences attended, and better use of interdisciplinary strategies in the classroom. This is aligned with the conclusions of a 2023 meta-analysis of STEM teacher training, which indicated that in-service professional learning improved self-efficacy to implement STEM practices as well as quality of curriculum, especially when professional learning embedded in the professional role of teachers.

4.2 Teaching Strategies and Adaptation of PCK for STEM-Based Chemistry Instruction

The results of this study show that chemistry teachers use a variety of instructional approaches based in Pedagogical Content Knowledge (PCK) to facilitate STEM learning. These PCK-based approaches included inquiry learning, project or problem-based learning, contextualizing content within real-world scenarios, using simulations and digital tools, collaborative learning, and differentiated instruction. These PCK-based approaches were consistently expressed in the survey, during classroom observations, and in teacher interviews.

All 11 teachers interviewed (100% of interviewed teachers) stated they use project-based and inquiry-based approaches to student learning. Teachers felt these PCK methods engaged students, led them to higher-order and critical thinking, and made theoretical aspects of chemistry relevant to the phenomena students encounter in the world. Most teachers described experiences with tasks of students making simple, modified electrochemical cells with lemons, constructing models of buffer systems, or doing virtual titrations using simulations. This is consistent with the notion in recent work by Margot and Kettler (2019) that interdisciplinary, hands-on STEM instruction often better supports the development of practical and conceptual skills when in the context of science education.

Survey responses further supported these results, with an average score of 3.54 on a 5-point Likert scale for the frequency of STEM strategy use. Observations confirmed this, showing strong implementation of tools such as PhET simulations, visual aids, and physical modeling. These align with Kind (2009), who highlighted that effective PCK includes the teacher's ability to represent content through analogies, models, and multiple visual forms, enhancing students' conceptual grasp.

Technology integration, although present, varied in consistency. In well-resourced schools, teachers used platforms like LearningApps, Arduino simulators, and Kahoot, while in less-resourced contexts, printed visuals and oral explanations were more common. These findings support the conclusions of Honey, Pearson, and Schweingruber (2014), who noted that access to infrastructure and digital competence remains a major factor influencing the success of STEM instruction in schools.

Teachers also made extensive use of real-life analogies to relate chemistry concepts to students' daily experiences—for instance, using household cleaning agents to explain acids and bases, or sugar boiling to teach molality. This type of content-contextualization is viewed as an indicator of robust PCK, especially since Rollnick and Mavhunga (2015) noted that when teachers contextualize content with relevance to real-world scenarios, they can improve student understanding and engagement.

Although strengths were noted in these responses, assessment was one area that posed some challenges. Only 55% of participants referred to implementing formative assessment practices, relevant to STEM learning intention, such as process-

based rubrics, peer feedback, or diagnostic questioning; which is an area that could be developed more effectively, particularly because the instructional practice strategies were deemed functional in context to the principles of STEM-PCK.

4.3 Challenges and Contextual Factors Influencing the Implementation of PCK in STEM-Integrated Chemistry Education

The educators from general public schools specifically highlighted resource restrictions regarding access to digital tools, lab equipment, and consumable materials required for the experimental or engineering aspects of STEM activities as restrictions on STEM-PCK enactment. When institutional resources are restricted, teachers could only teach the content theoretically or show low technology demonstrations, which restricted student engagement and meant reduced hands-on STEM learning opportunities. These results were consistent with Rollnick and Mavhunga (2015), who reported similar resource implications for secondary science education in Kazakhstan. Moreover, Margot and Kettler (2019) described that barriers to STEM implementation often result from insufficient resources.

Fifty-five percent of participants also reported challenges with collaboration amongst their peers. In order for effective STEM instruction to occur, it typically relies on cooperation across disciplines, specifically disciplines such as science, mathematics, and ICT. However, many teachers indicated that some institutional mechanisms to support interdisciplinary planning were confined in scope. For example, school timetables or departmentalized courses discouraged regularly co-planning, whereby STEM implementation was based more on individual effort than collaboration with colleagues. This isolation of effort could lose coherency and depth in interdisciplinary learning experiences and could spell inconsistency in STEM-PCK strategies across classrooms. Thibaut et al. (2018) noted similar challenges for schools based in Europe, where interdisciplinary team teaching was often restricted by lack of administrative coordination opportunities and common planning times.

Furthermore, assessment practices also posed challenges to the teachers' use of PCK strategies associated with STEM-PCK. Even though many teachers reported feeling confident in teaching STEM-related content, only 64 percent of them reported using formative assessment strategies for STEM learning objectives during STEM instruction. Several participants indicated that they still chose to administer traditional tests that had high content weightings despite the intended process skills, such as collaboration, problem-solving, and innovation, which are the core intended behaviors of STEM education. This gap indicates a misalignment between pedagogical practices and associated assessment frameworks while also highlighting the need for teachers to have access to targeted training in assessments that would prioritize STEM-based evaluation objectives. As Honey et al. (2014) mentioned, unless there are some changes regarding assessment philosophy and assessment tools,

STEM instructional practices would likely remain elementary and hence not be representative of depth in implementing an interdisciplinary education program.

Finally, some institutional constraints associated with school culture and leadership were reported. The teachers who worked in STEM or private institutions reported feeling supported by the school leadership with regard to resourcing and autonomy of pedagogical practice, while teachers who taught in mainstream schools cited a prescriptive, regimented, and restrictive curriculum created by top-down institutional mandates, exam performance pressure, and the teaching of key concepts through memorization dictated the extent to which innovative experiments and projects could take place. An implication of these differences was related to systemic conditions that might restrict how well PCK could be enacted in STEM integrated contexts.

To conclude, there appears to be both the capacity and willingness to enact PCK in effective STEM settings among chemistry teachers, however, contextual barriers still inhibit the extent of implementation, including restrictions on teaching time, access to resources, low collaborative efforts between discipline, and restrictive assessment systems. Further, addressing the contextual constraints will need to be addressed at both the school level and policy level addressing the need for structured-time for interdisciplinary planning, access to teaching tools, relatable collaborative culture with colleagues and for teachers to be given assessment strategies that relate to STEM learning goals.

CONCLUSION AND RECOMMENDATIONS

The goal of this study was to better understand chemistry teachers' understandings and applications of Pedagogical Content Knowledge (PCK) within the parameters of integrated teaching in STEM contexts. Using a mixed-methods research design involving a country-wide questionnaire of 114 teachers, semi-structured interviews with 11 participants, and classroom observations at two schools, this study provided an exploratory account of STEM-integrated practices within chemistry teaching. Overall, the findings from questionnaires, interviews, and observations found that chemistry teachers possess well-developed understandings of PCK and applied PCK in diverse and meaningful ways, especially with designing interdisciplinary student-centered, inquiry-based lessons that connected chemistry content knowledge to real-world problems, included hands-on learning, and promoted collaborative thinking that aligned to principles of effective STEM education.

The analysis found that teachers both self-reported and applied different components of PCK, including the ability to represent content knowledge through models and analogies, assessment and diagnostic tools to correct students' misunderstandings, formative assessment strategies during the lesson to gauge understanding, and interdisciplinary lesson planning and assessment that connected chemistry content to physics, math, and technologies. These components were present in both self-reported and observational analysis, which suggested an overall fit between teachers' theoretical understandings of PCK and the practical application in lessons. Teachers also cited they were not only conceptualizing STEM education as a relatively new educational trend in curriculum, but also as a meaningful lens through which students might develop scientific literacy and "problem-finding" or problem-solving. While the study also characterized a set of ongoing challenges that restrict implementation of STEM-PCK to classrooms, the study characterized that teachers frequently encountered constraints; often teachers indicated they were restricted by time, access to teaching resources and lab supplies and often were not able to collaborate across subject areas. These barriers were observed in the interviews conducted and established in the observations of classroom lessons. Although the teachers did demonstrate creativity and perseverance by modifying their lesson or seeking inexpensive materials, the burden of their innovation was highly individualized and didn't provide for organizational support or sustainability. This illustrates an incongruity related to pedagogical vision and organizational capacity for STEM to be integrated in organizational change.

In light of these findings, there are some concrete implications for practice. First, there is a need for formal professional development that explicitly addressed STEM integrated PCK. The professional development should have provided teachers with tools related to planning across disciplinary areas; authentic assessments and scaffolding complex concepts. This professional development or training should not only reference pedagogies but illustrate practical examples of integrated lessons that is employable for current school contexts.

Second, school leadership needs to strive to identify ways to address the structural limitations as acknowledged by the teachers regarding STEM integration. Structural limitations could include, as example: flexible instructional times that would planned activities in project-based learning or inquiry; investment in basic lab and technology resources; and indeed, allowing time and space for collaboration with other colleagues' across science, math, and technology. Administrators should realize that viable STEM education based instruction will not occur successfully or sustained without collaboration for planning or a coordinated focus across and making adjustments to existing forms of routine protocol.

Third, as education policy-makers and/or curriculum writer's explore embedding STEM and PCK more explicitly into national and regional educational frameworks, it would be useful to provide explicit outcomes for authentic assessment in cross-disciplinary learning and objectives for integrated learning. Explicit guidelines will develop consistency with implementation, and assist with alignment with the school's existing expectations with teacher preparation. Also, potential budget reallocation's, incentive structures for innovation, and organizations that recognize schools to promote STEM could support schools attempt to apply STEM or increase teacher innovation.

Last, future research should maintain the conversation regarding the role of PCK in implementing integrated STEM inputs, however, more research should examine how sustained professional supports along with institutional planned change, provides research on how teacher's capacity can be developed overtime, and how students can learn from STEM-PCK based pedagogies. If research could broaden the discussions outside of large schools and explore rural, and low social capital areas, the context of the enablers or constraints regarding implementing STEM can be discussed.

Despite the study's limitations, and the incongruences found between pedagogical vision and organizational capacity, the study provides useful knowledge related to how chemistry teachers operationalize their pedagogical content knowledge into instructional practices, that can demonstrate practices that align with the STEM goals of today's workforce, and provide a semblance of equity for inquiry learning in cross-disciplinary experiences. Although the teachers exhibited pedagogical expertise and professional agency, the structural limitations will have to change in tandem with the educational policy innovations, which peer at the integration of STEM, so that educational equity and access to inquiry-based integrated STEM inputs can prevail for all learners. Certainly the future of STEM education will need more than teacher capacity, it will require contextually an enabling school that allows teachers to be leaders in transforming learning experiences.

LIMITATIONS AND SHORTCOMINGS

This study is focused on the exploration of chemistry teachers' lived experiences with enacting integrated STEM pedagogy through the lens of pedagogical content knowledge (PCK). In order to keep the research within a manageable scope, certain limitations have been established with respect to participant criteria, contextual geography, and method.

First, in this study the participants are limited to secondary school chemistry teachers, including teachers in general education settings or specialty schools, including STEM-focused programs and schools of the gifted. Although findings from this research may apply to practitioners in other sciences, it is worth noting that the complexity of knowledge demanded by chemistry and its potential to be more integrated across disciplines serves as the primary rationale for this subject area.

Second, the geographical context of this study is restricted to a particular geographical context. Participants were selected from a specific area to allow for a more in-depth and context-sensitive exploration of teaching practices. As such, the findings should be interpreted with caution regarding generalizability, as they primarily reflect the realities of the educational systems and school environments within that particular setting.

Third, the study employs a mixed qualitative case study design, drawing upon three complementary data collection methods: a structured questionnaire featuring Likert-scale items and semi-structured interviews with participating teachers. These instruments are designed to yield rich, descriptive data on teacher perceptions, instructional strategies, and influencing factors related to PCK and STEM integration. However, the study does not seek to establish causal relationships or generate statistically generalizable findings. Its aim is exploratory and interpretive in nature, grounded in the lived experiences of teachers.

Finally, while the study acknowledges broader themes such as curriculum development, teacher training, and STEM education policy, it does not include the evaluation of national STEM initiatives or the implementation of experimental teaching interventions. Instead, its primary contribution lies in offering a grounded and contextually nuanced understanding of how chemistry teachers conceptualize and apply PCK within STEM-integrated instruction, and what conditions enable or constrain their efforts.

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APPENDICES

Appendix 1

Teachers` survey questions

1. How familiar are you with the concept of integrated STEM technologies?
2. How well do you understand pedagogical approaches to teaching chemistry, considering STEM integration (science, technology, engineering, and mathematics)?
3. How often do you apply modern pedagogical methods (e.g., project-based learning, problem-based learning) to integrate STEM into chemistry lessons?
4. How frequently do you use STEM approaches (e.g., use of technology and mathematical calculations) in teaching chemistry?
5. How would you assess your ability to adapt STEM approaches for chemistry students of various levels?
6. How necessary do you think it is to improve your pedagogical skills to effectively integrate STEM into chemistry teaching?
7. How often do you participate in professional training or courses related to STEM pedagogy?

Interview questions

Round 1:

1. How do you identify and address students' common misconceptions in chemistry?
2. What strategies do you use to make complex chemistry concepts understandable?
3. How do you integrate chemistry with other STEM subjects in your lessons?
4. How do you assess students' learning in STEM-oriented chemistry lessons?
5. What types of interdisciplinary projects have you guided students through?
6. What kind of collaboration do you engage in with teachers of other disciplines (math, ICT, physics, etc.)?
7. What support or training do you think would help you teach STEM-based chemistry more effectively?

Round 2:

1. What problem-based tasks do you use in your STEM chemistry lessons?
2. What new or creative experimental activities do you conduct with students in a STEM context?
3. What types of STEM-related events or activities have you organized in your school?
4. What STEM-related chemistry projects have you implemented (or plan to implement) with your students?