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How Can Evidence-Based Teacher Education Promote Relevant Chemistry Learning Through Teachers' Professional Agency?

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Abstract

Fostering teachers' professional agency is central to promoting relevant chemistry learning, as it enables future teachers to design accurate, evidence-informed and meaningful learning in a rapidly changing scientific landscape. This article summarises 25 years of evidence-based chemistry teacher education (EBTE) within the LUMA co design ecosystem. Situated in the Department of Chemistry, the Chemistry Teacher Education Unit collaborates closely with scientists and co designs pedagogical content knowledge (PCK) and Technological Pedagogical Content Knowledge (TPASK) courses that are both scientifically up to date and pedagogically effective. Developing strong PCK grounded in chemistry research, chemistry education research and classroom practice, strengthens scientific literacy, enabling teachers to translate often complex chemical ideas into accessible and relevant forms for learners. The EBTE model connects theory and practice, supports cross boundary collaboration and prepares research-oriented designer teachers for the demands of modern science, sustainability, digitalisation and AI. Co design within the co-design-based research (CoDBR) framework enhances teachers' professional, relational and epistemic agency by enabling research informed development and fostering close collaboration with chemists and societal partners through LUMAlab Gadolin. Agency driven co design within the LUMA ecosystem can build the capacity of student teachers, practising teachers and students to engage confidently with contemporary chemistry, and contribute to a scientifically literate and sustainable future.

Keywords: scientific literacy; chemistry education; teacher education; co-design; PCK; TPACK; professional agency; relational agency; epistemic agency; evidence-based practice; LUMA ecosystem; digitalisation; AI in education

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1. Introduction

Modern society requires scientifically literate citizens and future chemistry specialists capable of responding to increasingly complex global challenges. National priorities outlined in the Finnish LUMA Strategy 2030 emphasise strengthening STEM competence, promoting research-based teaching and supporting collaboration across educational levels and societal sectors. Internationally, the OECD's recent policy orientations highlight scientific literacy, interdisciplinary competence and agency as essential capabilities for navigating societal change (OECD, 2026). Promoting such competence demands chemistry teachers who can design relevant, accurate and evidence informed learning environments.

Supporting teachers' professional agency is a central aim of Finnish teacher education and essential for fostering a sustainable and future oriented society (Finnish Teacher Education Forum, 2025). In chemistry teacher education, professional agency refers to teachers' capacity to make intentional, evidence based and ethically grounded pedagogical decisions, and to co-design both their teaching and professional learning in chemistry.

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Figure 1 presents the LUMA co-design ecosystem embedded in our evidence-based teacher education (EBTE) framework. Professional, relational and epistemic agency sustain iterative design cycles that develop dynamic, evidence based PCK/TPACK. The model places student centred pedagogy at its core and supports teachers in becoming reflective, research oriented “designers of the future.”

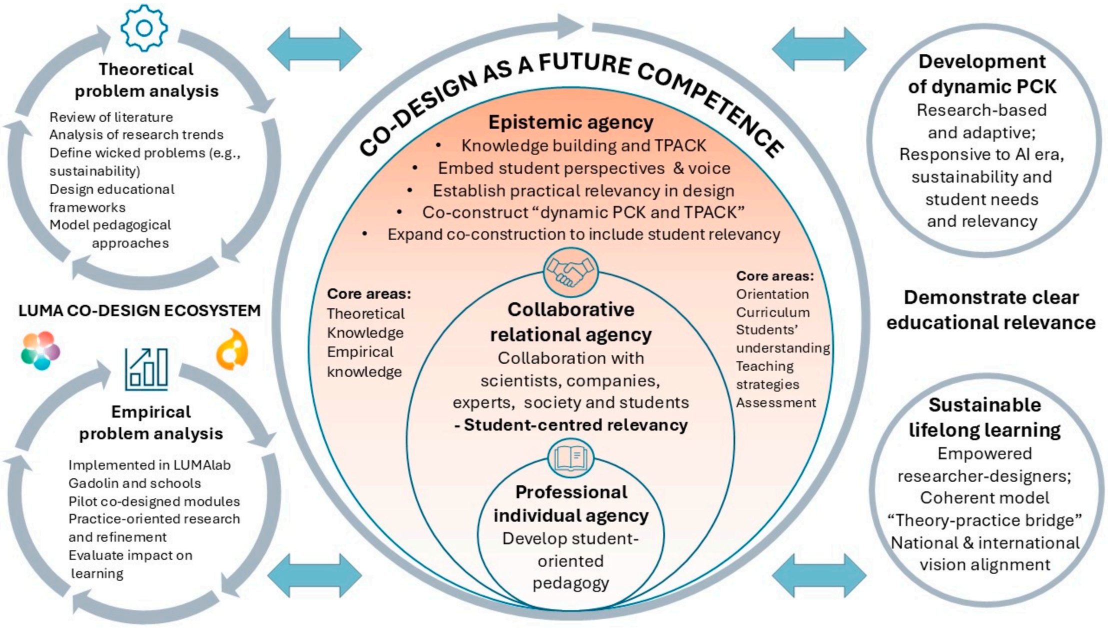

Figure 1. The LUMA co-design ecosystem within the EBTE model. **Note**: The EBTE visualization illustrates how professional, relational, and epistemic agency support collaborative design cycles that develop dynamic, evidence-based PCK/TPACK.

The ecosystem encompasses collaborative work carried out in LUMAlab Gadolin (Aksela et al., 2024, 2025) as part of the broader national LUMA (STEM) network (Aksela et al., 2018). Epistemic and relational agencies underpin the collaborative nature of co-design. Edwards (2017) emphasizes that relational expertise, common knowledge and purposeful joint action enable professionals to recognise and mobilise expertise across institutional boundaries. Such boundary-crossing collaboration is central to authentic Third Spaces such as LUMAlab Gadolin (Aksela et al., 2025), which provide research-informed environments for developing future-oriented chemistry learning. These non-formal STEM contexts have been shown to strengthen pre-service teachers’ professional growth and identity development (Haatainen et al., 2024).

The design-based research (DBR) approach (Edelson, 2002) has guided our teacher-education and research programmes for more than two decades (Aksela, 2005, 2019; Pernaa, 2013; Pernaa et al., 2022; Vuorio et al., 2025). Co-design-based research (CoDBR) can support the development of professional, relational and epistemic agency across formal and non-formal contexts (see Section 3). These iterative design processes promote evidence-based practice and prepare teachers to use emerging technologies in ethically grounded and pedagogically meaningful ways. The integration of digital tools – including molecular modelling, microcomputer-based laboratory (MBL) systems and artificial intelligence (AI) – strengthens design cycles by broadening available disciplinary representations while upholding professional and ethical judgement (Aksela, Pernaa, & Roiha, 2026).

Within our evidence-based teacher education (EBTE) model, co-design functions as a core future competence through which student teachers and/or practicing teachers collaboratively address pedagogical challenges and refine instructional decisions. These iterative design cycles build dynamic PCK and TPACK, as teachers integrate disciplinary chemistry knowledge, pedagogical reasoning and research evidence to create conceptually accessible chemistry learning. Because the

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Unit is located within the Department of Chemistry, student teachers and teachers benefit from direct engagement with chemists and contemporary chemical research, strengthening their disciplinary foundations and supporting the relevance of school chemistry teaching.

Taken together, the EBTE model rooted in co-design; dynamic PCK and TPACK; and teachers' professional, relational and epistemic agency equips chemistry teachers to act as "makers of the future." By linking chemistry research, chemistry-education research and classroom practice, the model supports the creation of meaningful, sustainable and research-informed chemistry education in an AI-rich world.

2. Evidence-Based Teacher Education (EBTE) Model

Since 2001, the Unit of Chemistry Teacher Education at the University of Helsinki has developed a coherent, evidence-based, and student-centred teacher education model aimed at preparing collaborative, reflective and research-oriented chemistry teachers (Aksela, 2010; Pernaa, Haatainen & Aksela, 2025). Established as the first unit of its kind within a Department of Chemistry in Finland, the programme embeds evidence-based teacher education directly within a scientific faculty. This positioning enables close integration of disciplinary chemistry expertise, pedagogical knowledge and societal collaboration, and forms a strong foundation for research-oriented and design-oriented teacher professionalism (Figure 2).

The EBTE model emerged in response to national educational needs—notably a shortage of qualified chemistry teachers and concerns about the quality and relevance of chemistry education in Finland. Within this model, "theory" encompasses both disciplinary chemistry and research on chemistry teaching and learning, together with systematic engagement with research methods in chemistry education. Research-based reasoning is intentionally woven throughout the curriculum so that evidence-informed decision-making becomes a continuous thread across the programme. Section 2.1 provides a detailed description of the curriculum and its chemistry education courses.

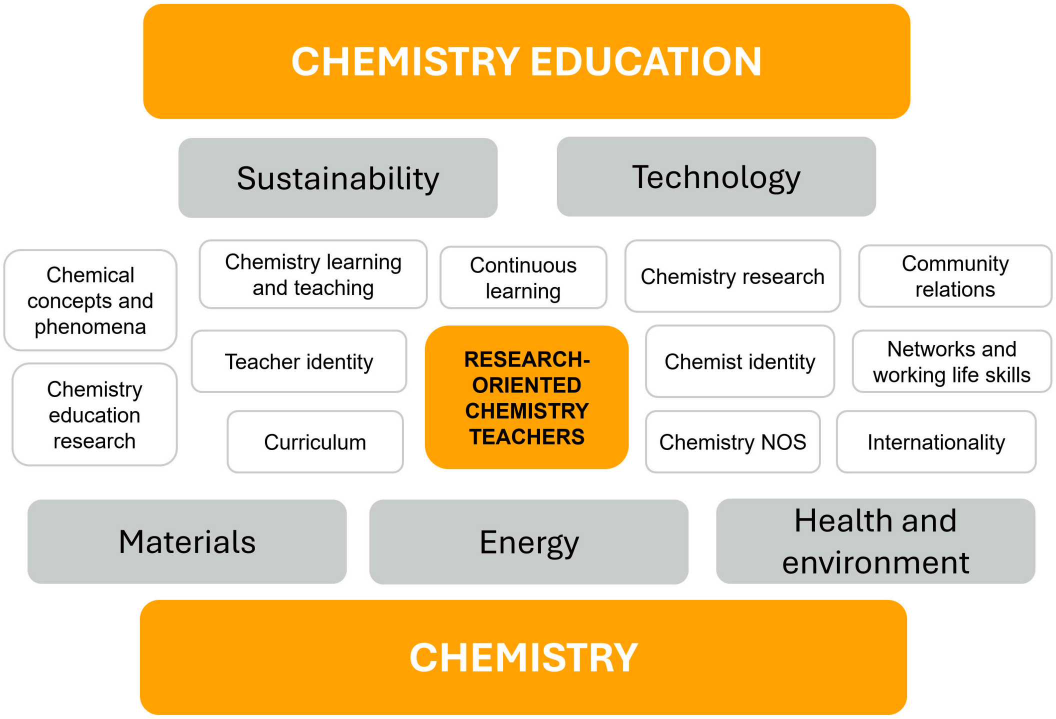

Figure 2. Research-oriented chemistry teacher (Pernaa, Haatainen et al., 2025).

Most studies of the programme are undertaken within the Faculty of Science over a four-year period, with pedagogical studies delivered during the M.Sc. phase at the Faculty of Educational

Sciences. A coherent structure of disciplinary chemistry, chemistry education and pedagogical studies supports the development of dynamic PCK and TPACK and teacher agency across the five-year programme. Figure 3 illustrates the curriculum structure and highlights the shared responsibilities of university-based and school-based partners.

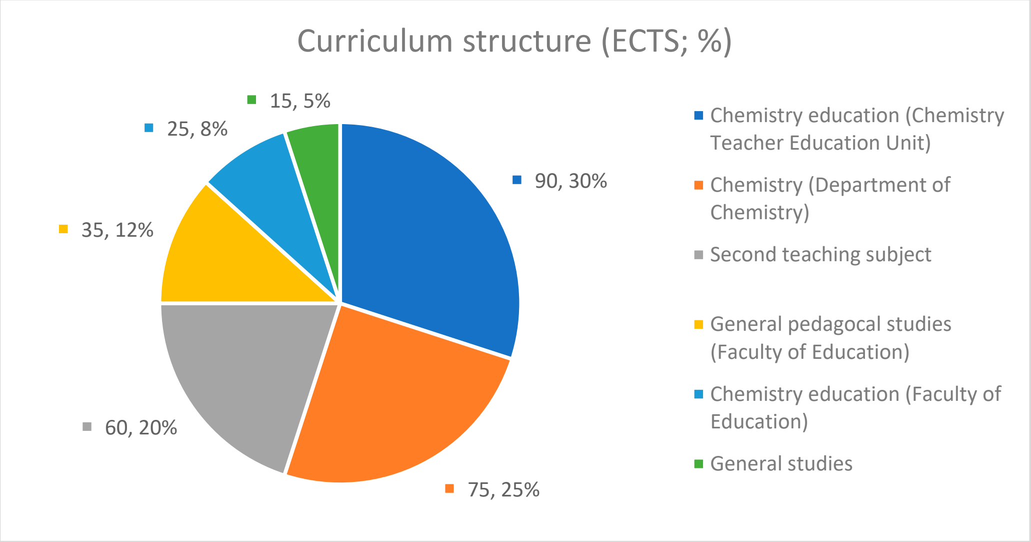

Figure 3. Curriculum structure for chemistry and chemistry education.

Students may enter the programme either directly after upper-secondary education or through the B.Sc. programme in Mathematics, Physics and Chemistry Teacher Education in the Faculty of Science. Throughout their studies, prospective teachers engage with advanced disciplinary chemistry, evidence-based pedagogical courses and collaborative design activities that support the development of professional identity, relational and epistemic agency, and research-oriented practice.

To date, approximately 500 chemistry teachers have graduated with chemistry as either a major or minor subject—often combined with biology, physics or mathematics—alongside 16 completed doctoral degrees and 10 ongoing doctoral projects in chemistry education. This sustained development of both agency and dynamic PCK demonstrates the long-term impact of the EBTE model within the Department of Chemistry and the wider national LUMA ecosystem. In addition, various in-service training models are developed and organised in collaboration with LUMAlab Gadolin and a range of partners since year 2001, for example during the Chemistry Education Days.

2.1. Promoting PCK/TPACK Through Chemistry Education Curriculum

The EBTE model integrates theory and practice through a co-design approach (see Section 3), which serves as a central mechanism for developing the dynamic Pedagogical Content Knowledge (PCK) and Technological Pedagogical Content Knowledge (TPACK) required for relevant chemistry education. The curriculum positions student teachers as reflective, research-oriented designers who use evidence to improve teaching through iterative cycles of design, enactment, analysis and redesign.

The chemistry teacher education programme comprises 300 ECTS credits, including a 180-credit B.Sc. degree and a 120-credit M.Sc. degree, in accordance with national requirements that all teachers in Finland hold a master’s degree. Over the years, we have continuously co-designed the curriculum and chemistry education courses based on the latest research, national priorities and systematic student feedback (Pernaa, Haatainen & Aksela, 2025). This iterative development has ensured that both PCK and TPACK remain aligned with advances in chemistry, sustainability challenges and emerging technologies.

The updated chemistry education courses for 2026–2029 are presented in Table 1. The Unit of Chemistry Teacher Education unit is organizing the most PCK in chemistry education courses at Department of Chemistry. Pedagogical studies (60 ECTS) are delivered by the Faculty of Educational Sciences and include two supervised teaching practice periods in the University of Helsinki's Training Schools.

Table 1. Chemistry education courses for 2026–2029 and credits.

#	Level	Course	Year
1	BSc	Introduction to Chemistry Teacher Education (5 ECTS)	1
2	BSc	Inquiry-based Chemistry Education (5 ECTS)	2
3	BSc	Concepts and Phenomena in Chemistry Education (5 ECTS)	2
4	BSc	Information and Communication Technology in Chemistry Education (4 ECTS)	3
5	BSc	Sustainability chemistry and circular economy (5 ECTS)	3
6	BSc	Bachelor's thesis and Seminar (6+1 ECTS)	3
7	BSc	Science Education: Integrated STEM (5 ECTS)	1–3
8	BSc	Contemporary Science and Future of Research (5 ECTS)	1–3
9	MSc	Integrated Chemistry Education (5 ECTS)	5
10	MSc	Sustainability in Chemistry Education (5 ECTS)	5
11	MSc	Master's thesis and Research Seminar (30+5 ECTS)	5

Within this coherent EBTE model, the chemistry education (PCK) courses mediate advanced university chemistry for school contexts by transforming disciplinary content into conceptually accessible and meaningful learning experiences. These courses help teachers interpret complex chemical structures, models and explanations in ways that align with school students' representational and developmental levels. Without such PCK-driven mediation, teachers may struggle to meet learners' needs, as Johnstone (1981) observed that teachers and students often operate at different representational levels and therefore fail to 'meet' each other conceptually.

Close collaboration with chemists also strengthens the holistic orientation of the EBTE model (Figure 4), which emphasizes teachers' ability to translate between macroscopic, submicroscopic and symbolic representations of chemical phenomena (Johnstone, 1991) and to connect these representational levels with broader sustainability perspectives (Aksela, Pernaa, & Haatainen, 2026). Embedding the Nature of Science (NOS) in this work deepens students' understanding of chemistry as a dynamic, evolving and societally relevant discipline. This representational and epistemic fluency enables teachers to design learning experiences that support societal decision-making, ethical reflection and global responsibility.

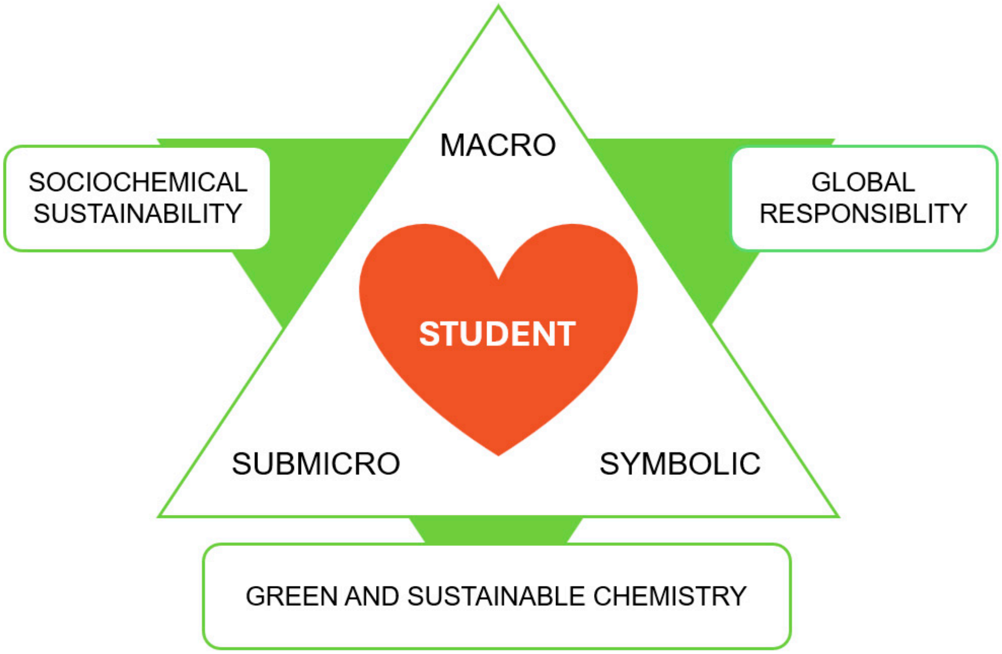

Figure 4. Holistic and student-centred approach towards a sustainable future through our chemistry teacher education.**Note:** In our holistic model, the student occupies the centre of the triangle, learning to translate between macroscopic, submicroscopic and symbolic levels through dynamic PCK.

2.2. Dynamic PCK, TPACK of Evidence-Based Teacher Education

Pedagogical content knowledge (PCK) provides the theoretical foundation for teachers' pedagogical reasoning (Shulman, 1986). It encompasses the professional knowledge required to transform complex chemistry into accessible, coherent and meaningful learning experiences. In chemistry education this work is especially demanding, as teachers must help learners navigate macroscopic phenomena, submicroscopic particulate models and symbolic chemical representations—forming the representational triad described in Johnstone's (1982) macro–submicro–symbolic framework.

Recent empirical evidence strengthens the importance of PCK for learning outcomes. She et al. (2025) demonstrated that science teachers' PCK is significantly and positively associated with student achievement. These findings further underscore the need to develop dynamic, evidence-based PCK within chemistry teacher education.

Contemporary chemistry education also demands an expanded understanding of PCK through TPACK, which accounts for digitalisation, artificial intelligence and sustainability transformations in the discipline. In our program, TPACK is integrated across curriculum courses and specialized modules in digitalization (Aksela, Pernaa, & Roiha, 2026). TPACK clarifies how technological tools—such as molecular modelling software, dynamic visualisation platforms, digital laboratory tools (MBL), simulations and AI-supported systems—interact with pedagogy and disciplinary content (Koehler & Mishra, 2009). Through this integration, teachers learn to design instruction that is both conceptually rigorous and technologically sophisticated, ensuring responsible, student-centered and future-oriented use of digital tools (Pernaa, Haatainen, et al., 2025).

Table 2 presents the five core domains of PCK as used within our EBTE model, which guide teachers in analyzing learners' prior conceptions, designing representationally coherent instructional strategies and using diagnostic assessment to support conceptual understanding.

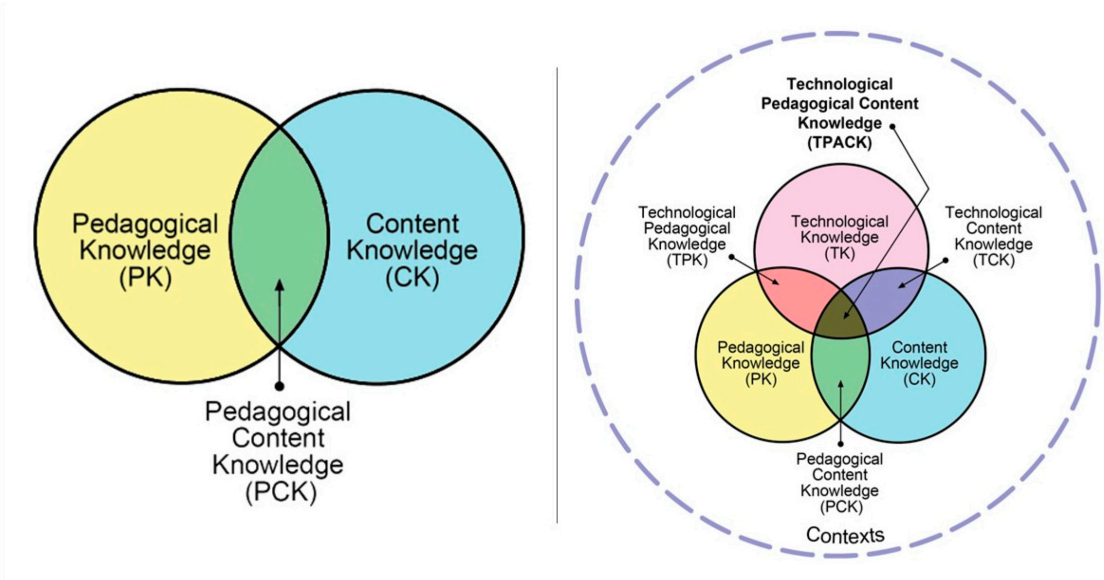

Figure 5. PCK and TPACK used in the EBTE model.**Note 1:** PCK is commonly represented using three intersecting circles (CK, PK and PCK). Content knowledge (CK) in chemistry is developed through the chemistry courses offered in the Department of Chemistry, while pedagogical knowledge (PK) is cultivated through the educational studies provided by the Faculty of Educational Sciences.

Note 2: TPACK diagram reproduced by permission of the publisher, ©2012 by tpack.org.

Table 2. Five core domains of PCK in the EBTE model (Magnusson et al., 1999).

PCK Domain	**Example of applying each domain in chemistry education”**
1. Orientations toward science teaching	Promote development of teachers’ aims, values and beliefs, inquiry-based strategies, relevance-focused approaches and professional networking.
2. Knowledge of curriculum	Understanding conceptual progressions and curricular structures across educational levels per each central concept.
3. Knowledge of students’ understanding (KSU)	Teach future chemistry teachers how to use latest empirical methods and research literature to identify insights into learners’ prior knowledge, representational difficulties and alternative concepts.
4. Knowledge of teaching strategies & representations (KISR)	Selecting and adapting student-centred teaching strategies: models, simulations, analogies and inquiry approach to support representational coherence.
5. Knowledge of assessment	Designing diagnostic and formative assessments that reveal conceptual understanding.

Within our student-centered EBTE model, PCK development places particular emphasis on two chemistry-specific domains developed at the Department of Chemistry:

1. Knowledge of Students’ Understanding (KSU): insights into learners’ prior conceptions, representational difficulties and alternative conceptions in chemistry.

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2. Knowledge of Instructional Strategies and Representations (KISR): selecting and adapting student-centred teaching strategies: particulate models, visualizations, inquiry tasks, analogies and simulations to support representational coherence.

2.2. Concepts and Phenomena in Chemistry Education Course as an Example

The Concepts and Phenomena in Chemistry Education course illustrates how the PCK and TPACK frameworks, together with CoDBR, are operationalized within the EBTE model. Developed continuously since 2001 (Aksela, 2010), the course has evolved through iterative co-design cycles, drawing on the latest research in chemistry education, national priorities and systematic student feedback. As one of the foundational chemistry education courses, it exemplifies how dynamic PCK develops when disciplinary chemistry, pedagogical reasoning and evidence-informed design are purposefully integrated.

A central focus of the course is representational fluency. Student teachers work with macroscopic, submicroscopic and symbolic representations, deepening their understanding of the macro–submicro–symbolic triangle and learning to design instructional strategies that support representational coherence. These activities explicitly enact several PCK domains listed in Table 1 – particularly KSU and KISR. Through guided inquiry tasks, model-based reasoning, molecular-level visualisations and diagnostic activities, student teachers practise transforming complex university-level chemistry into forms accessible to secondary learners.

The course nowadays includes several types of practical course assignments starting from getting to know the history and epistemic relevance of chemistry education research (CER) (Gabel, 1999; Taber, 2018; Teo et al., 2014). After getting to know the research field, the focus shifts to chemistry curricula and how they are applied Finnish chemistry textbooks. The evolution of textbooks explored from translated chemistry textbooks from the 1800s to modern day electronic learning materials (Aksela & Pernaa, 2017) that gives TPACK an excellent context. Next, the course focuses on PCK through higher-order thinking skills promoted by different kind of chemistry exercises (Aksela, 2005; Tikkanen, 2010). After the basics students start operationalizing central chemistry concepts (e.g., orbitals, bonding, reactions, equilibrium, structure, electrochemistry, acid and bases and periodic table). Altogether, the course includes 15 concepts across the curricula selected using previous research literature. The amount of delimited to 15 concepts due the 5 ECTS (135 hours) working hour limitation. The development PCK and TPACK needed in teaching each concept are promoted by individual information seeking, group work, reflective writing, teaching and peer evaluation assignments. Evidence-based research-oriented strategies are implemented throughout the course via previous research literature and CER research methods. For example, students conduct a case study where they measure conceptual understanding (Holme et al., 2015). In addition, a vital part of the course is to start building professional networks to academia and education field which are also integrated in course exercises by attending National Chemistry Days or other similar events offered each year.

Through this combination of disciplinary depth, evidence-based design, and authentic enactment, the Chemistry Concepts and Phenomena course demonstrates how EBTE, PCK, TPACK and CoDBR operate together to prepare reflective, research-oriented and future-ready chemistry teachers. The course also plays a central role in establishing student teachers' professional identity as chemists and educators and serves as an early bridge between university-based studies and the boundary-crossing practices strengthened throughout the program.

3. Co-Design as the Engine of the EBTE Model

As depicted in Figure 1, professional, relational and epistemic agency form the foundations of research-oriented teachers' design activity in our EBTE model, while CoDBR provides the iterative method that links theory and collaboration to sustained improvements in practice and the development of dynamic PCK/TPACK. In this framing, co-design is not merely a pedagogical technique: it is understood as a future competence, a methodological approach, and a capacity-building process enacted across the chemistry education curriculum and within the wider national LUMA ecosystem (Pernaa, Haatainen & Aksela, 2025).

This chapter places Table 3 (see section 3.1) at the centre as the empirical core that demonstrates how the mechanism illustrated in Figure 1 operates in practice. In line with Edelson's (2002) design-research model – characterizing educational design through *problem analysis*, *design solution*, and *design process* iterated in authentic settings—our cases show how co-design yields both robust pedagogical innovations and transferable theoretical insight. Within the Finnish LUMA ecosystem, co-design can be orchestrated across multiple stakeholders through staged DBR processes that bridge research and classroom practice at scale (Aksela, 2019). Table 3 presents concrete examples of how these processes unfold across different courses and contexts.

Consistent with Figure 1, our CoDBR cycles make the three forms of agency visible in purposeful action.

- Professional agency emerges as participants articulate intentions, make principled pedagogical choices and aim to influence student-centred learning and curriculum design.
- Relational agencies become evident when participants recognise, mobilise and integrate the expertise of chemists, teacher educators, peers and partners across boundaries within the LUMA co-design economy.
- Epistemic agency appears as participants justify decisions with evidence, interrogate models and representations, and iteratively refine their designs to meet students' representational and conceptual needs.

Small-scale co-design tasks (e.g., inquiry activities, modelling tasks, representational materials, teaching materials, chemistry exercises) are designed, enacted with students or teachers, and refined through evidence (see Table 3 from section 3.1). These cycles move outputs from initial prototypes to robust practices and, in some cases, to thesis-level research and resource banks. This illustrates the dual move described by Edelson (2002): generating usable solutions while simultaneously refining domain and design knowledge through iteration. Student teachers co-design and test representational activities and refine their instructional decisions based on this evidence. These CoDBR cycles allow them to experience how disciplinary and pedagogical evidence can be systematically used to develop dynamic PCK.

Many of the design activities in Table 3 are situated in LUMAlab Gadolin, our authentic third space where school groups, chemists, teachers, and industry specialists collaborate (Aksela et al., 2025). Gadolin enables: (i) enactment with real students; (ii) rapid evidence collection through artefacts, interviews and observations; and (iii) boundary-crossing collaboration with scientists, teachers and wider societal actors (such as companies, science centres and museums). These interactions strengthen relational and epistemic agency, aligning with the community-oriented co-design processes described by Aksela (2019).

3.1. Evidence of Co-Design in Action

Table 3 summarises how co-design is embedded from entry-level courses to master's theses and illustrates the types of outcomes produced across these collaborations—from family-science activities and research-informed materials to outreach models, thesis outputs and open online resources.

Table 3. Empowering student teachers and teachers in relevant chemistry education using the co-design approach in chemistry education courses and thesis work since year 2001. The solutions and materials are suitable for integration into the school curriculum.

Course	Co-designers and co-designing	Solution/product
Introduction to Chemistry Teacher Education	A practical component of the course: Student teachers co-designed inquiry activities in small groups based on research, guided these	Evidence-based activities for family science education

	activities during the Jippo days for families, and reflect on the feedback received.	
Chemistry Concepts and Phenomena	A practical component of the course: Student teachers co-design inquiry activities in small groups based on research, guide them during the Chemistry Days for teachers, and reflect on the feedback as part of the DBR cycle.	An evidence-based material bank with activities for upper-secondary chemistry education.
Chemistry in Environment	A practical component of the course: co-design of science-club activities for project-based learning with student teachers, schoolteachers and science-club students. Feedback also from family members (Aksela & Haatainen, 2025).	Students' project outputs and posters. Materials produced by student teachers A novel in-service training model enabling teachers to test ideas and later transfer them into their own lessons
Chemistry in Society	A practical component of the course: Co-designing a curriculum plan with student teachers, schoolteachers, industry specialists and international student teachers; learning through shared collaboration (Kousa et al., 2018).	Models for collaboration with the schools and industry Learning activities
Information and Communication Technology in Chemistry Education	Co-designed with collaborators such as other academics. One major focus in the course is molecular modelling that covers almost 25 years co-design period.	Software such as edumol.fi and learning material (Pernaa et al., 2017)
Sustainability chemistry and circular economy	Course co-designed with a chemistry professor and science educators in the Department of Chemistry.	A co-designed course plan
Integrated Chemistry Education	The course was co-designed with university partners such as University of Ljubljana and Aalto University (Ambrož et al., 2023; Pernaa, Ambrož, et al., 2025).	A co-designed course plan and assessment tools
B.Sc. and M.Sc. theses and seminars	Practical component of the thesis: co-designing new experimental activities with scientists and transforming authentic research into learning materials through LUMAlab Gadolin, followed by testing these materials	E.g., ionic liquid activity and materials for it

	during school visits as part of the DBR cycle (Pernaa et al., 2022).	
Natural sciences and society online courses within the LUMA ecosystem: Chemistry as science and in society; Stars and Space; Geosciences and sustainability	Co-designing online courses with specialists and partner organisations (e.g., around 50 research chemists, industry chemists and industry partners).	Free online courses accessible to all, with a particular focus on teachers, student teachers and youth.
AI LUMA online forum for chemistry teachers within the LUMA ecosystem	Course content co-designed with teachers according to identified needs.	Evidence-based teaching strategies (PCK) for using AI and related activities.
LUMA Stars programme within the LUMA ecosystem	Online clubs co-designed with upper-secondary students who visited research groups in the Department of Chemistry. In collaboration with the Unit.	Online LUMA Science Clubs and evidence-based materials.

The co-design across cases follows a common structure:

1. Problem analysis: identifying curricular, representational, or contextual needs informed by theoretical and empirical knowledge in chemistry and chemistry education.
2. Design and enactment: developing and trialing solutions in LUMALab Gadolin, schools or outreach events.
3. Evidence collection: gathering data from student responses, artefacts and feedback. Refinement: updating materials or models, revising tasks and preparing new implementations.
4. Product/solution: resource banks, course artefacts, thesis outputs, MOOC materials.
5. Dissemination: published materials, teacher training resources and scientific papers.

CoDBR can increase: (i) teacher empowerment—a shift from consumers to co-creators and increased confidence in teaching complex, research-based and digitally supported content (including AI-mediated representations), (ii) shared expertise—co-designed resources circulate across Gadolin, schools, teacher events and online platforms, (iii) dynamic PCK/TPACK development—representational strategies, inquiry tasks and diagnostic tools are refined through empirical feedback; and (iv) coherence—university theory and school practice are linked through the same design–enact–analyse–redesign logic depicted in Figure 1.

Finally, CoDBR can sustain long-term professional learning by integrating theoretical reasoning with empirical inquiry, strengthening relational networks across the LUMA ecosystem, and enabling teachers to refine PCK dynamically while using digital and AI tools ethically and pedagogically. In this sense, CoDBR acts as the engine of coherence in the EBTE model – the iterative process that keeps agency, design and knowledge growth tightly coupled over time, as envisaged in Figure 1 and articulated in Edelson's (2002) design-research paradigm.

4. Discussion

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This study synthesises 25 years of research-based chemistry teacher education within the LUMA ecosystem, showing how collaborative EBTE, dynamic PCK/TPACK and Co-Design-Based Research (CoDBR) provide a coherent and future-oriented foundation for supporting chemistry teachers for sustainable lifelong learning. Consistent with Figure 1, professional, relational and epistemic agency underpin teachers' design activity, enabling them to interpret pedagogical challenges, use evidence purposefully and create meaningful chemistry learning environments. The findings highlight the crucial role of structured co-design in supporting relevance, inquiry and representational fluency in contemporary chemistry education.

Across the LUMA ecosystem, co-design processes bring together student teachers, practising teachers, chemists, science educators and societal partners. Such collaboration strengthens professional agency, as participants learn to make intentional, ethical and research-informed pedagogical decisions, and enhances relational agency by enabling teachers to draw upon diverse expertise when designing conceptually relevant chemistry teaching. Co-design also develops epistemic agency: teachers evaluate explanations, interrogate models and justify instructional decisions using evidence in chemistry and its education.

Authentic learning environments, particularly LUMAlab Gadolin, serve as third spaces where theory and practice converge. These environments allow student teachers to design and trial inquiry tasks, modelling activities and representational strategies with real learners, while gathering empirical evidence to refine their pedagogical reasoning. Such boundary-crossing collaboration mirrors the multi-stakeholder co-design logic described by Aksela (2019) and strengthens teachers' relational and epistemic agency by deepening their understanding of learners' representational challenges.

The collaborative dimension of EBTE extends beyond pre-service contexts. Sustained participation in Gadolin activities, CoDBR projects and LUMA programmes fosters ongoing professional learning communities, providing opportunities for peer mentoring, shared innovation, collective reflection and cross-sector collaboration. Within these networks, teachers refine their dynamic PCK/TPACK and develop resilient professional identities grounded in evidence-based practice.

Throughout the EBTE model, PCK/TPACK forms the conceptual backbone of curriculum design and pedagogical reasoning. Iterative CoDBR cycles – moving from problem analysis to design, enactment, evidence collection and refinement – provide a coherent method for developing dynamic PCK. As shown in Table 3, these cycles enable student teachers or teachers to design representational tasks, inquiry activities and real-world learning environments that respond to learners' needs and curricular aims. The iterative nature of this process aligns with Edelson's (2002) view of design research as a method that produces practical innovations while refining theoretical understanding. This dual process sustains the evolution of dynamic PCK across contexts and career stages.

5. Conclusions

This article describes that collaborative, evidence-based chemistry teacher education characterised by co-design, dynamic PCK/TPACK, and professional, relational and epistemic agency can provide a sustainable foundation for preparing future-ready chemistry teachers. Co-design offers rich opportunities for modelling, representation, inquiry and feedback, while LUMAlab Gadolin support the refinement of pedagogical innovations in research-informed settings.

Our long-term experience shows (i) dynamic PCK/TPACK strengthens when grounded in iterative, evidence-based co-design; (ii) teacher judgement and agency remain central to designing conceptually coherent chemistry learning; (iii) Third-Space collaboration is essential for linking theory to practice; (iv) professional learning communities sustain growth across pre-service and in-service contexts; and (v) CoDBR acts as the methodological engine that maintains coherence between university knowledge and school-based practice.

When enacted through the EBTE model, co-design becomes a powerful means for cultivating reflective, research-oriented and socially responsible chemistry teachers capable of contemporary chemistry education. Ultimately, dynamic PCK/TPC developed through collaborative EBTE and evidence-based co-design can equip teachers to act as "makers of the future", contributing to sustainable, meaningful and research-informed chemistry education in a rapidly changing world.

In addition, the EBTE model directly supports the central aims of the Finnish LUMA Strategy 2030, the OECD's recent policy orientations, and the Finnish Teacher Education vision. By strengthening student teachers' professional, relational and epistemic agency, the model advances the LUMA Strategy's emphasis on research-based STEM competence, cross-sector collaboration and sustainable development. Likewise, the OECD's call for scientifically literate, future-ready learners—capable of working with interdisciplinary knowledge, digital tools and AI in ethically grounded ways—is enacted through the iterative development of dynamic PCK/TPACK and evidence-informed co-design. The model also embodies the Finnish Teacher Education vision for 2050, which highlights teachers' agency, reflective professionalism and the ability to co-design meaningful learning with diverse partners. Taken together, our findings demonstrate that the EBTE model provides a concrete pathway for realising these national and international policy goals within chemistry teacher education.

Furthermore, the EBTE model aligns with the contemporary view of chemistry as a dynamic and continuously advancing research discipline. By engaging student teachers with current chemical research, modern laboratory practices, emerging technologies and authentic representational tools, the model strengthens their ability to translate cutting-edge scientific developments into pedagogically meaningful forms. This orientation ensures that chemistry is not presented as a static body of knowledge but as an evolving scientific enterprise, thereby supporting research-informed, conceptually coherent and societally relevant chemistry education.

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