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Entry

Evidence-Based Research-Oriented Chemistry Teacher Education

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Definition: Chemistry teachers are the main agents for change towards sustainability. There is a great need for skilled chemistry teachers, which are the key agents in inspiring young people into chemistry and promoting a sustainable future. This article describes a novel model program of evidence-based research-oriented chemistry teacher education developed and applied at the University of Helsinki, Finland. The program produces research-oriented chemistry teachers (ROCTs). An ROCT has two professional identities, as a chemist and as a chemistry teacher. Both identities require extensive knowledge of chemistry and comprehensive understanding of chemistry as a science. Therefore, the most important competence of an ROCT is chemistry education research. Chemistry education is an independent research area of chemistry that builds the chemistry educational expertise that binds together the domains of chemical and pedagogical knowledge. This article describes how the development of both professional identities is supported through our current research focus areas, which are sustainable chemistry and modern technology. It will explain, for example, the degree structure, courses and research-based development strategies. Also, the article introduces the ways in which design-based research strategies are conducted collaboratively with the national and international chemical research community and the whole society, including stakeholders such as the chemical industry, schools, teacher associations, and museums. Overall, the novel evidence-based ROCT education program model described in this article can serve as a valuable example for teacher education curriculum development around the world.

Keywords: chemistry education research; teacher education; study program; professional identity

1. Introduction

High-quality chemistry education is extremely important, and this requires chemistry teachers with an extensive knowledge of chemistry and a comprehensive understanding of chemistry as a science. Chemistry is a versatile and rapidly evolving science. It is a massive research field with one of the world's largest industrial sectors – the chemical industry supports over 120 million jobs worldwide [1]. Chemical research is highly multidisciplinary, and chemistry is a key science in developing solutions to all major sustainability challenges, such as climate change, sustainable energy, clean water and a sufficient food supply for all people [2]. Despite its high societal relevance and excellent employment opportunities, the field has a major challenge in that there is a massive shortage of skilled workforce [3]. In other words, not enough students are studying chemistry.

The reason behind the lack of students is the result of two factors. The first issue is the lack of experienced relevance. Many scholars have reported that young people do not find chemistry interesting, or more precisely, relevant [4–8]. This affects the overall number of chemistry students, which has been a global concern for decades [9]. Fortunately, the chemistry education research (CER) community is aware of the relevance challenge. In recent years, CER scholars have actively been developing novel evidence-based relevance-oriented learning materials as a solution to the challenge

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[10–13]. The second issue is the high dropout rate. In many parts of the world, more than 30% of chemistry undergraduate students fail to finish their degrees [14–16]. Efforts to solve the dropout challenge have been made, for example, with enhanced student guidance [17], strengthening the vocational relevance via career weeks [18], and career-oriented inquiry-based activities [19].

The current authors agree that it is important to support higher education chemistry studies by strengthening its vocational relevance. However, it does not solve the first challenge. According to research, an interest in science is created in childhood [7,20]. Therefore, we claim that the most efficient way to improve the situation is to train skilled and enthusiastic chemistry teachers. Chemistry teachers are the key stakeholders in introducing the potential of chemistry to young learners and to inspire them into chemistry careers [21]. Therefore, high-quality chemistry teacher education (CTE) is the cornerstone of developing chemistry both as an academic and industrial field.

Future chemistry teachers are trained in tertiary education through academic study programs. The majority of chemistry teachers graduate from CTE or broader science teacher programs. Whatever the specific name, they are usually academic higher education degrees. Therefore, we argue that high-quality academic CTE needs to be evidence-based and research-oriented. At the University of Helsinki (Finland) we have been developing evidence-based CTE and training research-oriented chemistry teachers (ROCTs) for over 20 years. The initial model was published in 2010 under the authorship of Maija Aksela in the journal Chemistry Education Research and Practice [22].

However, there is a constant need to develop and update the program because chemistry as a science is itself developing rapidly. For example, there have continuously been major advances in sustainable chemistry, modern technology, and material sciences. Future chemistry teachers need an up-to-date understanding of the field so that they can integrate contemporary science into their teaching. This is particularly important because chemistry in schools is being taught predominantly from a historical perspective [23]. This does not seem to appeal to large numbers of learners, which leads to the main challenge in the field, namely that young people do not experience chemistry as relevant [13]. There is therefore a special need to strengthen the vocational and societal relevance of chemistry education [10,12].

Based on this background, the aim of this entry article is to describe the reformed model for evidence-based research-oriented CTE developed and applied at the University of Helsinki. We start by defining evidence-based CTE (Section 2) and continue by describing the characteristics of ROCTs (Section 3). Then we introduce ways of developing the program through a research-based design (DBR) approach in order to maintain its relevance (Section 4). The article ends with conclusions and take-home messages (Section 5).

2. Evidence-Based Chemistry Teacher Training

2.1. Definition of the Term "Evidence-Based"

We defined evidence-based CTE by reviewing several "evidence-based" educational terms and crafting a suitable concept for chemistry educational purposes. In the literature scholars have defined "evidence-based" from a content or educational research perspective. Ratcliffe et al. [24] discuss "evidence-based practices" when they refer to the usage of educational research methods for ensuring efficient pedagogical practices. They identified the need for evidence-based teaching through focus-group interviews of educational experts, researchers, policymakers, and teachers. Toom and Husu [25] use the term "research-based" for a similar context. They argue that a research-based orientation in tertiary teacher education is essential. It enables future teachers to engage and understand their teaching profession on a more comprehensive level.

Evidence-based practices encourage teachers to think like educational researchers. However, according to Valcke [26], the "teacher as a researcher" analogy does not mean that the teacher professional should be an academic research position. It is more of a practice-oriented approach applying simple research settings to develop their own teaching and learning, taking an inquiry-based approach. For example, an iterative collaborative design approach could be taken to develop

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local level pedagogical models alongside peer teachers. The decision making could be supported with up-to-date scientific literature and researcher consultation through networks built up during university studies. The solutions developed could be validated using data gathered through observation and feedback questionnaires [26].

In the context of CTE, the other building block of an evidence-based approach is chemical research. Therefore, in addition to the latest educational research insights, future chemistry teachers need to be able to include up-to-date chemical research in their teaching [22]. This can often be challenging because teachers are not active chemistry researchers, and the current research topics may not be included in their studies or the latest research results will have come after their graduation [23]. Fortunately, there are several ways of including contemporary research in the curriculum. Teachers can participate in in-service training events and courses to update their knowledge base [27,28] or use recent learning materials developed by CER scholars in collaboration with researchers. For example, our research group developed laboratory activity on ionic liquids in cooperation with an organic chemistry research group from the University of Helsinki [10].

2.2. Degree Structure

The CTE study program at the University of Helsinki has a standard European higher education degree structure. It comprises 300 ECTS credits, consisting of a BSc degree of 180 ECTS and an MSc degree of 120 ECTS (Table 1). The Bachelor's degree is planned as a three-year study track organized by the Faculty of Science. The Master's degree is planned to take two years. It is also administered by the Faculty of Science, but a 60 ECTS portion of the MSc degree consists of pedagogical studies organized by the Faculty of Education. Pedagogical studies include two teaching practice periods in the University of Helsinki Training Schools. Pedagogical studies are usually conducted in the fourth year. For their fifth and final year, the students return to the Faculty of Science and complete their CER Master's thesis in the Department of Chemistry. The MSc degree includes at least 75 ECTS of CER studies, which means that at least 25% of the program is allocated to CER. This is important because CER studies are the only way to ensure a research-oriented approach in CTE.

As described, the CTE program of the University of Helsinki is conducted as a collaboration between two Faculties and four Departments. Because of multiple stakeholders participating in the teaching, it is important to ensure coherence in the study program. In this context, it means that courses and study units are designed to build upon the previous knowledge and all courses contribute to the overall objectives set for the program [25]. In the University of Helsinki we support coherence between different Departments and Faculties through a co-design approach maintained by continuous communication and regular meetings [29].

Table 1. A structure analysis of CTE course allocations.

Courses	Allocation (ECTS/%)		Notes
	BSc	MSc	
Chemistry	65 / 36%	0–15/ 0–12.5%	The MSc degree has 15 elective credits, which can include courses in chemistry
Chemistry education	30 / 17%	45–60/ 37.5–60%	At least 75 ECTS of CER studies, including courses, theses and seminars
2nd teaching subject	60 / 33%	-	Includes 5 to 15 ECTS DBER studies depending on the subject
General studies	25 / 14%	-	Includes academic skills, career courses and language studies
Pedagogical studies	-	60 / 50%	Covers 50% of the MSc degree
Sum	**180 / 100%**	**120 / 100%**	

2.3. Chemistry Education Courses and Research Skills

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To ensure constant engagement with CER studies, we have divided CER courses evenly through the study years. The curriculum has been iterated for over 20 years in 3 to 4-year curriculum cycles. Courses and course contents are developed and updated to match the current professional needs of chemistry teachers.

In the BSc studies we offer 5 CER courses, a thesis (6 ECTS) and seminar (1 ECTS), and a few general science education courses. At the Master's level, there are 4 courses, a thesis (30 ECTS), and a CER research seminar (5 ECTS) (see Table 2).

Research skills are at the core of CER expertise. We have designed a course that focuses on methodological issues as well as integrating different skills into every CER course. Research skills range from simple tasks, such as information retrieval and essay writing, to more complex skills, such as case study and design-based research (DBR). The specialized CER course is optional for Master's students but mandatory for PhD students.

Table 2. An overview of CER courses offered at the University of Helsinki during the curriculum period 2023–2025, with research skills integrated in courses.

#	Level	Course	Research skills	Year
1	BSc	Chemistry in Everyday Life, Society and Environment (5 ECTS)	Information retrieval, academic writing (essay)	1
2	BSc	Inquiry-based Chemistry Education (5 ECTS)	Qualitative and mixed method case studies, questionnaires, content analysis, automatic citation tools	2
3	BSc	Concepts and Phenomena in Chemistry Education (5 ECTS)	CER as a field, pre-post measurement of conceptual change	2
4	BSc	Information and Communication Technology in Chemistry Education (4 ECTS)	Artificial intelligence in CER	3
5	BSc	Sustainable Chemistry and Education (5 ECTS)	Modelling of systems thinking	3
6	BSc	Bachelor's thesis and seminar (6+1 ECTS)	Narrative or systematic literature review or case study	3
7	BSc	Science Education (5 ECTS)	Designing research-based science education activities	1–3
8	BSc	Mathematics and Science in Society (5 ECTS)	NOS	1–3
9	BSc	Contemporary Science and Future of Research (5 ECTS)	NOS	1–3
10	MSc	Integrated Chemistry Education (5 ECTS)	Design-based research and chemical engineering projects	5
11	MSc	Chemistry Now and Future (5 ECTS)	NOS (chemistry specific), authentic chemistry research and researcher networks	5
12	MSc	Research Methods in Chemistry Education (5 ECTS)	Overview of research methodologies and methods usually applied in CER	5
13	MSc	Sustainable Education in Mathematics and Science Education (5 ECTS)	NOS	5
14	MSc	Master's thesis and research seminar (30+5 ECTS)	Independent CER research project	5

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3. Research-Oriented Chemistry Teacher

The aim of evidence-based CTE is to produce research-oriented chemistry teachers, i.e., ROCTs [22]. It is important to realize that the research component of an ROCT is CER. According to Taber [30], CER can be inherent, embedded or collateral (see Figure 1). The inherent approach focuses on research questions arising from the practices of chemistry education and chemistry as a science. Embedded CER research has a general educational focus that has been conceptualized in the context of chemistry. Collateral CER is educational research where, for example, data has been collected in a chemistry learning context without subject-specific conceptual operationalization. The CER community has a strong consensus that the intrinsic approach is most important for the development of the research field [30].

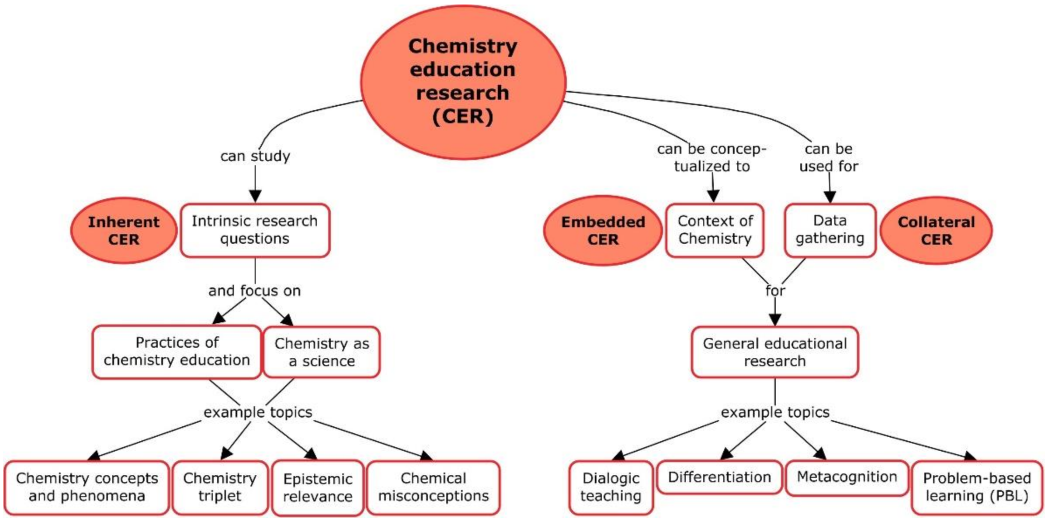

Figure 1. The three different research types of CER [30].

3.1. Required Knowledge Components

The ROCT's expertise is built up from various knowledge areas. To illustrate the diversity of the required knowledge components, we use a technological pedagogical science knowledge (TPASK) framework for modelling them. TPASK is an application of a technological pedagogical content knowledge (TPACK) framework designed especially for supporting the professional development of science teachers by integrating authentic research into the framework [31]. TPACK is similar to TPASK, but it does not emphasize authentic science. TPACK is a general model focusing on content knowledge rather than scientific knowledge [32].

TPASK can be visualized with a Venn diagram of technology, science, and pedagogy (see Figure 2). The overlapping knowledge areas are technological science knowledge (TSK), technological pedagogical knowledge (TPK) and pedagogical science knowledge (PSK) [31].

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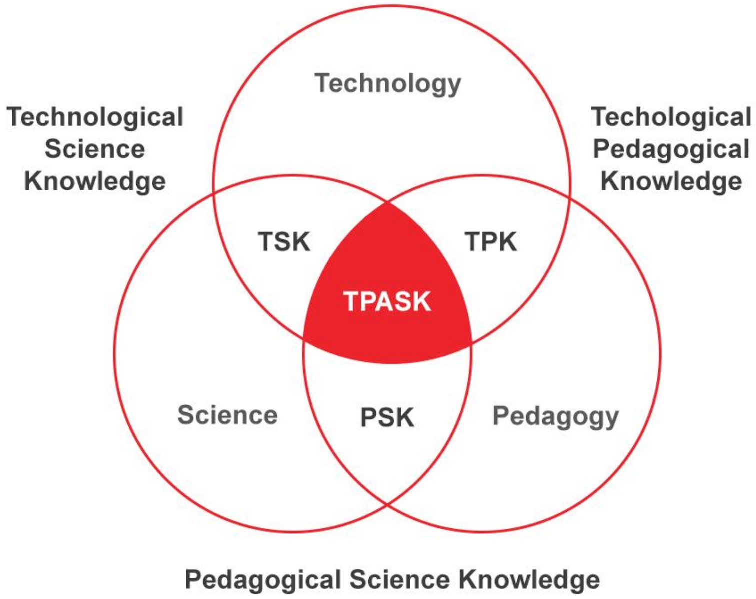

Figure 2. An overview of the TPASK framework [31].

By using the TPASK framework, we can illustrate the diversity of essential knowledge areas required of ROCTs:

PSK: The foundations of an ROCT's expertise are good chemistry knowledge, excellent pedagogical skills and chemistry educational understanding of how these two are combined meaningfully [33]. In addition, ROCTs care about their pupils' and students' learning. This knowledge is PSK because it combines chemistry and pedagogy [31].

Science: ROCTs understand the nature of science (NOS) both in the context of chemistry and educational sciences. This means, e.g., that they understand how science works as an institution and how it is evaluated, how new information is produced and why, what the role of science is in society, sustainability and politics and how science is financed [34]. This knowledge is purely science knowledge. Note that the emphasis is on science and not only content. In this regard, the TPASK framework enables a more comprehensive understanding of the required expertise than the TPACK model [31,32].

Pedagogy: ROCTs have curious minds and are interested in constantly learning new things [22]. To fulfil their learning needs, ROCTs have good meta level skills, and they can evaluate personal continuous learning needs. ROCTs apply an inquiry-based approach to personal learning and engage with non-formal in-service learning resources and events [28].

TSK, TPK, and Technology: Technology is integrated in everything. ROCTs need to master the usage of technology both in chemistry and education as well as in their chemistry educational interface. ROCTs follow the latest chemical, educational and chemistry educational research on both national and international levels. ROCTs are able to integrate contemporary science into the chemistry curriculum and their own teaching [22]. From the TSK and PSK perspective, following the latest research is vital because chemistry is a data-driven rapidly developing instrumental science [35,36]. Educational technology also takes huge leaps every year see example [37].

TPASK: ROCTs can develop their teaching via educational research methods on a practical level and disseminate results along the appropriate channels. In the best scenario, research and development projects are conducted in collaboration with peers and members of the personal learning network [25,29].

3.2. Professional Identities

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As mentioned, we aim to produce ROCTs that have two professional identities. We claim that chemistry teachers should consider themselves to be not only teachers but also chemists [22]. Our previous research indicates that the current chemistry teacher education model effectively supports the development of teacher identity [38]. However, the teacher identity is often so strong that we are currently developing the framework for specifically strengthening the chemist identity [39].

Teachers' professional identity, a complex construct of beliefs, attitudes, and behaviors that define them as educators, is crucial for teachers' efficacy and adaptability [40,41]. Therefore, this is an essential issue to address in chemistry teacher education, especially from the perspective of the under-represented chemist identity. Our solution is to engage future chemistry teachers with contemporary chemical research in the CER courses offered. In this context, the location within the University of Helsinki Chemistry Department is crucial because this gives us direct access to chemistry scholars and their research groups. As members of the chemical research community, we are able to design our teaching to highlight the precise research focus of the Chemistry Department. The Department's research areas are materials, energy, health, and environment and we approach these through our research group's focus areas, which are sustainable chemistry and modern technology. In Figure 3 we illustrate the interaction of different research focuses and their contribution to the ROCTs' professional development.

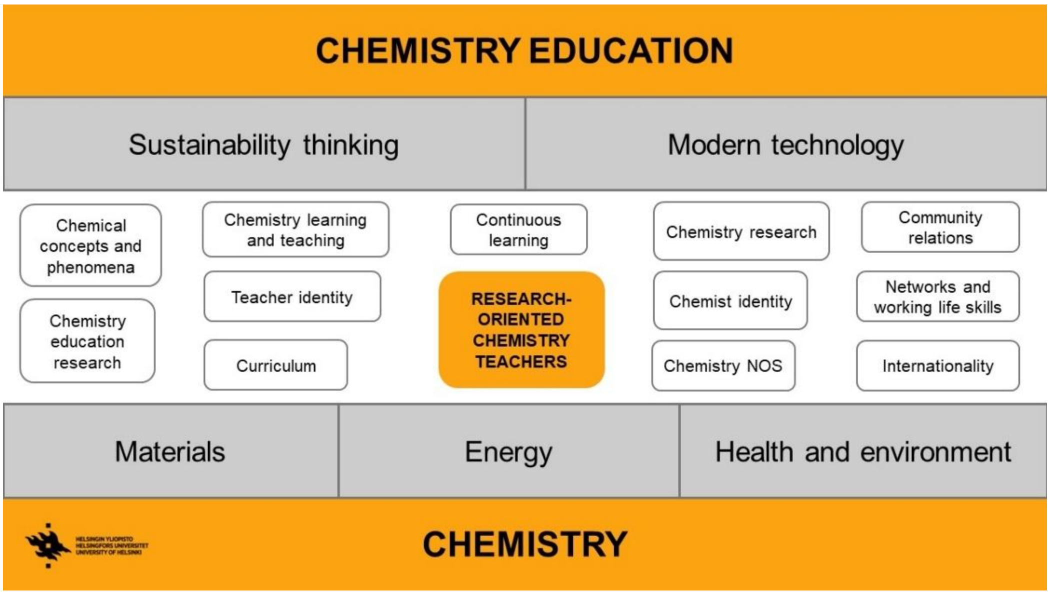

Figure 3. The Chemistry Department's research focus areas and their contribution to ROCT education.

We argue that engagement with contemporary science supports the relevance challenge. Learning from the latest chemical research and interacting with chemistry scholars develops future teachers' understanding of relevance holistically. This will strengthen their chemist identity and improve their ability to include up-to-date chemical research in their teaching. Further, engaging young people more with contemporary science could be the solution to the relevance problem that the whole CER community has been seeking for over a decade [13].

However, it should be noted that, before studying the subject, the teacher must encounter learners as people and create a good learning environment suitable for all. In this regard, pedagogical skills are extremely important, despite the fact that content knowledge is the core knowledge that every chemistry teacher should master. Teachers tend to teach as they themselves have been taught. Therefore, it is important to use versatile teaching and evaluation methods in university courses and demonstrate best-practice examples of good teaching. In addition, teachers' own examples of good teaching practices may have a positive impact. During our 20 years of experience, we have realized that our own enthusiasm and caring way of meeting learners is passed on to future teachers.

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4. Research-Based Co-Design

Because science is constantly advancing, we need to update our courses continuously. We use DBR [42] as an approach to ensure that our teaching and whole program is based on research. More precisely, we use a co-design model because developing up-to-date courses and learning activities require the expertise of multiple stakeholders. DBR therefore suits our needs perfectly.

Our initial analysis indicated that DBR activities are conducted at four levels simultaneously, with the perspective shifting from internal to external as the levels rise, as follows: 1) BSc and MSc projects focus on learning activities. On this level the perspective is usually internal when looked at from the program perspective. 2) PhD dissertations focus on developing larger learning modules or courses. 3) Research projects can be used at both levels but are especially needed in program level development. 4) The fourth level is an interaction interface between the program and society. Levels 2–4 usually require external research and development funding. See Table 3 for the overall picture of the different DBR levels, and more detailed descriptions of the approach and multiple design examples [29,43].

Table 3. Different levels of DBR conducted in developing the CTE study program.

Level	Focus	Research type	Perspective
1	Exercises, laboratory activities, web materials, etc.	BSc and MSc projects	Internal
2	Learning modules, larger materials and courses	PhD dissertations and research projects	Internal
3	Program level development	Research projects	Internal and partly external
4	Interface with society, e.g.,the chemical industry and educational policy decision makers	Research projects	External

4.1. Research and Development Hub: LUMAlab Gadolin

We conduct our CER on a research and development (R&D) platform called LUMAlab Gadolin [44]. It is a non-formal learning environment co-designed by our research group (SECO), research groups from the Department, chemical industry companies and LUMA Centre Finland[1] (see Figure 4).

Our research group develops novel solutions for supporting the relevance of chemistry education. For example, we explore new technology and craft it into the chemistry educational context [37,46] or we develop new learning materials in collaboration with chemistry research groups [10]. Much of the research is done with international collaboration [11,27,35]. Through the DBR approach, the learning materials developed can be used to explore their effect on experienced relevance [47]. Every year more than 4 000 learners and teachers make non-formal study visits to Gadolin and we use this for data gathering.

LUMAlab Gadolin is integrated into every CTE course that we offer [38]. Through Gadolin, future chemistry teachers learn how to teach in a laboratory and how to develop inquiry-based learning materials. This increases the professional relevance of our CTE program [38]. During the last 15 years we have collected data for over 100 Master's theses, 15 PhD dissertations and dozens of research articles. In the following, we present two case examples of the research conducted in the interface of LUMAlab Gadolin and CTE.

[1] LUMA Centre Finland is a science education network of Finnish universities [45].

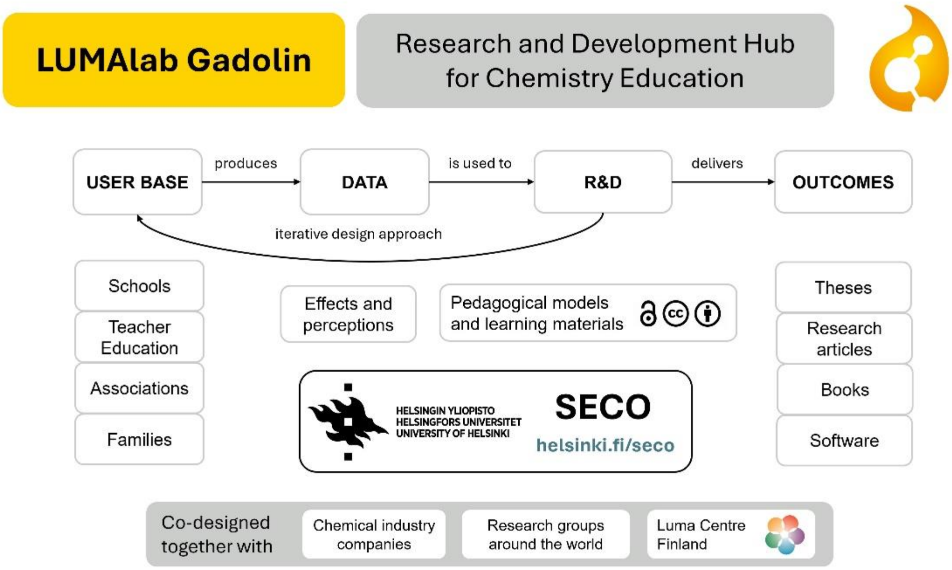

Figure 4. An overview of LUMAlab Gadolin as a research and development hub.

4.2. Case 1: Updating the Integration of Modern Technology for CER Courses

Modern technology is one focus area of our research group. In the past, we have worked with molecular modelling [28] and microcomputer-based-laboratories [48], but recently we have been focusing on educational cheminformatics [35]. Since new technologies are constantly being published, and they need to be integrated into our CTE in order to offer up-to-date education. For example, a few years ago 3D printing was growing in the CER field. In collaboration with an analytical research group from the Department, we conducted a systematic literature review of the possibilities that it offers for chemistry education [46]. Based on this review, we have designed learning activities that are included in one of the CER courses. LUMAlab Gadolin offers state-of-the-art laboratory equipment needed to impel the developed activities [49].

From another perspective, we can use the guests who make study visits to Gadolin to explore the relevance of our crafted technology. For example, in one study we developed molecular modelling activities for lower-secondary education, and the pupils we studied perceived relevance after engaging with the activity. LUMAlab Gadolin enabled the collection of a quantitative sample size [47] and this research started as a Master’s thesis and led to a full research article.

4.3. Case 2: Developing a Pedagogical Model for Teaching Systems Thinking and Sustainable Chemistry

Another focus area of our research group is sustainable chemistry. As an example here, we can describe an ongoing PhD project that aims to develop a pedagogical model of how to teach systems thinking in the context of sustainable chemistry. We started a course called “Sustainable Chemistry” that is a mandatory Bachelor’s- level course for future chemistry teachers. After a few courses, we noticed that systems thinking is one the key competences that should be included in the course. To ensure research-based development we started a PhD project around it.

Emmi Vuorio, a PhD researcher, started to explore the topic. First, she conducted a problem analysis on how sustainability development competences are taught in universities throughout Finland [50]. Based on the knowledge acquired, she developed a pedagogical model that was integrated into the course. The model uses authentic sustainable chemistry contexts retrieved from scholars working in the Department or in chemical industry companies. The chemists' perceptions ensured an evidence-based background [51]. Next, the model was tested empirically in the course. We are currently working on reporting the results of the empirical phase. In this research project, LUMAlab Gadolin served as the communication platform between our research group, scholars from the Department and industry. In addition, the course has laboratory activities conducted in the laboratory.

5. Conclusions

We want to emphasize the importance of evidence-based CTE in producing research-oriented chemistry teachers. It is necessary because a chemistry teacher is an academic professional who must be able to justify pedagogical decisions based on the latest research insights.

Everyone working in CTE should realize that chemistry teachers have two professional identities, i.e., they are both chemists and teachers. Given the importance of professional identities, this must be addressed in the CTE curriculum. Our suggestion is to engage future chemistry teachers with non-formal learning activities throughout their studies in order to maximize the educational vocational relevance, and also to foster interaction with the latest chemical research and scholars. In addition, continuous learning has to be supported. Chemistry teachers must be able to follow both chemical and educational research during their career.

Finally, the most important point is to ensure the development of CER skills. CER is the competence that binds together the domains of chemical and educational knowledge. It is at the core of high-quality chemistry education. In our CTE program the development of CER skills is supported by integrating some skills in every CER course. According to our research and over 20 years of CTE experience, we are convinced that it is important to train research-oriented chemistry teachers. They are the key stakeholders in engaging young people in chemistry and solving the urgent challenge of relevance. The evidence-based research-oriented chemistry teacher education model described in this article could be used as an example for local CTE development around the world.

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