POLYTECHNIC CHEMISTRY AS A MODEL FOR THE TRANSITION TO RESEARCH-BASED TEACHING

Abstract. The Research-Based Teaching/Learning methodology, well-established for over three decades, contrasts with under-examined traditional teaching approaches that prioritize factual content devoid of methodological depth. This persistence in traditional methods stems from their historical prevalence in teacher and student training. At the same time, university professors are involved in research but find it difficult to involve their students: the curriculum does not provide for this in most bachelor programs. After such a bachelor's degree, graduates are not interested in a master's degree and are not prepared to do research in it.

To bridge this gap, educational programs must be reimagined with a focus on adapted scientific texts. The «Polytechnic Chemistry» project exemplifies this approach, integrating research into traditional chemistry topics with a practical emphasis on industrial-scale substances. By strategically reducing the volume of facts and emphasizing historical context and contemporary research, this project promotes deeper understanding and critical thinking of students.

The «WTiM» project complements this initiative by exploring chemical and technological aspects of water treatment, offering a streamlined pathway to applied chemistry.

Computer simulations for research activity are essential for comprehensive learning, compensating for the time constraints of conventional laboratory sessions.

A proposed web platform and specialized journal could further enhance this educational model by publishing adapted research materials accessible to diverse audiences, from seasoned scientists to schoolchildren and their educators.

This transformative educational framework requires the cultivation of educators adept at preparing graduates for a dynamic life landscape. These
educators could play a pivotal role in fostering lifelong learning and cultivating research-oriented individuals who would be able to contribute meaningfully to the "Academy of Total Science", dedicated to preserving and developing the research potential of people across all stages of life.

**Keywords:** research-based, Total Science, Polytechnic Chemistry, critical thinking, lifelong learning, research potential, research activity

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ПОЛІТЕХНІЧНА ХІМІЯ ЯК МОДЕЛЬ ПЕРЕХОДУ ДО ДОСЛІДНИЦЬКОГО ТИПУ ВИКЛАДАННЯ

**Анотація.** Методологія викладання/навчання, що базується на дослідженнях, добре відома вже понад три десятиліття, контрастує з недостатньо вивченими традиційним підходом до викладання, який надає перевагу фактометричному змісту, позбавленому методологічній глибині. Така стійкість традиційного методу зумовлена його історичним пануванням у підготовці вчителів і студентів. Водночас викладачі університетів беруть участь у дослідженнях, але їм важко залучати до них своїх студентів: навчальні плани більшості бакалаврських програм не передбачають цього. Після такого бакалаврата випускники не зацікавлені в магістратурі і не готові займатися в ній дослідженнями.

Щоб подолати цю проблему, необхідно переосмислити освітні програми з акцентом на адаптовані наукові тексти. Проект "Політехнічна хімія" є прикладом такого підходу, інтегруючи дослідження в традиційні розділи хімії з практичним акцентом на речовинах промислового масштабу виробництва. Стратегічно зменшуючи обсяг фактів і роблячи акцент на історичному контексті та сучасних дослідженнях, цей проект сприяє глибшому розумінню та критичному мисленню студентів.

Проект "WTiM" доповнює цю ініціативу, досліджуючи хімічні та технологічні аспекти очищення води, пропонуючи спрощений шлях до прикладної хімії.

Комп'ютерне моделювання для дослідницької діяльності має важливе значення для повноцінного навчання, компенсуючи часові обмеження звичайних лабораторних занять.
Problem statement. In Ukraine, as in many developed countries, research work is becoming less and less popular and fewer applicants enter universities for natural sciences. In the universities themselves, students are reluctant to enter the master's program, especially graduate school. At the same time, the scientific activity of students at a Bachelor's stage is often optional even in the leading universities of Europe. This is an unnatural situation in the conditions of the modern world, so it is necessary to establish the cause of such a phenomenon and find a possible way out of this situation.

Analysis of recent research and publications. The crisis of secondary and higher education is not new. The reluctance of many of today's students in different countries to attend school and university is explained in different ways by different researchers, but critical-thinking teachers and educators still see the problem in the teaching methodology and offer alternatives, which we will consider below. The basic logic behind these alternatives is based on a simple idea: if students are not interested in learning, then we should use a methodology that will make learning interesting for them!

In my opinion, the most successful approach in school education was and is the problem-oriented Big Picture approach [1], which, however, requires a high level of commitment from the teacher, since it mainly implements the RBL model. We will emphasize the RBT model with RBL elements, which determine the literature sources we have reviewed below.

An excellent review by authors from the Netherlands [2] presents a modern history of different forms of research-type education (teaching and learning).
The 1992 paper [3] stands out, noting that the teaching-research nexus takes on various forms, allowing students to engage with research through learning from, about, and through it:

1. Learning from research involves students acquiring knowledge of important theories and research pertinent to their disciplinary fields.

2. Learning about research refers to students gaining familiarity with research methods and techniques, typically through coursework or in research labs.

3. Learning through research entails students actively conducting research themselves, thereby acquiring in-depth disciplinary knowledge through hands-on experience.

This multifaceted approach to the teaching-research relationship underscores the integration of research into the educational experience, offering students opportunities to both consume and produce knowledge within their fields [3].

The authors [2] continue their historical analysis based on various sources. Another valuable distinction, partly overlapping with previous concepts, is the classification of teaching approaches into 'research-led', 'research-oriented', 'research-tutored', and 'research-based'. This classification is based on two dimensions: the research focus (content vs. process) and the role of students (audience vs. participants):

1. Research-led teaching emphasizes research content, where students primarily serve as passive recipients or audience members.

2. Research-oriented teaching shifts the focus towards research processes while students still primarily assume the role of audience members.

3. Research-tutored teaching involves students as active participants, but the emphasis remains on research content.

4. Research-based teaching positions students as active participants in both research processes and content.

The preference for research-based curricula stems from the belief that universities should treat learning as an ongoing research process, recognizing that undergraduate education should universally incorporate research and inquiry experiences [2].

Norwegian researchers [4] very precisely emphasize the real needs of graduates and point out that one of the primary challenges facing universities today is adapting knowledge sharing to meet the needs of modern students.
Today's students seek education that is not only relevant, engaging, and interesting but also offers promising career prospects. However, predicting the future demand for specific knowledge poses a significant hurdle. Therefore, universities and colleges should prioritize fostering innovation, curiosity, interest, collaboration, and interdisciplinary cooperation, rather than focusing solely on specific topics that may quickly become outdated.

At Western Norway University of Applied Sciences (HVL) and Volda University College (HVO), efforts are underway to enhance teaching quality through research-based approaches. This approach allows educators to integrate research into their teaching practices and actively involve students in the process. The goal is to empower students to contribute to innovation and research, demonstrating that their ideas can be both intriguing and significant.

Swedish authors in their work [5] consider the process of training teachers capable of implementing RBE. A notable trend in education across Europe and internationally is the growing demand for research-based education, a phenomenon also observed in Sweden, the focus of this study. This shift has placed increased academic expectations on teachers, presenting a distinct challenge for educators whose training historically emphasized practical teaching skills over academic rigor. Therefore, it is particularly important to investigate how experienced teachers learn and develop as they transition toward a research-based educational approach. The theoretical framework draws upon concepts from communities of practice and social learning.

In an interesting paper by German researchers, aspects of RBL in the training of sociologists are considered [6]. Using latent change score modeling, their analysis revealed that students demonstrated an increase in cognitive research dispositions throughout these RBL experiences. Conversely, most affective-motivational research dispositions showed a decrease. Notably, instructors' demonstrated interest in students' work emerged as a significant predictor of changes in research interest and joy among students.

The use of an e-learning environment to improve the efficiency of education is presented in [7]. Current higher education curricula have transitioned from a focus on training and professional development to emphasizing capability development, shifting from work-oriented to life-oriented, and moving from a teaching paradigm to a learning paradigm. This shift necessitates innovation not only in the form of tools and digitalization of learning but also in fostering learning innovation within the learning process and enhancing student learning experiences.
To complete this review, here is a quote from my dialog with AI Claude in April 2024 [8]:

Prompt: «Please, make an overview of research-based teaching (RBT) and research-based learning (RBL) with examples from chemistry and chemical engineering.»

Claude's response, which supports the ideas and results outlined above:

«Research-Based Teaching (RBT) and Research-Based Learning (RBL) are educational approaches that aim to incorporate research principles, methods, and practices into the teaching and learning processes, respectively. These approaches are designed to enhance students' understanding, critical thinking, and problem-solving skills by actively involving them in research-like activities.

Research-Based Teaching (RBT): RBT involves incorporating research findings, methodologies, and practices into the design and delivery of teaching. In this approach, instructors model their teaching practices on the ways researchers conduct investigations, communicate findings, and engage in scholarly discourse. The goal is to expose students to authentic research practices and cultivate research-oriented mindsets.

Example from Chemistry: In a chemistry course, an instructor could use RBT by designing laboratory experiments that mimic real-world research scenarios. Students would be provided with an open-ended problem or research question, and they would need to develop hypotheses, design experiments, collect and analyze data, and communicate their findings like how researchers would. This approach not only teaches practical laboratory skills but also fosters critical thinking, problem-solving, and scientific communication abilities.

Research-Based Learning (RBL): RBL is a student-centered approach in which students actively engage in research-like activities as part of their learning process. They are encouraged to explore research questions, design and conduct investigations, analyze data, and communicate their findings, just as researchers do. RBL aims to develop students' research skills, problem-solving abilities, and a deeper understanding of the subject matter.

Example from Chemical Engineering: In a chemical engineering course, students could be tasked with investigating a real-world industrial process or developing a novel chemical product. They would need to review relevant literature, formulate research questions, design experiments or simulations, collect and analyze data, and present their findings and recommendations. This approach not only reinforces technical knowledge but also cultivates research skills, such as literature review, experimental design, data analysis, and communication, which are essential for professional practice in chemical engineering.»
Both RBT and RBL emphasize the integration of research practices into the teaching and learning processes, respectively. By exposing students to authentic research experiences, these approaches aim to develop critical thinking, problem-solving, and research skills, as well as a deeper understanding of the subject matter. The examples provided illustrate how these approaches can be applied in chemistry and chemical engineering courses, fostering skills and mindsets that are valuable for future researchers, practitioners, and professionals in these fields.

The purpose of the article is analysis of the reasons for the insufficient implementation of RBT/RBL in universities and schools not only in Ukraine but also in most developed countries of the world. To find out ways to implement such an education model in universities and schools in the field of chemistry and chemical technology. To use such a project as a model for the implementation of the RBT in other natural sciences.

Presentation of the main research material. This article is based on the ideas of the Total Science project [9]. The realization of this global project can systematically solve systemic problems that we observe in modern society in the context of learning and research activities of people. The main idea of this project is that a person is a researcher from birth and the process of his/her integration into society through education at different stages should preserve and develop his/her research potential (curiosity), rather than weaken or even suppress it to the point of complete disappearance.

Let us take the first concrete steps on this path and consider a small part of the integration process on the example of new, certainly research-based chemistry teaching.

«Polytechnic chemistry» - the study of chemistry in the context of research carried out for various chemical technologies. Such research results improve chemical production's technological and environmental parameters.

This is an alternative study of chemistry based on those reactions that are realized on an industrial scale, and the corresponding chemical technologies are already studied by chemical engineers. Due to the greatly reduced list of reactions to be studied, it is possible to study their history in depth in the same time frame: how and under what conditions the chemical facts given in traditional textbooks were obtained. In addition, the current state of research on the relevant substances can be studied, which makes it possible to simultaneously (or sequentially) study different chemistries: inorganic, organic, electrochemistry, the chemistry of polymers, and composite substances.

Both basic reagents and materials (e.g., ammonia synthesis and catalysts) and auxiliary materials (e.g., electrochemical sensors for analyzing gas mixtures) are covered.
The sequence of study should be determined by the complexity of the research (both historical and contemporary): from simple to complex. At the same time, the corresponding technologies may be studied (in polytechnics and schools) or not (in classical universities), but any new reaction should be studied exactly in the historical context of the corresponding research, which was performed last year or 100 years ago.

Virtually all reactions that are given in traditional chemistry courses can and should receive full research-based consideration. Which of them to include in the curriculum will depend on the scientific direction of the relevant departments in universities (classical and technical).

The obvious superiority of this approach is teaching by examples of real research, and as we know, this is how people usually learn - by examples.

«Water Treatment in the Middle» (WTiM). How can a research-based program based on the idea of Polytechnic Chemistry be implemented relatively quickly? Of course, it is possible to implement it in traditional sections of chemistry, preserving the existing specialization. But then we are limited by this specialization. In this connection, the WTiM program is offered, which allows us to study reagents and materials in water treatment within the framework of the Master's program. In this case, it becomes possible to get acquainted with practically all the main directions of chemistry.

Water Treatment is usually not part of Chemical Engineering (chemical technologies) in European and American universities, but refers to Environmental Science and Technology or Civil Engineering. In the proposed program, the emphasis on the technology of obtaining and researching auxiliary reagents and materials in water treatment makes such a program specifically for chemical technology both in Ukraine and abroad.

That is, auxiliary technologies for water treatment and corresponding chemicals are studied in depth. Water treatment technologies can be considered in the style of «General chemical technology. Chemical-technological schemes», where water purification technologies will be studied instead of various chemical technologies.

However, the same approach can also be applied at chemical faculties, but without emphasizing chemical technologies for obtaining auxiliary materials for water treatment. This will allow for shortening the training program or deepening the part of obtaining materials and studying their physical and chemical properties (mastering the appropriate analysis methods).

The greater emphasis on relevant chemistry makes it possible to use the proposed program for existing specialized fields of study. For example,
for organic chemistry (or technology), the amount of training and research is increasing specifically for organic auxiliary materials in water treatment.

Options for employment of a graduate under the proposed program:

- researcher of water treatment technologies;
- water treatment manager;
- chemical engineer in various industries.

The main parts of WTiM:

- synthesis and modification of reagents and obtaining materials used in modern water treatment;
- their testing in laboratory and industrial conditions;
- development of technologies for obtaining successful (according to test results) reagents and materials;
- development of training programs for mastering chemistry (organic, inorganic, polymer, ceramics,..) used for this water treatment technology (flocculation, coagulation, ionic materials, membranes...);
- teaching technologies for the production of reagents and materials for water treatment and water treatment technologies themselves with an emphasis on the historical aspect of their development;
- implementation of the content of the relevant disciplines based on teaching the methods of obtaining physical and chemical facts, rather than studying the facts themselves.

This program of study is well suited for the first year of a chemistry master's degree, followed by specialization (in chemistry) in the second year and the completion of a master's thesis.

Computer modeling of chemical research. Even though almost all chemistry is a set of experimental facts, databases that can be used to access them are not used in most undergraduate programs. Nor are the actual basics of creating and using SQL or noSQL databases studied. It is rather difficult to answer the question of why this situation has developed, although it is not too important for us (although interesting...). What is important is that such training should be a mandatory element of any chemist's training, and the use of such databases in teaching chemistry will make the process itself more interesting and provide graduates with an additional skill that is widely used in today's information-oriented society. It should be noted that those researchers who study and use DS and ML reach the point of studying databases.

An interesting feature of the modern stage of informatization is the emergence of No/Low Code visual tools not only for developing programs with graphical interfaces (frontend, FlutterFlow) but also programs for working with databases (backend, BuildShip) [10, 11].
Currently, programs are used that allow planning an experiment and processing the obtained experimental data. There are many solutions from the classical (for statistical data processing) R language [12] to Python library packages available in Google Colab [13] to any user with a Google account, as well as the modern specialized language Julia [14]. Programs for the interpretation of data from a variety of physical research methods are also widely used. Usually, such programs are used for real research, and in virtual simulator mode very rarely [15].

However, a comprehensive software environment that simulates the entire research process and allows for hands-on training has yet to be developed. At the same time, the above-mentioned visual development tools with built-in AI tools allow for solving these tasks (once they are mastered, of course) without the significant assistance of professional programmers by chemistry teachers themselves. One cannot but think of Data Orange Mining - a visual programming environment for data analysis [16]. Since the visual components of this program are developed in the Python language, it is possible to develop your components with the necessary functionality and embed them in the system.

Let us list the stages that are missing for a complete modeling of a chemical investigation:
1. calculation of the reagents amount and their preparation;
2. assembling the schematic diagram of the research unit;
3. generation of data obtained from the unit;
4. the procedure for evaluating the success of the experiment. In case of unsatisfactory results, the transition to the beginning of the modeling procedure.

Research-oriented learning environment. Unfortunately, both schools and universities most often lack a psychological atmosphere that supports the spirit of inquiry among students. Getting the necessary positive grades in compulsory disciplines is the main task for the majority. This situation can hardly be called problem-oriented, although the problem with scores is always present. It is obvious that such a situation is determined by the formal essence of the existing approach - do what you are supposed to do and you will get a result (a document confirming graduation from an educational institution). A pleasant exception is teaching programming, but this area is more engineering than scientific.

Let's simulate a suitable setting that has already been implemented in a few schools [1] and a few universities (see literature review). To do this, it is necessary to determine the goals of an educational institution of any type in terms of natural sciences. Now they are obvious: study what has been done
and learn as much as possible. To study what can be done by critically analyzing what has already been done (the study of facts remains) is a worthy and interesting task that can and should become the main one in the study of natural sciences in general and chemistry in particular!

Such a task will determine both a new psychological background for learning and formal structures that facilitate the research process. We are talking about virtual (in the beginning) laboratories that essentially solve innovative problems. For example, a teaching laboratory of modern inorganic chemistry will study modern research: what is relevant now, how research is carried out, and why people do it.

In studying chemical technology students have to explore opportunities to improve production parameters: quantity and quality of the product, its energy efficiency, and environmental friendliness. These issues are already being considered, but the emphasis remains more on facts. These topics are raised seriously within the framework of master's theses, but, as noted above, students at this stage do not have the necessary systemic skills - they were hardly taught it.

In fact, when teaching chemical technologies, the teacher should simulate the work of an engineering company that is engaged in the optimization of existing production facilities and their reconstruction. This is fully consistent with the desired employment of the graduate and allows for a critical assessment of the existing curriculum.

Supervising the research work of schoolchildren (RBL mode) should also be comfortable for their teachers, so their scientific specialization can be similar to the specialization of university teachers. At the same time, it becomes possible to supervise students from different schools in a virtual exchange mode between teachers with different specializations.

Thus, places for study should become places for research that are pleasant to go to and want to return even after their completion [9].

*Journal and the Academy of Total Science.* To ensure the high quality of the developed curricula based on the history of chemistry and modern research, it is necessary to create an open international platform where participants will be authors, editors, and critics of the proposed solutions.

To ensure broad international contacts, we can start publishing an original journal, in which the bulk of publications will be made by authors of articles from scientometric journals (Open Access, first of all).

In such journal, the authors will be able to present their results to students studying in the field of research. At the same time, taking into account the level of students, it will be necessary to provide an analysis of their article in terms of the necessary knowledge and skills required for
conscious participation in the research. Such an article will also be interesting for researchers working in other chemical fields, and if necessary, it can be adapted for beginners (schoolchildren and bachelor students) as part of an introductory course. In addition, such an article can become part of a new type of textbook in the relevant field.

To accelerate the process of transition to a new type of education, it is proposed to organize an international "Academy of Total Science" (like a social network). Its members could be not only professional scientists, but also university teachers with students, school teachers with pupils, as well as graduates of both schools and universities, who have not become scientists, but like research and want to participate in it as a hobby.

We are talking about organizing a club system aimed at creating a comfortable environment for doing science at a variety of levels - from academics to schoolchildren. Members of such a club can participate in different sections and migrate between them.

It should be noted that in modern society there are practically no well-known interest clubs that are not related to politics or religion. Of course, social networks perform a similar task, but the level of contact between people remains very superficial in most cases (the author’s experience).

The functioning of such a club can help to weaken social atomization and strengthen the holism of modern society [17]. Let me remind you that the atomization of society is expressed in a significant decrease in trust between people, and the loss of skills in collective problem-solving and collective interaction.

**Conclusions.** The RBT/RBL methodology has been widely known for at least 30 years and many papers have argued that this approach is much more effective and psychologically pleasing than the traditional approach, which has rarely been analyzed in such papers.

We emphasize, however, that the traditional approach is essentially an attempt to teach reference materials - facts without methods of obtaining and confirming them. This approach continues to be used for one simple reason: it is the approach that trains both school teachers and university students! In these conditions that ineffective teaching model is inevitably reproduced. The absurdity of this situation is that a university teacher is obliged to engage in scientific activity, but is not obliged to introduce scientific activity into the teaching process.

This situation is unnatural and must be overcome, and for this purpose, it is necessary to develop curricula based on adapted for training scientific monographs, articles, and dissertations in a concrete educational direction.

The Polytechnic Chemistry Project could be a model for organizing such curricula based on research (done a hundred years ago or last year) in all
traditional sections of chemistry but with consideration of substances widely used in practice. It is a subset of applied chemistry but with an emphasis on large-scale production. The balance of instructional time in this project is provided by a reduction in the number of chemical facts studied, combined with an in-depth study of the history of their derivation and current research related to these facts and the techniques of their derivation. The program of such training can become the basic core of curriculum for the chemical bachelor's degree.

The «WTiM» project is a quick way to enter «Polytechnic Chemistry» as it studies the ways of obtaining (chemical part) and utilizing (technological part) basic and auxiliary reagents and materials used in a variety of water treatment technologies. In addition, technical universities have to provide for the study and development of chemical technologies used to obtain such substances. Moreover, this approach can be used in teaching chemistry in schools, as it provides not only basic knowledge of all sections of chemical science but also its practical applications.

At the same time, the computer component of this approach is extremely important - it is the implementation of software simulators that allow one to model the research at all stages. Without such simulators, it is practically impossible to fully convey the lecture material to the students, since the usual laboratory practical training allows one to realize only a very small part of it - chemical research usually requires a lot of time relative to the time allocated for laboratory work.

For the qualitative implementation of the proposed approach, it seems natural to organize a web platform and a new type of chemical journal that will be engaged in publishing adapted research materials (preferably by the authors of these studies, but not only by them) for readers of various levels: scientists of other directions, graduate students and masters, undergraduate students, and, of course, for schoolchildren and their teachers.

It is extremely important to create a positive mood in science teaching spaces where research is carried out in virtual laboratories, not limited to a single institution. The proposed club system for researchers of different levels will create not only horizontal but also vertical connections between participants.

The new type of school work involves, of course, the training of a new type of teacher, who will prepare school graduates of a new type and, as a consequence, the same type of university students and their teachers. Such teachers will be able to become researchers of research and take a worthy place in the structure of the «Academy of Total Science» - an international club that implements the main goal of Total Science: people's research potential should be preserved and developed from childhood to old age - let to be Lifelong Researching!
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