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DEVELOPMENT OF CRITICAL THINKING IN CHEMISTRY TEACHING

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The critical thinking is an important part of education supported by the Czech curriculum documents, and its importance is now being discussed in the context of the development of artificial intelligence. In the teaching of (not only) chemistry, the critical thinking can be purposefully developed through appropriate activities. The article presents three comprehensive teaching tasks for chemistry education that have the potential to develop critical thinking: Genetically Modified Crops (a task using the problem-based learning and analysis of information sources), Nuclear Energy and Spent Nuclear Fuel Management (a task focused on critical reading of text, reasoning and working with artificial intelligence) and Reaction Kinetics (research-oriented laboratory work enhanced with elements of graph and data interpretation and reasoning). Building critical thinking skills in chemistry is essential for understanding abstract concepts and acquiring skills that enable students to approach chemistry topics responsibly and knowledgeably in everyday life.

Keywords: critical thinking, chemistry teaching, activation methods, argumentation

1. Introduction

Critical thinking is a crucial skill for the 21st century, identified by many researchers not only as one of the factors for successful learning but also as a pillar of a democratic society[1–3]. Critical thinking is one of the current topics – especially given the high availability of information, which can include misleading content (misinformation, hoaxes, fake news, etc.). This appeal is even more evident with the rapid development of artificial intelligence, whose output does not always correspond to reality.

Critical thinking can be learned and improved over time. For example, a teacher can develop critical thinking by using appropriate methods and following a few principles in his/her classes. This article aims to present the possibilities of developing critical thinking in teaching (not only) chemistry and to illustrate the methods and principles presented in three specific teaching tasks (research-oriented laboratory work, critical reading of a text, and group work with sources of information).

2. Definition of the term critical thinking and its importance in teaching

Although critical thinking is one of the most frequently used terms not only in the context of education, there is no consensus among experts as to what exactly it means or what it encompasses[1,4–6]. In particular, attempts to define critical thinking are complicated because different disciplines (especially philosophy and cognitive psychology, and to a lesser extent, education) approach the concept of critical thinking in different ways[7].

The consensus in the literature is that critical thinking represents a wide range of skills or attitudes, with higher-order cognitive operations (e.g., synthesis, analysis, evaluation), reasoning, questioning, or problem-solving being among the most important[1,6]. The most essential attitudes include a tendency to verify information, to work with credible sources, to be receptive to different views or ways of arguing, or to be motivated to use and improve critical thinking skills. An essential element of critical thinking is also a focus on the self (i.e., self-reflection, metacognition, or thinking about one's own thinking, evaluating one's arguments)[1,6].

Critical thinking positively impacts students' academic success, helps them solve problems more effectively, and is vital to advancement in any science field, according to researchers[2,8]. Developing critical thinking helps students better understand science and develop a scientific way of thinking or problem-solving skills related to science. In chemistry, it is essential to understand abstract concepts and evaluate chemical phenomena in everyday life[7–10]. It also positively impacts the development of students' social skills and active participation in a democratic society. It helps them make informed judgments about social issues, to adapt to a rapidly changing world, and to be able to function fully in it[3,4].

It is therefore not surprising that some governments (Czech Republic, USA, UK, Finland, Canada, etc.) have been making efforts for several years to make the development of critical thinking an integral part of their curriculum[11].

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3. Principles, methods, and barriers to the development of critical thinking in teaching

The general principle in the development of critical thinking in school teaching is the predominant activity of the students, the teacher acting more as a guide[2]. Constructivist methods are appropriate, in which students independently discover facts and construct their knowledge[6]. At the same time, it is necessary to cultivate critical thinking continuously and repeatedly incorporate appropriate activities that develop it[12]. The teacher should make the development of critical thinking a separate goal and communicate it explicitly to students. Critical thinking is most effectively developed when both the goal and the instruction are explicit (e.g., the teacher states along with the topic of the lesson that the focus will be on practicing argumentation, includes an activity during the lesson on creating or analyzing arguments, and then discusses with students the various aspects of argumentation)[5,6,13]. Critical thinking can be developed by working with the text to ask appropriate questions (*who is the author and recipient, what is the purpose of the text, or whether there are arguments or formulations in the text that persuade the reader*)[14]. Another appropriate method is inquiry-based science education, in which students set hypotheses, plan their work, and then interpret and reflect on the results[5]. Problem-based learning, where students find a solution to a problem that is usually interdisciplinary, comes from everyday life, and there is no single correct answer, can also support the development of critical thinking[9].

Several reasons are described that hinder the effective development of critical thinking. Among the most common are the transmission of isolated knowledge and the lack of integration of knowledge within and across subjects (which is crucial for developing critical thinking, especially since multiple disciplinary perspectives are required when considering different situations in everyday life). Another major obstacle is the teacher's overly dominant role in teaching (or the role of the 'know-it-all' teacher who only imparts ready-made knowledge) and pressure to perform or to get grades (to the detriment of developing critical thinking skills). Students' lack of information about the topic can also be critical. If students are to argue, debate, or engage in any way with a topic, they must be familiar with it. Otherwise, the development of critical thinking skills is severely limited. Finally, lack of learning activities aimed at targeted critical thinking development and lack of practice may hinder development, as critical thinking skills need to be practiced repeatedly.[2,3,7,9].

4. Critical thinking in the context of the Czech education

The importance of critical thinking is also reflected in Czech curriculum documents, specifically in the Framework Educational Programme for grammar schools (*Rámcový vzdělávací program pro gymnázia*); critical thinking is mentioned directly and indirectly in several places. Explicit references can be found in key competencies, for example:

– "(*The student) critically interprets and verifies knowledge and findings, finds arguments and evidence for their claims, and formulates and defends supported* conclusions.";[15]
– *"(The student) applies appropriate methods and previously acquired knowledge and skills in problem-solving, and in addition to analytical and critical thinking, uses creative thinking using imagination and* intuition."[15].

Other important references are made in the *Human and Nature* (*Člověk a příroda*) curriculum, of which chemistry is a part. In the description of the learning domain, emphasis is placed on the importance of discussion and argumentation, the scientific method, and the actual investigation or solution of scientific problems. In all of these cases, intersection with critical thinking can be found.

5. Learning tasks to develop critical thinking in chemistry

Based on a broad literature search of foreign expert sources on critical thinking and its targeted development in teaching, three comprehensive teaching tasks, including a methodology for teachers, were developed and piloted[16], which are available for teachers and the professional public at the link https://bitly.cx/lS6. To have the potential to develop critical thinking, the created learning tasks used elements supported by the publications mentioned above as effective for developing critical thinking (more detailed description of each task below). The level of critical thinking of the students before and after piloting the presented tasks was not tested because integrating such tasks into teaching is a long-term process, the results of which become apparent only after a longer period of systematic work.

As an example, we will look in more detail at a learning task called *Genetically Modified Crops*, which is a group work with sources of information and a problem-based task simultaneously. The introduction is an evocation, where the students work in pairs to tell each other what they already know about the topic. They then summarise their findings with the teacher. This is followed by an activity where the students work with two videos, one informative and the other a pros and cons reportage. The worksheet for this section contains 14

#	statement	before video	after video
first video (Nezkreslená věda)			
1	RNA is the bearer of heritage in organism and it consists of genes.	true / false	true / false
2	The very first modifications of genetic information were intentional.	true / false	true / false
3	Transgenesis is a method of modifying genetic information by transferring genes from one organism into another.	true / false	true / false
4	Plant genes can only be modified by inserting other plant genes; it is not possible to insert bacterial genes into them.	true / false	true / false
5	Wheat is the most commonly genetically modified crop.	true / false	true / false

Fig. 1. **Example of working with video**

statements from both videos, some of which contain false information (see Fig. 1 for an example). Before watching the videos, students mark the statements in the first column as true or false without having all the necessary information. This is followed ~~b~~by viewing both videos, during which students record the truthfulness in the second column according to the information in the video. They can also choose the number of statements to assess. This element of differentiation gives students a choice and considers their level of motivation, current state of mind, and other needs. After watching the video, students correct false statements, and the teacher assesses the activity collectively. The activity develops critical thinking by encouraging students to think about the topic before watching the videos, leading them to realize what they already know or need to learn. Indeed, the process of becoming aware of what the learner knows or does not know (evocation) and the subsequent reflection plays a significant role in the purposeful development of critical thinking[9].

This is followed by group work designed as jigsaw learning (students work in so-called expert groups according to different expertise, then in mixed groups). The first is to work in expert groups. Here, groups of students are asked to answer whether the fictional Chemical Republic should agree to the cultivation of genetically modified crops based on work with sources of information and peer discussion. The students look at the solution to this question from the perspective of different experts (biologist, agrochemist, pesticide expert, economist), each group completing a report summarising the information-gathering process and the arguments (Fig. 2). The work on the report itself starts with an evocation that leads the students to realize what they already know about the topic. Before the information discovery, they also formulate the facts they need to find out to answer the research question and articulate which sources they will use to obtain the information and why. They then work on the main research question and are asked to choose three other related subtopics. They choose at least one from a list (e.g., for agrochemicals*, water pollution and eutrophication*, *advantages and disadvantages of fertilization*, *types of fertilizers*). The work in the expert groups is completed by drawing three specific conclusions, which the students come up with in the mixed group.

In mixed groups, students share the conclusions of the expert groups, and the outcome is a joint decision on (not) growing genetically modified crops. The decision has to be based on three main pros and three main risks that the mixed group is aware of. This selection leads the students to share the findings of the different expertise, communicate and argue to select the most important points, and agree on a final position. Each mixed group then presents its conclusion to the class, explaining its reasoning.

This part of the learning task has the potential to develop critical thinking, as, in the case of the videos, it leads the learner to realize what they know and what they will need to find out. In addition, it involves working with sources of information and reasoning, where students have to justify their choice of sources. They are tasked with formulating a conclusion (decision) to support their arguments. The form of the task is also an essential factor, namely group work, where students work together to solve a problem and have to justify their position to others or listen to and consider their classmates' arguments before agreeing on a common conclusion.

The learning task is designed for two lessons, and due to the complexity of the topics, it is appropriate to include it in the last year when chemistry is taught. The students should have knowledge of inorganic chemistry (fertilizers), organic chemistry (pesticides), and biochemistry (nucleic acids, molecular basis of genetics); knowledge of biology (ecology, botany) or social sciences (economics) is also suitable. The task can be modified by much independent work (e.g., if the research questions are formulated in advance or the students invent them) or by

Report from the meeting of the expert group number …

This report is an internal document of the Interdisciplinary Group for Implementing Genetically Modified Crops into Agriculture, which was founded by the Government of the Chemical Republic.

Field: agrochemistry

Research question: *Will the consumption of fertilizers decrease if the Chemical Republic starts growing genetically modified crops?*

Authors:

Detailed report from the meeting

What do we know about the topic (before studying any materials)?
What do we need to learn or find to answer the research question?
Which sources of information will we use to find missing information?
Focus on **3 different subtopics** in your research. At least on subtopic will be chosen from the list below: **pollution and eutrophication of waters** **advantages and disadvantages of fertilization** **types of fertilizers**
Write down **3 main conclusions** of your research and back them with arguments:

The correctness of the report is guaranteed by (signatures):

________________ ________________ ________________ ________________ ________________

Fig. 2. **Sample of the output of the Agrochemistry Expert Group** (omitted free lines, standard A4 format)

modifying the roles (in a smaller number of students, some roles can be combined – e.g., agrochemist and pesticide expert, otherwise additional roles can be added – e.g., translator of foreign language sources).

The second learning task focuses on *Nuclear energy and spent nuclear fuel management.* Like the previous task, it deals with a controversial issue for a part of the population. In its introduction, students complete a SWOT analysis concerning nuclear power, which serves as a bridge to the subsequent critical reading concerning the management of spent nuclear waste as the main drawback of nuclear power. During the SWOT analysis, students write their ideas on the following categories: S (Strengths), W (Weaknesses), O (Opportunities) and T (Threats).

As part of the critical reading, students will assess two contradictory texts about the management of spent nuclear fuel – the first comes from the website Nechcemeuloziste.cz, the second text is a transcript of an interview about reprocessing spent nuclear fuel broadcast

How and what is written about nuclear fuel?

In today's world, we are overwhelmed by information from different sources and for that reason we will learn in this lesson how to:

- analyze the source of information thoroughly
- look for arguments in the text
- formulate my own conclusions based on the available information

About what, from whom, and for whom is the text?

1) Write down one main idea of both texts:

text 1 text 2

2) Who can be the recipient of the text? Justify your answer.

text 1 text 2

Fig. 3. **Sample of the introduction to the worksheet on reprocessing spent nuclear fuel**

on the Czech Radio. The students analyze both texts from different points of view (Fig. 3, the author, its relation to the topic, the probable purpose of the text and its target audience, and the similarities and differences between the two articles) and then have to respond to the model arguments in the worksheet. The learning task leads students to answer questions not only about the content of the text but about the questions listed above – in line with research findings; such analysis promotes critical thinking by teaching students to read information hidden in plain sight (e.g., the purpose of the article or the arguments contained)[14]. The task also involves working with artificial intelligence (*ChatGPT*), with students taking turns working through the text. The artificial intelligence work allows students to consult unclear information from both texts or to get tips on text analysis or argumentation. As part of the learning task, students also practice argumentation (recognizing it in the text and arguing independently), which is vital in developing critical thinking skills.

The learning task is designed for 1.5 lessons. In order to be effective, students should have knowledge of radioactivity, ionizing radiation and its effects, and f-elements, if applicable. The task can be modified by adding other texts (e.g., opinion pieces, scientific papers, popularisation articles), which students can analyze according to the instructions in the worksheet. Given the topicality of the teaching task for the Czech Republic in connection with the completion of nuclear power units, it is advisable to draw attention to this fact, for example, in the introduction and reflection of the task.

The third learning task is an inquiry introductory task on the chemical reaction rates called *Reaction Kinetics*. It consists of two parts – the first part serves as an evocation and theoretical preparation, where students work on theoretical questions and interpret graphs. Students do not have all the information available to describe the graphs and must argue why they have described them in a certain way or interpret the dependencies depicted. This encourages the development of critical thinking – students have only part of the information, and their task is to infer the remaining information, reason, and write why they think this.

In the practical part of the task, students are asked to test the hypothesis concerning the rate of chemical reaction between zinc and hydrochloric acid using the reaction of dilute hydrochloric acid and zinc. This includes questions on the methodology of the work (what will be an indicator of the rate of the chemical reaction for the students), students arguing why they have chosen a particular way of working, and finally, evaluating and reflecting on the work concerning the wording of the hypothesis. In the context of the development of critical thinking, it is crucial that the students plan their work. It is also their task to determine what and why will be an indicator of the rate of the chemical reaction for them. The task also encourages them to reflect on their work and to draw lessons for next time (e.g., what they would do differently next time and where and why measurement errors may have occurred). All this reflection on how the work is done, planned, and reflected upon has the potential to develop critical thinking.

The learning task is designed for 1.5 lessons and, due to its nature as an introductory motivational activity, can serve as the first task in this topic. The task can be modified by adding other commonly available metals or using lump and powdered limestone or baking soda.

6. Piloting of the created tasks in teaching at the high school

The developed teaching tasks were tested in chemistry lessons at the eight-year grammar school Gymnasium Altis, a faculty school of the Faculty of Science of Charles University. For the piloting, classes were chosen in which the students had already discussed the given topics (following the principle of having knowledge about the topic for more effective development of critical thinking). After the implementation of the tasks, the students provided feedback through questionnaires concerning the clarity of the task, the difficulty, and the benefit of the task (whether they believed that the task taught them new knowledge or skills). Based on these, the tasks and teacher guidelines were adapted into their final form. All students present always participated in the piloting.

The first learning task, called *Genetically Modified Crops*, was tested in the 7A classroom at the end of the school year (i.e., when students were in their last year of compulsory teaching chemistry). Thirteen students of this class participated in the verification of the task. The task's difficulty was rated as optimal by the majority of students (nine students); three rated the task as rather difficult, and only one perceived it as rather easy. Ten students perceived the task and the clarity of the instructions as rather understandable, two chose the understandable option, and one chose the rather incomprehensible option. All students agreed with the statement that the learning task had taught the student something new (nine students chose the yes option, the remaining four students chose the rather yes option). What students appreciated most about the task were the introductory motivational videos and how they were worked with, the inclusion of group work (some appreciated the rotation of groups) and discussion, the multidisciplinary view of the topic, and the interactive activity format. They also saw it as a benefit that they were guided to argue or defend their position, allowing them to practice this skill.

The piloting of the second task (*Nuclear Energy and Spent Nuclear Fuel Management*) involved fifteen students from class 6A in the middle of the school year (students had already discussed the structure of the atom, radioactivity, and f-elements). Four perceived the task's difficulty as rather difficult, ten perceived it as optimal, and one perceived it as rather easy. The task appeared to be easy to understand for the majority of students (eleven students) and rather easy for the remaining four students. Eleven students agreed with whether the learning task taught the student something new, and the remaining students chose the option rather than agree. What students valued most about the task were the texts (their choice, readability, and clarity), the opportunity to compare two opposing views, and to form their own opinions based on them. It is also noteworthy from the pilot was the initial SWOT analysis, in which students cited high efficiency of energy production and low carbon burden as strengths of nuclear power, while at the same time, e.g. the risk of a radiation accident or spent nuclear fuel as weaknesses. Opportunities were cited, for example, as efforts by some countries to reduce carbon emissions, while on the other hand, they perceived the negative view of nuclear power by certain groups as a threat to its continuation.

The learning task called *Reaction kinetics* was tested in the 5A lesson (students discussed the factors influencing the rate of chemical reactions at lower secondary school). Nineteen students took part in the verification of the task, of which ten students perceived the task as rather difficult, and the remaining students considered it optimal. The relatively large proportion of students perceiving the task as rather difficult can be explained by the fact that this learning task does not directly follow the material covered but is built as an introduction to a new topic and assumes knowledge from previous chemistry lessons. The comprehensibility of the task and the subtasks was described by two students as comprehensible, by a large part of the class (fourteen students) as rather comprehensible, and by the remaining three students as rather incomprehensible. Fifteen students agreed that the learning task taught them something new (five chose the option yes and ten chose the option rather yes), and four chose the option rather no. It is worth noting that, in addition to factual knowledge (reactions of hydrochloric acid with metals, the effect of reaction conditions on the reaction rate, etc.), students reported that they had learned, for example, how to work with time, how to describe graphs or how to divide work better in a group.

7. Conclusion

Critical thinking is one of the essential skills of our time and has an irreplaceable place in school education. To develop critical thinking, it is appropriate to use activating methods, to lead students to argue or question, and to incorporate appropriate activities (e.g., critical reading, problem-based learning, inquiry-based learning). The importance of critical thinking is illustrated by the fact that it is explicitly mentioned in several places in Czech curriculum documents. Three developed and validated complex learning tasks aimed at the targeted development of critical thinking in chemistry teaching in secondary schools (group work with sources and problem-solving tasks simultaneously, critical reading of text, and research-oriented laboratory work) were presented according to valid recommendations from the literature. Teachers have access to the methodology and all necessary teaching materials (including solutions). The authors will build on the theme of developing critical thinking in chemistry education by further developing teaching tasks and testing the impact of their long-term inclusion in the chemistry classes on the level of critical thinking in chemistry.

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