Scientific paper

To What Extent do Freshmen University Chemistry Students Master Chemistry Calculations?

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Abstract

The research mapped chemistry-oriented university freshman students' ability to solve chemical calculations. Their success was monitored based on several factors such as their faculty, field of studies, the type of calculation and the assignment type (word problem vs. formula). The results indicate a significant need to change the approach to teaching chemical calculations - the students were rather unsuccessful in the tasks. The obstacles they face include the ability to identify a problem, understand the concepts of calculation and appropriately adjust the correct use of the mathematical apparatus. These findings represent an impulse for teaching in upper-secondary school as well as to introductory university courses.

Keywords: Chemistry calculations; students' success; teaching chemistry; freshman students

1. Introduction

Chemistry calculations are a widely discussed area of chemistry in many countries.[1–4] On the one hand, they represent a very substantial base for chemistry students, which they apply practically throughout their entire university studies, mainly in the laboratory.[5] On the other hand, research[6–7] has shown the topic is considered critical in schools for several reasons: it is a link between mathematical skills and chemical content, pupils consider it difficult and unimportant.[7] In professional discourse, questions arise as to whether this topic is appropriate in the chemistry curriculum at primary school and in the general educational fields of secondary schools.[8]

As research shows various parallels worldwide, this research conducted in Czechia has the potential to inform other researchers as well as teachers internationally.

2. Theoretical Background

2. 1. Research on Chemistry Calculations

Chemistry calculation tasks represent a special form of tasks. They build on field concepts, however, these are not the only variable. Mathematical skills, reading skills as well as general problem-solving skills are necessary for successful solutions.

The already mentioned difficulty in students ability to do chemistry calculations has been reported in several studies.[2–4,9,10] Firstly, some identified the aforementioned mathematical skills to be the cause of pupils or students' failure in chemistry calculations. Leopold and Edgar [10] argued that students' unsatisfactory mathematical skills (mathematics fluency) could be the reason for the limited skills necessary to further understanding of chemical concept development. In connection with this, another study[9] found unsatisfactory skills among students entering chemistry-oriented university studies. In reaction to this phenomenon, some authors suggested new algorithmic approaches which would make the topic more accessible to students.[11]

In other studies,[3,4] however, students' mathematical skills were not found to be such a strong factor, although they appear to play a role. A possible explanation for students' lower ability to solve chemistry calculations may also be caused by the lack of the students' ability to operate with concepts as well as their ability to identify the problem in the given role. Research showed that pupils have significant gaps in this area.[12] With the obstacle constituted by the difficulty of chemistry concepts and the need to select only the most important,[13] supportive formulas to work with the commonly used rules were also suggested.[14]

Secondly, students' results can be affected by the tasks' context which is carried by text. Added context on one hand brings relevance,[15] but on the other hand it increases the task's difficulty, as students need a certain level of reading literacy.[16,17] In contrast to rigid tasks containing only values and variables together with a problem to solve, tasks containing context are word problems requiring text processing and understanding and realization of the problem. Only then can particular relationships be understood and a correct mathematical model applied in order to solve the problem.[18,19]

Thirdly, calculation tasks represent a special form of problems, therefore require problem-solving skills. A significant body of research stresses problem-solving skills as a vital agent in chemistry education.[20–22] However, several studies suggest these skills are underdeveloped in many students.

As far as particular chemistry calculations topics are concerned, there was only a limited amount of information on the topics' difficulty. Childs & Sheehan found the most difficult topic for upper-secondary and university students were volumetric analysis calculations, redox reactions and concentration of solutions.[1] Rusek et al. identified pH calculations, calculations with the equation of state, calculations from chemical equations to be the most difficult.[3] There was an intersection with the aforementioned research in the topic of redox reactions, dilution solutions calculations and calculations of molar concentration.

2. 2. Chemistry Calculations in the Czech Curriculum

According to the currently valid chemistry curriculum, chemical calculations are already encountered by lower-secondary school students and later by the overwhelming majority of upper-secondary school students. The current version of the lower-secondary chemistry curriculum[23] contains the expected outcomes as follows: „calculates the composition of *solutions, practically prepares* a solution for a *given composition*". The grammar school curriculum[24] mentions „a student performs *chemical calculations and applies them in solving practical problems*". This general outcome is complemented by, in secondary schools, binding subject-matter: *quantities and calculations in chemistry*. Therefore, there is no concretization, so the scope of teaching is left to individual schools or teachers. In the Framework Educational Programmes for Secondary Vocational Education (FEP SOV) with a non-academic focus,[25,26] the topic of chemical calculations is represented by two expected outcomes: „expresses the composition of solutions in different *ways,* prepares a solution of the desired composition" and „performs simple chemical calculations in solving practical chemical *problems*" and further specifies the subject-matter „calculations in *chemistry*". However, the importance of the turnover of ‚simple calculations' is further unspecified. As can be seen above, although the topic of chemical calculations is mandatory in teaching, the content is not further specified and is thus influenced mainly by tradition or with regard to the use of numerous published textbooks[27] based on former curriculum (cf. [28]).

3. Aims and Methodology

3. 1. Aims

As mentioned above, the extent of chemistry calculation subject-matter may vary from school to school. It is therefore very difficult to map the entire student population's chemical calculation solving skills. However, this skill plays a crucial role for students who have chosen chemistry as their field of study, especially in the early stages of their studies. These students are, on one hand, expected to have mastered the topic of calculations at a higher than basic level, thanks to their study ambitions and interest in the field. At the same time, it is these students who, in case of chemistry calculation solving skills deficits, can be significantly limited in their university studies.

With respect to understanding the results of secondary education in this area as well as mapping the baseline to which higher education courses must respond, the aim of this study was to find out *what chemistry calculation knowledge and skills freshman university students focused on chemistry have at the beginning of their studies.*

The general expectation was that the students are able to solve the chemistry calculation tasks at the chosen level. The study's aim was specified by the following hypotheses:

$^0H_1$: There is no statistically significant difference in chemistry calculation test results between students in study programmes focused on chemistry and on chemistry education.

With regard to the double task type (word problem and symbols), the second hypothesis was tested:

$^0H_2$: There is no statistically significant difference between the students' results in word problems and tasks assigned using symbols.

This hypothesis was supported by Tóthová and Rusek.[12]

3. 2. The Research Sample

The research sample consisted of 220 students in the first year of bachelor's degrees. 42 % were students of chemistry-focused fields (environmental chemistry, biochemistry, restoration, etc.), 58 % of the sample were students of chemistry teaching-focused fields (combined with biology, mathematics, health education, etc.). In the academic year 2020/2021, these students studied at four different universities in Czechia.

3. 3. The Research Tool

A test consisting of five pairs of tasks was used in the study. The tasks focused on: mass fraction, mixing solutions, molar concentration of solutions, calculations from chemical equations and pH calculations. Each pair of tasks was represented by a word problem and an example specified in symbolic notation using formulas and variables. The aim was to include only basic calculations with few partial steps,[19] which would then not allow us to map the causes of possible solver failures. For illustration, two types of example are shown:

The word problem example

Saline used for medical purposes is a solution of sodium chloride in water in 0.15 mol/dm^3 concentration. Count how much sodium chloride is needed to prepare 30 litres of saline. Molar mass of NaCl is 58.5 g/mol.

The symbol type example

Count $m(CuCl_2)$ in a solution when you know that: V(solution) = 24 dm^3, $c(CuCl_2)$ = 0.1 mol/dm^3, $M(CuCl_2)$ = 134.45 g/mol.

The test underwent a multi-cycle validation process in an expert panel consisting of six university teachers focused on chemistry calculation teaching and/or on chemistry education. The resulting test was piloted on a convenient sample of bachelor students. After slight changes in formulations, the final version of the test arose. It was given to freshman university students at the beginning of their studies (late September – mid October) in order not to affect the results of ongoing courses.

3. 4. Used Methods

Statistical analysis was performed in IBM SPSS Statistics 26. Based on the normality test, which did not enable rejection of the hypothesis about normal distribution of the data (the Saphiro-Wilk test results $p > 0.05$), non-parametric tests were used. To examine differences among students from different universities/faculties, Kruskal-Wallis' test designed for K independent samples' comparison was used. To evaluate both students' results according to their study field as well as the results divided according to the task type, Wilcoxon's single-rank test designed for two dependent samples comparison was used. To calculate the effect-size, r was used as an alternative to the parametric Cohen's d test.

4. Results and Discussion

4. 1. Overall Results

The results of the statistical analysis among the students from different universities/faculties ($p > 0.05$) suggested there are no statistically significant difference – the students from faculties of science did not reach better results than students from the faculties of education. Likewise, the differences between the students focused on chemistry and chemistry education ($p > 0.05$) did not suggest any statistically significant difference. The original expectation about chemistry students outperforming chemistry education students was not proven. The sample was then considered homogenous.

The students' success in solving individual calculation types is shown in Figure 1. The students achieved the highest success rate in the mass fraction calculations, with some distance from solutions' concentration and composition. However, even these results do not correspond to expectations for students who have chosen chemistry as

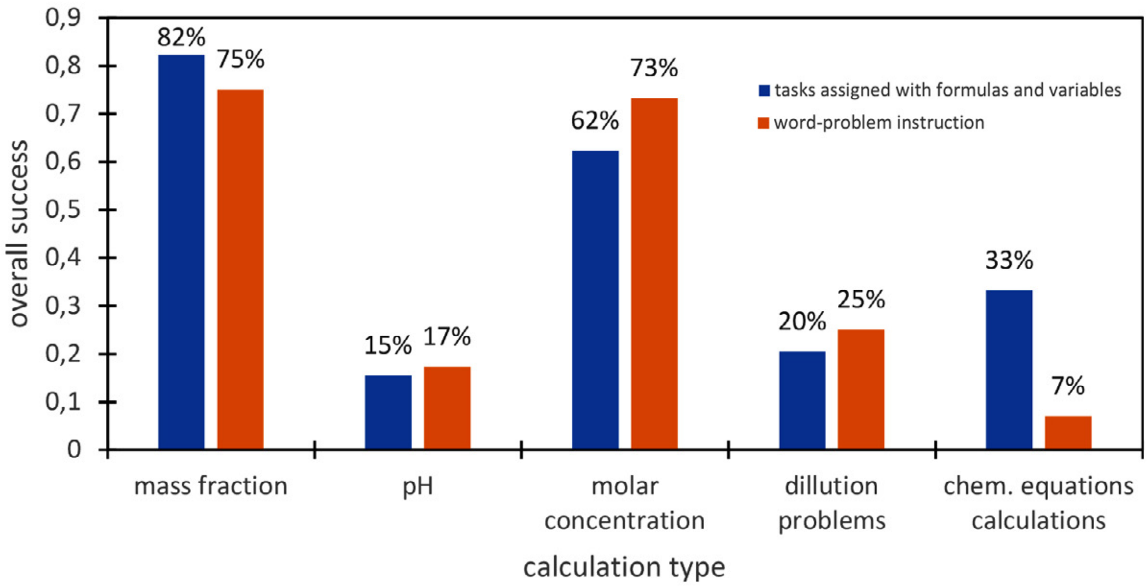

Figure 1. Students' success in solving individual types of chemical calculations depending on the type of assignment

their field of study. Although the composition of solutions calculation is already an obligatory output in lower-secondary education,[23] a fourth of the students failed to solve the task about the components of the mixture's mass proportions. The results for pH calculations, solution mixing and chemical equations, which were solved by only a third of students, are all the more dramatic. These results complete the previously identified problematic calculation types.[1,3]

4. 2. Differences Between Students' Results by Assignment Type

As proven by Drummond and Selvaratnam,[9] students often struggle to process mathematical information given in word problems and convert them into appropriate relationships and formulas. This involves both the use of the corresponding mathematical relationships expressed in the word input and the conversion of the verbally described quantities into the marks used in the formulas. Therefore, a higher success rate was assumed when using chemical formulas and variable symbols to specify examples, due to a clearer definition of the example type leading directly to the placement of specific symbols in known definition relationships. Based on previous research, reading demands were considered a hurdle too.[6,17]

The Kruskal-Wallis test value ($p < 0.05$) enabled us to reject the zero hypothesis of comparable student outcomes according to the assignment type. Specifically, there were differences in calculations focused on the mass fraction ($p = 0.022$; $r = 0.01$), molar concentration and composition of solutions ($p = 0.03$, $r = 0.143$), and calculations from chemical equations ($p < 0.001$, $r = 0.337$). While for examples of calculating the mass fraction and chemical equation calculations, students were statistically significantly more successful in the tasks assigned in formulas and variables, but in the solution concentration calculations, this was the opposite. However, the effect-size value in cases of mass fraction and concentration calculations indicates a *low* effect-size. For calculations from chemical equations, the effect-size was medium. For this reason, the initial assumption was only partially confirmed, and further research is needed on the effect of longer text on student results. Especially in calculations from chemical equations, the result could also be influenced by students' reading literacy. The task focused on this type of calculation contained the longest text describing the reaction, its course and amount of individual reactants due to the information needed to describe the situation. In contrast, in the assignment using chemical equations and variable symbols, it was not necessary to analyze the input to understand the context and identify the variables, and the information was already ready to apply the algorithmic calculation.

A sufficient level of reading literacy appears to be a prerequisite to develop scientific literacy[29] and in consequence also for problem solving, including chemical calculations. To initiate any change in this area, it seems desirable to shift the choice of teaching from tasks focusing on isolated field knowledge[30] towards the use of tasks including analyzing and choosing appropriate solutions. Since chemistry textbooks do not seem to offer such opportunity,[31] before the new chemistry textbook paradigm takes over, it is important to develop other supporting materials.

Another explanation could be in the context of the word problems. Students are known to be more active in task solving when they relate to the context.[32] The word problem in which the students reached better results – molar concentration – built on a medical context. This could be closer to the students than the chemistry context of the other two types of calculations.

4. 3. Causes of Students' Failure

In the tasks aimed at calculating the mass fraction, the most common cause of students' failure was the non-mention of the relevant mathematical relationship for the weight of the individual components and the whole system. The students who failed usually did not include the dissolved substance's mass to the solvent's mass. Also, some of them failed to provide a mathematical formula or other proportional calculation. Furthermore, numerical errors or unit mis-indications appeared, indicating a fairly common misunderstanding of the concept of mass fraction as a relative quantity. Similarly, for the second type of expressing the solution's composition included in the test (examples of molar concentration calculation), typically unsuccessful students did not even state the basic relationship (formula) required for the calculation. 77 % of the students reported a general formula or otherwise expressed mathematical relationship to calculate molar concentration, and most of them were also able to use it. A similar proportion of students (78 %) introduced a relationship to calculate the weight of a substance from a substance amount. Lower shares of successful solutions were mainly due to the addition of specific values according to the assignment or numerical errors.

While in simple calculations focused on solution composition the success rate was relatively higher, in the examples aimed at mixing solutions, only 34 % of students reported a relevant mathematical relationship (mixing equation or other calculation involving weight-to-mass fraction relationships in mass fraction) and only 30 % of respondents used it in their calculation. Many students were able to express the composition of solutions only in simple examples based on the application of a direct algorithmic solution. Nevertheless, their conceptual understanding of individual quantities and their relationships may not be sufficient to use them in examples requiring more comprehensive judgment. This problem seems to have a wider validity in relation to chemical problem solving (cf.[21,33]). At the same time, the problems identified in introducing adequate relationships for calculations further confirm that the low success rate in solving chemical calculations cannot be attributed only to students' insufficient mathematical skills[3–4] and there is a need to focus more on the conceptual understanding of calculated quantities.

Students' difficulties were also identified in the field of using the relationships of quantities students encounter already in the early years of science education. Only 57 % of students provided the relationship for calculating weight when volume and density is given in these examples. This in itself does not represent any significant problem, nevertheless only 50 % used the calculation correctly in their test, which was represented as their understanding of this relationship.

In the examples aimed at calculating pH, ignorance of basic relationships was significant. Only 49 % of students reported the correct relationship to calculate pH and 27 % of pH–pOH relationship which was later mirrored in their test results. However, even if the right relationship was stated, there was a lack of conceptual understanding. Only 20 % of students took into account that sulfuric acid is dibasic. The rest of these only mechanically added a concentration value to the pH calculation formula. The result suggests that these students do not understand the principle of calculation and do not distinguish between the concentration of hydronium and the concentration of acid.

As far as the calculations from chemical equations are concerned, many students failed at the very beginning, i.e. balancing the formula. The chemical formula in the word-problem task was correctly solved by 50 % students, 64 % wrote reactants and products without balancing the formula. The symbolic-assignment task's formula was correctly balanced by 77 % students.

Since in both cases the equations contained only two reactants and one product, which can be considered one of the easiest versions, the result is surprising. Both the nomenclature of inorganic compounds and the balancing of chemical equations are given extensive attention in chemistry teaching,[7] these topics also take up a significant number of textbook pages even for lower-secondary schools, although at the state curriculum level the emphasis on this topic is being gradually limited.[28] The findings show that, although it is a traditional chemistry subject-matter, teaching does not seem to lead to the desired educational outcomes, whereby the series of problematic topics is extended.[34] The seriousness of the findings is enhanced by the fact that the respondents were students interested in the field of chemistry. It therefore seems desirable to revise general education leading either to a large-scale innovation in teaching of this topic or to some form of its replacement with other key topics (big ideas), leaving the focus of nomenclature and chemical equation balancing for special seminars.

Although 48 % of respondents correctly established the relationship to calculate the amount of substance in the context of calculations from chemical equations, only 12 % of respondents correctly used it. The most common problems were the faulty determination of the reactant in surplus, and by far errors in the stoichiometry. These problems suggest only a superficial understanding of the chemical equations' meaning. The simple algorithmic application of relevant quantities' relationships does not subsequently lead to the correct result. A similar problem was found by Mensah and Morabe [35]. For the relevance of learning numerical algorithms, it is necessary to closely link the tasks with the described situation's conceptual understanding. The teaching process based on the expectation that students will understand the concept of the reaction's course and its outcome based on learning the algorithmic numerical procedures was proven ineffective.[35]

Due to the fact the student sample was convenient, their relatively high number still did not allow the generalization of results to the entire population of students in the fields of chemistry or chemistry teaching. However, due to the variability of the sample (students came from a high number of secondary schools), the results show possible shortcomings in their preparation and significant limitations that need to be addressed at the beginning of chemistry's higher education.

5. Implications

The results showed critical problems in students' ability to solve chemistry calculations consists in their lack of conceptual understanding to the included variables (cf.[13]). This finding seems to be a product of the contemporary conception of chemistry (calculations') education. Its improvement, however, heavily depends on students' actual potential as too abstract concepts cannot be processed by students not even at lower-secondary,[36] but also in upper secondary school.[37] With respect to the results, implications for lower-secondary school chemistry calculations' education will be omitted with just a brief remark that only mass-fraction calculations and basic calculations of the amount of substance seem to be sufficient.

More concrete implications in the light of this research's results need to be divided in two parts respecting the actions: 1. secondary school curriculum and 2. reaction from universities.

In order to promote interest in the study of natural sciences as well as the use of skills acquired in general education in an extracurricular environment, rethinking the concept of a curriculum for chemical education needs to be considered. Since there are only sporadic situations when people need to solve a specific chemistry calculation task (in many cases mere rule of three suffices), the topic can hardly be considered important for the field's inner structure. Therefore, it can be removed from the core subject-matter topics placed among broadening topics taught in selective seminars for students with further chemistry studies ambitions. This act is also in accordance with other research which identified this topic is seen by students as too difficult, useless and with too much attention given to it.[7] Considering its negative effect on students' attitudes and the fact that despite the perceived high number of lessons devoted to the topic, students mostly fail the tasks, its removal from core-curriculum (at the current extent) should be considered.

The finding that students' results coming into higher education from secondary schools are insufficient in the field of chemical calculations should be reflected in the relevant courses at higher education institutions. This condition represents a potential risk to their successful study. The courses simply cannot start as an extension of upper-secondary subject matter but need to consider starting from a considerably lower level. Also, the students' problems should be taken into account and tackled in the university courses to prevent the students from unnecessary struggle at the very beginning of their university studies. The key aspects are: understanding the key concepts, understanding the role of the formulas and relations in particular calculation types, followed by mastery of these procedures' application first on known, and later on unknown problems.[38] Also, with the less-problematic topics identified in this study, such introductory courses could save time not focusing on these topics and directly address the bigger, conceptual, problem before indulging in calculations as such.

6. Conclusion

Although the research sample does not fully allow generalization of the findings, parallels with previous research suggest that students‘ results in chemical calculations have significant reserves. This is an impulse for a wide range of areas and actors in education. The result is a message towards the content as well as concept of teaching this topic in upper-secondary, and even lower-secondary schools.

According to these partial findings, teaching chemistry at secondary school does not lead to the students mastering basic calculations. The study's results suggest that the output of secondary education is to adopt some algorithmic procedures consisting of placement in remembered definition relationships, but with conceptual understanding of calculated quantities and their relationships at a very low level. The findings are even more dramatic when the research sample is considered. Low conceptual understanding was found in individuals interested in chemistry. It is therefore reasonable to assume that the results would be even more unsatisfactory for secondary school students with interests in a different field than chemistry. For this reason, suggestions to remove this topic from the chemistry curriculum for everyone and its placement among a broadening topic for students with interest in chemistry was made. However, even for the group of students with chemistry aspirations, the identified problems need to be taken into account during this topic's instruction. This naturally applies also for university courses. Being better prepared for these students' chemistry calculation problems could significantly improve their dropout rate and make their freshman semesters, but also following years, more pleasant and efficient.

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Povzetek

Raziskava je prikazala zmožnost reševanja nalog s področja kemijskega računstva pri študentih prvega letnika s kemijsko usmeritvijo. Uspešnost reševanja nalog smo spremljali glede na več dejavnikov, kot so fakulteta, smer študija, vrsta računske naloge in vrsta naloge (besedilna naloga ali formula). Rezultati kažejo na precejšnjo potrebo po spremembi pristopa k poučevanju kemijskega računanja, saj so bili študenti pri nalogah dokaj neuspešni. Ovire vključujejo sposobnost prepoznavanja problema, razumevanja konceptov kemijskega računanja in nenazadnje ustrezna uporaba matematičnega znanja. Ta opažanja predstavljajo vzpodbudo za poučevanje kemije na srednjih šolah in uvodnih univerzitetnih predmetih.