

STOICHEIOMETRY WITHIN THE FRAMEWORK OF GREEK SECONDARY EDUCATION CHEMISTRY CURRICULUM

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Abstract

A study is carried out by means of distributing a duo of questionnaires to secondary education students in a variety of schools in Northern Greece. The first of these questionnaires is aiming at the identification of the initial degree of general chemical concepts and ideas assimilation by the students and is distributed by their teachers during an early teaching hour in the senior high-school grade B class. The second questionnaire is distributed during the final weeks of the school year and aims at the mapping of integration of concepts related to stoichiometry to students' chemical background, since grade B of senior high-school is loaded with introductory organic chemistry and the corresponding wide variety of reactions on which a vast amount of problems to be solved is based. The validity of the questionnaires and their efficiency in fulfilling the scope of the current research is carried out by means of the application of certain post-statistical indices with the final goal being their utilization as a diagnostic tool for probing student understanding of chemical concepts.

Keywords: secondary education, chemistry curriculum, stoichiometry, questionnaire

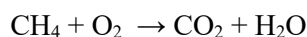
1. INTRODUCTION

There are several concepts which may be regarded as cornerstones with respect to the teaching of chemistry to young students and each one is accompanied by a corresponding load on the cumulative education program set by the authorities and carried out by the individual teachers within the classroom. The corpuscular nature of matter, the basic atomic structure in both the early and the current quantum mechanical representation, the nature of the chemical bond, the properties of acids and bases and the characteristic reactions of specific functional groups are all main to the understanding of chemical concepts and founding a sound understanding of chemistry. Extensive teaching is devoted to each one of the above topics and a lot of experimentation, where applicable, as well as problem solving is utilized in an effort to get the students acquainted with the topics and their importance in the context of chemistry and consequently to everyday life.

Stoichiometry¹ is a topic within chemistry, interrelated to several other topics in a multitude of ways and lies in the very core of chemistry making its understanding an correct application of central importance in the assimilation of chemical ideas. It is applied in every aspect of the representation of chemical substances and chemical changes since it is related to the correct writing of chemical formulae and correctly balancing chemical equations, furthermore aiding the effort to interpret and forecast the current state and the outcome of chemical equilibria. Junior high-school students, especially during their early encounter with chemistry, are encouraged to “keep in mind” that water is represented by H₂O and carbon dioxide by CO₂, however, when they come to discuss in class the periodic table of the elements and later the typical bond formation they have to apply at least in a practical way the octet rule of Lewis, developing in this way an understanding of the reasons underlining the necessity of subscripts in the above formulae. It is straightforward (or at least it should be) to understand that the above

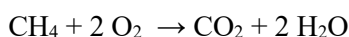
¹ Stoichiometry is the spelling used throughout this text although several of the well-known dictionaries adopt the “stoichiometry” form for the word. We do so in view of the fact that in Greek, the corresponding original word is “στοιχειομετρία” derived from the words for element and count. In our belief, there are two possible ways to transfer the Greek word into Latin characters and they involve either the retention of the writing (in which case both oi and ei sound equivalent to i in modern Greek) or the adoption of a simplistic way to do it, i.e. converting all the different “i-like phthongs” into i, in which case the outcome should be stichiometry.

representations stand for H_2O and CO_2 respectively and refer to a ratio of (i.e. the stoichiometry) of 2:1 and 1:2 of the corresponding element atoms in the molecules. The law of mass conservation during chemical reactions is relatively easy to teach and to understand since it was common belief long before Lavoisier explicitly stated it (Pomper, 1962). The law is followed without exception when writing any chemical equation. Several algorithmic processes exist for ensuring that the law is applied correctly and they all converge to the final form of each equation where the number of each participating atom on either side of the reaction is constant. In a typical example, the combustion of methane (CH_4 , 4 valence electrons for C, 1 for each H atom, 4 covalent bonds through which every H atom completes the duet required for its outer electron shell and C its octet) produces water and carbon dioxide. In a first approximation the chemical equation may be written in the form:



This presentation just describes in the chemical symbolic language the reactants and the products of the reaction, however, it is not balanced as there appear to be four hydrogen atoms among the reactants and only two among the products while for oxygen the corresponding numbers are two and three.

A balanced equation would have the form:



where the numeric coefficients preceding the compounds' formulae account for both the correct application of the law of mass conservation and for the correct molar ratio of the reactants required for and the products produced by the reaction. These coefficients are also used by students in the process of solving problems where quantities of reactants or products are required for a given set of quantities of the rest of the chemical species involved. At a subsequent stage during the secondary education span, the same stoichiometric factors will be used in order to determine, initially the percent yield of a reaction and finally the equilibrium constant of the reaction. Stoichiometric calculations have to be carried out for a reaction in order to define the expected amount of a product, prior to dividing by it the experimentally obtained one, in order to obtain the yield of the reaction. In a similar fashion, given the percent yield, the initial stoichiometric calculation will make it easy to report the right amount of the product realized. Furthermore, when dealing with reaction kinetics or equilibria (Waage and Gouldberg, 1864; van't Hoff 1884), the numerical coefficients of the compounds present in a medium are used to determine the order of the reaction from the reaction rate equation which applies the law of mass action as well as the equilibrium constant through the formalism of the active masses of the compounds. Assuming all compounds to be in the gaseous state, the rate law of the reaction can be formulated as

$$u = k[\text{CH}_4]^1[\text{O}_2]^2$$

from which the order of the reaction may be inferred as the sum of the exponents, i.e. 3.

Finally, the equilibrium constant of the above reaction may be expressed as

$$K = \frac{[\text{CO}_2]^1[\text{H}_2\text{O}]^2}{[\text{CH}_4]^1[\text{O}_2]^2}$$

Being related to several aspects of chemistry, stoichiometry cannot but be considered as part of the foundation of chemical knowledge and understanding and as such is being taught in every level of education involving the sciences and especially chemistry (Ahtee and Varjola 1998). The topic is not, of course, free from erroneous assumptions or misconceptions (Kind 2004) and coupled with lack of mathematical skills may provide hindrance to a thorough understanding of the chemical reaction observation, its presentation in the form of a chemical equation and further working on the quantities involved in the reaction in efforts to consume reactants or realize products at the optimum level (Katsikis et al 2017).

2. DESCRIPTION OF THE SURVEY

2.1. *Brief description of the status quo*

The questionnaires were constructed keeping both the student and the teacher who would distribute them in mind. Several surveys have revealed the fact that students generally adopt the least effort pathway in dealing with examinations, avoiding as much as possible extensive descriptions other than the citation of standard rules and laws. Therefore, questions requiring extensive discussion were kept to a minimum. Furthermore, the set of questions were limited so as to require about half a teaching hour to complete, taking into account the introduction required to be carried out by the teacher (Treagust 1988). The first questionnaire consisted of nine distinct questions covering a broad spectrum of topics which are taught within the chemistry curriculum of the Greek high-school.

The recent decades have seen several overall educational reforms within the Greek high-school teaching program, a few of them including changes in the sequence and depth or width of chemical concepts taught, however, Chemistry is constantly held to be taught in the junior high-school grades B and C for a single didactic hour per week (Vandoulaki et al 2016). Through them an approach to the general utility of Chemistry is provided, with extensive reference to its unfruitful uses (Karageorgiou et al 2017). In grade B a broad discussion is conducted about the environment and chemical phenomena and changes within it and the symbols of several elements are presented while there is only one specific reaction mentioned, the one regarding water formation, without proper introduction to the meaning of the numeric values of subscripts or multipliers involved. In grade C the topics discussed begin with electrolytes, their reactions and the concept of pH, followed by an introduction to the Periodic Law and the classification of elements within the Periodic Table. Reference is made to carbon and its compounds. It must be noted at this point that junior high-school is the last stage of the compulsory education in Greece. It is apparent from the above that junior high-school provides a rather thin layer of understanding depth over a rather wide span of chemical topics and therefore students entering the senior high-school regime are not expected to possess a firm chemical background. It is therefore imperative to perform a thorough and consistent repetition of everything that has already been taught during the two hour per week course of Chemistry in senior high-school grade A, introducing in this way an unavoidable rather than sought application of spiral curriculum (Bruner 1960). The curriculum adopts the atoms-first approach in contradiction to the process used in junior high-school and proceeds from the description of the atom to its electron configuration to the construction of the Periodic Table. The bonding is described for the first time to the students followed by an introduction to chemical reactions and stoichiometry to which the concepts of mole, molecular mass and concentration are attached. It is apparent again that the required breadth and depth of the concepts included in the course cannot practically be met resulting in a diminishing of material described and related skills acquired by the students.

2.2. *Questionnaire evaluation*

Prior to the initiation of the study, the contents of the questionnaires were examined by a group of persons with knowledge of the chemical concepts involved. The reviewers belong to the teaching staff of the Chemistry Department of the Aristotle University of Thessaloniki (two, 2) to the secondary education teaching staff (three, 3) and to the post-graduate students of the Department who attend a course on Chemistry Didactics (five, 5). Each reviewer was given a gross description of the typical Bloom taxonomy (Bloom et al 1956) and was asked to complete a table for each test sheet, indicating for each of the questions involved the highest cognition objective that needed to be mastered by a person in order to correctly answer it. The matching of the critical thinking verbs with the numerical notation used was 1= remembering, 2= understanding, 3= applying and 4= analyzing. The summation over all the reviewers' answering sheets for each question produced a total which was then used to derive an average value for the specific cognition skill level of a question. We may term this simple index as "skill level" of the i th question, S_i . Summation over all the questions resulted in a total of points for the specific questionnaire which in turn produced an average "cognition skill level" required for the questionnaire, which may be presented as CL. A very easy quiz (and correspondingly a very easy question within it) would result in an average total cognition level of approximately 1 while a very demanding one would give a number close to 3. The boundaries set by the reviewer group on the

questions included in the current questionnaires are 1.50 and 2.80 respectively. Questions of the first, preliminary quiz range between 1.50 and 2,80 with an average CL of 2.13, while for the second and more demanding one they range from 2.40 to 2.80 giving an average of 2.68.

A total of 245 students from 8 different schools located in small urban centres and in rural areas of Northern Greece provided answering sheets which were assessed in the formal manner for in-classroom tests. A wide range of marks were obtained giving, for the first questionnaire an average of 11.81 (on a 0-20 scale) with a standard deviation of 4.62. For the second questionnaire the corresponding values are 8.88 and 4.46. The preliminary quiz was aiming at the defining of the starting point with respect to which the evolution of stoichiometry concepts understanding could be measured and it is a practice that has helped in analogous efforts before (Kontopoulou et al 2017). In view of the above cited results it seems that following almost one school year of studying organic chemistry, where the reaction stoichiometry plays an essential role in determining the products and in specific set problems, the constitution of reactant mixtures, the understanding of stoichiometry has moved backwards. However, taking into consideration the general character and the less demanding character of the preliminary test relative to the focused and demanding final test (i.e. the ratio of their overall skill level requirement of 2.68/2.13) the mean mark for the second test is re-evaluated as 11.18 with a corresponding standard deviation of 5.61.

question	First questionnaire			Second questionnaire		
	S _i	P _i	r _i	S _i	P _i	r _i
1	1.90	0.64	0.37	2.80	0.34	0.58
2	2.80	0.74	0.33	2.70	0.57	0.56
3	1.60	0.75	0.32	2.40	0.48	0.56
4	2.60	0.74	0.51	2.70	0.44	0.50
5	1.60	0.62	0.56	2.80	0.50	0.51
6	1.50	0.31	0.48	2.60	0.30	0.28
7	2.20	0.74	0.51	2.70	0.47	0.30
8	2.50	0.32	0.44	2.70	0.45	0.32
9	2.50	0.65	0.62			
average	2.13	0.61	0.44	2.68	0.44	0.45

Table 1. Summary of the skill level index S_i, the difficulty index P_i and the discrimination index r_i for each question of the two questionnaires. The last line reports the average values for each of the questionnaires.

A couple of post-assessment indices were applied in a study of the suitability of the provided questionnaires for deriving the conclusions aimed at from the current population studied. The first and more simple of them may be referred to as the difficulty index, indicating how many of the students answered correctly each specific question, therefore having the formula

$$P = \frac{N_i}{N}$$

where N is the total number of answers and N_i is the number of the correct answers given. It is widely accepted that, values close to the boundaries of 0 and 1 would represent extremely difficult and

extremely easy questions respectively; therefore generally the accepted margins for the index value are 0.2 and 0.8 (Eggen et al 2017).

Furthermore, a question specifically and a questionnaire on average is required to discriminate between students with high and low achievements in the quiz, therefore demanding that the more difficult questions be answered primarily by students with high achievement marks. The formula of this index is

$$r = \frac{\overline{X_i} - \overline{X_o}}{\sigma} \sqrt{\frac{P}{1-P}}$$

with $\overline{X_o}$ and $\overline{X_i}$ being the average assessment marks of the whole population and of those who answered correctly the specific question, P being the previously defined difficulty index and σ the standard deviation of the whole population (Kiviniemi et al 2018). The values of the index are expected to lie above 0.2 with the distance from that limiting value being analogous to the discriminating ability of the question under consideration.

The results of the present study are presented in Table 1. The values of the discrimination index are reported based on the normalized scores, i.e. following the adjustment of the raw score to account for the difficulty of the questionnaire. Adjustments were made relative to the scores, averages and the rest of the data of the preliminary test. The cognition level values as defined above are in line with the computed index of easiness values and verify the statement made about the preliminary character of the first test as well as the demanding character of the second.

3. RESULTS AND THEIR DISCUSSION

3.1. Introductory questionnaire

The results of the first quiz account for the starting point from which the students enter grade B of senior high-school and provide the basis to better understand their achievements in the second quiz. Regarding the symbolic language of Chemistry, the results are good but not excellent; of the formulae given 87% of the students recognize H_2SO_4 as representing a molecule, 63% do so for NH_3 and 44% for CO , maybe mistaking it for Cobalt, an error occurring also among undergraduate students. Interestingly, 4% think that He also represents a molecule. In filling in the missing words in a paragraph constructed to describe the layout of the Periodic Table 75% of the students correctly filled more than 4 of the missing words, 50% did so for more than 6 and a 16% completed correctly all 9 missing words.

A 74% reported the correct electron configuration for element $_{19}\text{X}$ out of the four possible configurations provided but only 62% were able to report the correct verbal description of the neutralization reaction out of four provided rearrangements of acid, base, salt and water.

The definition of solutions presents an obstacle to the students in accordance with literature sources. In the present study, where four options were available, the majority, 44% believe it to be any mixture containing at least two different species, 23% that it should contain mainly water, 13% that it consists of liquid substances and only 31% that it has to be homogeneous. Of course, the use of solely aqueous solutions in the experiments, whenever they are carried out and almost solely in problems may account for the belief that a solution is composed mainly of water and probably the extensive reference to air pollution confines homogeneous mixtures to the liquid state, however, these contributions to the background of students cannot be easily circumvented.

Carelessness may account for the relatively low percentage of correct answers to the maybe easiest question, where the most dilute solution had to be identified among solutions of 2%, 4%, 6% and 0.8% respectively. It is appealing that 17% stood for the 6% solution and only 74% gave the obvious answer. Advancing further into the solution properties the students were asked to determine which property of a non-defined aqueous solution would diminish upon adding water to it. It is still unresolved why 12% believe this will be the volume of the solution while the 17% who stated that the mass of the solute would do so certainly are not able to distinguish between quantity and concentration of a solute, a

problem well know, for the circumvention of which we have proposed an appropriate simple experiment (Koumoutsis et al 2018).

The quantities of sugar and water contained in 200 g of a 5% w/w aqueous solution proved to be the trickiest of the questions since it is well documented that the distinction between solvent, solution and solute is not clear to students. Actually, 35% of the students believe the contents to be 10 g and 200 g respectively while an additional 19% stick to the numbers provided, i.e. 5 g sugar and 200 g water and a further 13% advance by a semi-step towards the correct answer thinking it is 5g sugar and 200-5 g water, leaving only 32% to provide the correct answer. Finally, mixed results were obtained relative to the understanding of the basic subatomic particles and their relation to atomic and mass weight and the charge of monoatomic ions.

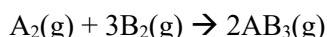
3.2. Second questionnaire

Working out the formula of an organic compound based on its percent per weight constitution is an essential part of checking the understanding of student conception level of organic chemistry and as such the formula of a hydrocarbon having 80% w/w carbon content was required given a set of four possible compounds. However, only 48% of the students were able to carry out the calculations required. The percentage is almost steady when a more complex problem was put forward in the form of a $C_nH_{2n+1}OH$ alcohol for which the mass ratio of oxygen vs hydrogen was given. Only 46% provided the correct answer the rest being almost equally distributed among the other three possible answers offered.

The sum of the smallest integer coefficient for the complete combustion of $C_5H_{12}O$ was, in our belief, the simplest question regarding a chemical reaction. The answer involves understanding and application of the law of mass conservation as well as remembering the formulae of two well-known compounds, however, only 39% of the students provided the correct answer. This can be interpreted in terms of the Greek school textbooks where often fractional stoichiometric coefficients occur, a fact which combined with the known lack of mathematical skills may lead to the observed miscalculations. In a somewhat more complex question along the same line, the application of the Avogadro hypothesis was essential since an alkyne had to be identified based on the fact that its complete combustion produced a fourfold amount of carbon dioxide. It is of interest to note, with respect to the results of the previous question that 59% correct answers were collected on this question. In between the above two results is the outcome of the question where a mixture of two alkanes and two alkenes for which the exact amounts are given, is passed through a solution containing an excess of elemental bromine and the net change of the bromine solution is required. Although the answer only requires summing the weights of the hydrocarbons capable of reacting with bromine, it appears that only 49% of the students can make the distinction in the reactivity of alkanes and alkenes. It is of interest to note at this point that the formulae of the hydrocarbons were given therefore making it easy to identify visually the unsaturated ones. In another question of analogous complexity, the correct couple of alkynes among four couples provided was required, given the total volume of an equimolar mixture of the alkynes and the total volume of dioxygen required for their complete combustion. It was specifically stated that the volumes were recorded under the same conditions. A totally unexpected result, in view of the previous observations, was that 46% of the students responded in the right way. Totally expected though, was the fact that 98% of those who gave the correct answer to the previous question answered correctly this one, providing in this way evidence that they achieved a real understanding of the behaviour of hydrocarbons and that they may continue evolving in the field of organic chemistry even further. This step was taken in the next question where two successive reactions are carried on a starting compound, namely reaction with bromine solution which is decolorized and further interaction with acidic medium under elevated temperature. The percent mass content of the final product is given and the sequence of the three compounds, including the intermediate one is required. A 70% of the students correctly identified the last product as an ether, however, only 46% reported the correct triplet of compounds involved in the process; the other two offered answers had alkene and alcohol as the end product.

Last but not least, we would like to present the results on two questions which mark an interesting field in the teaching of science, namely the ability to retrieve information from graphs or pictorial representations. It has been a continuous finding in recent local studies that young students are not acquainted with the pictorial information incorporated within a text and can only relate one to the other

only if certain spatial arrangement of the two is present (Kasiara et al 2019). The corresponding part of the questionnaire sheet is presented in Figure 1. The reaction was given in the form



and the contents of a box where the reaction was carried out represented at both the initial and the final stage of the reaction.

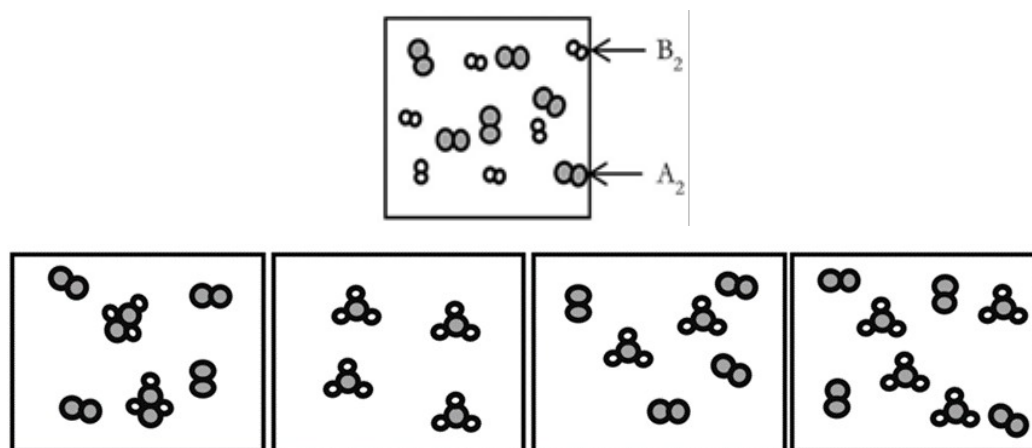


Fig. 1. Graphical representation of an initial (top) and proposed final states (bottom) of a generic reaction of the type $A_2 + 3B_2 \rightarrow 2AB_3$.

The mental task to be undertaken is, of course, to break the bonds of the starting materials and proceed with constructing from them the product molecules following the chemical equation provided. Its completion requires, therefore, prior understanding of concepts related to the corpuscular nature of matter, conservation of mass, limiting reactant and reaction coefficients, which is difficult to achieve (BouJaoude and Barakat 2000). Interestingly, the last three representations of the final stage of the reaction achieve almost equal consideration as being the correct ones for the reaction. This points out to some anticipated difficulties of the students to apply chemical knowledge to diagrammatic representations. In the second representation, the possibility of a reactant in excess is not considered and as soon as the B atoms are all used to form the product molecules the excess of A atoms vanish. In the third picture the situation is more complex but it certainly reveals a more severe lack of understanding since molecules and atoms are clearly not distinguishable; as soon as the B_2 molecules, used as B atoms are consumed to form AB_3 (actually, $A_2((B_2)_3)$ the reaction is over, in this case the remaining A_2 molecules actually being visible. It is of interest to note that those who chose this diagram did better than the average on questions where stoichiometry was accompanied by algorithmic processes while they trailed behind the average on purely stoichiometric questions in accordance with extensive analogous studies cited in the literature (Kind 2004, section 9.4). The finding is not unexpected since it has long been discussed and demonstrated that when dealing with complex tasks requiring the execution of various simple tasks it is not straightforward that misconceptions or even mathematical mis manipulations will be carried over from the simple tasks to the complex ones which are composed of these simple tasks (Eylon et al 1987).

3.3. Further considerations

Partition of the observed results was carried out on the basis of the location of the schools participating in the survey. Two groups were formed with schools in small urban centres (N= 172) and in rural areas (N= 73) respectively. The average values of the corresponding group achievement accompanied by the relative standard deviation as well as of the average of the P and r indices are reported in Table 2.

questionnaire	location	Average	St.dev.	P	r
A	urban	12.62	4.02	0.65	0.46
	rural	9.83	4.43	0.51	0.50
B	urban	12.36	5.71	0.49	0.46
	rural	8.78	4.56	0.35	0.41

Table 2. Partition of the results into schools located in urban and rural areas respectively. The average of the corresponding P and r indices is reported.

It is apparent that the students in urban area schools are doing significantly better than those in rural areas. There appears to be even a step backwards in the overall achievement of the rural school students which merits some investigation. There are several factors affecting the attitude of these students towards science in general and chemistry in particular. The young students believe in a foreseeable future in agricultural and livestock production and merchandising, viewed within the locality and unaware of the contributions of science to it. The teachers are appointed by the central government and their large majority consists of new teachers but having passed a considerable period following their graduation during which it is not certain that they kept contact with any new developments in the field or refreshed occasionally their existing knowledge. It is therefore a matter of less experience and incompletely updated knowledge of the subject on the part of the teachers, coupled with the non-permanent position they occupy. A typical reaction in this situation would be one of adopting a standby mode waiting for their transfer to a school in a small and later maybe to a large urban centre which will be coupled at least with the accumulation of the experience of the past assignments. A factor further contributing to the diversity between urban and rural area schools is that the latter are in several cases not fully staffed which is coupled, in this case, by the government's consideration of science teachers as a unified group. This allows, for example, the assignment of a teacher who studied Biology or Physics to teaching Chemistry (or vice versa) in which case the limited knowledge of the subject is apparently a major factor contributing to the limited assimilation of the new aspects taught.

4. CONCLUSIONS

In summary of the above observations, nomenclature has to be clarified to young students at this level of their scientific education (exemplified by the Co for CO interchange and misunderstanding of the role of subatomic particles in constituting the atomic number and atomic mass respectively).

In addition, when referring to solutions, care should be taken to indicate explicitly that the solutions used for classroom experiments are aqueous due to simplicity and security and that solvent does not equal water (it has been observed that such a distinction is still problematic among undergraduate students where, in addition, distinction between tap water and deionized water is not clear to them). The basic electronic structure of atoms is handled well while that of the corresponding ions is problematic. Although solutions and the corresponding terms and definitions represent topics discussed even at the late stages of primary education there exist some misconceptions concerning the partition of solution to solvent and solute although the algorithmic problems on the topic can be handled adequately.

The study is by no means complete or conclusive. Further examination of results from different types of schools existing within the Greek secondary education is required. Furthermore, a more detailed account of the degree of assimilation of stoichiometry concepts can be given following an investigation of the results relying on long term memory and such a project is underway with the construction and distribution of a third questionnaire targeting the same students during their senior high-school grade C studies.

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