ESI Preprints

Not Peer-reviewed

Understanding of stoichiometry by learners from Form Four to final year of general secondary education in Cameroon

Jeremie Awomo Ateba, PhD
Senior Lecturer, ENS-University of Yaounde 1, Cameroon
Josephine Nita Tematio Woukeng, MA
FSE-University of Yaounde 1, Cameroon
Lawrence Ntam Nchia, PhD
Senior Lecturer, ENS-University of Yaounde 1, Cameroon
Ayina Bouni, PhD
Associate Professor, ENS-University of Yaounde 1, Cameroon

Doi: 10.19044/esipreprint.6.2025.p20

Approved: 08 June 2025
Posted: 10 June 2025

Cite As:
Ateba J.A., Woukeng J.N.T., Nchia L.N. & Bouni A. (2025). *Understanding of stoichiometry by learners from Form Four to final year of general secondary education in Cameroon.* ESI Preprints. https://doi.org/10.19044/esipreprint.6.2025.p20

Abstract

The aim of the present research is to determine the conceptions of learners from Form Four to upper sixth (13-19 years) of general secondary education in Cameroon about the concept of stoichiometry. A preliminary analysis of the didactic transposition of the concept of chemical reaction in the Form Four textbook, combined with an epistemological study of the concept of stoichiometry, enabled us to design an 8-item paper-and-pencil questionnaire. The questionnaire was administered to 239 learners from four to Upper Sixth students of five general secondary schools. The data collected were analyzed using Dehon's (2018) significance level model. The results show that many learners attribute irrelevant meanings to the concepts of the stoichiometry conceptual network. These meanings are mainly at the symbolic meaning level. In this article, we hope to provide teachers with starting points for better teaching of the integrative concept of stoichiometry. Thus, teachers should insist on the constant composition of molecules when teaching chemical reactions.

Keywords: Chemical reaction, stoichiometry, levels of knowledge, stoichiometric coefficient, conceptions

Introduction

Chemical reaction is a fundamental concept in chemistry that poses enormous learning difficulties. Its complexity lies in the fact that it encompasses other concepts, and its understanding requires a shift between the macroscopic and microscopic levels. To explain a chemical reaction, we need to understand not only the structure of the reactants and products, but also the proportions in which they react. At the microscopic level, a chemical reaction can be interpreted as a rearrangement of atoms from well-identified chemical species to other, new species with different natures and organizations, often described for the first time in the case of new compounds (Barlet & Plouin, 1994). The result of this chemical effect can be represented by a simple formula which, like all algebraic formulas, is nothing more than reasoning put into tight form (Fourcroy & Vauquelin, 1797). This is the reaction equation, an integrating concept (Barlet & Plouin, 1994) introduced into Cameroonian general secondary education in Form Three (12-15 years) under the name of "literal equation".

Balanced equation is a topic of study in Form Four onwards and is used as the preferred tool for quantitative study in chemistry (Barlet & Plouin, 1994). To speak of a quantitative study in chemistry is to speak of stoichiometry. According to Zumdahl (2002), stoichiometry is a chemical concept based on mathematical principles that makes it possible to determine the quantity of product that will be formed from a specific amount of reagent. And determining the amount of product to be formed from a given amount of reactant is the task regularly assigned to students in chemistry exercises. Students' difficulties in solving these exercises form the basis of much research in chemistry education research (Çelikkiran, 2020; Frazer & Servant, 1986; Gauchon, 2008; Gauchon & Méheut, 2007; Laugier & Dumon, 2000).

Some research highlights the difficulties learners face in understanding stoichiometry (Frazer & Servant, 1986; Gauchon, 2008; Gauchon & Méheut, 2007; Laugier & Dumon, 2000). In this regard, Laugier & Dumon (2000) show that over 75% of form five students believe that none of the copper and hydroxide ions will remain after mixing a copper sulfate solution and a sodium hydroxide solution, whatever the initial proportions. In addition, Gauchon & Méheut (2007) show that for learners, when the reagents are in different physical states, the solid reagent is entirely consumed whatever the case, while the liquid reagent remains in excess. Moreover, when students become aware of the proportionality relationship between the reagents, they encounter another difficulty, that of determining the proportional quantities. Thus, the quantities concentration, mass and volume are often used instead of the quantity of substance (Frazer & Servant, 1986; Laugier & Dumon, 2000).

Çelikkiran (2020) has shown that the idea of conservation of elements during a chemical reaction is not understood by grade 11 learners. Furthermore, they do not understand that stoichiometric coefficients represent stoichiometric ratios rather than simple numbers used to balance equations.

However, in the Cameroonian context, the concept of stoichiometry is not prescribed in the official curriculum. It is addressed implicitly in the study of the concept of chemical reaction. The objectives of this study are: to define the concepts of chemical reaction, reactants, products, balance equation; to state the law of conservation of matter; to write and balance a reaction balance equation; to exploit a reaction balance equation. Stoichiometry evolves in the shadow of the balance equation. Our empirical observation is that, in classroom situations, teachers insist on the algorithmic balancing of balance equations, to the detriment of the construction of relevant meanings for the signs contained in the equation. We are thus witnessing an overemphasis on algorithmic techniques in teaching stoichiometry, which may explain students' struggles with novel problems; in the transition from symbols, theories and models to the macroscopic aspects of chemical reactions, and in the construction of the meaning of the symbols contained in the reaction balance equation (BouJaoude & Barakat, 2003; Çelikkiran, 2020; Dehon, 2018; Dehon & Snauwaert, 2015; Ducamp & Rabier, 2005; Nakhleh & Mitchell, 1993; Nurrenbern & Pickering, 1987; Stamovlasis et al., 2005).

Generally speaking, stoichiometry is not just about moles, balancing reaction equations, or even stoichiometric coefficients. Stoichiometry has many aspects that are not necessarily linked to a purely algorithmic idea. These concepts make up the conceptual network. Cedran et al. (2022) have shown that the conceptual network of stoichiometry includes: the conservation of matter, the symbolism of atoms and molecules, the concept of the mole, the proportions between reactant quantities of matter, and the constant composition of compounds.

The teaching of stoichiometry, as it is carried out in the Cameroonian context, leads us to predict that learners, once taught, will have mostly irrelevant meanings of the concept of stoichiometry by Form Four. What precisely are these meanings, and how do they evolve as learners progress through the curriculum?

Theoretical framework

According to Johnstone (2000), the difficulties encountered by learners in learning chemistry can be explained by its multi-representational nature. He defines three levels of thought according to which knowledge in chemistry can be structured: a macroscopic level, a submicroscopic level and a symbolic level. The various representations (symbols, icons, etc.) at the symbolic level enable us to communicate about chemical experiments at the macroscopic level and models at the submicroscopic level. These representations constitute what Talanquer (2011) and Dehon (2018) have called "visualizations". In the Cameroonian context, visualizations are central to teaching/learning, as they are the starting point (Awomo Ateba, 2022). They are a set of dynamic and static visual signs, symbols and icons, which enable the elaboration and communication of qualitative and quantitative relationships relating to experiences and models (Dehon, 2018). Dehon has thus proposed a framework for addressing the question of the meanings that students lend to elements of language used in the popularization of knowledge in chemistry. In this framework, the learner can, on the basis of a visualization, construct meanings at three distinct levels:

- The macroscopic level of meaning: the student refers to the observable by citing empirical observations (colour change, disappearance during a chemical reaction, etc.); by using macroscopic concepts such as substance, metal, solid, etc.; or even describes certain properties of the substance under consideration (states of matter, brightness, etc.). Empirical observations also fall within this same level of meaning.
- The microscopic level of meaning: students refer to the constituent entities of matter (molecules, atoms, and ions), molecular geometry, microscopic properties or subatomic particles (electrons, protons, neutrons).
- The level of symbolic meaning: the student is limited to reading the sign(s) as a signifier (association of letters, position in a combination of symbols, number in a mathematical equation, etc.). At this level, the student can also give the visualization a meaning outside the strict framework of chemistry.

Methods

The present research explores the conceptualizations made by learners taught about the "notion of chemical reaction" and their understanding of the concepts within the conceptual network of stoichiometry. It is therefore descriptive in nature (Thouin, 2014). Given that the notion of chemical reaction (in which most of the concepts of the conceptual network of stoichiometry are addressed) constitutes a topic of study in Form Four in Cameroon's official curriculum, and that these concepts are used as tools for quantitative analysis as early as in form five, this study seeks to examine the meanings that learners from Form Four to Upper Sixth lend to the concepts of the conceptual network of stoichiometry. This would make it possible to assess the impact of manipulating these concepts on the meaning's students attribute to them. The data collection tool is a questionnaire consisting of 8 open and semi-open questions. This questionnaire was validated with 35 learners from the fourth to the final year of secondary school, who did not belong to our sample. It was then administered to 239 students from 5 schools in the cities of Yaoundé and Bafoussam and their suburbs, including 105 in Form Four, 40 in the Form Five, 56 in Lower Sixth and 38 in the Upper Sixth. The test was administered by the teachers of the respective classes, during class time and in the presence of the researcher, for an average of 45 minutes.

Results and Discussion

Balancing reaction equations: symbolic meanings of the stoichiometric coefficient

The first question assesses learners' ability to balance reaction equations. It is divided into two cases as follows: Balance each of the following equations:

$$a.\ \dots\dots..H_2 + \dots\dots..Cl_2 \rightarrow \dots\dots\dots HCl$$

$$b.\dots\dots\dots.Al + \dots\dots\dots CO_2 \rightarrow \dots\dots\dots Al_2O_3 + \dots..C$$

The respective results are shown in the following tables:

Table 1 : Learners' significance of the stoichiometric coefficient at the symbolic level case a

Category name	**Frequencies**				**General percentage**
	3ième/105	**2nde/40**	**1ière/56**	**Tle/38**	
1- Simple coefficients	52,4%	50,0%	50,0%	76,3%	55,2%
2- Multiple coefficients	16,2%	25,0%	39,3%	13,2%	22,6%
3- Using of rational stoichiometric coefficients	0,0%	7,5%	1,8%	7,9%	2,9%
4- Failure to master the rule	18,1%	10,0%	7,1%	2,6%	11,7%
5- Erroneous conception of the index	10,5%	2,5%	1,8%	0,0%	5,4%
6- No answer	2,9%	5,0%	0,0%	0,0%	2,1%

Table 2 : Learners' significance of the stoichiometric coefficient at the symbolic level case b

Category name	**Frequencies**				**General percentage**
	3^{ième}/105	**2nde/40**	**1^{ière}/56**	**Tle/38**	
1- Simple coefficients	47,6%	55,0%	76,8%	68,4%	59,0%
2- Multiple coefficients	0,0%	0,0%	1,8%	2,6%	0,8%
3- Using of rational stoichiometric coefficients	1,9%	15,0%	5,4%	7,9%	5,9%
4- Failure to master the rule	41,6%	27,5%	14,3%	21,1%	33,2%
5- No answer	2,9%	2,5%	1,8%	0,0%	2,1%

On average, 80.8% of learners at all levels were able to balance the first reaction equation correctly. However, 55.2% of learners use the simplest integer coefficients, i.e. the triplet (1, 1 and 2) (from left to right respectively) to balance the equation. They seem to have constructed the idea of a stoichiometric coefficient as a 'proportion'. 22.6% of learners used multiples of the previous coefficients, namely (2, 2 and 4) and even (3, 3 and 6). For these students, the most important thing is to balance the equation, whatever the 'numbers' used. For them, balancing a reaction equation has no meaning in the context of chemistry, but remains a mathematical game. In addition, 2.9% of learners use rational stoichiometric coefficients. These are certainly relevant at the macroscopic and symbolic levels, but not at the microscopic level.

Furthermore, 5.4% of the students between the third and first grades thought they were balancing the equation using the triplet (2, 2, 2). They have an erroneous conception of the index and lead us to believe that when simple pure bodies of the same valency react to form a single product, the students disregard their indices when balancing the balance equation. Finally, 11.7% of learners were unable to balance the balance equation, probably because of their poor grasp of the balancing 'rules'.

The rate of correct answers recorded in the first case rises to 65.7% in the second. This suggests that the learners' ability to balance the reaction equations depends on the case in question.

Constant composition of compounds: role of the index at the symbolic level

The second item is designed to check that the students have assimilated the unique identity of compounds, which translates into a constant composition at the symbolic level. The question, in the form of a MCQ, is worded as follows: Hydrogen sulphide (H_2S) reacts with sulphur dioxide (SO_2) to form water (H_2O) and sulphur (S). The balanced chemical equation for the reaction is as follows:

a. $2H_2S + SO_2 \rightarrow 2H_2O + S_3$

b. $2H_2S + SO_2 \rightarrow 2H_2O + 3S$

c. $H_2S + SO_2 \rightarrow H_2O_2 + 2S$

d. $H_2S + SO_2 \rightarrow H_2O + S$
e. other

Although equations a and c are balanced, they do not retain the formulae of the compounds mentioned in the text. Equation b corresponds to the balanced reaction equation and d to the unbalanced equation. The results obtained are shown in Table 3.

Table 3 : Learners' meanings of the composition of the compounds when writing the reaction balance equation

Category name	**Frequencies**				**General percentage**
	$3^{ième}$/105	**2^{nde}/40**	**$1^{ière}$/56**	**T^{le}/38**	
1- Preserving compound identity	41,9%	37,5%	64,3%	68,4%	50,6%
2- Modification of compound identity and preservation of elements	36,2%	37,5%	26,8%	19,1%	31,8%
3- Preservation of identity but not of elements	17,1%	22,5%	7,1%	10,5%	14,6%
4- Others	2,9%	2,5%	1,8%	0,0%	2,1%
5- No answer	1,9%	0,0%	0,0%	0,0%	0,8%

Table 3 shows that 50.6% of the students correctly identified the balanced reaction equation. They were aware of the constant composition of the compounds. We can assume that they have constructed relevant meanings for the index and the stoichiometric coefficient at the symbolic level. 14.6% opted for a not balanced equation in which the identity of the compounds was preserved. They have therefore constructed a symbolically relevant meaning for the notion of index, but not for that of stoichiometric coefficient. Finally, 31.8% retained the number of elements, but not the identity of the compounds. They have constructed a relevant meaning for the notion of stoichiometric coefficient at the symbolic level, but not for the index. However, this poor conceptualisation of the index at the symbolic level tends to disappear as the learners progress through their course.

Meaning of the stoichiometric coefficient at the macroscopic level

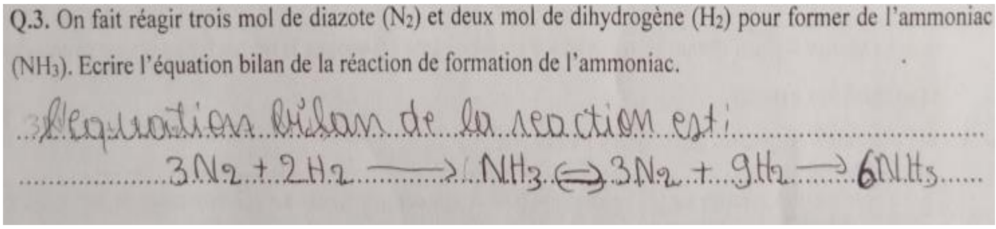
The third question in the questionnaire aims to bring out the meanings attributed to the stoichiometric coefficient at the macroscopic level, in particular its relationship with the initial quantity of matter of the reagents introduced. The question is worded as follows: Three moles of nitrogen (N_2) and two moles of hydrogen (H_2) are reacted to form ammonia (NH_3). Write down the balance equation for the reaction to form ammonia. The results are shown in table 4.

Table 4 : Learners' meanings of the stoichiometric coefficient at macroscopic level

Category name	Frequencies				General percentage
	$3^{ième}$/105	2^{nde}/40	$1^{ière}$/56	T^{le}/38	
1- $N_2 + 3H_2 \rightarrow 2NH_3$ $N_2 + H_2 \rightarrow NH_3$ $N_2 + \frac{1}{2}H_2 \rightarrow 2NH_3$	47,6%	30,0%	41,05%	42,2%	42,2%
2- $3N_2 + 2H_2 \rightarrow NH_3$ $3N_2 + 2H_2 \rightarrow 6NH_3$ $3N_2 + 2H_2 \rightarrow 2N_2H_3$ $3N_2 + 9H_2 \rightarrow 6NH_3$	21,9%	40,0%	35,7%	39,5%	33,9%
3- Failure to identify reactants and products	23,8%	20,0%	10,7%	13,2%	18,5%
4- No answer	6,7%	10,0%	1,8%	2,6%	5,4%

Table 4 shows that 42.2% knew that the initial quantities of matter of the reactants are not taken into account when writing a reaction balance equation. They therefore constructed relevant meanings for the stoichiometric coefficient at the macroscopic level. Only 26.4% (of the total sample) wrote a balanced reaction equation. They also constructed relevant meanings for the stoichiometric coefficient at the symbolic level. 12.5% did not balance the equation. They are aware that the initial quantities of matter of the reactants do not appear in the balanced reaction equation, but have not constructed a relevant meaning for the stoichiometric coefficient at the symbolic level. Finally, 3.3% of learners had difficulty balancing the reaction equation.

In addition, 33.9% of the students confused the stoichiometric coefficient with the initial quantity of reactant. They had constructed an irrelevant meaning for the stoichiometric coefficient at the macroscopic level. However, 3% of them seem to have constructed a relevant meaning for the stoichiometric coefficient at the symbolic level. Although they initially positioned the initial quantities of the reactants in place of the stoichiometric coefficients, they then readjusted the equation to ensure the conservation of the elements.


Q.3. On fait réagir trois mol de diazote (N_2) et deux mol de dihydrogène (H_2) pour former de l'ammoniac (NH_3). Ecrire l'équation bilan de la réaction de formation de l'ammoniac.

l'équation bilan de la réaction est :

$3N_2 + 2H_2 \rightarrow NH_3 \Leftrightarrow 3N_2 + 9H_2 \rightarrow 6NH_3$

Figure 1 : irrelevant significance of the stoichiometric coefficient at the macroscopic level of a learner

Strangely enough, this misconception seems to increase as students' progress through the curriculum. Finally, 18.5% of learners have difficulty correctly identifying the reactants and products of a reaction described at macroscopic level.

Conservation of elements during a chemical reaction

The fourth question assesses the students' understanding of the conservation of elements during a chemical reaction at the microscopic level. The aim is to recognise that no new elements are created during a chemical reaction, but that the elements that make up the reactants are rearranged. The question is formulated as follows: The combustion of a substance A in the oxygen (O_2) in the air produces carbon dioxide (CO_2) and water (H_2O). Where do the carbon and hydrogen elements in the products come from? The results obtained are shown in Table 5.

Table 5 : Learners' understanding of the conservation of elements during a chemical reaction

Category name	Frequencies				General percentage
	3ième/105	2nde/40	1ière/56	Tle/38	
1- Substance A	2,9%	0,0%	23,2%	29,0%	11,3%
2- Chemical reaction	26,7%	50,0%	32,1%	23,7%	31,4%
3- Writing of an equation	0,0%	0,0%	1,8%	7,9%	1,7%
4- Products	8,6%	5,0%	3,6%	0,0%	5,4%
5- Reactants	8,6%	0,0%	7,1%	2,6%	5,9%
6- Answers out of context	13,3%	32,5%	14,3%	10,5%	16,3%
7- No answer	40,0%	12,5%	17,9%	26,3%	28,0%

Table 5 shows that only 11.3% of learners think that the elements carbon and hydrogen come from the substance A. This proportion of students seems to have constructed relevant meanings of the conservation of elements during a chemical reaction at the microscopic level. Compared to the high rate of learners who correctly balance the balance equations obtained in the first question (65.7 to 80.8%), we can deduce that many learners have difficulty moving from the symbolic level to the microscopic level. We share the idea (Dehon, 2018) that learners' ability to balance reaction balance equations is not synonymous with constructing relevant meanings of the underlying concepts. The high non-response rate obtained in Table 5 (28%) confirms this idea.

Furthermore, 31.4% of learners thought that chemical reactions produce chemical elements. The formulations used by these learners were as follows: "the elements carbon and hydrogen come from the complete combustion of body A in the oxygen in the air", "... from the combustion of the reactants", "... from the combustion of carbon and hydrogen". They did not construct a relevant meaning of the concept of chemical reaction at the microscopic level.

5.9% of learners think that the elements carbon and hydrogen come from the reactants but are unable to identify the reactant in question precisely. They simply recited the rule from the 3rd year textbook, which states that “the atoms present in the reactants are all combined differently in the products obtained”. A formulation used by some of them is: “the elements carbon and hydrogen come from body A and O_2”. They were not aware that O_2 contained neither carbon nor hydrogen.

5.4% of the students thought that the carbon and hydrogen elements present in the products came from the products themselves. Their answer was based solely on the raw formulae of the products, in which they identified the letters C and H. They therefore remained at the level of symbolic meaning.

16.3% of the pupils gave answers outside the context of the situation described, such as “a black deposit and escaping water”, “hydrolysis”, “methane”. These are at the level of symbolic meaning (Dehon, 2018).

Stoichiometric mixing at macroscopic level

The fifth question in the questionnaire aims to determine what learners mean by stoichiometric mixing at the macroscopic level. The aim is to recognise that the quantity involved in a stoichiometric relationship is the quantity of matter and not the mass or volume. It can be stated as follows: Consider the chemical reaction symbolised by the following balance equation: $C + O_2 \rightarrow CO_2$. At the initial instant, one gram of carbon (C) and one gram of oxygen (O_2) are mixed. Are the reactants in stoichiometric proportions? Justify this.

Table 6: Learners' meanings of stoichiometric proportions

Category name	**Frequencies**				**General percentage**
	3ième/105	**2nde/40**	**1ière/56**	**Tle/38**	
1- yes	41,9%	55,0%	42,9%	36,8%	43,5%
2- No	9,5%	25,0%	37,5%	44,7%	24,3%
3- No answer	48,6%	20,0%	19,6%	18,4%	32,2%

Table 6 shows that this question had a considerable rate of non-responses (32.2%). Of those who answered the question, very few (24.3%) thought that the reactants were not in stoichiometric proportions. Of these, only 1.7%, exclusively in first and final year classes, justified that the reactants are in stoichiometric proportions if the ratios of their initial quantities of matter by their respective stoichiometric coefficients are equal. They have constructed a relevant meaning of the notion of stoichiometric mixture at the macroscopic level. In addition, 15% think that the reactants are in stoichiometric proportions if their initial quantities are equal. These learners have relevant meanings of the particle counting unit at the macroscopic level. However, the fact that they did not mention the stoichiometric coefficients suggests that they have not constructed relevant meanings of the proportions in which the reactants react.

On the other hand, 43.5% think that the reactants are in stoichiometric proportions. In this category, 10.9% justified that the reactants were in stoichiometric proportions because the equation was balanced. Some backed up their statements by saying that “the stoichiometric coefficients are equal to the masses”. These students therefore carry around the erroneous meaning mentioned above: the stoichiometric coefficient represents the initial quantity of reactants. They do not understand that mixtures of different amount of the same reactants can obey the same equation. In addition, 7.5% thought that the reactants were in stoichiometric proportions because “the mass of the reactants is equal to that of the products”. This justification, which is used in a context where the mass of the products has not been given, is based on a recitation of Lavoisier's law of conservation of mass studied in class.

Finally, 5.4% of learners thought that the reactants were in stoichiometric proportions if their coefficients were equal.

Meaning of the concept of stoichiometry at the macroscopic level

The sixth question probes the meanings associated with stoichiometry at the macroscopic level. The aim is to determine from a balance equation the quantity of a reagent that can react completely with a known quantity of the other reagent. The reaction of iron with oxygen is modelled by the following balance equation. What quantity of oxygen (O_2) is needed to completely react 2 moles of iron (Fe)? The results obtained are given in Table 7.

Table 7: Learners’ meanings of stoichiometry at macroscopic level

Category name	**Frequencies**				**General percentage**
	3ième/105	**2nde/40**	**1ière/56**	**Tle/38**	
1- Correct use of the proportionality relation at the macroscopic level	4,8%	40,0%	62,5%	84,2%	36,8%
2- Poor conceptualisation of the amount of substance	18,1%	0,0%	7,1%	5,3%	10,5%
3- Poor use of the rule of 3	1,9%	2,5%	0,0%	0,0%	1,3%
4- Random/unjustified answers	10,5%	12,5%	3,4%	2,6%	8,0%
5- Using of m/M	33,3%	17,5%	9,0%	2,6%	20,1%
6- Using of the Avogadro number	3,8%	2,5%	0,0%	2,6%	2,5%
7- No answer	27,6%	25,0%	17,9%	2,6%	20,9%

Overall, 36.8% of the students questioned were able to determine the quantity of a reagent needed to react completely with a precise quantity of another reagent. They seem to have constructed relevant meanings for the proportionality relationship between reactants at macroscopic level. However, the fact that the rate of correct answers increased with the level of study indicates that this correct application of the relationship of proportionality between reagents is due more to its frequent use than to an understanding of stoichiometry.

Furthermore, 20.1% of the students (mostly in the third year) used the relationship to determine the quantity of O_2. Almost all of these students assigned arbitrary values to the different variables in the relationship in order to obtain a result. This relationship therefore remains constructed at a symbolic level. In addition, 8% of the learners questioned had a poor conceptualisation of the quantity of matter. They sometimes equated it with the stoichiometric coefficient, sometimes with the molar mass. 2.5% of students used the relationship between the number of moles and Avogadro's number, this time confusing the number of atoms with the quantity of matter. Finally, 8% gave haphazard answers, without any justification, and 1.3% of the students misused the rule of 3 to answer the question.

Meaning of the concept of stoichiometry at the microscopic level

The seventh question explores the meanings associated with stoichiometry at the microscopic level. It involves determining from a balance equation the number of molecules (or atoms) of one reactant that can react completely with a known number of molecules (or atoms) of the other reactant. It is formulated as follows: the reaction of iron with oxygen is modelled by the following balance equation: $4Fe + 3O_2 \rightarrow 2Fe_2O_3$. How many molecules of oxygen (O_2) are needed to react completely with 8 atoms of iron (Fe)? The results obtained are shown in Table 8.

Table 8: Learners' meanings of stoichiometry at the microscopic level

Category name	**Frequencies**				**General percentage**
	3ème/105	**2nde/40**	**1ère /50**	**Tle/38**	
1- Correct use of the proportionality relation at the microscopic level	1,0%	0,0%	8,0%	2,4%	3,1%
2- Multiplying the stoichiometric coefficients of the equation	1,0%	25,6%	34,0%	26,8%	17,3%
3- Poor use of the Avogadro's number	6,2%	9,3%	12,0%	14,6%	9,5%
4- Poor use of the proportionality relation at the macroscopic level	0,0%	16,3%	10,0%	12,2%	7,4%
5- Inappropriate use of the formula n=m/M	7,2%	0,0%	0,0%	2,4%	3,5%
6- Incorrect answers without justification	27,8%	16,3%	12,0%	14,6%	19,9%
7- No answer	56,8%	32,6%	22,0%	24,4%	39,0%

Table 8 shows that (20.4%) of learners correctly determined the number of molecules (or atoms) of one reagent needed to react completely with a known number of molecules (or atoms) of the other reagent. This rate of correct answers increases with the level of study. However, the fact that the rate of correct answers was higher in the first year of secondary school than in the final year is cause for concern. Of these, 3.1% correctly applied the relationship of proportionality between reagents at the microscopic level. They seem to have constructed a relevant meaning of stoichiometry at the microscopic level. 17.3% chose to multiply the stoichiometric coefficients of the balance equation by two. These students constructed a relevant meaning for the stoichiometric coefficient at the microscopic level as the number of molecules (atoms) of reactants that react.

Comparing this percentage of correct answers (20.4%) with that for question 6 (36.8%), it appears that stoichiometry is better conceptualised by the learners at the macroscopic level than at the microscopic level. The high rate of non-response (39%) and of unjustified wrong answers (19.9%) supports this idea.

Furthermore, 9.5% of the learners used the relationship n = $\frac{N}{N_A}$ (where n represents the quantity of matter, N the number of molecules and NA the Avogadro number). They do not take into account the balance equation. They have therefore constructed an irrelevant significance of stoichiometry at the microscopic level. 10.9% of learners calculate the quantity of matter instead. 7.4% use the proportionality relation and 3.5% used the relationship $n = \frac{m}{M}$. They remain at the macroscopic level.

Determining the quantity of product formed from a non-stoichiometric mixture

The eighth question tests the students' ability to determine the quantity of product formed from a non-stoichiometric mixture. In particular, we want to check whether the students, given the initial quantities of two reagents, take the trouble to find the limiting reagent before looking for the quantity of product formed. This will enable us to highlight the meanings they have constructed around the concept of the limiting reagent. The question is formulated as follows: 5 moles of oxygen (O_2) and 3 moles of iron (Fe) are mixed. The reaction that occurs is modelled by the following balance equation: $4Fe + 3O_2 \rightarrow 2Fe_2O_3$. The quantity of iron oxide III (formed at the end of the reaction is: (circle the letter corresponding to the correct answer):

a. 4 mol
b. 2 mol
c. 1,5 mol

d. 3,33 mol
e. Other

The answers are given in Table 9.

Table 9: Learners' understanding of the concept of limiting reagent

Category name		**Frequencies**				**General**
		3^{e}/105	**2^{nde} /40**	**$1^{ière}$/56**	**Tle/38**	**%**
1- Correct application of the proportionality relation after determining the limiting reagent		0,0%	0,0%	4,0%	12,1%	3,0%
2- Correct application of the proportionality relation without determining the limiting reagent	Use of the limiting reagent	4,1%	12,2%	22,0%	19,5%	12,2%
	Using excess reagent	1,0%	4,9%	4,0%	4,9%	3,1%
	Uncertainty between reagents	0,0%	0,0%	6,0%	4,9%	2,2%
3- Incorrect application of the proportionality relation		0,0%	2,4%	4,0%	7,3%	2,6%
4- Stoichiometric coefficient		13,4%	39,0%	26,0%	12,2%	20,5%
5- Multiplying the index and the stoichiometric coefficient		21,7%	0,0%	4,0%	7,3%	11,4%
6- Unjustified answers		37,4%	34,1%	16,0%	17,1%	28,8%
7- No answer		21,6%	7,3%	14,0%	14,7%	16,2%

Table 10 shows that only 3% of learners found the limiting reagent and correctly determined the quantity of product formed. They had constructed a relevant meaning for the limiting reagent at macroscopic level.

On the other hand, 17.5% of the learners, although correctly applying the relationship of proportionality between the quantities of reagent consumed and product formed, did not determine the limiting reagent beforehand. They had constructed an irrelevant meaning for the notion of limiting reagent. The fact that 2.2% of learners determined two values for the quantity of the product from the quantities of the two reagents supports this idea*:* “if you use oxygen, you get 3.33 moles and if you use iron, you get 1.5 moles”. The use of the limiting reagent (without prior determination) by 12.2% of learners could be explained by the position of the two reagents in the balance equation. In fact, they would have spontaneously used the first reagent to appear in the equation.

In addition, 20.5% of the learners confused the quantity of iron (III) dioxide formed with its stoichiometric coefficient. They have an irrelevant meaning for the notion of stoichiometric coefficient at the macroscopic level. The same applies to the 11.4% who multiply the stoichiometric coefficient of the product by the index of the element iron. They also have a poor conceptualisation of the role of the index.

Conclusions

We have surveyed learners' conceptions of the concepts in the stoichiometry conceptual network using a test consisting of eight open-ended and semi-open-ended questions. The data were analysed using Dehon's (2018) significance level model. The results showed that, although learners had little difficulty in balancing chemical equations, they constructed meanings for the concepts in the stoichiometry conceptual network that were largely irrelevant. In fact, the stoichiometric coefficient is better constructed at the symbolic (number that enables the balance equation to be balanced) and microscopic (number of reactant molecules that react) levels than at the macroscopic level, where it is considered as the quantity of reactant introduced or the quantity of product formed. Furthermore, learners who manage to balance chemical equations have difficulties moving between the symbolic and microscopic levels. Specifically, the idea of atoms being rearranged during a chemical reaction is poorly understood by learners, most of whom think that the chemical reaction itself produces chemical elements.

Finally, the concept of stoichiometry is better constructed at the macroscopic level than at the microscopic level. Furthermore, it is unfortunate that the other concepts in the conceptual network of stoichiometry (stoichiometry, limiting reagent, stoichiometric coefficient) are not given much space in current secondary education in Cameroon, in favour of the balancing of reaction equations. A better construction of these concepts in classroom situations would allow a better conceptualisation of this integrating concept. In the future, we will test this working hypothesis by proposing a learning sequence that includes the different concepts of the stoichiometry conceptual network.

Conflict of Interest: The authors reported no conflict of interest.

Data Availability: All data are included in the content of the paper.

Funding Statement: The authors did not obtain any funding for this research.

References:

1. Awomo Ateba, J. (2022). Difficultés des élèves dans l'apprentissage du concept d'équilibre chimique au secondaire camerounais. Contribution à une épistémologie appliquée à la construction curriculaire. [Thèse de doctorat], Université de Yaoundé 1, Yaoundé. DOI: 10.13140/RG.2.2.26695.06561
2. Barlet, R., & Plouin, D. (1994). L'équation-bilan en chimie. Un concept intégrateur source de difficultés persistantes. Aster:

Recherches En Didactique Des Sciences Expérimentales, 18(1), 27–56.
3. BouJaoude, S., & Barakat, H. (2003). Students’ problem solving strategies in stoichiometry and their relationships to conceptual understanding and learning approaches. The Electronic Journal for Research in Science & Mathematics Education.
4. Cedran, D. P., da Costa Cedran, J., & Kiouranis, N. M. M. (2022). Panorama histórico da construção do campo conceitual da estequiometria. Revista Dynamis, 28(2), 152–170.
5. Çelikkiran, A. T. (2020). Examination of Secondary School Students’ Ability to Transform among Chemistry Representation Levels Related to Stoichiometry. International Journal of Progressive Education, 16(2), 42–55.
6. Dehon, J. (2018). L'équation chimique, un sujet d'étude pour diagnostiquer les difficultés d'apprentissage de la langue symbolique des chimistes dans l'enseignement secondaire belge, développement d'une séquence de leçons en s' appuyant sur un modèle des niveaux de signification. Namur: PUN.
7. Dehon, J., & Snauwaert, P. (2015). L’équation de réaction: une équation à plusieurs inconnues. Étude de productions d’élèves de 16-17 ans (grade 11) en Belgique francophone. RDST. Recherches En Didactique Des Sciences et Des Technologies, 12, 209–235.
8. Ducamp, C., & Rabier, A. (2005). L’avancement de réaction en classe de première scientifique. 4iemes Rencontres Scientifiques de l’ARDIST.
9. Fourcroy, A.-F.;Vauquelin, L.-N. (1797). De l’action spontannée de l’acide sulfurique concentré sur les substances végétales et animales. Annales de Chimie, 194–195.
10. Frazer, M. J., & Servant, D. (1986). Aspects of stoichiometry titration calculations. Education in Chemistry, 23(2), 54–56.
11. Gauchon, L. (2008). *Comprendre les titrages-Représentations d’élèves de première et terminale scientifiques et effets de quelques variables*. Université Paris-Diderot-Paris VII.
12. Gauchon, L., & Méheut, M. (2007). Learning about stoichiometry: from students’ preconceptions to the concept of limiting reactant. *Chemistry Education Research and Practice*, *8*(4), 362–375.
13. ohnstone, A. H. (2000). Teaching of chemistry-logical or psychological? *Chemistry Education Research and Practice*, *1*(1), 9–15.
14. Laugier, A., & Dumon, A. (2000). Travaux pratiques en chimie et representation de la reaction chimique par l’equation-bilan dans les registres macroscopique et microscopique: Une etude en classe de

seconde (15-16 ans). *Chemistry Education Research and Practice*, *1*(1), 61–75.
15. Nakhleh, M. B., & Mitchell, R. C. (1993). *Concept learning versus problem solving: There is a difference*. ACS Publications.
16. Nurrenbern, S. C., & Pickering, M. (1987). Concept learning versus problem solving: Is there a difference? *Journal of Chemical Education*, *64*(6), 508.
17. Stamovlasis, D., Tsaparlis, G., Kamilatos, C., Papaoikonomou, D., & Zarotiadou, E. (2005). Conceptual understanding versus algorithmic problem solving: Further evidence from a national chemistry examination. *Chemistry Education Research and Practice*, *6*(2), 104–118.
18. Talanquer, V. (2011). Macro, submicro, and symbolic: The many faces of the chemistry “triplet.” *International Journal of Science Education*, *33*(2), 179–195.
19. Thouin, M. (2014). *Réaliser une recherche en didactique*. Éditions MultiMondes.
20. Zumdahl, S. S. (2002). *Chemical Principles: Steven S. Zumdahl*. Boston, MA: Houghton Mifflin.