AFRICAN JOURNAL OF CHEMICAL EDUCATION
AJCE

Vol. 13, Number 2, June 2023

SPECIAL ISSUE: LECTURE SERIES FROM ACRICE-5

SJIF Impact Factor Evaluation [SJIF 2012 = 3.963]
SJIF Impact Factor Evaluation [SJIF 2013 = 4.567]
Indexed and Abstracted by CAS

A Publication of Federation of African Societies of Chemistry
FASC
Chemistry for Sustainable Development in Africa

ISSN 2227-5835 **www.faschem.org**

AFRICAN JOURNAL OF CHEMICAL EDUCATION

AJCE

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EDITORIAL

LECTURE SERIES FROM ACRICE-5: SPECIAL ISSUE

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The African Conference on Research in Chemistry Education (ACRICE) is a flagship conference of the Federation of African Societies of Chemistry. It also become one of the IUPAC conferences. ACRICE was launched in Addis Ababa/Ethiopia in December 2013. The 2nd ACRICE was in Venda/South Africa, in 2015; the 3rd in Setif/Algeria in 2017; and the 4th in Jos/Nigeria in 2019.

The 5th African Conference on Research in Chemical Education [ACRICE-5], hosted by Ain Shams University, Cairo, Egypt, was conducted on 7-9 December 2022 with a theme: **Teaching Chemistry for a sustainable future**. ACRICE-5 was endorsed by the Egyptian Academy of Scientific Research and Technology, International Union of Pure and Applied Chemistry (IUPAC), the Federation of African Societies of Chemistry [FASC], 10 Academy, Falconess.

The June 2023 issue of AJCE has published a Special Issue entitled Lecture Series from ACRICE-5. Selected papers presented at the Conference were peer-reviewed and published as in this issue. We hope you will enjoy reading them.

INTERPRETATION OF CHEMICAL REACTIONS ON SUB-MICRO LEVEL WITHOUT LABORATORY JARGON

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ABSTRACT

From experiences all over the world, we know that formulae and chemical equations are memorized very often or only equalized by counting the number of "atoms on the left and right side of the equation". Looking to our Chemical triangle (Fig. 1) lecturers and students are jumping from the Macro level just to the Symbolic level. If we would go first from Macro level to Sub-micro level and explain chemical reactions with involved atoms, ions and molecules, learners would understand chemistry more successfully. With a special questionnaire we are investigating the ability of university students and chemistry teachers in Indonesia and Tanzania to interpret given chemical equations with involved particles. We found a lot of misconceptions and proposed how to challenge them. Another problem may be the Laboratory jargon. Very often lecturers and teachers are mixing Macro and Sub-micro level, they read the well-known equation $2H_2 + O_2 \rightarrow 2H_2O$ with the words: "two hydrogens plus one oxygen form two water". Every expert knows that the molecules are meant, but the young learner asks: "grams or milliliters of those gases"? So please stay on the Macro level and read "hydrogen and oxygen react to water". Or take the Sub-micro level and read: "$2H_2$ molecules + $1O_2$ molecule react to $2H_2O$ molecules". Otherwise, misconceptions may arise, more examples can be found in the text. *[African Journal of Chemical Education—AJCE 13(2), June 2023]*

INTRODUCTION

There is a true story of the year 2003 at one of the Secondary schools at Kilimanjaro area in Tanzania. The teacher of a Form-VI class (highest level in schools) did a titration of hydrochloric acid, asked the students to interpret the change of indicator color – and soon the well-known equation was developed at the blackboard: HCl + NaOH → NaCl + H_2O. Author BARKE interrupted the lesson with the question: "Please let me know which particles are reacting". The teacher looked irritated and pointed out that „HCl and NaOH" are involved. So BARKE went to the blackboard, sketched a beaker model and wrote inside „H^+(aq)" and separated „Cl^-(aq)". Suddenly a young girl came up with a beaker-model of NaOH solution: „Na^+(aq) and OH^-(aq)". After some discussion about the function of sodium and chloride ions the students recognized that H^+(aq) ions and OH^-(aq) ions react to form H_2O molecules – other ions remain without reacting. The 50-years-old teacher came to BARKE and noticed: „Thanks for opening my eyes for interpreting neutralization. Why did you not come 30 years earlier – I would have explained neutralization every time like you have done it today".

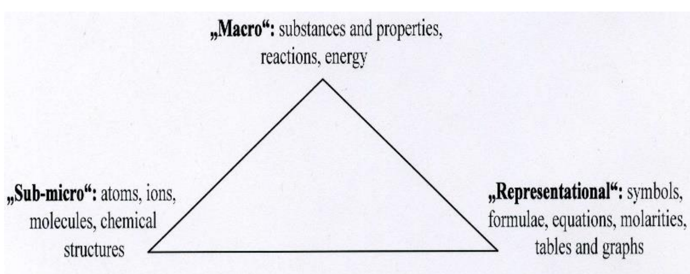

Fig. 1: JOHNSTONES Chemical triangle for Chemistry education [1]

This story shows that the Sub-micro level (see Fig.1) seems so important to understand neutralization in the scientific way. Also other acid-base and redox reactions are confusing learners if only full equations are stated: School-made misconceptions are coming up [2]. These reactions should be discussed and explained by reacting ions. Since 1928 BROENSTED proposed his idea to look not only to *substances* of chemical reactions but to involved *particles* which react [3]: for example, to $H_3O^+(aq)$ ions which are proton donors and transfer protons to $OH^-(aq)$ ions or other base particles.

In Chemistry teaching atoms and molecules as smallest particles of matter are well-known – but ions have been ignored in many curricula around the world: Misconceptions can be stated if particles in salt solutions or in mineral water are asked [2]. One example: If precipitation of barium sulfate from barium chloride and magnesium sulfate solutions should be described, one is mostly writing: „$BaCl_2 + MgSO_4 \rightarrow BaSO_4 + MgCl_2$".

But there are misconceptions of „partner change" and some curricula tell the precipitation as „double replacement reaction" [4]: „Barium and magnesium are changing partners". Taking the involved ions into account it is easy to write: $Ba^{2+}(aq) + SO_4^{2-}(aq) \rightarrow BaSO_4(s)$.

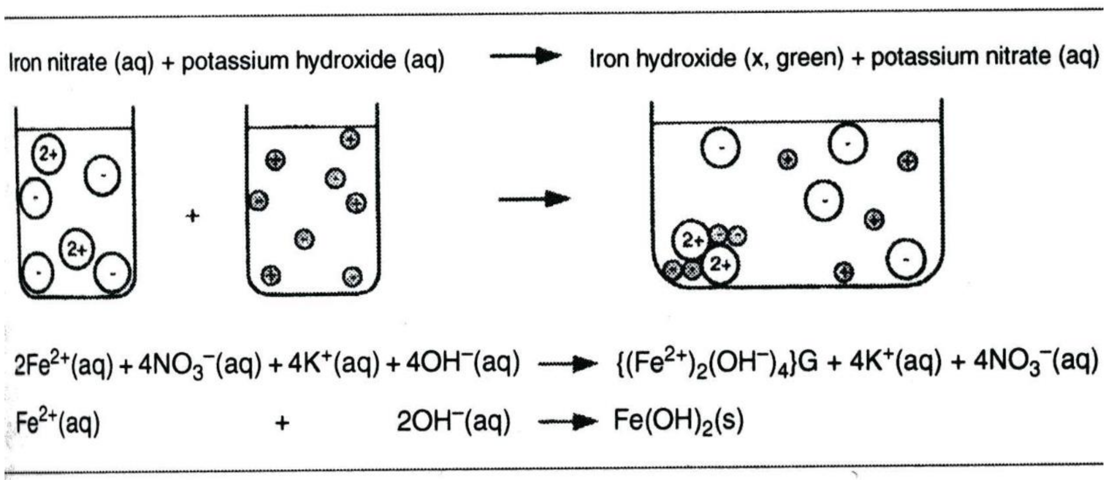

Fig. 2: Beaker model of iron (II)-hydroxide precipitation by salt solutions [5]

These ions are joining to form a $Ba^{2+}SO_4^{2-}$-ionic lattice, the other Mg^{2+}(aq) and NO_3^-(aq) ions are „spectator ions" in the sense of not reacting particles: those ions *remain*. The best way is to draw a concrete model of a precipitation (Fig. 2) and discuss this beaker model with the aim to develop a scientific mental model on the Sub-micro level [5]. We will investigate those abilities of students in higher semesters of several universities.

EMPIRICAL RESEARCH ACCORDING TO THE SUB-MICRO LEVEL

ASIH WISUDAWATI [6] developed a questionnaire to give university students the usual chemical equation of acid-base and redox reactions and asked questions according to the involved atoms, ions or molecules, also according to particles which do not react, according to the decision if there is an acid-base or redox reaction and the connected transfer of protons or electrons (see one example in the appendix).

At Indonesian universities of Yogjakarta and Bandung she applied the 10-tasks questionnaire (see appendix) and tested objectivity, reliability and validity successfully. During 60-minutes period students should solve the tasks, and about 75 answer sheets have been received. She got the following results [6]:

- Most of the tasks 2, 5 and 6 are answered in a right way and interpreted as redox reactions. But not in all cases students could mark those particles which are giving electrons, and particles which are taking electrons.
- Reactions 1, 3, 4 and 7 are interpreted in a right way as acid-base reactions – but nearly no student can mark particles which give protons or take protons. Acid-base reaction in task 8 gives problems: it is interpreted as redox reaction without explaining the decision. The weak acid “HAc molecule” is mostly seen as completely protolyzed into ions without explaining weak acids by equilibria between molecules and ions.
- Solid salts are often described without ions: “Na_2CO_3, $CaCO_3$ and MgO molecules” exist in the mind of students. So according to the question which particles are not reacting, metal ions composing all salt crystals are mostly not mentioned.

- **Question 9** asks about the most difficult alternative out of (a) – (d). Students are deciding mostly (d) according to the transfer of protons or electrons with following comments: „Proton or electron transfer confuses me; I need basic concepts of chemistry; we need to understand (a) – (c) for an answer; we need a lot of theory and more time to answer“. Also (c) about “spectator ions” is confusing a lot of university students.
- **Question 10** concerns student‘s wishes for going deep into the Submicro level or not. Students answers: „yes – because it is important to learn what particles are doing; to differentiate acid-base and redox reactions better; it helps to understand chemistry; it can support to be a better teacher; I can improve my understanding of chemistry“.

Just the last answers may give us an impression how much students will appreciate to get more information about atoms, ions and molecules which are involved in chemical reactions. As soon as learners interpret reactions on the Submicro level successfully, they understand the Chemistry behind – and chemical equations must not be memorized, they may be used as short information connected to mental models of those reacting atoms, ions and molecules. Especially the decision wheather an acid-base or a redox reaction occur and which particle donates or takes a proton or an electron can be completely understood.

BARKE gave in September 2018 same questionnaire to 20 experienced teachers during a one-week-teacher-training seminar in Moshi, Tanzania. The results are very different: some teachers answered nearly perfect, the majority has big problems [6]:

- Teachers cannot avoid the mixture of particles and substances: „H^+ ions and OH^- ions form *water*, H^+ ions and CO_3^{2-} ions form *water* and *carbon dioxide gas*“. But we have this problem around the world: particles and substances are mixed (see later „Laboratory jargon“).
- They also interpret reactions with „salt molecules”, and if they want to show chemical structures of compounds they cut formulae into not existing ions: „$2H^+O^{2-}$, $Na^+O^{2-}H^+$, $2H^+S^{6+}O^{2-}$ “ are some examples. Especially with combined ions like sulfate, nitrate or carbonate ions there are difficulties with indizes and exponents in formulae.
- Redox reactions and the equivalence of electrical charges on both sides of equations are other difficulties. Concerning reactions of iron and copper chloride solution Fe and Cu atoms are ignored: „$Fe^{2+} + Cu^{2+}Cl^- \rightarrow Fe^{2+}2Cl^- + Cu^{2+}$“. Charges are also misunderstood and wrong calculated: „$Cu^{2+} - 2e \rightarrow Cu$ or $2\ Ag^+ \rightarrow Ag + 2e$ or $Zn + 2e \rightarrow Zn^{2+}$ “ are examples.
- Acid-base reactions have been explained by „electron transfer“ because teachers don’t know proton transfers (this idea was given through the seminar): „$2\ H^+ + 2\ OH^- \rightarrow 2\ H_2O + 2e$ or $2\ H^+$ gain 2 e, OH^- looses 2e or H^+ is reduced, and OH^- is oxidized“ are misconceptions.

Later after the seminar another a posttest has been performed – and the teachers could show their new knowledge concerning acid-base reactions with proton transfer, and redox reactions with electron transfer. So, we have to admit that teacher education in science and especially in Chemistry is very poor around many parts of the world because lecturers at teacher colleges mostly are not used to interpret those reactions on the Submicro level.

- Asking **task 9** about the difficulties according to (a) – (d) all four alternatives have been irritating the teachers because they have never answered those questions – and have not really understood differences in acid-base and redox reactions. At the end of the seminar they were very thankful to get new insights in the seminar and are now more sure how to explain those reactions scientifically, how to move successfully on the Sub-micro level.
- Even at the begin of the seminar teachers have grabbed the big meaning of the Sub-micro level and answered according **task 10** that they want to go deep into the Sub-micro level: „Indeed – there is much knowledge in this topic which is very important for teaching, on this way we want to understand more Chemistry“, have been some comments.

LABORATORY JARGON AND MISCONCEPTIONS OF STUDENTS

According to the Sub-micro level we have in chemistry another problem. Lecturers mostly use a "laboratory jargon" during their lessons and the question comes up whether teacher students take this jargon for their terminology, or even develop „school-made misconceptions" [2]. If they transfer them later as teachers to their students at schools, those misconceptions are going on and on. One example: "2 hydrogen react with 1 oxygen to form 2 water" is often stated by experts (and experts know that the involved molecules are meant). But students look to substances and may ask: "2g or 2 mL of hydrogen are involved?" As soon as they hear the scientific interpretation "2 H_2 molecules and 1 O_2 molecule are forming 2 H_2O molecules", they understand Chemistry - this last statement is totally clear and should be used.

JOLINE BUECHTER [6]. A German empirical pilot study has shown first results: About half of the investigated participants at University of Muenster could reflect and correct given jargon statements – but even after three years of studying chemistry the other students are staying with that jargon or other alternative conceptions. One example of the questionnaire where students have to mark the scientifically correct answer:

"2) Lab. Jargon: "Hydrochloric acid gives off a proton"

a) Hydrochloric acid can be deprotonated.

b) Hydrochloric acid can also absorb protons.

c) H_3O^+(aq) ions are present in hydrochloric acid, they can emit protons.

d) HCl molecules are present in hydrochloric acid, they release protons" [6].

The right answer is of course (c): "H_3O^+(aq) ions are present in hydrochloric acid, they can emit protons". BUECHTER took the famous misconception (d) and was waiting of "HCl molecules in solution". Because of the well-known idea of "deprotonation" we offered alternative (a), answer (b) is a fake [6]. The right answer (c) is chosen by 40 % of participants, the real misconception about "HCl molecules in hydrochloric acid" is fortunately taken by only 5 %. But answer (a) has reached the majority of 55 %: Many students are thinking of a scientifically sound of deprotonation. The questionnaire may be studied by BUECHTER [7].

Question	Germany	Indonesia	
1	68	92	84
2	40	15	19
3	90	54	50
4	77	63	59
5	55	48	45
6	22	25	33
7	50	15	22
8	82	83	65
9	64	79	87
10	55	23	31
	Year 3	Year 3	Year 1-4

YULI RAHMAWATI [6]. She created the English version of the questionnaire and took it to students of UNJ University of Jakarta/Indonesia. Similar results have been obtained (see Table). In question 2 Indonesian students took mostly answer (d) "Proton donor HCl".

In question 7 "Neutralization" many students decided "salt formation" as right answer – and not the reaction of H^+(aq) ions and OH^-(aq) ions. Related to question 10 "Amphoteric H_2O molecule" most students don't look to the H_2O molecule as proton donor and acceptor, but chose the substance: "water can be an acid or a base".

In Indonesia most explanations are given on base of substances – like problems experienced in Tanzania and Ethiopia – curricula should be improved to instruct also the Sub-micro level for understanding Chemistry.

CHALLENGE OF MISCONCEPTIONS

What shell we do to avoid those mentioned misconceptions with ions as important particles? As soon as atoms are well-known and metal atoms in metal structures are visualized by densest sphere packings, molecules should be introduced by ball-stick models and their molecular structural symbols. Also, the ions, the third group of smallest particles, should be introduced by their symbols and by models of the ionic lattice of salt crystals.

Usually, during the introduction of atoms the Periodic table is shown with all atomic symbols, numbers, and masses. If one takes spheres to visualize that every atom has a specific diameter, it is easy to also symbolize the corresponding ions with their specific diameter (see Fig. 3): Charge numbers are given without comparing any protons in the nucleus and electrons in the shell – the ions can be introduced without the differentiated atomic model! Later during higher classes students may work with the nucleus-shell model of atoms and ions and their number of electrons can be discussed for explaining ion charges.

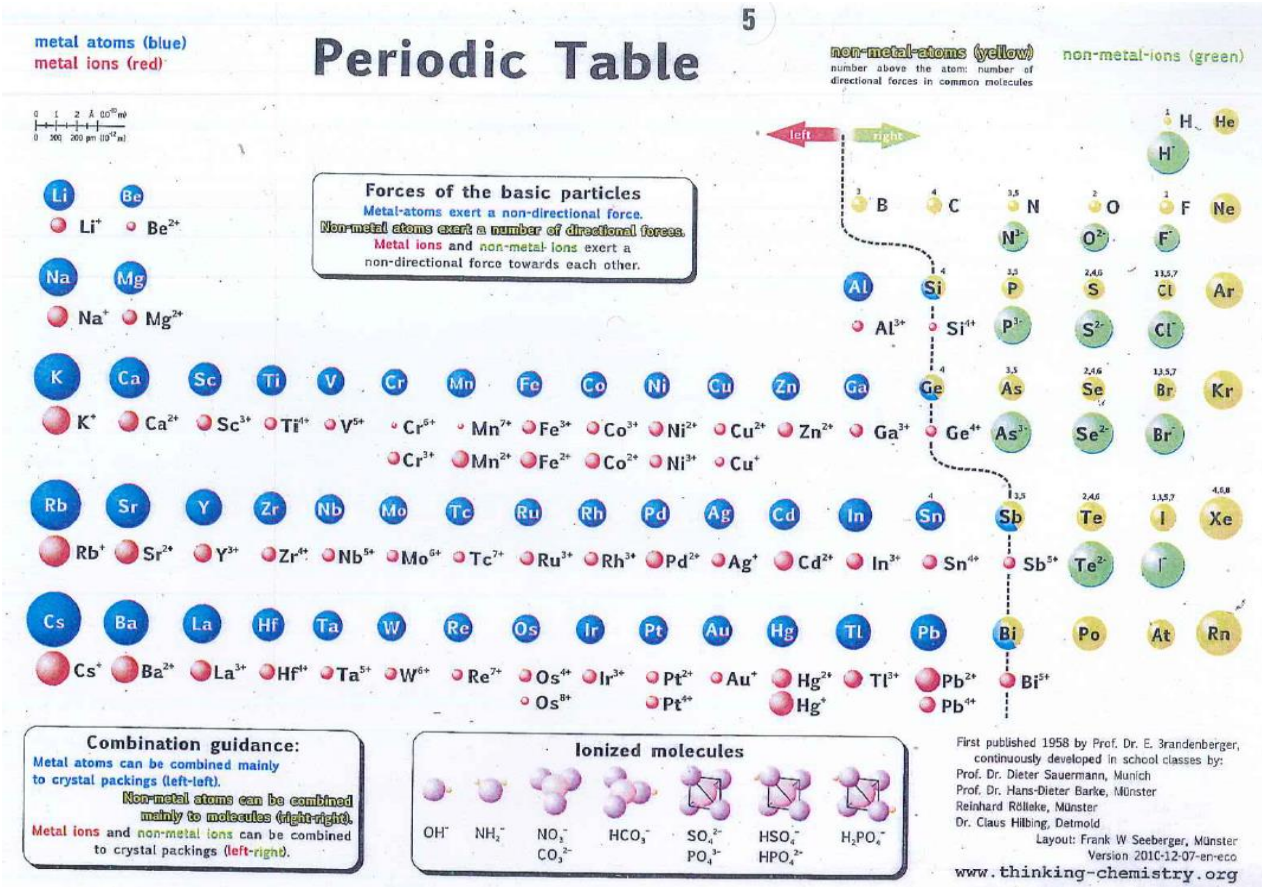

Fig. 3: PSE-depiction of a selection of atoms and ions and their spherical models [8]

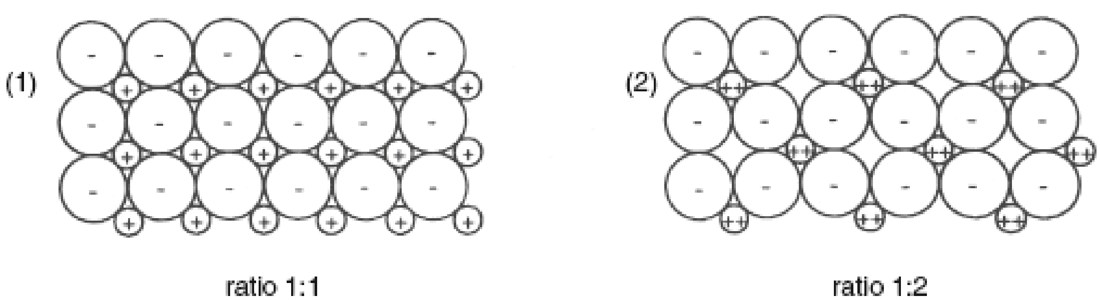

Fig. 4: 2-D models of ionic lattices in the ion ratio 1 : 1 (NaCl) and 1 : 2 ($MgCl_2$) [5]

Analogically to the composition of a water molecule by two H atoms and one O atom, one may state that sodium chloride is not composed of molecules, but of Na^+ ions and Cl^- ions in an ionic giant structure (Fig. 4, left side). If possible, a 3D-sphere packing of two different kinds of colored spheres should be offered or even built by students themselves [5] and discussed according to the 2D-model. By questions about the forces which hold the ions together, the idea of ionic bonding can be given: Ions with same charge are repelling, but ions with different charges are attracting – last forces are much higher and bind all ions in an ionic lattice. One can even discuss the melting temperatures of different salts: Sodium chloride melts by 800 ^oC, Magnesium oxide with same ionic lattice structure by 2850 ^oC.

In every case the ionic symbol for sodium chloride should be shown as $(Na^+)_1(Cl^-)_1$ or Na^+Cl^-. If only the NaCl symbol is used, the misconception according "NaCl molecules" may come up. The same will be repeated and reflected for magnesium chloride: $(Mg^{2+})_1(Cl^-)_2$ and the 2D-model (Fig. 4, right side). On this way students have chances to know that ions are composing those salts – and may avoid misconceptions of "salt molecules" [2]. After discussing the meaning of symbols those ionic formulae can be shorten to NaCl and $MgCl_2$ – but the involved ions should be in the mind of learners, in their mental model!

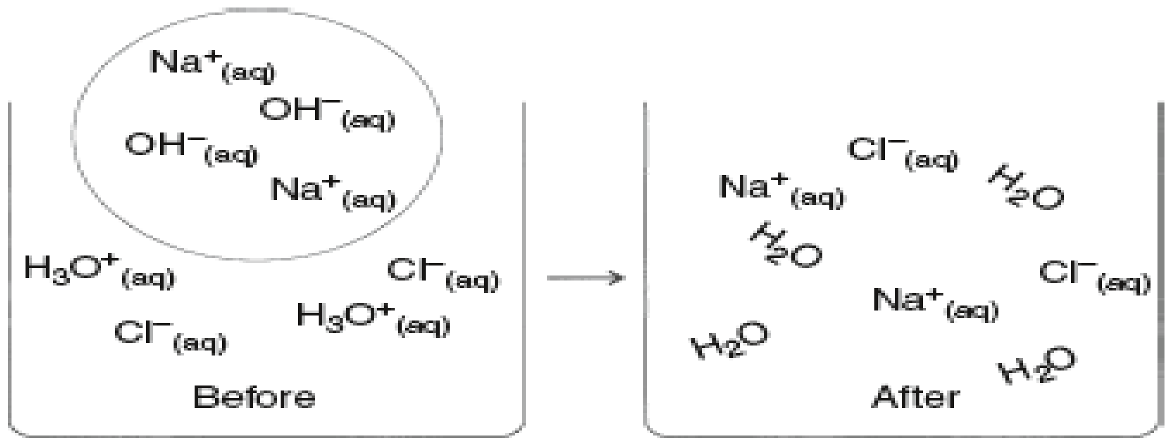

Fig. 5: Beaker model for neutralization of hydrochloric acid by sodium hydroxide solution [5]

If salt solutions will be introduced, (aq)-symbols should be added: Na^+(aq) ions and Cl^-(aq) ions for sodium chloride solution, Mg^{2+}(aq) and Cl^-(aq) ions in the ratio 1 : 2 for magnesium chloride solution. Those ratios can be visualized by beaker models to show that the ions are not organized by ion pairs but move separated from another in solutions (Fig. 2).

Students know the common equation for neutralization, in case of hydrochloric acid and sodium hydroxide solution: HCl + NaOH → NaCl + H_2O. Asking about the particles which are reacting often HCl and NaOH molecules are mentioned. So it is important to point out that H^+(aq) ions and OH^-(aq) ions are reacting, or in sense of BROENSTED [3] better an H_3O^+(aq) ion gives a proton to an OH^-(aq) ion:

H_3O^+(aq) ion + OH^-(aq) ion → 2 H_2O molecules

Even the neutralization of acids and bases should be reflected by beaker models (Fig. 5). The (aq)-symbol is important because the learner knows that different charged ions are attracting and may join together. The (aq)-symbols show hydrated ions: 4, 5 or 6 H_2O molecules are connected to every ion – avoiding the strong attraction of ions like in solid or molten salts.

It is also possible to open the discussion by a Concept cartoon (Fig. 6): Students can show their explanation out of four given answers, or can explain other conceptions – teachers know how students are thinking. The discussion may go in the direction of the boy on the right side: "After the reaction there are Na^+(aq) ions, Cl^-(aq) ions, and H_2O molecules".

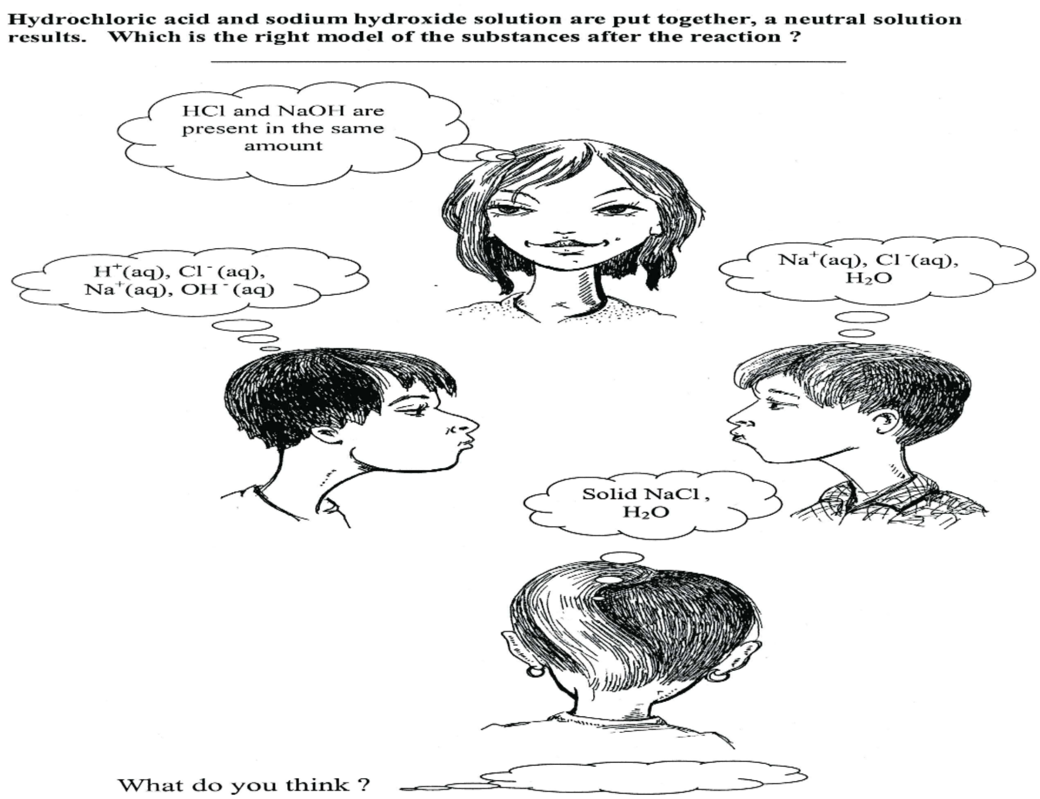

Fig. 6: Concept cartoon concerning neutralization reactions [9]

If acids like nitric acid or sulfuric acid are involved, the special Periodic Table (Fig. 3) shows also "combined ions" or "ionized molecules" like OH^-, NO_3^-, HCO_3^-, CO_3^{2-}, SO_4^{2-} and PO_4^{3-}. By this information students can even derive formulae of most acids, and salts like hydroxides, nitrates, carbonates, sulfates or phosphates: Na^+OH^-, $Mg^{2+}(NO_3^-)_2$, $Ca^{2+}CO_3^{2-}$, $(Na^+)_2SO_4^{2-}$ or $(K^+)_3PO_4^{3-}$. It seems important that students know composition and charge of those combined ions because they may separate formulae incorrectly into single ions – another misconception!

CONCLUSION

Chemistry is not easy to understand – if for example only full chemical equations are offered by lecturers even students at universities develop misconceptions. To challenge those misconceptions our curricula, have to extend chemical interpretation on the Sub-micro level. In chemical reactions involved atoms, ions and molecules should be discussed, especially to differentiate acid-base and redox reactions for answering successfully the question: “Which particle is giving protons or electrons, which particle is taking protons or electrons”?

Concerning the work with ions, ionic formulae of acids, bases and salts should be included into lectures. With help of the special Periodic system of atoms and ions (Fig. 3) one should combine the involved ions to ionic formulae, to models of salt crystals and ionic-lattice models (Fig. 4). One should also draw beaker models for visualizing solutions of acids, bases and salts (Fig. 2, 5). Students should develop accurate mental models – so misconceptions may be challenged.

One way to get information about misconceptions of students, special Concept cartoons [9] can be offered (Fig. 6). These cartoons contain the most well-known misconceptions in form of statements of students – only one answer is the scientific right one. In the shown example the boy on the right side

(Fig. 6) comes up with the correct answer: "Na^+(aq) ions, Cl^-(aq) ions, H_2O molecules". After diagnosing most mentioned misconceptions by the Concept cartoon in class the instruction can be planned accordingly – and after instruction the Concept cartoon can be applied another time to see if the scientific interpretation has reached most students. By this way students will understand Chemistry – and are even motivated to learn more!

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APPENDIX: Asih W. Wisudawati June 2018

Questionnaire "Redox or Acid-base reaction"?

For understanding Chemistry we need three levels of reflection:
1. **Macro level** of observations according to substances and chemical reactions,
2. **Submicro level** with interpretation of all observations with mental models by particles of matter like atoms, ions, molecules and by chemical structures,

3. **Symbolic level** with shortenings of mental models by chemical symbols like atomic, ionic, molecular symbols, and chemical equations. In following problems the macro and symbolic level is presented in this questionnaire, the submicro level is asked by participants.

One example for the wanted answers in the following eight problems:

Macro level: Magnesium reacts with hydrochloric acid, gaseous hydrogen is observed.

Symbolic level: $Mg(s) + 2 HCl(aq) \rightarrow MgCl_2(aq) + H_2(g)$

Submicro level: **a) Which particles (atoms or ions or molecules) are involved?**

Answer: Mg atoms / H^+ ions, Cl^- ions / Mg^{2+} ions Cl^- ions (1:2) / H_2 molecules

b) Write down equation of those atoms, ions or molecules which react!

Mg atom + 2 H^+ ions $\rightarrow$ Mg^{2+} ion + H_2 molecule

c) Which atoms, ions or molecules are NOT reacting?

Cl^- ions are „spectator ions"

d) Redox or acid-base reaction? Explain transfer of electrons or protons.

Redox: Mg atom gives two electrons: Mg atom $\rightarrow$ Mg^{2+} ion + 2 e- (oxidation)

2 H^+ ions take two electrons: 2 H^+ ions + 2 e- $\rightarrow$ H_2 molecule (reduction)

Try to solve the next eight problems in this way!

Take a blank white paper and write down your answers according to (a) – (d).

1. Solid sodium carbonate reacts with hydrochloric acid, gaseous carbon dioxide is observed:
$Na_2CO_3(s) + 2 HCl(aq) \rightarrow 2 NaCl(aq) + H_2CO_3(aq)$ ($H_2CO_3 \rightarrow H_2O + CO_2$)

2. Zinc reacts with diluted sulfuric acid, gaseous hydrogen is observed:
$Zn(s) + H_2SO_4(aq) \rightarrow ZnSO_4(aq) + H_2(g)$

3. Acetic acid solution reacts with sodium hydroxide solution, small heat is observed:
$HAc(aq) + NaOH(aq) \rightarrow NaAc(aq) + H_2O$ (**H**Ac = **H**$OOCCH_3$)

4. Hydrochloric acid reacts with sodium hydroxide solution, big heat is observed:
HCl(aq) + NaOH)aq) $\rightarrow$ NaCl(aq) + H_2O

5. Iron reacts with blue copper chloride solution, brown copper develops on iron:
$Fe(s) + CuCl_2(aq) \rightarrow FeCl_2(aq) + Cu$

6. Copper reacts with silver nitrate solution, silver crystals are growing on copper:
$Cu(s) + 2 AgNO_3(aq) \rightarrow Cu(NO_3)_2(aq) + 2 Ag$

7. Solid calcium carbonate reacts with acetic acid, gaseous carbon dioxide is observed:
$CaCO_3(s) + 2 HAc(aq) \rightarrow CaAc_2(aq) + H_2CO_3(aq)$ ($H_2CO_3(aq) \rightarrow H_2O + CO_2$)

8. Solid magnesium oxide reacts with hydrochloric acid, magnesium oxide dissolves:
$MgO(s) + 2 HCl(aq) \rightarrow MgCl_2(aq) + H_2O$

9. Let us know which of alternatives (a) – (d) was the most difficult for you. Explain.

10. Do you like to go with (a) – (d) so deep into the Submicro level? Explain.

REPOSITIONING 21ST CENTURY CHEMISTRY EDUCATION THROUGH INNOVATIVE TEACHING STRATEGIES: THE CASE OF PROBLEM-BASED LEARNING TEACHING STRATEGY IN NIGERIA

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ABSTRACT

The advancement in science and technology has ushered the 21st century education into a new era characterized by a lot of innovation that promotes the reform of practices and methodologies of teaching and learning at all levels of education. This is to ensure the proper understanding by student to cope with the current trend in the chemistry community. The world is undergoing series of reformations geared towards recovery from aftermath of the traumatic experiences of COVID-19 pandemic that ravaged the world between 2019 and 2020. In chemistry education sector, the main focus is expected to center around curriculum reform processes geared towards provision of best practices that enhance individuals thinking, towards their physical and mental development as an imperative for the 21st century chemistry education in the post COVID-19 era. This study therefore, explored the usage of innovative teaching approaches in chemistry pedagogy, particularly, problem-based learning and the effect of students' achievement in chemical reactions in Nigeria. Quasi-experimental research design was adopted using 79 Senior Secondary 2 Chemistry Students as sample. The instrument was a 25-item Chemical Equilibrium Performance Test Two validated by science education lecturers with reliability coefficient of 0.79 determined by test-retest method. Findings of the study revealed that problem-based learning approach enhanced critical thinking and problem-solving skills of students in Chemical Equilibrium. Students taught with problem-based learning approach performed significantly better with higher achievement scores than those taught with lecture teaching method. Significant difference in achievement of students taught with problem-based learning and lecture teaching method was obtained while there was no significant gender related difference in students' performance. It was recommended among others that teachers should adopt problem–based learning as an effective strategy in teaching Chemical Equilibrium. *[African Journal of Chemical Education—AJCE 13(2), June 2023]*

INTRODUCTION

Developing and underdeveloped nations of the world are constantly engaged in dynamic approaches towards advancement in science and technology to measure up with the developed economies of the word by providing the basic needs and improving the standard of living of the populaces. The growth of any nation is a product of its advancement in science and technology and the crucial role of education as "the bedrock of the development of any notion" in this process cannot be undermined in this process. Considering this essential role, science teaching and learning requires proper reformations to meet the 21st century demands of the "digital age" where the introduction of mobile technology has provided electronic devices that has the ability to transform the system of information processing to support effective lesson delivery. This is anchored on the development of innovative student-centered teaching and learning strategies that could enhance proper understanding of abstract scientific concepts.

Problem based learning is one of the innovative strategies for teaching science. This strategy ca be considered as type of learning where problems that give students opportunity to design and investigative activity using problem-solving to arrive at a conclusion is given to the student. [1] however, defined problem-based learning as "the learning that results from the process of working toward the understanding or resolution of a problem". Form the above, problem-based learning can be viewed as an instructional method that challenges learners to learn by working cooperatively in groups to seek solutions to real world problems This approach covers many teaching strategies which include problem solving, project-based teaching, inquiry, case-based teaching and grounded instruction.

Problem-based learning is a student-centered teaching strategy where the problem drives the learning with the central focus on students' active involvement in trying to solve some problems or answer some questions. The problem drives the learning while the teachers plays the role of a facilitator coaching the students to acquire knowledge and to become "self-directed learners". One of the outstanding characteristics of this strategy is that the students work in smaller groups to critically discuss the problem and possible ways of exploring and reflecting the problem as well as content. Similarly, they try to source for information, access learning material and share ideas among themselves while working in small groups. Moreover, they research, explain, and cooperate in order to find meaningful solutions to real life problems [2,3,4].

Furthermore, problem-based learning is a constructivist teaching strategy that emphasizes on learner's active participation in the process of "knowledge construction" and "making meaning". It recognizes the fact that learners possess preconceived ideas which are usually different from the acceptable scientific ideas as a result of interaction with their peers, teachers, and the environment. They construct understanding or meaning by making sense of their experiences and fitting their own ideas into reality. Due to the outcome of this, learners come to learning situations with a variety of knowledge, feelings, and skills which exists within the learner and is developed as individuals [5, 6].

Scientifically, the process leading to answer is more important than the answer itself, therefore, problem-solving, emphasizes on the use of information from different sources to arrive at multiple solutions rather than the solution itself. This process makes knowledge more relevant to learners and also enhance its retention [7]. Also, problem-based learning aims at teaching learners how to carry out analysis of the problem in consideration, assess the importance of various pieces of information, and to decide which information should be used to understand, explain, or solve the problem and plan subsequent study actions. Problem-solving skills are the processes used to reach the solution to a problem [8].

The theoretical underpinning of this study hinges on constructivist learning theory. The emphasis of constructivism lies on construction of knowledge from prior knowledge. Accordingly, knowledge cannot be transferred from one individual to another. Knowledge construction is greatly influenced by individuals' prior experiences and learners make sense of the world by integrating or synthesizing new ideas or experiences into the previous ones. Consequently, each learner constructs meaning for himself by connecting new information or idea to his already existing knowledge, experiences, or conceptualizations in other to make interpretations. The teacher therefore plays the role of creating an enabling environment for learners to think and make their own connections in order to arrive at valid internalized meaning

Problem-based learning has numerous applications in teaching especially science concepts. Problem-based learning promotes better understanding of course concepts and improves the problem- solving skills of students as well as their communication, presentation and teamwork skills. Students are more engaged in class because they recognize that they are acquiring important skills which will help them succeed in their future careers [9,4]. Furthermore, it provides learners with opportunities to develop conceptual and practical skills and practically apply them as they process knowledge and information from various sources. Problem-based learning provides learners with opportunities to develop conceptual and practical skills and practically apply this as they process knowledge and information from various sources,

Problem-based learning offers students the opportunity to appraise their own understanding, and detecting their learning needs as they play an active role in the teaching and learning process. Higher order thinking skills can be developed by students through logical thinking and probing questions can encourage retrieval of prior knowledge and discussion with group members which enhance accumulation, organization, storage and retrieval of information [10]. As a technique that in-corporate advanced levels of thinking, it helps learner acquire problem solving skills in addition to the skills of communicating, analyzing, researching and accepting others. Furthermore, Problem-based learning enhances self-confidence, boost students" self-efficacy and encourages critical thinking skill irrespective of gender. It also instills perseverance in students for reaching their set targets, promotes curiosity in learners and make them yearn to know the details of what they are engaged in and it de-emphasizes memorization of content [11].

There are seven phases involved in developing a good problem-based learning which forms what is popularly known as the "Problem-Based Learning Cycle". The steps are:

1. The teacher presents a real like problem to the students.
2. Students discuss the problem and formulate hypothesis.
3. Students first retrieve prior knowledge and experience relative to the problem
4. They identify knowledge deficiencies
5. Start making their research;
6. Students apply their knowledge to check the validity of their hypotheses in light of what they have learned
7. At the finish of each problem, students make their own reflection on the knowledge acquired [2, 12].

Moreover, center for teaching recommended the following seven steps for designing problem-based learning that can help teachers in preparing lessons.

Step 1: Explore the issue: Get required information; study new ideas, principles, and skills about the projected topic.

Step 2: State what is known: Individual students and groups list what they already know about the scenario and list what areas they are lacking information.

Step 3: Define the issues: Frame the problem in a context of what is already known and information the students expect to learn.

Step 4: Research the knowledge: Find resources and information that will help create a compelling argument.

Step 5: Investigate solutions: List possible actions and solutions to the problem, formulate and test potential hypotheses

Step 6: Present and support the chosen solution: Clearly state and support your conclusion with relevant information and evidence.

Step 7: Review your performance: Students must evaluate their performance and plan improvements for the next problem.

In developing a good problem-based instruction, the teacher must ensure that the problem is complex, open-ended, ill-structured, has multiple solutions with none clearly superior, be realistic and resonate with the students' experiences, support intrinsic motivation, lead students to generate hypotheses and defend them to others in their group, challenge students to develop higher order thinking skills, afford feedback that permits students to evaluate the effectiveness of their knowledge, reasoning, and learning strategies. An ill-structured problem is the problem that is not completely defined and not easily resolved with a degree of certainty [13].

It is imperative to note that, problem-based learning when well-designed provide students opportunities to develop related skills connected to working in team, handling projects and holding leadership role, oral and written communication, working independently, critical learning and analysis, applying content to real world examples, and problem solving among disciplines [13]. However, the teacher needs to articulate the learning results of the project, create a problem, create ground rules at the commencement, consider students playing different roles establish how to evaluate and assess the assignment and introduce the students to their groups

There are several studies on the use of problem –based learning in various chemistry concepts apart from other science concepts.[14] examined the effects of Problem-Solving teaching strategy on secondary school students' academic performance and retention in Chemistry in Obio-Akpor Local Government Area of Rivers State, Nigeria. It also examined the effect of Problem-Solving teaching strategy on gender of Chemistry school students. Purposive and stratified random sampling techniques was used to select a total sample of 85 SS II Chemistry students (this sample was divided into 40 students in experimental and 45 students control group) from two Senior Secondary schools in Obio-Akpor Local Government Area of Rivers State, Nigeria. Three research questions and two hypotheses null hypotheses were formulated and tested at 0.05 level of significance. The instrument for this study was Chemistry Achievement Test (CAT). The data collected were analysed using t-test statistical analysis package. The results of the analyses revealed that no significant difference between academic achievement of learners in experimental group and control group involved in the study at pretest (this showed initial academic homogeneity of the groups). However, students' academic performance in the experimental group and control group at post-test level was establish to be significantly different in favour of the experimental group. This indicated that Problem-Solving teaching strategy significantly affects students' academic performance in Chemistry in Senior Secondary School. The performance of male and female students exposed to Problem-Solving teaching strategy did not differ significantly as female students were found to have similar achievement in Chemistry as their male counterparts Founded on the findings of the study, conclusion and recommendations were made.

[11] investigated the influence of problem-based learning approach on chemistry students' performance and interest in Mole concept using quasi-experimental pre-test, post-test, control group design. The sample comprise 110 SS 2 chemistry students from the seven public co-educational schools in Abuja Municipal Area Council (AMAC), Karshi Zone of Abuja, while the instruments were: Mole Concept Achievement Test (MCAT) and Mole Concept. Interest Scale (MCIS) with reliability coefficient of 0.96 and 0.95 respectively. Findings shown that, students taught mole

concept with problem based learning strategy performed better and expressed better interest than those taught using lecture method. Problem-based learning improved the achievement of both boys and girls equally but fostered more interest in male students. [10] studied the effect of problem-based learning on students' academic achievement in chromatography and science learning activation. The study adopted quasi-experimental design and mixed research method and the sample comprised 92 grade 10 learners of Nyamphande boarding secondary school in Petauke, Eastern province, Zambia. The instruments were: chromatography achievement and problem-solving skills test and science learning activation questionnaire. Results from the achievement test and a science learning activation questionnaire survey revealed that problem-based learning approach contributed positively to learners' achievement and science learning activation and had a positive impact on learners' academic achievement and science learning activation.

[15] examined problem solving method and Brainstorming technique on learners achievement in Chemistry in Obio-Akpor Local Government Area of Rivers State. Two research questions and one hypothesis guided the study. Quasi-experimental design specifically non-equivalent control group design was used. 150 senior secondary II (SS2) Chemistry students was the sample size gotten via simple random sampling technique. One intact class were assigned to experimental group (problem solving method and one intact class to control group brainstorming method). The research instrument comprised of Chemistry Achievement Test (CAT) . The reliability

coefficient of the instrument is 0.71. The data was scrutinized using mean, standard deviation and analysis of covariance (ANCOVA). The finding shows that students taught Chemistry with problem solving teaching method performed better than the learners taught with brainstorming instructional method. Therefore, the researcher recommends the use of problem solving method in all senior secondary schools that offer Chemistry in Rivers State and other state in Nigeria, also teachers should be sponsored by Governments to attend special workshops and conferences on effective use problem solving method

[16] conducted research on problem-solving technique of teaching on students' academic achievement in Physics and Chemistry in Calabar Municipality, Cross Rivers State Nigeria. Quasi experimented design was the research design. The sample size consisted of 200 senior secondary 11 students. The instruments for data gathering was Physic/Chemistry Performance Test (PPT and CPT) the reliably coefficient for PPT and CPT were 0.85 and 0.89 via the Kudar Richardson. The data gathered were scrutinized using mean difference. The finding of the research revealed that learners in the experimental group performed better in Physics and Chemistry than the control group. The researchers recommend among others that problem-solving strategy to be applied in teaching Physics and Chemistry.

[17] studied the influence of problem-based learning method on senior secondary school students interest and performance in physics in Bauchi State, Nigeria. The study adopted a quasi-

experimental research design, specifically, non-randomized pre-test post-test research design. The sample comprised to students in four intact science classes from two equivalent co-educational secondary schools. The tools used for the data collection were Physics Achievement Test (PAT) and Electricity Interest Inventory (EII). The results also showed that the problem-based learning approach had a more positive effect on students' achievement than the conventional approach. Male students had a marginally higher mean interest rate when they learnt electricity using problem-based learning method than their female colleagues, but the difference was not significant.

[18] studied problem solving instruction on middle school students' physical science learning interplay of knowledge, reasoning and problem solving. The quasi-experimental design specifically the on factorial design and 126 students constituted the sample. The instrument for data gathering was a science achieved test. Data gathered were scrutinized using Analysis of Variance (ANOVA) and MANCOVA. The result shows that problem solving group achieved better than the conventional group and rate of retention was significant. The study recommends that problem solving is an effective method and must be incorporated in school curriculum as a means of instruction for high school students.

[3] investigated the effect of problem-based learning on students' achievement in chemistry. Quasi-experimental design was employed for the study. 101 equivalent students in KwaZulu-Natal province in South Africa were designated for the study. The control group was taught with the

traditional lecture method while the experimental group were taught with problem-based learning. Findings revealed that there was significant difference in chemistry performance of students between control and the experimental group after teaching. This confirms that problem-based learning is an efficient technique to teach chemistry as it improves students' critical thinking and problem-solving skills.

Abanikannda [2] investigated the influence of problem-based learning in chemistry tutelage on academic achievement of school students. The study adopted a descriptive survey design. Purposive sampling method was used to select 300 senior secondary two (S.S.2) science students of ten (10) high schools in Oriade local Government Area of Osun State in Nigeria which served as the sample. The instrument was questionnaire on the effect of problem-based learning in Chemistry education on academic achievement of school students. The findings of this study revealed various activities engaged in by students during PBL lessons.

[19] investigated the effect of problem-based learning on the science academic performance of prospective science teacher and the stability of knowledge in terms of the boiler stone problem. The design was pretest and post-test control group design of quasi experimental design. The sample comprised 74 3rd grade students in Department of Science Education and the instrument was Science Academic Achievement Test (SAAT). Finding of the study revealed that there was a significant difference between the experimental and control group students in favor of the experimental group.

Problem based learning had a positive influence on students' science achievement and the permanence of knowledge**.**

[20] carried out a study on students problem-solving skills and their understanding of chemical rate and their performance on this issue. The sample size consisted of 122 students in the department of Science Education Gazi University. The instrument for data collections was Logical Reasoning Test (LRT) and Scientific Process Skill Test (SPST). The reliably coefficient of LRT and SPST was 0.79 and 0.82 respectively. The data generated were scrutinized using mean, standard deviation, t-test and ANOVA. The findings of study revealed that there was significant difference in achievement between the experimental and control group. The problem-solving group achieved better in chemical concept than the control group. The effect of problem-solving in performance of male and female undergraduates was in favor of the females.

STATEMENT OF THE PROBLEM, OBJECTIVES AND RESEARCH QUESTION

Statement of the Problem

Science teaching and learning over the years has been confronted with myriad of problems pointing towards students' poor performance in examinations at all stages of education and its attendant adverse effect on the quality of education in Nigeria. This unwelcomed development has attracted stakeholders" concerns and triggered the quest geared towards ongoing researchers in chemistry and other disciplines with a view to proffering answer to the problem. Ideally, the availability of instructional materials and conducive learning environment in an educational setting only cannot guarantee the anticipated good performance of students in examinations without proper harnessing of these facilities and blending them with appropriate teaching strategies. Therefore, the teachers' method of lesson delivery which is a means of realization of instructional objectives or learning outcomes usually measured in terms of students' performance in examinations becomes an imperative that must be prioritized in exploring the problem of students' poor performance in examinations, mostly, chemistry which is abstract in nature. From available studies, although many teaching methods has been considered in different research, problem-based learning as a teaching strategy has not been fully explored. In Nigeria, there are limited studies on this strategy in other states with none in Rivers State. Therefore, it is not clear whether the results obtained in these studies are applicable to other states in the country particularly, Rivers State where there appears to be no available study in this regard. To address this gap in knowledge this study is carried out in Port Harcourt metropolis of Rivers State.

Objectives of the Study

This study explored the effect of problem-based learning teaching strategy on academic performance of students in senior secondary schools in Port Harcourt Metropolis, Nigeria. Specifically, the study tends to determine:

1 students' performance in chemical equilibrium when taught with problem-based learning teaching strategy and lecture teaching method.

2 male and female students' performance in chemical equilibrium when taught with problem-based learning teaching strategy.

3. private and public-school students' performance in chemical equilibrium when taught with problem-based learning teaching strategy.

Research Questions

1 What is the difference between students' performance in chemical equilibrium when taught with problem-based learning teaching strategy and lecture teaching method.

2 What is the difference between male and female students' performance on chemical equilibrium when taught with problem-based learning teaching strategy.

3. What is the difference between private and public school students' performance on chemical equilibrium when taught with problem-based learning teaching strategy.

Hypotheses

HO1 There is no significant difference between students' performance in chemical equilibrium when taught with problem-based learning teaching strategy and lecture teaching method.

HO2 There is no significant difference between male and female students' performance on chemical equilibrium when taught with problem-based learning teaching strategy.

HO3. There is no significant difference between private and public-school students' performance on chemical equilibrium when taught with problem-based learning teaching strategy.

METHODOLOGY

This study adopted quasi-experimental design, specifically, the pretest posttest nonrandomized design. The sample comprised 79 SS2 chemistry students in intact classes of two senior secondary schools in Port Harcourt Metropolis purposively selected for the study. The instrument was a 25-item Chemical Equilibrium Performance Test (CEPT) developed by the researcher and subjected to face and content validity by two lecturers in Department of Science Education and one expert in Measurement and Evaluation in Rivers State University. The reliability coefficient of the instrument was 0.76 determined by test-retest method using Pearson Product Moment Correlation Coefficient formula. The research questions were answered using mean and standard deviation while the hypotheses were tested using Analysis of Covariance (ANCOVA). The hypothesis was accepted when the calculated value of t is less than the table or critical value and accepted when the calculated value of t is greater than the table or critical value.

RESULTS

Research Question 1

What is the difference between students' performance in chemical equilibrium when taught with problem-based learning teaching strategy and lecture teaching method?

Table1: Mean and standard deviation of students' performance in chemical equilibrium when taught with problem-based learning teaching strategy and lecture teaching method

		Mean			Standard Deviation		
Group	**N**	**Pre-test**	**Posttest**	**Diff.**	**Pre-test**	**Post-test**	**Diff.**
Problem-based learning Strategy	41	42.09	74..22	32.13	11.04	9.12	1.92
Lecture Teaching Method	38	37.64	44.62	6.98	9.97	8.54	1.43
Diff. between		4.45	29.60	25.15	2.74	0.58	0.49

Research Question 2

What is the difference between male and female students' performance in chemical equilibrium when taught with problem-based learning teaching strategy?

Table2: Mean and standard deviation of male and female students' performance in chemical equilibrium when taught with problem-based learning teaching strategy.

		Mean			Standard Deviation		
Group	**N**	**Pre-test**	**Posttest**	**Diff.**	**Pre-test**	**Post-test**	**Diff.**
Male	55	40.21	78.11	37.90	0.99	1.78	0.79
Female	24	39.15	73.41	34.26	1.22	1.01	0.21
Diff. between		1.06	4.7	3.64	0.23	0.77	3.98

Research Question 3

What is the difference between private and public-school students' performance in chemical equilibrium when taught with problem-based learning teaching strategy?

Table 3: Mean and standard deviation of private and public senior school students' performance in chemical equilibrium when taught with problem-based learning teaching strategy and lecture teaching method

		Mean			Standard Deviation		
School type	**N**	**Pre-test**	**Posttest**	**Diff.**	**Pre-test**	**Post-test**	**Diff.**
Private	45	56.45	76.67	20.22	1.12	1.45	0.33
Public	49	24.23	53.23	31.00	0.88	1.43	0.55
Diff. between		32.22	23.44	9.22	0.24	0.02	0.22

Hypothesis1

There is no significant difference between students' performance in chemical equilibrium when taught with problem-based learning teaching strategy and lecture teaching method.

Table 4: Analysis of Covariance private and public senior secondary students' performance in chemical equilibrium when taught with problem-based learning and lecture teaching method

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Corrected Model	1172.054[a]	2	8121.531	106.769	.000
Intercept	247.441	1	273.450	3.654	.010
Pre	10426.186	1	10478.187	146.730	.000
Groups	714.871	1	654.881	9.549	.003
Error	7668.846	76	76.432		
Total	334771.001	79			
Corrected Total	22054.011	78			

a. R Squared = .697 (Adjusted R Squared = .690)

Table 4 shows that F1, 76 = 9.545, *P*<.05, the null hypothesis which states that there is no significant difference in students' performance in chemical equilibrium when taught with problem-based learning teaching strategy and lecture teaching method is rejected. This infer that **t**here is a significant difference in students' performance in chemical equilibrium when taught with problem-based learning teaching strategy and lecture teaching method.

Hypothesis 2

There is no significant difference between male and female students' performance in chemical equilibrium when taught with problem-based learning teaching strategy.

Table 4: Analysis of Covariance of male and female students' performance in chemical equilibrium test when taught with problem-based learning and lecture teaching method

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Corrected Model	1260.111[a]	2	6178.443	105.789	.000
Intercept	342.365	1	269.365	3.657	.010
Pre	22131.096	1	123567.098	1345.675	.000
Groups	705.762	1	567.652	0.067	.865
Error	4466.563	76	84.541		
Total	124563.123	79			
Corrected Total	12153.051	78			

Table 5 shows that F (1, 76) = 0.067, *P*>.05. For that reason, the null hypothesis which states that there is no significant difference in male and female students' performance in chemical equilibrium when taught with problem-based learning teaching strategy is accepted. This infer that there is no significant difference between the performance of male and female students on chemical equilibrium when taught with problem-based learning teaching strategy.

Hypothesis 3

There is no significant difference between private and public-school students' performance in chemical equilibrium test when taught with problem-based learning teaching strategy.

Table 4: Analysis of Covariance private and public senior school students' performance in chemical equilibrium when taught with problem-based learning

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.
Corrected Model	12067.033[a]	2	7978.531	118.769	.000
Intercept	354.225	1	167.450	2.452	.030
Pre	11315.215	1	12357.187	234.531	.000
Groups	823.965	1	632.881	9.549	.003
Error	6798.897	76	66.432		
Total	387654.010	79			
Corrected Total	11123.023	78			

Table 6 shows that F (1, 76) = 9.549, *P*>.05. Therefore, the null hypothesis which states that there is no significant difference in private and public students' performance in chemical equilibrium when taught with problem-based learning teaching strategy is rejected. This infer that there is a significant difference between private and public-school students' performance in chemical equilibrium when taught with problem-based learning teaching strategy.

DISCUSSION OF FINDINGS, CONCLUSIONS AND RECOMMENDATIONS

Discussion

Results of research question 1 and test of hypothesis 1 (Tables 1 and 4) revealed a significant difference between the performance of students' performance in chemical equilibrium when taught with problem-based learning teaching strategy and lecture teaching method. The students taught with problem-based learning obtained higher performance test scores than those taught with lecture teaching method. This result agrees with that of [11] which showed that students taught mole concept using problem-based learning strategy performed well and showed interest than those taught using lecture technique in Abuja Municipal Area Council (AMAC), Karshi Zone of Abuja.

This result further agree with that of [15,17] which showed that problem-based learning approach had a more positive effect on students achievement and interest than the conventional approach in Bauchi state of Nigeria and that of [19] which showed a significant difference between the experimental and control group students' in favor of the experimental group. Problem based learning had a positive impact on students' science achievement and the permanence of knowledge.

Furthermore, it agrees with the results of [10] in Eastern province of Zambia which showed that that problem-based learning approach contributed positively to learners' achievement and science learning activation and had a positive impact on learners' academic achievement in chromatography and science learning activation as well as that of [14,16,17] where similar results was obtained showing that the problem based learning approach had a more positive effect on students' achievement than the conventional approach.

Results of research question 2 and test of hypothesis 2(Tables 2 and 5) showed no significant difference between the performance of male and female students on chemical equilibrium when taught with problem-based learning teaching strategy. Male students obtained similar higher performance test scores compared to their female counterparts implying that the teaching strategy is not gender selective. This results agree with that of [11,14] which showed that problem-based learning improved the achievement of both male and female students equally but fostered more interest in male students but disagree with that of [17] where male students had a slightly higher mean interest rate when they learnt electricity using problem-based learning approach than their female counterparts but the difference was not statistically significant. The results of research question 3 and test of hypothesis 3 (Tables 3 and 6) showed that there is a significant difference between private and public-school students' performance on chemical equilibrium when taught with problem-based learning teaching strategy.

Conclusion

Problem-based learning teaching strategy is more effective and enhance students understanding of chemical concepts than lecture teaching method. Moreover, the strategy is not gender and class level selective.

Recommendations

1 Teachers should embrace problem-based learning teaching strategy in teaching chemistry at all stages of education.

2. Enabling environment that promote collaboration of knowledge among students should be created by teachers

3. Teaches should endeavor to ensure that classroom activities are dominated by the students while he or she plays the role of a facilitator.

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Contributions to knowledge

1. Findings of this study expands the existing knowledge on the application of problem-based learning in teaching science.
2. It offers teachers unlimited alternatives to selecting suitable teaching strategies to arrive at effective lesson delivery.

HOUSEHOLD CHEMICAL EXPERIMENT IN THE DISTANCE LEARNING

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ABSTRACT

A case study on several distance learning activities including household chemical experiments is presented. The case includes school curriculum course for 8th grade (14 y.o.); two distance learning courses for 8-11 y.o. students; two courses supporting school curriculum for 8th grade. The framework of chemical experiments within the distance learning, the sources of material supply, synchronous and asynchronous modes of conducting experiments are described. *[African Journal of Chemical Education—AJCE 13(2), June 2023]*

INTRODUCTION

Distant learning has been drastically developing since the beginning of the COVID pandemic. However, it is older than the pandemic and even older than computers. For example, in 1964 the Moscow State University organized The All-Union Distance Learning Mathematical School. The secondary school students got textbooks and tasks, sent the solutions and received feedback – everything by snail mail. In some years more than ten thousand students studied there. In 1989 the "Distance Learning School of a Young Chemist" was organized – still using a snail mail and with no experiment.

At any rate the main demanders of the distant learning outside pandemic are:

- the students from the remote places with no good schools;
- expats – the students who live outside their country of origin and prefer to get education on their native language;
- the homeschoolers;
- students from big cities who don't want to waste their time for the traffic.

Herein we are going to share our experience in organization of hands-on chemical experiment within the distance learning chemistry courses (Table 1).

Table 1: The distance courses that were conducted

Name	Age	Number of sessions	Mode	Materials
Materials around us	7-10	4	Synchronous	Household (countryside)
Introducing chemistry	11-13	3x4	Both	Household + burner
Substances around us	11-13	12	Both	Household + burner + "Young Chemist"
Supporting school chemistry	14-15	20	Synchronous	Household + burner + "Young Chemist"
Chemistry for 8th grade	14-15	50	Asynchronous	Household + special kit (in progress)

In our country there are several types of the audience for the distance learning course. Surprisingly the largest audience is the children of 8-13 y.o. despite there is no chemistry in school curriculum for this age. We elaborated face-to-face laboratory activity for this audience [1] but after the beginning of COVID and due to demands of people from outside our city we transferred it into the distant course.

The smaller audience is the students of 8-9th grade (14-15 y.o.). Some of them study in a distant mode totally and don't attend school. The others attend schools but claim experimental support for the regular school course because there is no experiment in the majority of the schools.

There are also a small number of the students, who needs distant learning courses to prepare for the State Exam, but there is a strong competition between courses for this audience and we didn't work with it.

There are several possible solutions on incorporation of chemical experiment in the distance chemistry courses [2-3]:

- face-to-face experiments;
- household experiments ("kitchen" or using home study lab kits);
- remote control experiments;
- self-guided field trips;
- virtual labs;
- videotaped experiments.

We did not employ remote control experiments, when the glassware and reactants are somewhere, and the student manages them via Internet. It requires sophisticated but manageable equipment. Thus, it can be used for a limited number of complicated experiments such as preparation of a plastic foam [4]. However, our audience requires greater number of simple experiments. We also don't have facilities to arrange the necessary equipment.

We also did not employ field trips – it is much more time consumable than household experiments.

We do use videotaped experiments within the school curriculum course if they can not be conducted at home (for example, reaction of sodium with water). However, there is nothing to discuss about the videotaped experiments.

We also use virtual labs within the school curriculum course just to fulfill the formal requirements.

Face-to-face experiments are also used in supporting of the school curriculum course. Students attend the lab for one day or for several days and conduct all the experiments on the topics they had been studying for several weeks or even months. However not so many students that attend the school curriculum course perform face-to-face experiments. The first reason is the small capacity of the laboratory. The second reason is the difficulty to get to the lab from the places outside our city. Moreover, the face-to-face experiments for distance learning have no difference with experiments for face-to-face learning.

The most interesting and most challenging is the household experiment and we will discuss this type in details. Many teachers are afraid of household experiments believing that they can be performed only at the laboratory. However, it is wrong. Many “kitchen” experiments basing on household goods are described (and were described before the computer era [5-6]. There are single experiments [7-8], sets of experiments [9], courses [10-11]. The experiments can be quite complicated, for example using smartphones as spectrometers [12]. The safety issues also prevent teachers from organizing household experiments, but these issues can be resolved.

THE FRAMEWORK FOR THE EXPERIMENTS

There is a mutual consent that experiments are essential for chemistry teaching that is confirmed by numerous reviews [13-16] For 8-13 y.o. students we arranged the experiment as a basis to developing observational and procedural skills and accumulating experience that would serve as groundwork for further studying chemistry [1]. In general, we are trying to develop "the sense of substance" as an ability to operate with substances errorless without explicit instructions. For 14+ y.o. students we used experiment as a basis for introduction of theories and concepts and as a tool of falsification them according to Karl Popper that fully presents the scientific method [17-18].

SOURSE OF THE MATERIALS

Now there are many chemicals around us – so many, that a simple chemical laboratory can be based just on household ones. Here is a list of chemicals, available in our country. The list is country-specific (for example, alcohol solution of iodine is unavailable in the majority of European and Muslim countries. On the contrary, sodium hydroxide is unavailable in our country but is sold as a household good in New Zealand.

- in farmacies: iodine solution, potassium permanganate, hydrogen peroxide, glycine, glycerol, ascorbic acid, glucose, activated carbon etc.;

- in food stores: salt, sodium hydrocarbonate, starch, sugar, aluminum foil, charcoal, acetic acid, citric acid, food dyes etc;
- in household stores: hypochlorite solution, sodium carbonate, sodium phosphate, acetone, xylene etc;
- in farming stores: copper sulfate, iron sulfate, urea, sodium and potassium nitrate etc.
- in building stores: copper and aluminum wires, lime etc.

The glassware can be bought also in household stores, as well as gas torches or burners for heating.

Marketplaces greatly widen the list of available reactants and glassware. One can easily buy on Aliexpress or Amazone very different chemical goods – from test-tubes to autoclaves. The author bought on Aliexpress different chemicals up to elemental selenium and tellurium. However, it takes a long to deliver goods from some marketplaces, especially from the overseas.

When the experiments become diverse or complicated, buying all the necessary equipment and consumables requires much time from the student. This problem can be solved by the kits for household experiments. They are widely used [19-21]. The author had elaborated and the kit "Young Chemist" (Fig. 1) at 1999 for household experiments guided just by a manual. It contains simple equipment as test-tubes or evaporating dish and 27 reactants allowing to conduct 145 experiments.

It has been selling since that time in amount of 5-10 thousand a year. After COVID pandemic it turned to be a good support for the distance learning courses.

Fig. 1. The kit “Young Chemist”.

Organizing a course, one should decide whether the students will rely on the household materials or use specific kits (Fig. 2). If one uses household goods or kits external manufacturers, they will determine the list of possible experiments and consequently the list of concepts that could be delivered. It restricts the possibilities of the course. This approach is suitable for outreach courses, non-systemic teaching or for teaching the concepts related to household processes. But it hardly works when we need to create a distance learning course for the systematic course. Then one should use reverse order: elaborate the course, compile a list of experiments, assemble a list of equipment, and launch its production. It is much more difficult and needs production facilities. However, the kits adapted to specific courses (predominantly for high schools) are described [22]. We produced the specialized kits for the topics "Hydrogen and oxygen", "Dissociation" and "Redox reactions" (Fig. 3).

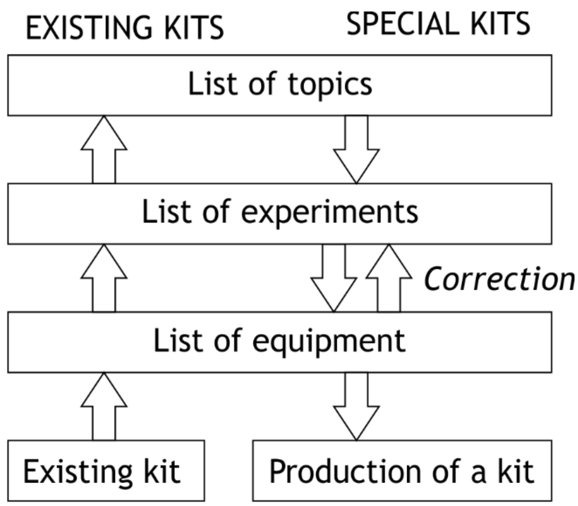

Fig. 2. Workflows for elaboration of a course employing household labs.

Fig. 3. Specialized kit "Redox reactions"

Whether we count on just household goods or use kits, some household equipment is necessary. It is listed below.

- Plastic or oilcloth tablecloth (to protect the table from the reactants and flame).
- Bottle with water (to make solutions or to extinguish fire if something goes wrong).
- Glass cane for wastewater.
- Kettle with the hot water (if slight heating is necessary).
- Small beakers of glass or of polypropylene (to dissolve substances or conduct reactions in solutions).
- Porcelain saucer (to conduct the drop reactions).

- Metallic ashtray (to heat objects over it or to put hot objects on it).
- Pliers or iron tweezers (to hold hot things)
- Toilet paper (to wipe out the rubbish or remove drops of water from the glassware).
- Iron spoon (to heat substances in it).
- Rubbish bin.

SYNCHRONOUS VS AYNCHRONOUS EXPERIMENT

There are two general modes of the distance learning: synchronous and asynchronous [23]. In synchronous mode all students and the teacher attend the session at the same time and the teacher guides the students' activity in "real-time". The teacher instructs, shows the procedures, comments, asks questions watches what the students do and, what is the most gives immediate feedback

In asynchronous mode, the students study whenever they want. The teacher sends instructions (illustrated text or video); answers written questions (not immediate) and comments the reports (if the students sent them – also not immediate). Asynchronous mode has many advantages:

- students work on the suitable schedule;
- students work on their own pace;
- students have possibility for side experiments;
- prearranged instructional materials require much less time than alive instructions;

- doesn't require good web-camera and strong Internet connection;
- almost has not restrictions for the amount of the students;
- does not overburden the teacher with different activities in one moment.

Moreover, asynchronous mode requires mush less teachers than synchronous (and even than face-to-face learning) thus good asynchronous courses can ease the shortage of the qualified teachers.

Synchronous mode is very difficult for a teacher. At the same time the teacher have to conduct experiments, manage the camera, switch the windows between the students, watch what the students do and react on their actions… The author's experience shows that after 1.5 hour session he needed to have a rest al least for half an hour. However, synchronous mode has one advantage that often overweighs all the advantages of asynchronous mode: the student gives immediate and personal feedback. The choice between the modes is after the students.

The organization of synchronous and asynchronous mode is completely different and will be described separately.

To conduct a synchronous session the students should get a list of equipment and consumables 3-4 days before. The teacher needs at least an idea what will the students do. However the written synopsis of the session, containing the list of the questions and the blank fields for the answers is also favorable. The written instructions for asynchronous sessions can be used instead of the synopsis too.

To conduct the sessions, we used Zoom. The common workflow is the following.

- The teacher asks to conduct an experiment and shows the preparatory operations (taking test-tubes, adding reactants and so forth, but avoiding showing the final study, when the effect should observe. For example, exploring decomposition of sodium hydrocarbonate in water the teacher puts hydrocarbonate in a small beaker, adds water, dissolves, and takes a can and a kettle with boiled water.
- The students repeat the operations after the teacher. The teacher watches the processes via their cameras (Fig. 4). He corrects the errors of the students, comments the good steps and answers numerous questions. For example, “what to do if I have a mug instead of a beaker». Very often the students (the age doesn’t matter), ask when to stop adding reactants or what to do if something goes wrong.

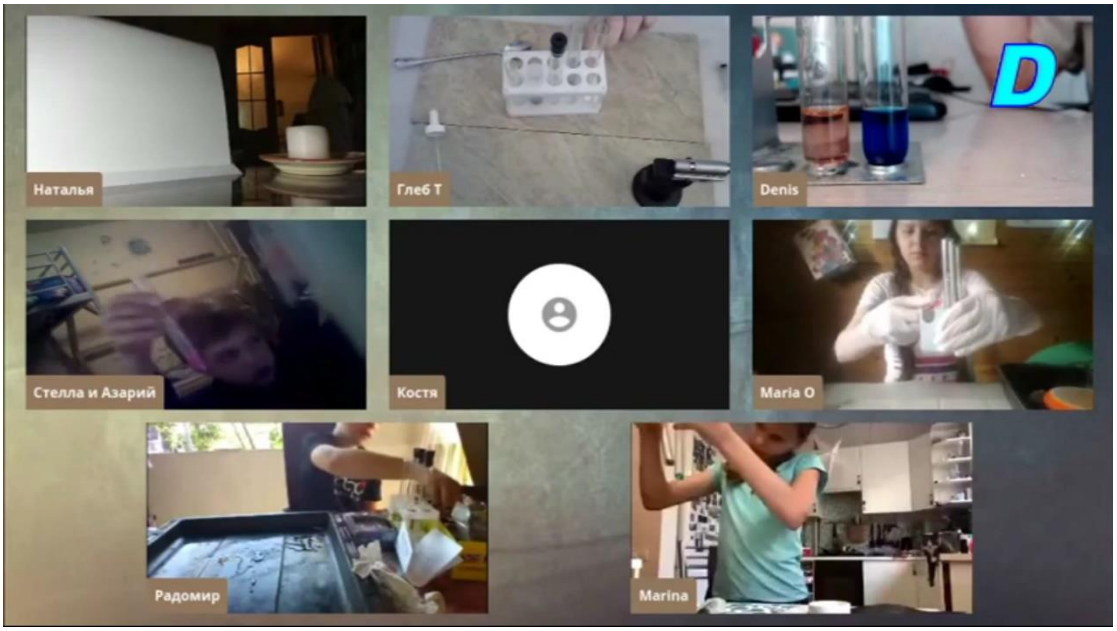

Fig. 4. A typical screen during the synchronous session.

- The teacher tells what to do to complete the experiment and completes it himself. In our examples he pours the hot water into a cane, put a test-tube there and attracts the student's attention to the test-tube. Then the teacher asks the students what they observe, comment the observations and compare the results of different students.
- The teacher asks the questions to provoke a discussion "what has happened". In our example – what gas was observed, could it be a boiling of water, how to check the suggested hypothesis.

- After discussion the teacher sometimes should follow the discussion, for example trying to implement the students' ideas (for example, to put a test-tube without sodium hydrocarbonate into hot water and watch, whether the gas releases.
- At the end the teacher explains what has happened and gives some theoretical ideas. In our example – that hydrocarbonate decomposes into sodium carbonate, water, and carbon dioxide.
- Then he can ask a question how to check this explanation (for example, how to distinguish sodium carbonate from sodium hydrocarbonate).

This scheme is ideal. In reality there are many disruptions. The most widespread are the following.

- The students don't switch on their cameras.
- The students don't ask the questions.
- The students take side activities.

If all the students don't switch on the camera so the teacher can't see and comment what they do, the time for the same activity shrinks l least twice, but nobody knows about the effectiveness of the activity.

Asynchronous mode demands instructional materials – both video and text with illustrations. Videoinstructions are better to demonstrate manipulations. However, if we use videoinstructions, we should incorporate there questions and explanations also – otherwise the student will have to switch between video and text that overloads the working memory (split-attention effect [24]). On the other hand, the text instructions are also necessary because it is much easier to ask information in text, than in video.

To prevent overloading the working memory the instructions should give the information by portions and then ask questions to let the information be proceeded and transferred into the long-term memory. Bearing in mind that the asynchronous mode doesn't provide immediate feedback the workflow for it is much easier than for the synchronous mode.

- the student performs the experiment that is described in the instructional materials ("what to do");
- the student observes the results of the experiment under the guidance of the instructions ("where to look at")
- the student thinks about the results answering the questions in the instructional materials ("which questions to answer");
- the student gets explicit theory or concept from the instruction.

If we expect the students to conduct experiments themselves, we conceal the results in the video instructions and illustrations.

There is a common mistake to use videorecords of the synchronous session as instructional materials for asynchronous. It is a bad solution because the videorecord takes three times much time than the instruction recorded according to the prescribed scenario. Too much time is taken for pauses, stumbling, thinking what to say, repetitions, individual discussions etc. Even cutting of all those episodes the time of the record shrinks twice. The prescribed scenario requires at least one day of

The text instructions contain the list of equipment and consumables; the safety precautions; instructions what to do; the questions with blank fields for answers; the theoretical commentary. We use different text styles (font color and background color) for all that blocks. The compromise format for the electronic instructions (that is easy to compile and easy to use on the desktop computer) is the *.pdf form. The reasonable dimension of the instruction for 45 minutes is two A5 pages with font size 12 plus illustrations.

The problem we face using written instructions is the functional reading – even 14-15 y.o. students sometimes don't possess this skill.

CONTENT OF THE COURSES

Within any course we develop many manipulative skills. We use the scaffolding learning approach. First, we describe simple manipulations in details (take the test-tube; using a spoon put there a substance for 1 cm by height; take the neck of the test-tube by a clamp; hold the test-tube at the angle 90°…”. When we see (or suppose) that they gained the necessary skills we just point the manipulation (“heat the substance”) and develop more complicated skills (for examples distillation or melting metals). Here is the list of elemental skill that we form within any beginning course:

- mixing;
- dissolving substances;
- heating;
- measuring temperature;
- weighting;
- obtaining and collecting gases;

The complex skills are much more diverse including:

- reactions in solutions;
- filtering;
- melting substances; preparing alloys of fusible metals;
- solid state reactions;
- distillation (from heated to a cold test-tube);
- extraction (using syringes).

The development of the manipulative skills is not as easy as one can expect. The students make numerous stupid and unexpected mistakes even when the teacher shows all the manipulations and draws their attention to all the subtleties. For example, very often the students

- don’t stir the substances after mixing
- don’t understand when a substance dissolves and when doesn’t dissolve
- heat anything but the substance
- don’t understand when to stop heating
- don’t understand how much substance to add.

Here is the example of an introduction course. It’s aim is to get the 11-13 y.o students acquainted with chemical substances and processes. It consists of three partly independent blocks (to let the students join the course at any block).

Block 1. Chemical and physical processes.

1.1. Temperature and heat exchange (teaching how to heat substances).

1.2. How substances behave while heating (classification of phenomena).

1.3. Mixing of liquids and what prevents it (teaching how to mix substances; introducing the concepts of solubility, density and diffusion);

1.4. Solutions and dissolution (introducing the concept of solution and solubility; teaching how to make solutions)

Block 2. Objects of chemistry.

2.1. Candle (getting acquainted with burning and melting).

2.2. Metals around us (the general properties of metals: electrical conductivity, polishing, melting).

2.3. Surface (getting acquainted with the properties of surface, contact angle, adsorption).

2.4. Shaping materials (teaching how to add a shape to a material: casting, stamping etc.)

Block 3. Substances (getting acquainted with the variety of the properties).

3.1. Household and washing soda.

3.2. Iodine.

3.3. Potassium permanganate.

3.4. Hydrogen peroxide.

The promising idea of the self-assessment was a practical homework. The students can perform the practical task such as making a heart of a paraffin, estimating the concentration of a substance to feel its taste, obtaining hydrated sodium chloride $NaCl \cdot 2H_2O$, cleaning the surface of a coin etc. The teacher doesn't need to assess the performance: the children will see their success (or failure) themselves.

CONCLUSION

It is very possible to broadly implement the household experiment into the chemistry course, at least for the secondary school students. It can be performed in synchronous mode (the teacher shows the manipulations, watches what the students do and provoke discussions in real time) or in asynchronous mode (the students work using video- and textual instructions). Household reactants and glassware as well as specialized kits for household experiments can be used.

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PREDICTABILITY OF THE MUST (MATH-UP SKILLS TEST)

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ABSTRACT

In the USA for the most part, completion of a first-semester general chemistry (Chem I) course lays the foundation deemed necessary for understanding second-semester general chemistry (Chem II) topics. Successful completion of Chem I and II gives students permission to progress to organic chemistry I (O-Chem). A series of studies undertaken by the NSA (Networking for Science Advancement) Texas team began in 2016. Texas is one of five majority-minority states in the USA and hosts a significant Hispanic population. The purpose of this research line is to evaluate the influence of basic arithmetic automaticity (what students can do without a calculator) skills needed to succeed in lower-level chemistry. Over 9,000 students from nine universities have contributed to this research. Results suggest a strong correlation between procedural arithmetic preparation, automaticity, and student performance in Chem I, II, and O-Chem courses. The NSA collaborative uses the Math-Up Skills Test (MUST) as an assessment instrument along with student demographics to identify at-risk students from these contributing populations at the beginning of a course with high reliability (*KR-20* = 0.863) and effect size (Cohen's $d \geq 1.20$). The hand-graded MUST requires only 15 minutes of class time to administer and combined with specific demographic categories consistently predicts students' success rate in lower-level chemistry about 80 percent of the time therefore providing adequate time to identify and help at-risk students. This paper is about the evolution of the MUST and how following the NSA team's research line has advanced its use and interpretation. *[African Journal of Chemical Education—AJCE 13(2), June 2023]*

INTRODUCTION

One of the hallmarks for chemical education research (CER) is that the researchers choose a meaningful (i.e., significant, important) problem. When searching for a problem that others would find meaningful, sometimes you only have to observe what is around you. The Scholastic Aptitude Test (SAT) is an accepted college entrance exam. The problem observed in Texas was that the state's SAT scores (blue line, Fig. 1) were declining rapidly as compared to the mean scores of the USA (red line, Fig. 1). Wanting to investigate what the issue(s) might be and having read a 2016 article by Hartman and Nelson [1], it seemed reasonable that students' lack of automaticity (what they could do without a calculator) skills might be the source of the problem. Hartman and Nelson's CER had compared what students could do without a calculator to what they could do with the use of a calculator. Repeating this study might be interesting, so the NSA (Networking for Science Advancement) Texas team was formed expanding the studied population to more than a single university. Hartman and Nelson did not name their 16-question (16-Q) quiz, but the NSA team did. This 15-min., hand-graded, 20-Q instrument was named the MUST (Math-Up Skills Test). To date, the project has produced 13 published research papers with one more submitted [2-15] and in addition, the NSA team collectively has presented 44 oral presentations. Currently, Macmillan Publishers (Austin, Texas) is piloting an online version of the MUST through the online *Achieve* program of the Macmillan Learning System (see: https://www.macmillanlearning.com/college/us/digital/achieve).

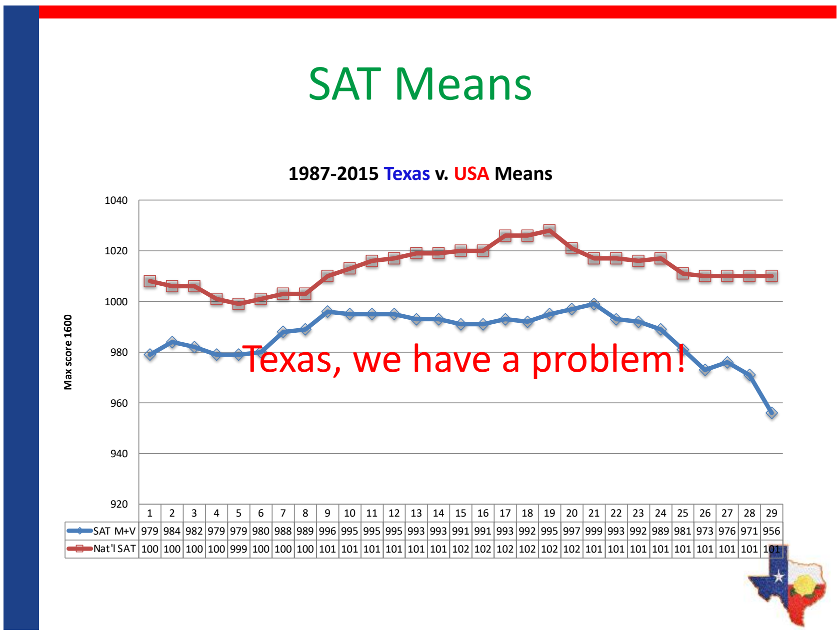

Figure 1. Comparison of Texas SAT annual means (blue) and SAT annual means in the USA (Petros et al., 2017).

The original team members were from six universities (blue line, Fig. 2) across the state of Texas (black border, Fig. 2). For comparison, Egypt (red border, Fig. 2) is about 1.5 times larger than the state of Texas. Both Austin, Texas and Cairo, Egypt are capital cities established on the same latitude of 30º north. The original team was composed of eight CER instructors, all with IRB

(Institutional Review Board) permission to conduct human subjects research from their respective institutions. The protocol was that general chemistry students would take the MUST twice, once without a calculator and then take a similar version with a calculator along with answer some general demographic questions. Attempting to discover what students could and could not do using a calculator was not only of interest to the authors but also to others who were concerned about the noted downward trend in the Texas SAT scores compared to those of the USA (Fig. 1). Another known fact was that calculator usage in Texas started as early as the seventh grade (middle school), so maybe students' automaticity skills not fully developed were being hampered by encouraging calculator use so early in the approved state curriculum.

Figure 2**.** Comparison of the size of Texas compared to the size of Egypt (1.5 times larger) and the territory (blue-dotted outline) covered by the NSA team from six institutions spread over 45,000 mi^2 or about 117,000 km^2 of the state of Texas, USA.

EXPERIMENTAL

Instrument

The 16-Q quiz [1] evolved to the 20-Q MUST (Math-Up Skills Test) after the pilot study [9] when the NSA team suggested that a few additional questions regarding the use of fractions needed to be added to the original quiz (for a copy of the 20-Q MUST see reference [14]). Over the past seven years, the diagnostic value of the MUST has produced some very interesting results for the NSA team. Three of the first data analyses that grab the team's attention are presented (see Figs. 3-5). The first eye-opener was that there was a stronger correlation between students' MUST scores and their final course averages when calculators were not used than when they were used (Figs. 3 and 5). Yes, students scored higher when they used calculators vs. when they did not (red vs. blue bars, Fig. 5), but the correlation to their final course average was stronger when they did not use a calculator (Fig. 3). The next observation that caught the team's attention was how the same "up and down pattern" of question means at each university stayed consistent (Fig. 4). These calculator-free, open-ended, hand-graded quizzes revealed that across the state students who had experienced an isomorphic curriculum (aka Texas Essential Knowledge and Skills) held similar misconceptions and had remembered (or not remembered) how to correctly solve certain arithmetic exercises. Yes, students from the premier post-secondary institutions performed at a higher level but the trendlines between all six institutions are very similar (Fig. 4).

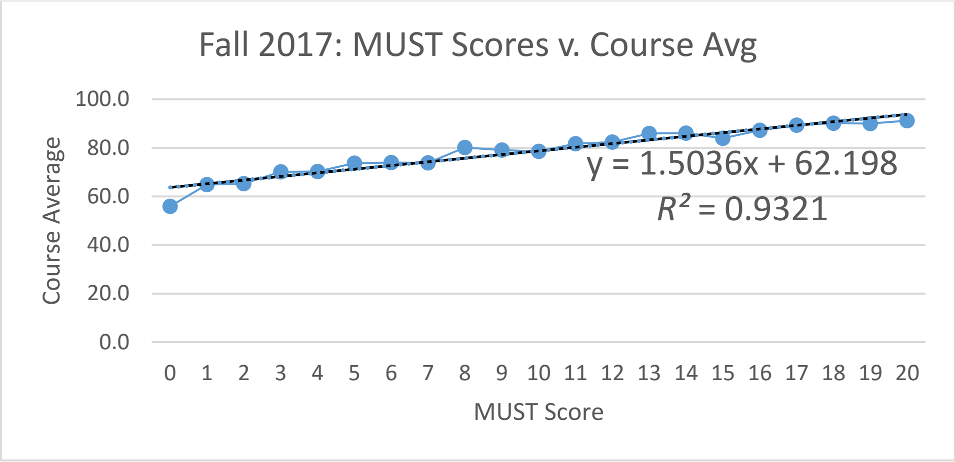

Figure 3. Course averages (n = 1,415) and their relationship to MUST scores without using a calculator.

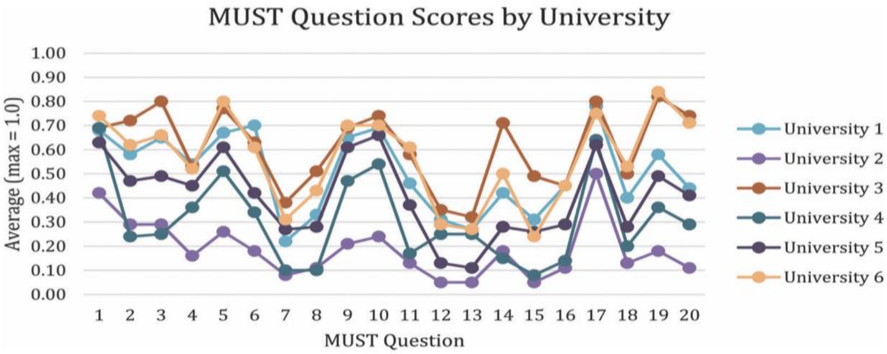

Figure 4. Mean scores for each question on the MUST. Note the similar up and down trends between each question mean at the six participating institutions (n = 1,073).

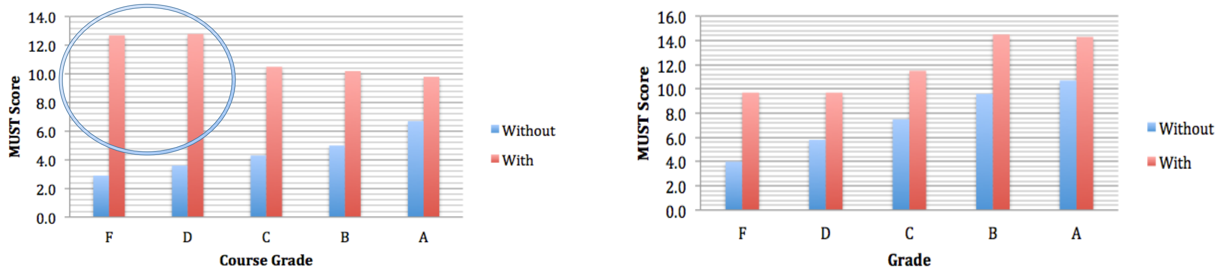

Figure 5**.** Bar graph of Chem I (left) and Chem II (right) of students' course grades compared to their average MUST scores. The most interesting trend (circled) was the Chem I students with a calculator (red bars): Students who were unsuccessful in the course (grades of D, F) scored higher than the successful students (grades of A, B, C).

The initial reaction was that this quiz simply covered basic arithmetic so this must be the problem behind students' lack of success in general chemistry. Some of the weakest students in Chem I can perform very well on the MUST (circled red bars, Fig. 5 left side), but they have very weak automaticity skills or what they can do without a calculator (blue bars, Fig. 5 left side). These students must be compensating for their lack of basic arithmetic skills by undoubtedly depending on the calculator. Since 2016, the MUST has evolved, the noted trends and correlations have remained the same, but our insights due to the NSA team's continued research have broadened.

METHODOLOGY

The first week of each semester students responded to 20-Q, timed MUST (15 minutes) and, during additional time (10 min.), complete a demographics survey. There are two versions of the MUST that differ only in minor number changes. For example, Q1 is 87 × 96 on one version and 78 × 96 on the other. The two versions of the MUST were validated by two mathematics professors, one chemistry professor, one chemistry education professor, and one science educator substantiating that it measured what it was intended to, and that it was appropriate for students enrolled in general chemistry. To date, no statistical difference (*t*-test) between versions has been observed.

Participants

Each instructor at the various institutions emailed deidentified student data to the NSA team lead, the first author of this paper. All unusable student data were eliminated (e.g., post-baccalaureates (small group), students with final course grades of < 10% (lack of participation), any student without a score for the MUST diagnostic quiz (absence), and students who did not give IRB consent to participate). Student demographics included that about 95% attended Texas secondary schools, 60% were freshman, 40% male, 30% Hispanic ethnicity, and about 50% worked either part- or full-time. Only 1% of the students did not take a high school chemistry course; however, almost 20% of the general chemistry students failed to meet the stated (suggested) mathematics prerequisites for enrollment.

Three more institutions have joined the NSA team bringing the number of members to 16. Over the past seven years of research studies, over 10,000 students have consented to participate. Of these, n = 9,315 Chem I and II students satisfied the research criteria mentioned above: Chem I = 6,303 (67.7%) and Chem II = 3,012 (32.3%). All studies until 2022 evaluated only Chem I and II students. In 2022, the investigations were expanded to include organic chemistry I (O-Chem I) as a separate population.

RESULTS

After choosing a meaningful problem and getting some interesting preliminary results, the next hallmarks to be met are: (1) Are the data statistically reliable and can the results be repeated? and (2) To what extent does the MUST predict which students will have a satisfactory course average (69.5% or higher)? Table 1 is a list of some of the publications by the NSA team members and the reliability and predictability statistics. Different studies emphasized different research questions, so not all of the same statistical data were generated for each study justifying why some of the data is missing in Table 1.

Table 1. Chem I and II statistical data: effect size, reliability, and predictability of the MUST

Publication	Date	Subject of Publication	Pop.	Effect size (Cohen's *d*)	Reliability (internal consistency)	Predictability
Petros et al. [9]	2017	Math preparation	2,127		KR_{21} = 0.821	
Albaladejo et al. [2]	2018	Math preparation	2,127		KR_{21} = 0.821	
Williamson et al. [14]	2020	Chem I student success	1,073		Cronbach's alpha = 0.856	78%
Powell et al. [10]	2020	Chem II student success	1,599	0.962	Cronbach's alpha = 0.853	83%
Weber et al. [13]	2020	Careers	4,113	1.43 Chem I; 1.20 Chem II	KR_{20} = 0.874	
Alivio et al. [3]	2020	Chem I impact of math review	325			
Shelton et al. [11]	2021	Chem I and II warning signals	1,915	1.21	KR_{20} = 0.855	
Dubrovskiy et al. [5]	2021	Gender gap	6,694	1.43 Chem I; 1.20 Chem II	KR_{20} = 0.874	
Villalta-Cerdas et al. [12]	2022	Personal characteristics of unsuccessful Hispanics	69	1.40	KR_{21} = 0.856	
Mamiya et al. [8]	2022	Environmental characteristics of unsuccessful Hispanics	69	1.40	KR_{21} = 0.856	80%
Willis et al. [15]	2022	Chem I common questions; linear and logistic regression models	1,020		Cronbach's alpha = 0.85	83.4%
Lee, Rix, & Spivey [7]	2022	Organic Chemistry	123	1.29	Cronbach's alpha = 0.861	82%
Ford, Broadway, & Mason [6]	submitted	Chem I e-homework	273	1.22	KR_{20} = 0.845	44%

Note: KR_{20} and KR_{21} (Kuder and Richardson 21) is a simplified version of *KR-20* that can be used when the difficulty of all items on the test are known to be equal. After analyzing data for multiple studies, the *KR-20* is a better choice for determining the reliability of these data that analyzed a binary or dichotomous choice (right/wrong) score on the hand-graded MUST. A high KR value indicates a stronger relationship between items as to their inter-item consistency. Like Cronbach's Alpha, 0.70 and above is good, 0.80 and above is better and 0.90 and above is the best, but above 0.90 also suggests that some items are redundant and make the data analyzed questionable.

Table 2 documents the most dramatic results for the population (n = 9,315): Chem I (top) and Chem II (bottom) students who were unsuccessful in the courses (grades of D or F) had limited automaticity skills based on MUST scores (maximum score = 20) and performed significantly lower than those who were successful ($p < 0.05$). Both successful and unsuccessful Chem II students did perform slightly better than successful and unsuccessful Chem I students, but still even the successful Chem II students averaged 11.40/20 = 57% on the MUST without a calculator.

Table 2. Performance on the MUST for successful and unsuccessful students

Chem I (*n* = 6,303)	***n* (Course Avg.)**	**MUST Score (*SD*)[a]**
Successful (≥ 69.5%)	4,356 (69.1%)	9.26 (4.95)
Unsuccessful (< 69.5%)	1,947 (30.9%)	5.70 (4.16)
Chem II (*n* = 3,012)	***n* (Course Avg.)**	**MUST Score (*SD*)[a]**
Successful (≥ 69.5%)	2,134 (70.8%)	11.40 (4.43)
Unsuccessful (< 69.5%)	878 (29.2%)	7.73 (4.67)

[a] Successful students performed significantly higher than unsuccessful students ($p < 0.05$).

Research Question #1

To what extent are the data from the MUST scores statistically reliable and can the results be repeated?

As can be seen in Table 1 above, the reliability data (based on Cronbach's alpha and KR data) and effect size data (Cohen's *d*) have consistently produced repeatable values. Alluvial diagrams (i.e., rivers showing *associations between categorical variables*) are constructed from the following online resource: https://app.rawgraphs.io. Fig. 6 is one of many alluvial diagrams that have been generated from NSA team data. The average MUST range was determined from the mean score and one standard deviation (*SD*) around the mean. The average range was determined by taking one half of the *SD* on either side of the mean. Possible scores on the MUST range from 0-20. For example, if the mean was 6.0 and the *SD* 4.0, then the average range is between 6 – 2 and 6 + 2 or a range of 4-8 leading to the low MUST range of 0-3 (L = low) and an above average range (U = upper) of 9-20. Can students in the upper MUST range make a D or F in the course? Yes! Can students in the lower level on the MUST succeed in the course? Yes! But the odds are that if you have skills that allow you to correctly respond to basic arithmetic problems without a calculator, you will succeed (follow the top violet river, Fig. 6); if students perform low on the MUST (follow the salmon-colored river starting on the bottom left, Fig. 6), a few do succeed but over half of the D's and F's flow from this group.

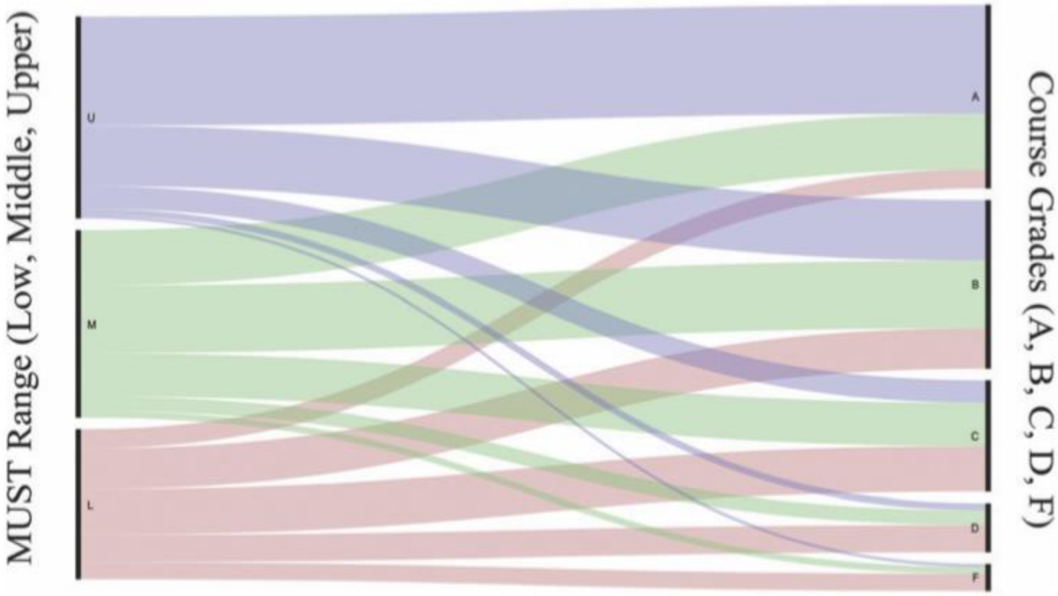

Figure 6. Chem II student data comparing MUST ranges of upper (U), middle (M), and lower (L) scores linked to students' final course grade. Follow the "rivers" to explore how each range of scorer performed.

Table 3 supports how the MUST scores correspond to final course grades of students in general chemistry. Must scores can also be used to predict students' success or failure in the respective classes. For more information regarding our predictability LASSO (Least Absolute Shrinkage and Selections Operator) models see the published results for Chem I [14] and Chem II [10].

Table 3. Classic averages and corresponding MUST scores for Chem I and II combined

Grade average	***n* (%)**	**MUST (*SD*)[a]**
A: 89.5-100.0+%	1,985 (21.3%)	12.22 (4.47)
B: 79.5-89.4%	2,352 (25.2%)	9.95 (4.63)
C: 69.5-79.4%	2,154 (23.1%)	7.87 (4.59)
D: 59.5-69.4%	1,312 (14.1%)	6.62 (4.48)
F: 0-59.4%	1,512 (16.2%)	6.05 (4.36)
Overall (76.0%)	**9,315**	**8.88 (5.04)**

[a] Statistical difference between all nearest grade groups (A to B, B to C, etc.)

O-Chem Results

Having spent the first six years of research investigating Chem I and II students' automaticity skills, the conclusion was that the MUST results supported that the problem is in students' basic arithmetic preparation and their lack of automaticity skills. One of the NSA team members relayed the result that students who could do basic arithmetic problems without a calculator were by far the best students on to her organic chemistry (O-Chem) colleagues. Out of curiosity, the O-Chem professors gave the MUST to their students and the same results were obtained [7]: the students who were better on the MUST did better in O-Chem! Not fully convinced, the study was repeated with three universities pooling results [4]. In Fig. 7, the MUST ranges I (above average MUST) – III (below average MUST) (left side) were linked to whether students were S (successful) or U (unsuccessful) in O-Chem I. The results were even more defined than for Chem I and II—very few students in MUST group I were unsuccessful in O-Chem I. Why did the unexpected results produced?

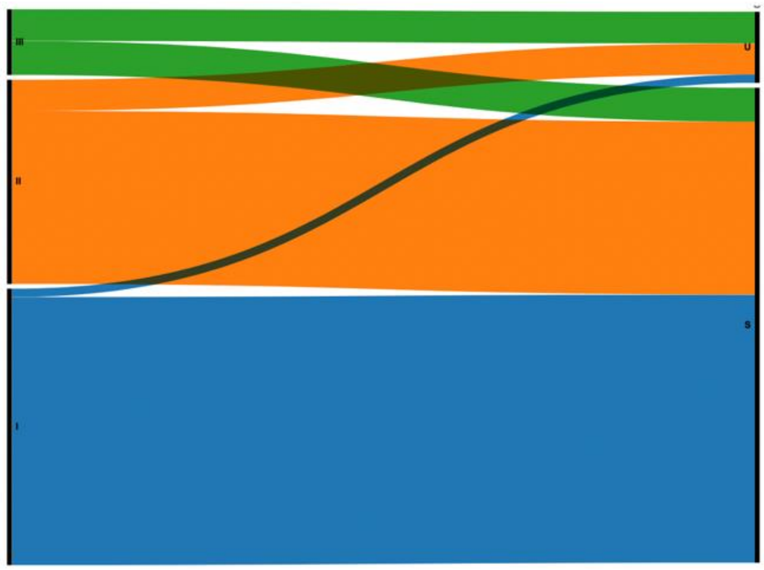

Figure 1. Alluvial diagram comparing MUST scores to completion level of O-Chem I students. Left vertical bar identifies three MUST groups (I = above average scores, II = average scores, and III = below average scores). Right vertical bar identifies two student groups (U = unsuccessful and S = successful). Alluvial diagram source: https://rawgraphs.io/learning/how-to-make-an-alluvial-diagram/#01-paste-your-data

Figure 7. O-Chem MUST ranges and course success [4] (open-source, reprinted with authors' permission).

Why are students in O-Chem, who have completed most of the courses in mathematics needed for their degrees and two semesters of general chemistry still not performing well on the MUST and subsequently not doing well in O-Chem. Regardless of how the data are evaluated what is consistent is that many of the unsuccessful students in Chem I, Chem II, and O-Chem I, began the course with low MUST scores. As stated at the beginning of this paper, the MUST is not just assessing arithmetic skills as was originally thought. Many of the exercises on the MUST require structured established procedures to be solved that go beyond simple arithmetic knowledge. How do these exercises that require procedures to be solved relate to the skills needed to solve O-Chem problems? Both are testing students' ability to learn procedures. Yes, different procedures but still to recall needed procedures. In O-Chem the procedure may be as simple as acid + alcohol → ester + water, but yet this needs to be an overlearned procedure.

Since the NSA team began this project with Chem I and II and now have extended our studies to include O-Chem, our expectations have evolved. The current insights are that the MUST also assesses students' ability to follow known procedures. For example, to solve Q2 on the MUST, the student multiplies (0.50×10^{-6}) (6.4×10^{21}). It is not a given that students know the procedure of how to solve this exercise. Students may be aware that they can take ½ of 6.4 but do they remember that when multiplying base-10 values with exponents, all you need to do is add the exponents? Some may try to take these numbers out of exponential notation, do the multiplication and then put the result back in exponential notation. It is obviously still possible to get the correct answer, but the latter process takes additional time and provides a greater opportunity to make a mistake.

Research Question #2

To what extent does the MUST predict which students will have a satisfactory course average (69.5% or higher)?

Predictability

The NSA team has published three studies that have use the LASSO regression method to determine the predictability of the MUST in determining students' final course success possibility [7,10,14]. LASSO suggests that a 2/3 random sample be used and if possible, then a stratified random sample making sure that all categories evaluated are represented before the predictability values are generated. A practical description of being stratified is when the statistician makes sure that each university is represented by a random sample of 2/3 of each student body. The purpose is to predict students' success (i.e., a course average of ≥ 69.5% or a grade of A, B, and C) or failure (i.e., a course average of below 69.5% or a grade of D and F). All categorial demographic variables (e.g., gender, university level or classification, academic major, ethnicity, first-generation status, and work hours) are combined with the numeric MUST score (0-20 points) to determine the predictability of the

MUST. It was determined in all cases that the MUST has good predictability for both numerical course average (linear regression) and the binary successful vs. unsuccessful (logistic regression).

The statistical modeling using the demographic variables mentioned above provided the following accuracies: 78% in Chem I, 83% in Chem II, and in O-Chem the MUST alone had a 64% accuracy but when the demographic variables of each student's entering science-course GPA (grade point average), and the score on their first exam were added to the equation the predictability rose to 97.0% for the successful student (grades of A, B, or C) and to 82.2% for those predicted to be unsuccessful (grades of D or F) [7]. In all studies, the student's MUST score had a highly significant effect and was a dominant covariate to the overall predictability. The effect of the MUST score is bolstered by the inclusion of other predictive factors, but by itself alone is one of the most influential positive contributors. Another positive contributor to the predictability was when students who are from families where parents and grandparents held degrees, their course success was improved. The variable that appeared to be doing the most harm was when students need to work for over 30 hours/week. However, working on-campus for 1-10 h appeared to have a small positive influence on course success.

Overall, the MUST data are consistent with large effect sizes and repeatable, strong internal consistency. The linear relationship between the MUST scores and course success (Table 2) is just one of many examples that reflect the same trend: the higher the student's entering MUST score the better the chance for student's success in Chem I, II and O-Chem. Keep in mind that these data are combined from multiple universities with varied demographics (public or private institutions; large, medium, and small universities; Hispanic-serving (> 25% Hispanic ethnicity) or Hispanic-emerging (16-24% Hispanic ethnicity) institutions; R1, R2 (Carnegie classification of research 1 or 2 status); and located over a large area of the state of Texas. Even to this day, this CER team still marvels at how a 15-min, 20-Q assessment given to students the first week of classes in varied lower-division chemistry courses can tell us so much about the students in front of us.

RESULTS AND DISCUSSION

Limitations

The results obtained from these data are consistent, reliable, and have provided excellent predictability results requiring no more than 30 min. of class time when taking into consideration the time needed to distribute, explain, sign, and collect the paperwork. Since the MUST is hand-graded, the time needed to score is dependent upon the number of students participating. Students must also pay attention to the instructions and provide the answer that is appropriate, not an alternative correct answer. For example, if asked to give the answer as a decimal number, then that is the only accepted answer (an equivalent fraction is counted as wrong). What needs to be done now is to see if other institutions can obtain similar results.

CONCLUSIONS

The MUST is not limited to assessing the four basic arithmetic operations (addition, subtraction, multiplication, and division). It goes much deeper and identifies students who are proficient in solving exercises that are based on known procedures. The importance of using this valid, reliable diagnostic assessments is that we can identify students who have the potential to struggle with lower-level chemistry courses and identify these students early in the semester when time is still available to institute one or more corrective measures on how to master the procedures needed to succeed. Removing students trusted calculating devices to impress upon them the value of automaticity is a possible start to helping students with low MUST scores. An incentive to remove calculators from the general chemistry classroom is that the MCAT (medical school entrance exam) is a calculator-free entrance exam (over 50% of these students plan to enter the health professions) and this exercise will give them some needed mental-math practice.

In the NSA team's zeal to impress upon the general chemistry community that students' dependence on a calculating device may be hindering their ability to routinely use and make sense of quantitative information [16] in an increasingly data-driven world, we neglected to consider a less intensive mathematics course, like O-Chem. Quantitative reasoning matters in almost every discipline and in every adult role: worker, citizen, and family member [17]. Even the college-educated often lack an understanding of how to make sense of numerical information [18]. Today's people need to be quantitatively literate, (i.e., they need to be able to process and understand quantitative information) [19]. “We need to encourage our students to put aside their calculators and associated cyborgian-thinking patterns, so they can surpass their calculators’ capabilities and learn to think conceptually and creatively about quantitative chemistry” [20, p. 730].

We have also learned that students who have committed certain procedure to their long-term memories, may have an easier time with committing other procedures like those needed to succeed in organic chemistry to memory so that these too can be more easily recalled. Success on the MUST goes beyond basic arithmetic understanding and reflects what students have “overlearned.” When students possess an ability to retain certain facts in long-term memory this human quality provides an edge to succeed in O-Chem [4]. It is with these types of results from the 15-min. MUST assessment combined with selected demographics that this instrument has proven to be a very valuable tool for identification of at-risk students at a time (first week of class) when it is still possible to provide students with an intervention that may serve to improve their course success.

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ACKNOWLEDGEMENTS

The author thanks all CER instructors for their participation in the Networking for Science Advancement team. In addition, thanks are extended to the ACRICE 5 organization team with special appreciation to Professors Fahmy and Bassioni, and to Ain Shams University for hosting the conference.

INTERDISCIPLINARY APPROACHES TO CHEMISTRY EDUCATION

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ABSTRACT

This paper describes the application of a framework for K-12 integrated STEM to the teaching and learning of high school chemistry. The paper draws on a detailed conceptual framework for K-12 integrated STEM education that includes seven characteristics: (a) focus on real-world problems, (b) centrality of engineering, (c) context integration, (d) content integration, (e) STEM practices, (f) twenty-first century skills, and (g) informing students about STEM careers. Examples relevant to high school chemistry are used to illustrate each characteristic and its role in improving chemistry education. *[African Journal of Chemical Education—AJCE 13(2), June 2023]*

INTRODUCTION

Over the past decade, K-12 science education across the world has been shaped by policies that aim to address concerns about the increasing needs of the STEM workforce [1]. These policies are based on the premise that continued progress and prosperity depends on the development of the future generation of STEM professionals [2]. The development of a robust STEM workforce is essential for African economies to be competitive in the global market, create jobs, and improve economic outcomes. However, within the African continent, less than 25% of students in higher education pursue a STEM-related degree [3]. This issue is compounded by the significant under-representation of women in STEM [4]. For example, in most Sub-Saharan African countries, less than 30% of engineering graduate from institutions of higher education are women [5]. This is problematic not only in terms of the number of students entering the STEM fields, but also because the unique contributions and perspectives of women are absent from the development of solutions to real-world problems. New approaches to K-12 science education are needed to motivate students, particularly women, to pursue STEM careers.

Changes to K-12 science education also need to address the ever-changing world in which we live and to support the development of solutions to the critical challenges facing humanity, such as sustainability, climate change, health, and the environment [6-7]. To quote Albert Einstein, "the significant problems we face today cannot be solved at the same level of thinking we were at when we created them." These problems are inherently complex and multidisciplinary in nature and require new and creative thinking to develop possible solutions. As such, the future STEM workforce not only needs strong STEM content knowledge and skills, but also strong twenty-first century skills (e.g., critical thinking, communication, collaboration, and creativity) [8-9]. Indeed, more than half of today's Kindergarteners will end up working in jobs that do not currently exist [10]. It is no longer enough for students to simply learn scientific content, rather students should be involved in knowledge construction and the application of scientific content and twenty-first century skills to analyze, evaluate, and create possible solutions to real-world problems [11].

In response to these calls for improving K-12 science education to address current and future STEM workforce needs, there is a global push for integrated STEM (science, technology, engineering, and mathematics) approaches to science teaching and learning [12 – 15]. Research shows that teaching approaches which integrate disciplinary STEM content can greatly improve student learning [16-19] and improve student interest in science and engineering [20 – 22]. However, this research has predominantly been conducted at the elementary and middle school levels, with limited attention to high school chemistry settings [23]. In this paper, integrated STEM approaches to K-12 science learning are described with a focus on applications in chemistry classrooms.

LITERATURE REVIEW

Despite the proliferation of integrated STEM in the literature, no single accepted definition of integrated STEM instruction exists. Common across all definitions is that learning should be contextualized within a real-world problem [7, 24 - 25]. However, debate remains about whether integrated STEM requires integration across all four of the STEM disciplines [26 – 27] or more common within the literature the integration of at least two of the STEM disciplines [6]. For example, Moore and colleagues defined integrated STEM education as "an effort to combine some or all of the four disciplines of science, technology, engineering, and mathematics into one class, unit, or lesson that is based on connections between the subjects and real-world problems" (p. 38) [28]. Similarly, Kelley and Knowles defined integrated STEM as "the approach to teaching the STEM content of two or more STEM domains, bound by STEM practices within an authentic context for the purpose of connecting these subjects to enhance student learning" (p. 3) [24].

In addition, researchers and educational practitioners do not agree on what integrated STEM looks like in practice [6]. However, there is growing consensus on the central characteristics of integrated STEM education: (a) centrality of engineering design, (b) driven by authentic problems, (c) context integration, (d) content integration, (e) STEM practices, (f) 21st century skills, and (g) informing students about STEM careers [29].

Focus on Real-world Problems

Proponents of integrated STEM education argue that using real-world problems as a context for learning provides motivation for learning STEM [24, 30]. However, the nature of the real-world problem needs to attend to students' interests and lived experiences [30 - 32], as well as the context of the educational setting. For example, Fomunyam argues that "elements of Africa's ideologies, concepts and culture have to be incorporated into the engineering curriculum for easier assimilation and practical application" (p. 2429) [33].

Unfortunately, integrated STEM classroom activities tend to focus on the technical aspects of engineering related to the design of "things", such as designing cars and rockets [34], which perpetuate male dominance in STEM and negatively impact girls' interest in STEM careers [35]. Girls are motivated by projects with a communal goal orientation that highlight how STEM can improve the human condition related to societal issues such as health and the environment [35 - 37]. Thus, an approach grounded in care and empathy that engages students in considering the societal implications, as well as technical considerations, of their design solutions is an important consideration [34, 38].

Specific to chemistry classrooms, Gilbert notes that the traditional chemistry instruction lacks relevance for students because of its focus on isolated facts [39]. Researchers are turning to contextualizing chemistry instruction within real-world problems to promote student learning. For example, Fortus and colleagues used the context of developing environmentally friendly batteries to help students develop electrochemistry concepts [40]. Apedoe and colelagues used the context of designing heating and systems to promote learning about atomic interactions, reactions, and energy [41]. Hadinugrahaningsih and colleagues designed a curriculum to promote the learning of concepts related to acids and bases using the context of aquariums and hydroponics [42]. Burrows and colleagues explored gains in student learning using a unit that used the development of biodiesel as a context for learning [43]. A common thread across these examples is the use of sustainability and the environment to contextualize student learning, contexts that have the potential to motivate female students and help to diversify the STEM fields.

Centrality of Engineering

Engineering is a systematic and iterative approach to designing solutions to real-world problems [15]. Given the expectation of integrated STEM, that students should be engaged in developing solutions to the real-world problem, design or engineering practices are highly relevant [7, 15 - 16]. The limited body of research in chemistry education shows that "situating learning chemistry in an authentic practice, like design, meaningfully connects chemistry content and practices around a shared practical purpose" [44]. The integration of design practices in chemistry education has been found to promote students' understanding of chemistry concepts [40 – 41, 45] and problem-solving skills [46].

Context Integration

The real-world problem or engineering design challenge used to contextualize learning should engage learners in applying and expanding their knowledge of the STEM disciplines [16, 30]. Specific content learning objectives need to be aligned with the needs of the real-world problem to promote students' application of STEM content knowledge toward generating possible designs and making evidence-based decisions. Without this explicit integration between the real-world problem and content learning goals, students will resort to tinkering (a form of trial and error), limiting the learning of scientific concepts [47 – 49]. Thus, integrated STEM activities should provide students with opportunities to apply developmentally appropriate mathematics or science content within the context of solving engineering problems [15, 50 - 51].

As a chemistry example, Apedoe and colleagues designed a high school STEM unit where students were challenged to design a heating or cooling system that uses chemical energy to meet a personal need in their own life [41]. Central to the unit were learning goals related to specific chemistry concepts: atomic interactions, reactions, and energy changes. These concepts were selected as they are conceptually important to understanding chemistry, included in state and district science standards, and relevant in designing possible solution to their personal heating or cooling problem. Thus, the unit included specific lesson targeting the central chemistry concepts. For example, students explored the concept that "energy transfers from particles with high kinetic energy to particles with lower kinetic energy through collisions" and applied this to the design of the container for their heating or cooling system. Through this approach, the design challenge creates a need-to-know and motivation to learn the chemistry concepts [40, 52 - 53].

Content Integration

Integrated STEM approaches can improve students' learning of scientific concepts [16 – 19], however students' have trouble in recognizing the ways in which different content areas support and complement each other [7, 54]. Although teachers may understand the connections across the different content areas, students often struggle to make these connections on their own [55 – 56]. Therefore, teachers need to help students to recognize these connections and make them explicit for students [24, 54].

For example, it is difficult to imagine teaching and learning chemistry without engaging in mathematical practices. However, chemistry teaching has traditionally over-emphasized the symbolic level, which includes the use of mathematical equations [57] and the connections between mathematical representations and scientific concepts are not transparent to students [49]. Students are expected to interpret the mathematical and scientific meaning represented by an equation [58 – 59], however, students rely on algorithmic procedures without making connections between the mathematical equation and the scientific phenomenon [60]. However, when instructors explicitly integrated science and mathematics through blended sensemaking, students' scientific and mathematical knowledge is activated which improves students' quantitative problem solving [61 – 63].

STEM Practices

Engaging students in STEM practices is a common component of definitions of integrated STEM education [6, 24]. The range of STEM practices in which students should engage is vast, however, the nature of integrated STEM is focused on engaging students in generating, evaluating, and iteratively improving design solutions. Thus, a prominent practice is the expectation that students "justify design choices and science explanations with sound reasoning and evidence" [40]. Siverling and colleagues refer to the practice of justifying design decisions as evidence-based reasoning, arguing that students should be explicitly engaged in evidence-based reasoning throughout the design process [64]. Evidence-based reasoning requires students to make claims about their designs and design decisions that are supported by both evidence and reasoning [65].

Specific to chemistry education, Stammes and colleagues argue that improving students' reasoning in chemistry is a valuable goal of design in chemistry education [66]. However, students tend to focus on pragmatic reasoning such at cost and materials, rather than using scientific concepts to justify and explain their design choices [67 – 68], thus students need to be encouraged to reason when designing [40, 69]. The design cycle used by Apedoe and colleagues includes a step that calls for students to generate reasons [41]. For example, when designing their heating and cooling system, students generated reasons for why different materials did not allow for sufficient transfer of energy and the teacher helped students to understand how thermal conductivity had important implications for their design. As another example, researchers engaged students in designing environmentally safe batteries and students had to provide chemical justifications for their choice of electrodes and electrolytes [40].

21st Century Skills

The skills needed for students to thrive and succeed in today's world, and more specifically the STEM workforce, include knowledge construction, real-world problem solving, skilled communication, collaboration, use of information and communication technology for learning, creativity, and collaboration [11, 70]. While demographic projections show decreases in the workforce in developed countries in Europe, North America, and East Asia, the workforce will increase in sub-Saharan Africa [71 - 72]. A policy focus within developing countries on 21st century and STEM skills has the potential to stimulate the national economies and development in these countries [72]. For example, the Kenyan government prioritized of 21st Century Skills in their Vision 2030, with the Ministry of Education, Science and Technology focusing on equipping citizens with 21st Century Skills required for the modern economy [73]. As another example, Egypt has focused on the development of STEM schools as central to re-envisioning education in Egypt (Egypt vision 2030). The mission of these schools is to foster the development of socially responsible leaders who are equipped with the knowledge and 21st century skills to address the grand challenges of Egypt [74].

Integrated STEM instruction provides a rich environment to support the development of 21st century skills [48, 75]. Real-world problems and engineering design challenges are complex with multiple possible solution paths, thus requiring that students engage in critical thinking, drawing on their STEM content knowledge to propose possible design solutions. The lack of a single correct solution when engaging in the engineering design also promotes creativity and the potential of transformative and innovative design solutions [76 – 77]. Specific to chemistry education, Ah-nam and Osman reported on a STEM intervention where students designed digital games to help their peers to learn chemistry concepts that was successful in improving students' chemistry knowledge and 21st century skills [78]. In another example, Hadinugrahaningsih and colleagues showed that their STEM approach to teaching acids and bases was successful in developing students' **critical and creative thinking, problem-solving skills, collaboration and argumentation skills, leadership and responsibility, information, and literacy skills [42].**

Promoting STEM Careers

Given the policy goal of promoting future participation in STEM careers, integrated STEM education should expose students to details about STEM careers [79 – 80]. One strategy is for students to engage in the authentic work of STEM professionals as they participate in STEM activities [81 – 82]. Engagement in chemistry practices is important in preparing students to use chemical knowledge to make decisions as scientifically literate citizens, and for potentially continuing a career in chemistry [59]. However, debate remains about whether implicit modeling of STEM professions by engaging students in hands-on STEM activities leads to durable and robust understandings about the work of engineers and other STEM professionals [83]. Whereas explicit discussion of STEM professions can help students to understand specific career opportunities and align these professions with their interests [81 – 82].

Students typically have limited understanding of chemistry-related careers, seeing teaching and laboratory research as the only options [84]. A variety of career-focused interventions have been reported at the undergraduate and graduate levels [85 – 88], however less attention has been placed on addressing chemistry careers at the K-12 level. Burrows and colleagues embedded career connections into their biodiesel curriculum but did not report on the impact on students' career interests [43]. Conversely, Apedoe and colleagues reported on the positive impact of their STEM approach to teaching chemistry on students' interest in engineering careers rather than chemistry-related careers [41].

Rather than focusing explicitly on careers, K-12 chemistry education has focused on helping students to see chemistry as relevant outside of school [89]. Indeed, research suggests that chemistry instruction should include real-world contextual issues to promote interest in chemistry [90 – 91].

More research is needed to better understand the role of instruction about STEM careers in K-12 chemistry instruction.

DISCUSSION

Each of the seven characteristics of quality integrated STEM education has important implications chemistry education both globally and specifically in Africa. At the highest level, chemistry education needs to be driven by real-world problems to motivate students to persist in the pursuit of STEM careers. Careful consideration is critical in selecting the context for an integrated STEM lesson, as research shows motivation for female students is driven by topics that promote positive societal impact, such as sustainability and healthcare [35 - 37]. Such topics are rich contexts for teaching chemistry concepts as demonstrated in the chemistry education literature [40 - 43].

While the integrated STEM framework described here [29], calls for engaging students in engineering practices and the contextualization of the real-world problem as an engineering design challenge, this may not be appropriate in the African context. The focus on engineering is relevant to countries that call for the integration of engineering into K-12 science standards [12 – 15]. Some of the examples within the chemistry education draw on engineering and design-based approaches [35 – 37], whereas others provide a real-world scenario to contextualize a chemistry lab without a heavy emphasis on engineering [92]. Attention to selecting real-world problems and related engineering design challenges that promote positive STEM identities for students that are under-represented in STEM not only addresses reported workforce needs but brings new perspectives and approaches to how STEM content and practices are applied in the real-world [29].

Regardless of whether the real-world problem is framed as an engineering design challenge, it is critical that the context is aligned with specific chemistry learning objectives. The context could be used to reactivate prior knowledge, or the lessons would include the explicit teaching of the relevant chemistry content. In other words, quality integrated STEM units should include lessons designed to explicitly teach relevant chemistry content as described in the chemistry education literature [40 - 43]. However, given that students rarely make connections between disciplines spontaneously [56], it is critical that teachers use specific pedagogical approaches, such as evidence-based reasoning [64 – 65], to help make these connections explicit. Strong teacher facilitation and questioning is needed to help students recognize the connections across the disciplines [29].

Most critical to the integrated STEM approaches to teaching science is the use of student-centered pedagogies that engage students in STEM practices and 21st century skills. However, the educational structure in Africa does not lend itself to such approaches and the current skills taught do not align themselves with the needs of the future workforce [93]. Indeed, pedagogical change is constrained by issues such as class size, hierarchical school structures, and examination requirements [94]. There is an urgent need to improve teacher recruitment, teacher preparation, and curriculum upgrades to promote integrated STEM approaches and improve educational outcomes in African nations [93 – 94]. Some hopefully cases of systemic change exist that could be used as the groundwork for other countries. For example, in Rwanda has promoted STEM education across K-12 and university levels, implementing new curriculum STEM and ICT (Information and Computer Technologies) integrated curriculum [95].

The integrated STEM framework described in this paper provides guidance on teacher practices to improve chemistry education. Teachers and researchers can use these characteristics of integrated STEM education as a grassroots effort to improve the teaching and learning of chemistry for specific topics in support of the necessary larger systemic changes needed within the education system itself.

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CHEMISTRY AS A KNOWLEDGE BASE FOR THE DEVELOPMENT OF SUSTAINABLE CEMENTITIOUS MATERIALS

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ABSTRACT

The globe is challenged with developing new materials that will guarantee resilience, sustainability, and performance of infrastructure. Of the materials globally in dare need of, to bridge the gross deficit in infrastructure, cementitious materials top the list. Their premier position is justified by the fact that they are required to build almost all forms of infrastructure needed to meet the sustainable development goals. Cementitious material like concrete has witnessed great evolution since it was first discovered and is still witnessing many innovations in its manufacturing processes. Despite this, cementitious material remains a major threat to climate change due to high greenhouse gases emission that is attributed to its production. Therefore, developing new materials that are environmentally friendly without compromising quality, is very important for the future development. In this article, overview of developmental stages of cementitious materials is presented, and the inevitability of cementitious materials for future development is equally established. The role of chemistry at every stage of development of cementitious materials is underscored. The paper further links the capacity to develop new materials to the understanding of chemistry of the materials. Similarly, capacity to deploy the knowledge of chemistry to this important area is also emphasized. It is concluded that chemistry is a sine qua non for future material development. *[African Journal of Chemical Education—AJCE 13(2), June 2023]*

CEMENTITIOUS MATERIALS IN HISTORY

Binder, or cementitious material in whatever form, has been the sine qua none of construction since existence of man on earth, which was put to be about two million years ago. Though at the initial stage of life, man used available materials to protect himself from harsh weather, while also migrating to regions of favourable weather [1].

In the early Neolithic period, man started putting materials together to build the first ever *permanent* structure. Since there was a need to provide wall and floor that will provide shelter, there in need for binding material to achieve a stone-like structure that can stand on its own. The loosely available materials then were sand, clay and other earthen materials, which must be bonded together to provide the needed structure. History has it that the plain mud, with or without straw, was the earlier binder that was just used, though the chemistry of its usage was not well understood then.

Some thousands of years after, which some authors put at about 9,000 years ago, inorganic binding materials were discovered. This discovery seemed to be coincidental and fortunately, it was found to be similar to the concrete found in the early structures built in the Galilee of Israel [2]. It was found that the “binder” was limestone-based, which hardened on adding water. Several other civilizations employed different material for binding loose earthen materials. While the Assyrians and Babylonians used raw clay, the Egyptians adopted lime and gypsum [1]. Furthermore, in another version of the use of binder in Egypt, it was reported that they used more of gypsum than lime because there was lack of fuel to generate enough heat energy to decompose limestone into lime [3]. Egyptians utilized this material as binder for stone to build the magnificent pyramids around 2,600 years back. Materials that were mainly calcium carbonate containing silica, were often used in China as found at a location near Xi'an as far back as about 5,000 years ago [4].

Ancient Greek also used slaked lime with some volcanic ash as binder to pieces of rock around 1,000 BC. As for the Ancient Rome, based on the knowledge acquired from the Greek, they made monumental structures with binder made from burning of mixture of gypsum and limestone with plaster of Paris to produce hydraulic binder. Similar trend was found in some countries in Sub-Saharan Africa, where mud with straw was commonly used as building material. One thing that is certain from this trend is that mankind, based on experience, found that some materials if heated, could become hardened in the presence of water. Meanwhile, at these times, the knowledge of chemistry was too limited to offer explanation for the performance of these materials. Thus, the knowledge of chemistry was never the basis for the development, but experience. As time goes on, the chemistry knowledge based on experimentation with these materials advanced the understanding of the cementing performance of these materials, which subsequently reflected in the new binders that are being developed in the modern world.

Scientists began to understand the chemistry behind the cementitious materials used in the early age, by the earlier 17th Century. During this period, hydraulic cement surfaced. In about 1756, after the Industrial Revolution, John Smeaton built Eddyston Lighthouse with stones bonded by mortar, which he produced from the burning of binary mixture slaked lime and clay [2]. In his experiment about 40 years after, James Parker burnt limestone-clay mixture up to a temperature of 1,100°C and ground the resulting product to produce a powder similar to the cement we have today. This is reported to be the foundation for the production of modern hydraulic cement.

Joseph Aspdin, who is known as father of Portland cement, refined the method of producing hydraulic cement. He mixed quicklime with clay in a certain proportion which he burnt to around 1200°C and added water to the mixture. Thereafter, he ground the mixture to fine particles, then dried it before reburning it in a shaft kiln [5]. This cement was later known as “Portland cement”. The name “Portland” was attributed to Portland stone found on the Isle of Portland, in South Dorset Coast. His invention serves as basis for rapid research in cement chemistry as a number of issues were generated from his method. Some of the questions that spur further research included the temperature at which the mixture should be burnt, and the proportion of quicklime and clay that should be used.

As of 1850, four cement plants were developed in UK, though production of Portland cement started in 1825. Portland cement production did not start in France until 1848, while it started in Germany and United States in 1850 and 1871 respectively [2]. In 1884, Isaac Charles Johson conducted a separate study from which he found criteria to produce homogenous product, which can be achieved by "burning the mix of limestone and clay at high temperatures of 1250ºC or above until semi-molten" [5]. This was the foundation for the modern cement manufacturing. What is certain is that understating of cement chemistry is a complex one, thus improvement continues. The more the chemistry of the materials get clearer, the more the understanding and potential to improve on what has been earlier developed.

RELEVANCE OF CEMENTITIOUS MATERIALS TO INFRASTRUCTURAL DEVELOPMENT

As shown in the previous section, the use of cementitious materials started with the existence of man. As long as the man needs shelter, road and other infrastructure, there would always be a need for cementitious materials.

Rapid urbanization with geometric increase in population is a global challenge of the 21st century, posing a serious threat to livelihood. More than half of global population now live in the cities. By 2050, the number will increase by 75% with Sub-Saharan Africa having the lion share of rapid urbanization - with its global share rising from 11.3% in 2010 to 20.3% in 2050 [6].

According to the United Nations Population Division, the population density for Africa is projected to increase from 34 to 79 persons per square kilometer for the period between 2010 and 2050 [6]. The attendant import of this scenario is that the existing infrastructure in most urban cities are strained beyond their carrying capacity, leaving a chunk of the population to vulnerability. Gross deficit in housing and gridlock on the highway as a result of limited paved roadway, as well as epileptic power and energy supply, are consequents of urbanization. All urban cities of the world are experiencing shortage of adequate housing, but more alarming in the rapidly urbanized cities in Africa. About 60 million housing units was found as deficit in Africa in the period of 2001 and 2011. Going by the increase in population, the gap between the demand and supply will subsequently increase. It is estimated that about $63 trillion will be invested to meet the global infrastructure deficit [7].

A cursory look at the trend in the need for infrastructure indicates that substantial quantity of materials will be needed to build these structures. Materials like timber, steel, plastic, glass, bitumen as well as concrete (cementitious material) are very much essential. Nevertheless, of all these materials, concrete seems to be the only material that is environmentally friendly due to its relatively low carbon footprint compared to other materials (Figure 1).

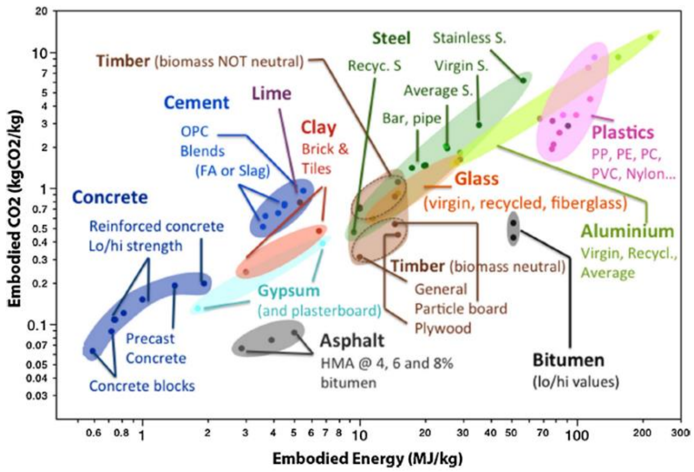

Figure 1: Carbon footprint of construction materials [8]

Concrete is a composite material that is needed much more than any other materials in construction industry. It is made up of cement, aggregates (fine and coarse) and water as well as other construction chemicals as the need may arise. Concrete has been in use for over 2000 years. The relative low cost, ease of production, possibility of forming different needed shapes and higher durability as well as low energy consumption gave concrete an edge over other materials (Table 1). In 2015, annual global cement consumption was 4.6Gt and this is projected to increase to between 6 and 13.5 Gt/a in 2050 [9]. Since concrete is needed to provide needed infrastructure, Africa has witnessed increase in investment in cement production. Figure 2 shows the network of cement distribution in Africa.

Though there is no alternative to cementitious materials in building the needed infrastructure, the huge consumption has created a big concern about the CO_2 emission from cement production.

Burning of fossil fuels and carbonation of limestone which is decomposed into lime and carbon dioxide are the major sources of CO_2 emission from Portland cement production. For a tonne of cement produced about 1 tonne of CO_2 is emitted [10]. This shows that to meet the estimated demand for cement of 50 billion tonnes in 2030 equal amount of CO_2 will be emitted into the atmosphere. Hence, there is urgent need to find alternative to cement, or create a better cement to ensure carbon net zero by 2040. No doubt, understanding the chemistry of earthen materials is a prerequisite to creating ecofriendly cementitious material.

Table 1: Estimated energy, water requirement and carbon emission between 2015 and 2030 [7].

Materials	Cumulative Material Demand (billion tonnes)	Energy	Water	CO_2	Energy	Water	CO_2
		Per tonne of material			In total		
		(kWh/t)	(Litres/t)	($kgCO_2$)	(kWh/t)	(Litres/t)	($kgCO_2$)
Cement	50.1	110	307	914	5,518	15,400	45,850
Steel	26.7	5,700	28,500	2,000	152,147	760,733	53,385
Aluminum	1.7	72,000	88,000	20,900	120,967	147,849	35,114
Total					278,632	923,982	134,349

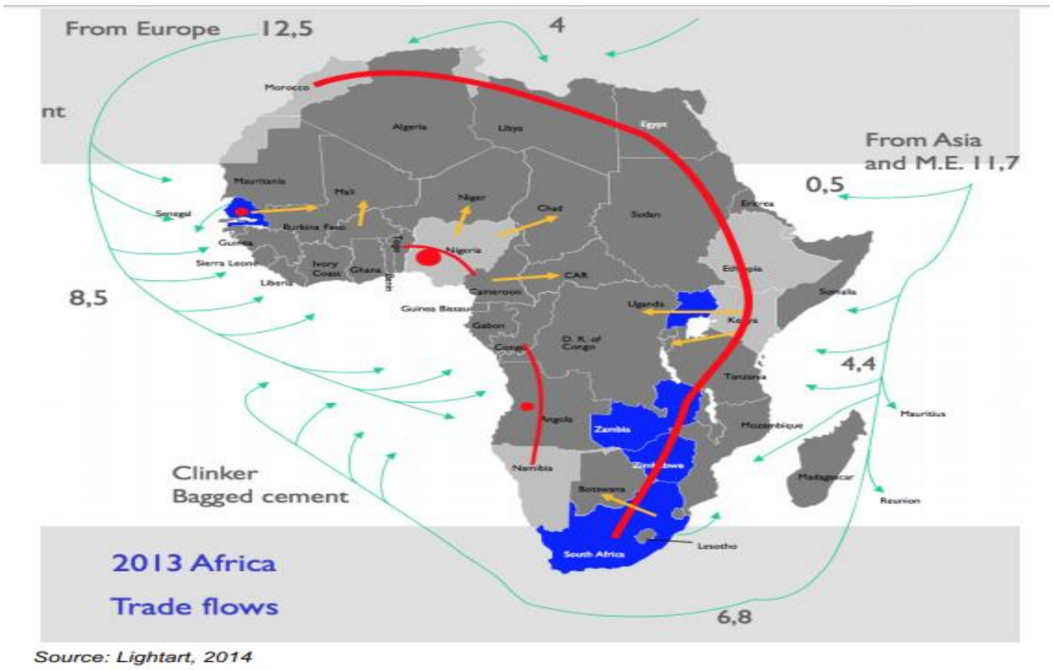

Figure 2: Clinker distribution in Africa [11].

CHEMISTRY AS BASE KNOWLEDGE TO UNDERSTAND THE PERFORMANCE OF CEMENTITIOUS MATERIALS

Cement as well as concrete are man-made materials and as such, a knowledge of their chemical composition is very important for optimal performance in service. The chemical compositions of these artificial materials are so important that they are the basis for the production, classification, and selection of the materials for use.

The cement production process is an entirely chemical-based process which begins with the mining and crushing of limestone and other materials (calcium, silicon, aluminum, and iron oxides) to produce a specific size and composition of the crushed powder. This raw material mixture is then pre-heated in cyclones to save energy and begin the dissociation of calcium carbonate ($CaCO_3$) into calcium oxide (CaO) before being sent to the kiln [12]. The heating temperature in the kiln is kept constant at around 1200-1450°C, during which calcium silicates and aluminates (Ca_2SiO_4 and $CaAl_2O_4$) are formed. This chemistry produces clinker, which is subsequently transferred to silos where it is pulverized and combined with gypsum to regulate the setting time of the cement produced [12 – 14] The coagulating effect of gypsum can lead to poor dimensional stability and decreased strength when a high quantity (>5%) is mixed with the clinker in the kiln. On the other hand, when the quantity used is less than 3%, the retardation effect will be almost ineffective, thus making it necessary to specify an accepted range of around 3-5 wt.% of the cement composition.

Also, considering the effect of the milling temperature on the performance of the cement, it has been reported that the risk of producing a false setting cement can be reduced by any of the following: supplying the mill with a relatively cool clinker, recirculating cool air into the system or by using an internal water spray mechanism [15]. Considering the process enunciated above, one would realize that a sound knowledge of chemistry is essential to ensure that the performance of the product is as expected at all times. This is the same for other cementitious materials.

Portland cement is made up of four main crystalline components namely, Tricalcium silicate (Ca_3SiO_5), dicalcium silicate (Ca_2SiO_4), tricalcium aluminate ($Ca_3Al_2O_6$), and tetra calcium alumino ferrite ($Ca_4Al_2Fe_2O_{10}$) [16] The concentration of these compounds in different cement types determines performance-oriented properties like strength, sulphate resistance, low heat of hydration, hydrophobicity, and resistance to seawater. When the focus is on strength development, it is standard practice to add various secondary elements, such as fly ash, silica fume, and granulated slag to the cement composition. If sulphate resistance is the priority, the tricalcium aluminate (C_3A) content is limited to a maximum of 8%. Whereas the addition of saturated fatty acids to the gypsum and clinker mixture produces a cement that repels water and is typically difficult to mix [17 – 19]. To achieve all these reactions, a careful and thorough understanding of cement chemistry is necessary. Table 2 summarizes all the chemistry of cement right from production up to the hardened stage of 28 days, when water is added. The table underscore the relevant of knowledge of chemistry in understanding performance of cementitious materials.

The understanding of cement chemistry is also essential during the hydration process. When mixed with water, each of these substances reacts to produce extremely potent hydration products, such as calcium hydroxide $Ca(OH)_2(s)$ and calcium silicate hydrate (C–S–H) as shown in equation 1-2. These hydrates form the basis for the selection of the most suitable supplementary cementitious materials to complement the basic compositions of ordinary Portland cement (OPC). While C-S-H produced from the hydration of cement aids cement's strength development process, $Ca(OH)_2$ on the other hand is soluble and vulnerable to leaching. As a result of this, the pore structure of the cement-based material is increased thereby weakening the cement matrix and reducing the compressive strength.

Table 2: Summary of chemistry of cement at different stages of production and use

Stage	**Chemistry**	**Remarks**
Calcination	$CaCO_3 \longrightarrow CaO + CO_2$	Major source of carbon emission
Clinkering	$2CaO + SiO_2 \longrightarrow Ca_2SiO_4$	Dicalcium silicate (C_2S) is formed and represent 45 – 75% of mass of clinker
	$3CaO + SiO_2 \longrightarrow Ca_3SiO_5$	Tricalcium silicate (C_3S) is formed and represent 7 – 32% of mass of clinker
	$3CaO + Al_2O_3 \longrightarrow Ca_3Al_2O_6$	Tricalcium aluminate (C_3A) is formed and represent 0 – 13% of mass of clinker
	$4CaO + Al_2O_3 + Fe_2O_3 \longrightarrow Ca_4Al_2Fe_2O_{10}$	(Tricalcium aluminoferrite (C_4AF) is formed and represent 0 – 18% of mass of clinker
1st Day Hydration	$C_3A + 6H_2O \longrightarrow C_3A.6H_2O$	It is an exothermic reaction with release of about + 880 kJ/kg energy.
Early Setting	$C_3A + 3CaSO_4.2H_2O \longrightarrow C_3A.3CaSO_4.2H_2O$	To avoid early setting, gypsum is added
2 – 7 Days Hydration	$2C_3S + 6H_2O \longrightarrow C_3S_2 . 3H_2O + 3Ca(OH)_2$	Tobermonite gel is formed, which has high surface ares and high cementing property with release of energy of about + 500 kJ/kg
7 – 28 days of Hydration	$2C_2S + 4H_2O \longrightarrow C_3S_2 . 3H_2O + Ca(OH)_2$	Hardened material is formed with about 90% of strength achieved and released of + 250 kJ/kg energy

Furthermore, the weakened matrix allows the ingress of hazardous ions (SO_4^{2-} and Cl-) into the concrete, which initiates spalling and steel corrosion in reinforced concrete [20]. For this reason, the selection of silica (SiO_2) rich supplementary cementitious materials as a measure to reducing the quantity of hydrated $Ca(OH)_2$ and producing more C-S-H in the concrete mix, is a common practice among concrete experts to improve the durability, resistance to acidic and chloride attacks. The summarized chemistry of the reactions is shown in equation 3. Therefore, it is convenient to say that understanding the basic chemistry of cement and supplementary cementitious materials (SCMs) is very essential to fully grasp the relationship between the material's composition and performance.

$$Ca_3SiO_5 + H_2O \rightarrow C - S - H_{(S)} + Ca(OH)_{2\,(s)} \qquad (1)$$

$$Ca_2SiO_4 + H_2O \rightarrow C - S - H_{(S)} + Ca(OH)_{2\,(s)} \qquad (2)$$

$$xCa(OH)_2 + SiO_{2\,(s)} + 5H_2\,O \rightarrow 3CaO\,.2SiO_2\,.8H_2\,O \qquad (3)$$

MODERN CEMENT AND CLIMATE CHANGE

Recent studies have shown that the global cement sector is a significant source of industrial greenhouse gas emissions, accounting for around 5-7% of all anthropogenic global warming emissions [21 - 22]. With the current spate of emissions, it is believed that CO_2 emissions must be reduced by half before 2050, if the sustainable development goals on climate change must be achieved. This reverie is rather amusing, given that worldwide CO_2 emissions from cement plants have tripled in the last two decades and are still rising as at the time of writing, as shown in Figure 3; with countries like China, India and United States of America topping the list of main contributors to annual CO_2 emissions from cement industries.

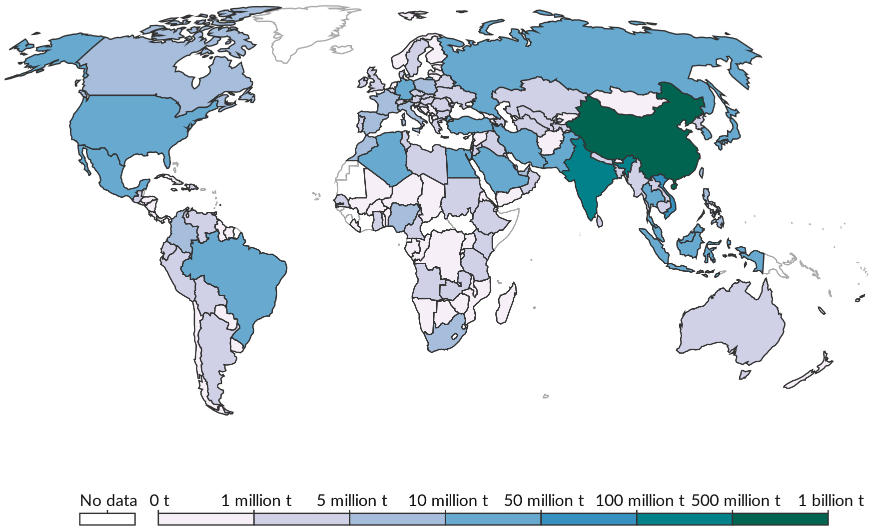

Figure 3: Annual emission of CO_2 by countries from 1880-2020 [23]

Given this trend and the exponential rate of the modern industrial revolution, CO_2 emissions from the global cement sector will be around 25 billion tons by 2050. What is more worrisome however, are some of the damages that this phenomenon will inflict on nature if not addressed [24 - 25]. Therefore, it becomes imperative for the modern cement industry to begin to adopt technologies and methods that promote carbon neutrality from the production of cement to its final drop in concrete elements. One recent discovery that has a strong potential to promote the decarbonization of cement is the use of biogenically manufactured limestone as a replacement for conventional limestone. This material is biologically produced from microalgae through photosynthesis [26].

Findings from a recent study have shown that if the current global demand for limestone could be met by biogenically generated limestone, the annual CO_2 emissions from cement and concrete manufacturing would be reduced by 2 gigatons.

The use of Graphene-based Nano Sheets (GNS) reinforcement has also been reported to be an effective method of addressing the environmental difficulties associated with cement and concrete production. According to Basquiroto de Souza et al [27], this is conceivable because of GNS's superior mechanical, permeability, and densification capabilities in the cement matrix. By using as little as 0.05% of GNS, concrete's mechanical and durability properties can be improved by as much as 80% and 500%, respectively, thereby resulting in a reduction in the demand for OPC in ordinary concrete. Furthermore, its exceptional electrical and thermal properties make it an excellent choice for use as a smart property inducing agent in concrete [28 - 29]. Considering its impressive performance, it is reported that if GNS could replace OPC by up to 50% while maintaining building loadings, this would result in a 0.45-tonne CO_2 reduction for every tonne of cement produced [27].

Another alternative with great potential for CO_2 reduction is the use of alkali-activated geopolymers as binders in concrete. These binders can outperform typical cementitious binders in a range of applications while producing significantly lesser amount of greenhouse gas. Furthermore, alkali-activated binders have been recognized for their excellent resistance to high temperatures and high thermal insulation, shorter curing period and increased durability in harsh environments [30 – 32].

NEW MATERIAL AND DEPLOYMENT OF KNOWLEDGE OF CHEMISTRY

It is evident from the discussion above that a thorough understanding of the production process as well as the chemical properties of cement is crucial to developing a sustainable solution to the carbon emission issue. As reported by Czigler et al. [33], improvement in operational advances can only reduce emissions by approximately 20% from their current levels. Therefore, if there is to be a considerable reduction in CO_2 from cement related activities by 2050, new line of technologies and alternative materials must be developed in order to achieve that goal. In addition to this, multidisciplinary approach among diverse specialists in the cement sector would also be beneficial as this will help to have a broader view of how to address the decarbonatization of cement across various disciplines. Furthermore, since a significant portion of the CO_2 produced at cement plants comes from the calcination of clinker, efforts should be made to develop smart cement factories by implementing Carbon Capture and Sequestration (CCS) systems on-site. As such, instead of releasing the potentially dangerous greenhouse gases into the atmosphere, the plants can self-capture the CO_2 and store it for use as biofuels, carbamate derivatives, carbonates, polycarbonates, and carboxylic acids, which are raw materials used in power generation, the paint industry, and pharmaceuticals [34 - 35] The clinker can also be substituted with other materials that have similar properties and lower carbon footprints.

On the part of the material, the successes recorded in the adoption of carbon-neutral materials like biogenically produced limestone, limestone calcined clay cement (LC3), alkali-activated geopolymers and rapidly evolving materials like graphene should be built on and scaled up for larger-scale implementation. Also, as shown in Figure 4 emphasis should be placed on the use of alternative building materials such as cross laminated timber (CLT) which has been reported to have high mechanical and temperature resistance and is capable of reducing the carbon footprint by nearly 25%, by simply using 10% of CLT as against cement-based structure [33].

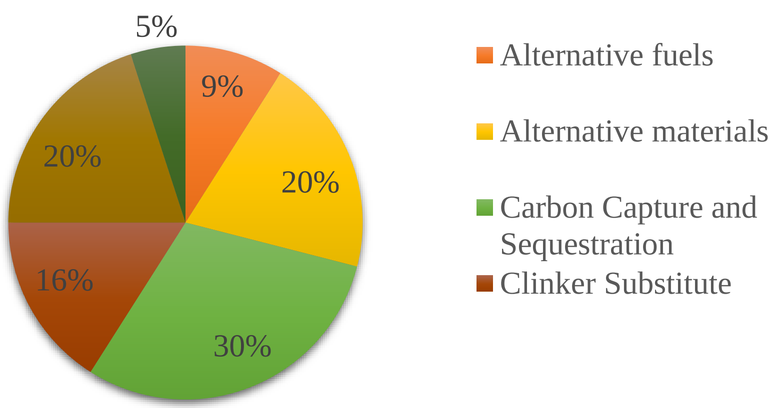

Figure 4: Projected reduction in CO_2 from cement industry as a result of innovative technologies by 2050 [35]

CONCLUSION

Cementitious material is an agelong material known in the history of man. The material is indispensable as there is need for binding loose earthen materials for building structures. Almost all the infrastructure needed for good livelihood needs cementitious material as one of its ingredients. Though the usage of the material in the early age was based on mere practice and experience as against understanding the science of performance. As the knowledge of chemistry of materials grew the principle behind the formation of artificial stone became clearer. Thereafter, scientist deployed the knowledge of chemistry to develop new cementitious materials that are less costly to the environment. Hence, knowledge of chemistry played and will continue to play crucial roles in furthering the understanding of cementitious materials.

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IDENTIFICATION OF UNSUCCESSFUL STUDENTS IN GENERAL CHEMISTRY

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ABSTRACT

The Networking for Science Advancement (NSA) team collected data from multiple general chemistry courses at nine universities within a broad geographic setting in a majority-minority US state. Data include diagnostic scores on the Math-Up Skills Test (MUST), quantitative literacy/quantitative reasoning (QL/QR) quiz, along with student demographics, and overall course grades. From these data the team determined how automaticity skills in procedural arithmetic and quantitative literacy and reasoning can be used to predict success in lower-division chemistry courses. By expanding this dataset, we extended our investigations to discover what characterizes successful and unsuccessful students in general chemistry, first and second semesters (Chem I and II) categorizing by on- and off-sequence courses. Student characteristics studied include factors such as ethnicity, gender, location of residence, and employment status. In a short amount of required classroom time (approximately 35 minutes is needed for students to complete both assessments and a demographic survey), it is possible to identify students at the start of the semester who will struggle in general chemistry. The MUST is the preferred predictor but using the MUST and QL/QR together enhances predictability. *[African Journal of Chemical Education—AJCE 13(2), June 2023]*

INTRODUCTION

The Republic of Texas was established in 1836 and became a state of the United States of American (USA) on December 29, 1845, serving under two flags, the Republic of Texas flag and the USA flag until February 19, 1845, Statehood Day. Texas has always been concerned about the education of our students. In fact, the second president of the Republic of Texas (1838–1841) Mirabeau B. Lamar is called the Texas Father of Education. His most famous quote is a "Cultivated mind is the guardian genius of democracy" and can be found on The University of Texas' seal as the motto *Disciplina Praesidium Civitatis*. By Egyptian standards, about 5000 years older, Texas still has a lot to learn. Even though Texas is the second largest US state by land mass (only Alaska is larger), Egypt is 44% larger and has 79M more people. Texas is one of five majority-minority states in the USA with a minority population of 40% Hispanics, 13% Black, and about 7% other minorities leaving about 40% classified as White, non-Hispanic. The area of Texas covered in the studies by the Texas Networking for Science Team (NSA) can be seen in Fig. 1. The area covered by the NSA investigations is over 45,000 mi^2 or about 117,000 km^2. Within this area, six New England states (Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island and Vermont) could be placed with almost as much land in Texas still remaining.

Figure 1. Location of Texas institutions within the red-boxed area that participated in the NSA team studies.

Given the wide variety of participating institutions across a broad and diverse ethnic and geographic setting, the research population provides a representative view of an even larger population lending credibility to the study that reflects beyond what is typically reported for a single institution. In this study, we focused on evaluating students in general chemistry I and II (Chem I and II) who were unsuccessful (grades of D and F) and those deemed successful (grades of A, B, and C). The study compared how struggling students' automaticity skills or what they can do without a calculator differs from those of successful students. Two instruments were used to evaluate students' automaticity: the MUST (Math-Up Skills Test) and a QL/QR quiz that investigated their quantitative literacy/quantitative reasoning abilities. To broaden the applicability of this study, students enrolled in on- and off-sequence courses in Chem I or II were investigated. Typically, Chem

I on- and Chem II off-sequence courses are offered in the fall semester and Chem II on- and Chem I off-sequence courses are offered in the spring semester.

Initial Results

The MUST was inspired by a 16-question (16-Q) quiz in a publication by [1]. Since then, the NSA team has added four questions (Qs) to the original version stressing the arithmetic associated with using fractions. The MUST instrument has been used in multiple studies resulting in 13 publications and one more submitted manuscript [2-15] where it has been shown to give consistent and repeatable results. The MUST assesses basic overlearned procedural arithmetic skills of students when they not allowed to use their calculators for this 15 min., open-ended quiz the first week of class. A copy of the MUST can be found in [14]. Correctly solving the MUST exercises requires students to not only know the basic operations (add, subtract, multiple and divide) but also to know the procedures needed to correctly solve the problems. The QL/QR assessment does not require a calculator to solve the exercises. It assesses the ability of students to read and understand questions that require data usually in the form of images (graph, chart, diagram, etc.) to answer the 20 multiple-choice questions [11]. Students' QL/QR skills in our data-driven world are becoming a more and more important factors in students' education. Results show a strong correlation between students' automaticity MUST skills and their QL/QR abilities (r = 0.60) [11]. Published MUST results for predicting success of at-risk Chem I students is around 78% [14] and for Chem II students is about

83% [10]. Adding the QL/QR as an additional diagnostic quiz improved our ability to identify potentially about 9% more at-risk students [11].

METHODOLOGY/EXPERIMENTAL

Instruments

The MUST assesses a student's ability to conduct basic mathematical operations including multiplication, division, square roots, fractions, logarithms/ exponents, and symbol manipulation without the use of a calculator and has consistently produced strong reliability ($r_{KR20} = 0.855$) and a very large effect size data (Cohen's $d > 1.2$). The KR-20 formula used to determine r follows, where k is the number of questions asked and p = percent correct, q = 1 − percent correct, and σ^2 is the standard deviation squared: $r_{KR20} = [k/(k-1)][1-(\Sigma pq/\sigma^2)]$.

The QL/QR quiz was specifically developed as an instrument where calculators would not be needed to answer the exercises. Many of the problems were selected from questions in Eric Gaze's database of questions (NSF DUE 1140562 project). The QL/QR assessment showed a medium effect size (Cohen's $d = 0.54$) and acceptable reliability of (KR-20 = 0.738). The exercises on the QL/QR consists of three distinct components: arithmetic, algebra, and problems with images. Analysis of these three components indicated that there is the existence of a very large effect size of problems with images on course averages ($d > 1.2$), but the overall effect size of the complete QL/QR is lower ($d > 1.6$) than that of the MUST on courses averages. When comparing the MUST and QL/QR scores, there is also a large effect size indicating that procedural arithmetic skills as measured by the MUST has a strong relationship to the skills needed to correctly solve the QL/QR exercises.

Participants

A population of n = 1,915 from nine institutions broken into subgroups based on their general chemistry enrollment status (on- and off-sequence) was evaluated: Chem I on (n = 735), Chem I off (n = 624), Chem II on (n = 381), and Chem II off (n = 175). The students attend public and private institutions, those located in small towns and metropolitan areas, and schools that are considered to be small (under 4,000 enrollees) to large (enrollment over 50,000). The lecture class enrollment ranged from around 30 to over 300 students. All students evaluated consented to participate in these IRB-approved studies. No constraints were dictated to any of the instructors at these schools; all were encouraged to teach the courses as deemed acceptable by their departments. Given the large number of students and the ethnic and geographic diversity, results are considered as more generalizable than results typically reported for a single institution.

See Table 1 for the demographic breakdown of this population students who did and did not succeed in Chem I and II. Table 1 is repeated (R) in terms of Table 1R to illustrate that students' course average, MUST and QL/QR means are aligned from high to low score averages. Also, in Table 1R, note that the percentage of unsuccessful students increased as their respective diagnostic scores decreased. Table 1R also points to the fact that the best students are those who are enrolled in Chem II on courses.

Table 1. Diagnostic course and quiz averages and numbers of unsuccessful students from these courses

Course	***n***	**Course Average (%) (*SD*)**	**MUST Mean (*SD*)**	**QL/QR Mean (*SD*)**	**Unsuccessful *n* (%)**
Chem I on	735	76.4 (15.9)	38.8 (24.3)	64.2 (17.0)	209 (28.4%)
Chem I off	624	69.0 (17.8)	34.6 (21.8)	59.6 (16.6)	263 (42.1%)
Chem II on	381	82.5 (12.6)	53.2 (24.8)	69.8 (17.0)	57 (15.0%)
Chem II off	175	64.3 (16.9)	30.1 (18.8)	59.4 (16.6)	116 (66.3%)
Overall	**1,915**	**74.1 (17.0)**	**39.5 (24.3)**	**63.4 (17.3)**	**645 (33.7%)**

Table 1R. Repeat of Table 1 to show align of course average and MUST and QL/QR means from high to low scores along with an increase of unsuccessful students as scores decrease

Course	***n***	**Course Average (%) (*SD*)**	**MUST Mean (*SD*)**	**QL/QR Mean (*SD*)**	**Unsuccessful *n* (%)**
Chem II on	381	82.5 (12.6)	53.2 (24.8)	69.8 (17.0)	57 (15.0%)
Chem I on	735	76.4 (15.9)	38.8 (24.3)	64.2 (17.0)	209 (28.4%)
Chem I off	624	69.0 (17.8)	34.6 (21.8)	59.6 (16.6)	263 (42.1%)
Chem II off	175	64.3 (16.9)	30.1 (18.8)	59.4 (16.6)	116 (66.3%)
Overall	**1,915**	**74.1 (17.0)**	**39.5 (24.3)**	**63.4 (17.3)**	**645 (33.7%)**

Of the 1,915 students, 645 students (33.7%) were not successful in their respective courses (Table 2). The score alignment found in the complete class (Table 1R) does not track to the subset of unsuccessful students where the trend no longer matches. All averages in Table 2 when compared to their corresponding entries in Table 1 are statistically lower ($p < 0.05$). Other demographic information gathered about students from a one-page, open-ended questionnaire includes whether or not students who lived on campus or not made a difference in their final course average and what impact did working have on students' course averages. Residence location did not make a difference but whether students did or did not work made a difference. The greatest negative effect on final course averages was due to working full time, but students who worked for only 10 h/week on campus had a slight positive grade boost. Females outperformed males in Chem I, but enrollees in Chem II on showed male students with higher course averages. For the most part, white non-Hispanics and Asians outperformed Hispanics and the other ethnicities.

Table 2. Diagnostic course and quiz averages for unsuccessful students

Course	***n***	**MUST Mean (*SD*)**	**QL/QR Mean (*SD*)**	**Course Average (%) (*SD*)**
Chem I on	209	26.8 (17.7)	56.4 (16.1)	56.7 (12.1)
Chem I off	263	27.6 (17.9)	55.2 (15.6)	52.7 (14.6)
Chem II on	57	32.2 (19.9)	62.0 (15.3)	61.1 (8.7)
Chem II off	116	26.3 (17.8)	56.4 (16.0)	55.4 (12.4)
Overall	**645**	**27.5 (28.0)**	**56.4 (15.9)**	**55.2 (13.2)**

RESULTS

Figs. 1 and 2 display charts for the MUST and QL/QR assessments, respectively. In all cases, the mean scores of each question on the MUST and QL/QR illustrate the same up and down patterns regardless of the class in which these unsuccessful students were enrolled (Chem I and II, on and off semesters). Considering that over 90% of these students attended a secondary school in Texas and were exposed to an isomorphic curriculum, it is noteworthy that they appear to hold similar misconceptions. In general, there is little observable difference between the diagnostic quiz's means of these unsuccessful students regardless of the course enrolled.

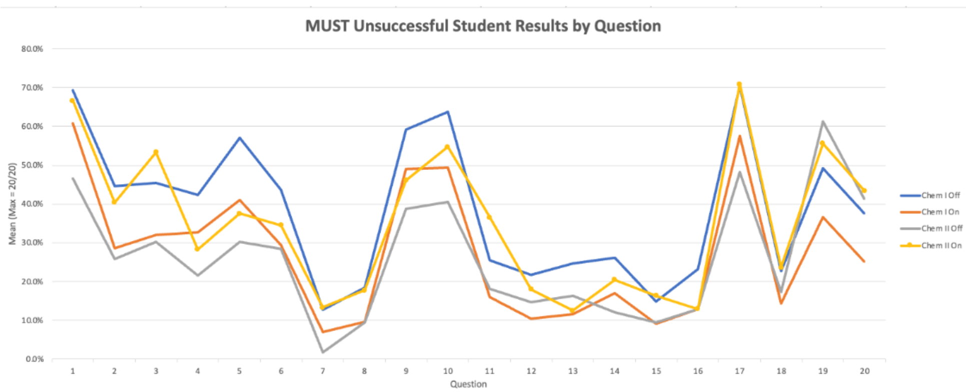

Figure 1. MUST exercises' means by question.

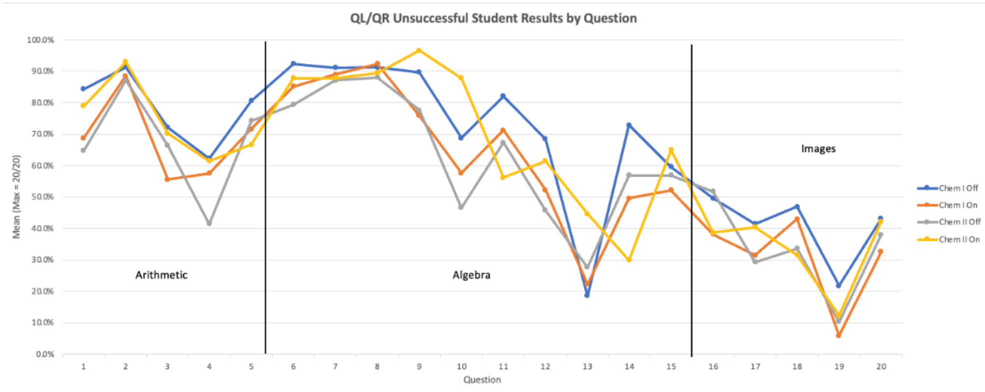

Figure 2. QL/QR exercises' means by question: questions (Qs) 1-6 assessed arithmetic, Qs 6-15 assessed algebra, and in Qs 16-20 used images (graphs, charts, diagrams, etc.) to solve the problems. In addition to the overall similar up and down pattern, there appears to be a downward trend of success from arithmetic exercises to problems that require the interpretation of images to be solved.

Another way to evaluate the data is to look the predictability of the MUST and QL/QR assessments using alluvial diagrams to display the results. The first task is to determine the middle score range for the MUST and QL/QR for each class. With the average known, subtract one-half the *SD* and add one-half the *SD* to that average. For example, if the average score is a 40% and the *SD* is 24, then the middle range is 40 – 12 = 28 and 40 + 12 = 52, resulting in a middle range of 28-52%; the under average range is for students who score below 28% and the above range is over 52%. See Table 3 for the categorial data (under, middle, above) for each course as to their MUST and QL/QR scores. Figs. 3-6 are the supporting alluvial diagrams for each course. Can students score in the above average range on the MUST and the QL/QR and still be unsuccessful in the course? Yes! Can students score under average on the MUST and the QL/QR and still be successful in the course? Yes! BUT the odds are against you. In Fig. 3 for Chem I on-sequence students, follow the blue river from the left side to the middle and note the much smaller percentage of students who scored above average on the MUST and were not successful. This flow is consistent in Figs. 4-6. The QL/QR does not produce as clear of picture until Fig. 6 where it is obvious that the students who were not successful were the ones who not only had under average MUST scores but also were the majority of the unsuccessful QL/QR students (note the purple and orange rivers).

Table 3. MUST and QL/QR score ranges for the alluvial diagrams

	MUST Ranges (%)			**QL/QR Ranges (%)**		
Course	**Under**	**Middle**	**Above**	**Under**	**Middle**	**Above**
Chem I On	< 26.7	26.7 – 51.0	> 51.0	< 55.7	55.7 – 72.7	> 72.7
Chem I Off	< 23.7	23.7 – 45.5	> 45.5	< 51.3	51.3 – 67.9	> 67.9
Chem II On	< 40.8	40.8 – 65.6	> 65.6	< 61.3	61.3 – 78.3	> 78.3
Chem II Off	< 20.7	20.7 – 39.5	> 39.5	< 51.1	51.1 – 67.7	> 67.7
Gen Chem	**< 27.4**	**27.4 – 51.7**	**> 51.7**	**< 54.8**	**54.8 – 72.0**	**> 72.0**

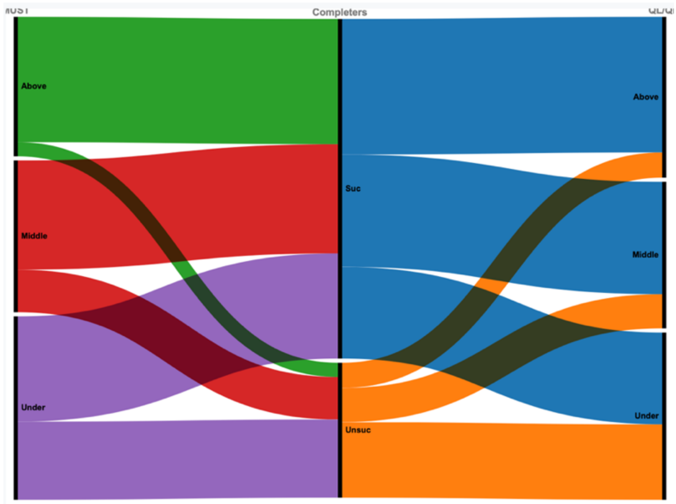

Figure 3**:** Alluvial diagram for Chem I on-sequence course. The MUST ranges are on the left-side bar and the QL/QR ranges are on the right-side bar. The center bar represents the blocks of students who were successful (Suc) and unsuccessful (Unsuc) in the course. Only a small percentage of these Unsuc students who entered with above average MUST scores were unsuccessful in the course (follow the green river from the left bar to the bottom of the center bar). A slightly greater percentage of the Suc students performed better on the QL/QR (blue river) than the MUST (green river). Over half of the Unsuc students scored under average on the MUST (purple river) and on the QL/QR (orange river). Source: https://www.rawgraphs.io/learning/how-to-make-an-alluvial-diagram

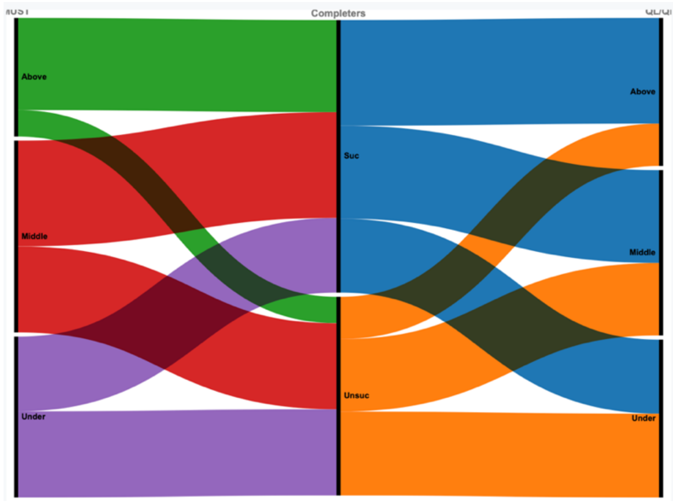

Figure 4: Alluvial diagram for Chem I off-sequence course. The MUST ranges are on the left-side bar and the QL/QR ranges are on the right-side bar. The center bar represents the blocks of students who were successful (Suc) and unsuccessful (Unsuc) in the course. For this group of students, the notable observation is that the students who were above on the MUST (green river) were more likely to succeed than not. Source: https://www.rawgraphs.io/learning/how-to-make-an-alluvial-diagram

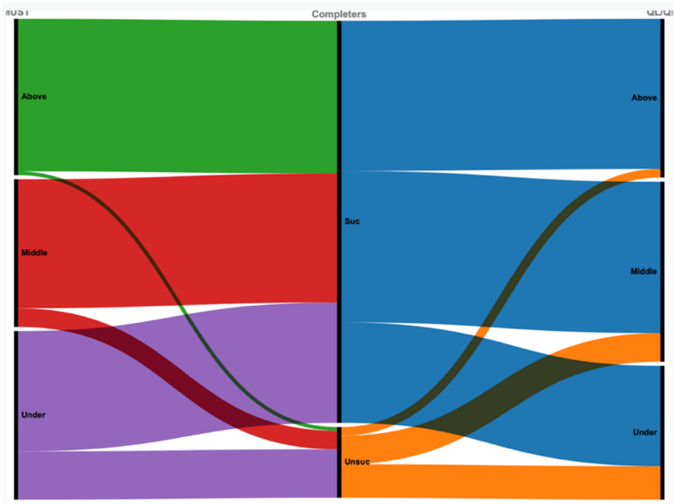

Figure 5: Alluvial diagram for Chem II on-sequence course. The MUST ranges are on the left-side bar and the QL/QR ranges are on the right-side bar. The center bar represents the blocks of students who were successful (Suc) and unsuccessful (Unsuc) in the course. Very few students who scored in the above average range on the MUST (green river) were Unsuc in the course and likewise with the students who performed well on the QL/QR (orange river). However, there was a significant percentage of students who scored under average on the MUST (purple river) and under average on the QL/QR (blue river) who succeeded in the course probably due to their improved background from successful completion of Chem I. Source: https://www.rawgraphs.io/learning/how-to-make-an-alluvial-diagram

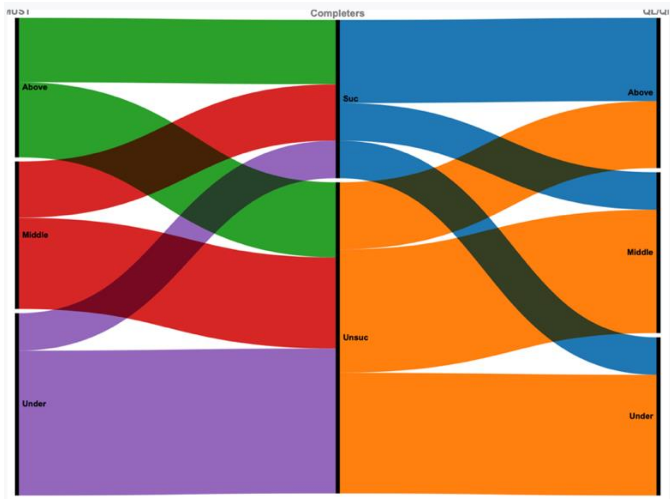

Figure 6: Alluvial diagram for Chem II off-sequence course. The MUST ranges are on the left-side bar and the QL/QR ranges are on the right-side bar. The center bar represents the blocks of students who were successful (Suc) and unsuccessful (Unsuc) in the course. There were more Unsuc students than Suc students in this course (center bar). About a quarter of the Unsuc students scored in the above average range on both the MUST (green river) and QL/QR (orange river). About half of the Unsuc students scored in the under average range on both diagnostics (purple and orange rivers). Source: https://www.rawgraphs.io/learning/how-to-make-an-alluvial-diagram

Research Question

To what extent are the data from the MUST and QL/QR diagnostic instruments statistically predictable of success in Chem I and Chem II, on- and off-sequence courses.

Data from this study were split into five pairs of unequal samples. The first sample consisted of a balanced random selection of Chem I students on and off sequence and Chem II students on and off sequence to ensure that both the training and validation samples contain balanced proportions from each student group. Students with missing data (one of the diagnostics not available) were deleted leaving three-fourths of a full sample as n = 1,303 used for the training model and the remaining one-fourth (n = 433) to be held out to test the accuracy of the model's prediction [16]. Table 4 list samples consisting of Chem I and II, on and off sequence divided into training and validation samples. The LASSO method is a regression analysis method that regularizes, smooths, and shrinks model covariates in an effort to find the set of model coefficients that optimize prediction accuracies in balance with predictive effects for subject covariate variables [16,17]. The linear model uses cross validation selection criteria to minimize the function's estimate of the mean square error (MSE). As a consequence, it selects the most parsimonious model with the largest out-of-sample explained variance. R^2 values between 0.3-0.5 are moderate correlations.

Table 4. Goodness of fit for linear and logistic LASSO regression predictive models

Model	*Sample*	*MSE*	R^2	*Observations*
LASSO Linear	Training	194.9540	0.3016	1,303
	Validation	220.6942	0.2943	433
MUST Only	Training	222.6510	0.2024	1,303
	Validation	244.0774	0.2195	433
QL/QR Only	Training	238.9954	0.1438	1,303
	Validation	273.5914	0.1251	433
Chem I On				
LASSO Linear	Training	168.0483	0.3398	500
	Validation	195.5938	0.2406	166
MUST Only				
	Training	193.5125	0.2398	500
	Validation	219.9153	0.1462	166
QL/QR Only				
	Training	211.3044	0.1699	500
	Validation	223.6718	0.1316	166
Chem I Off				
LASSO Linear	Training	256.5008	0.1620	431
	Validation	285.0799	0.1290	143
MUST Only				
	Training	273.8302	0.1054	431
	Validation	287.2640	0.1223	143
QL/QR Only				
	Training	284.628	0.0701	431
	Validation	306.5000	0.0636	143
Chem II On				
LASSO Linear	Training	111.7107	0.2708	258
	Validation	112.2044	0.2458	86
MUST Only				
	Training	113.1920	0.2611	258
	Validation	111.0082	0.2538	86
QL/QR Only				
	Training	137.3789	0.1032	258
	Validation	119.5837	0.1962	86
Chem II Off				
LASSO Linear	Training	262.0698	0.0498	114
	Validation	272.5452	0.0241	38
MUST Only				
	Training	253.1177	0.0823	114
	Validation	273.6034	0.0204	38
QL/QR Only				
	Training	266.9475	0.0322	114
	Validation	235.2931	0.1575	38

Derived from a post-selection model with un-penalized coefficients.

The process of finding the LASSO penalty parameter (*lambda*, λ) that minimizes MSE in linear regressions is visualized in Fig. 7. In the graph, the *y*-axis starts with the smallest MSE from a cross-validation function containing no coefficients. As the curve moves along the *x*-axis, the MSE is reduced as λ shrinks to the lowest penalty before the MSE increases. In Fig. 8 graph, the selection of λ corresponds directly to the number of covariates included in the predictive models and the strength of their coefficients. The MUST score is the first covariate selected and has the largest contribution to the prediction. The QL/QL (Fig. 8) however does not perform as well at scores lower than 30%, but it does become a better linear predictor above that.

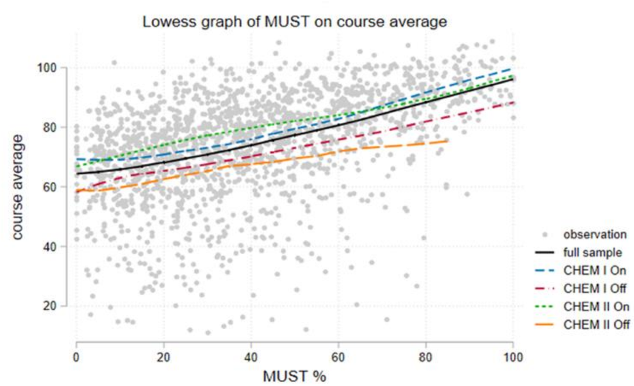

Figure 7. Course average vs. MUST percentage correct.

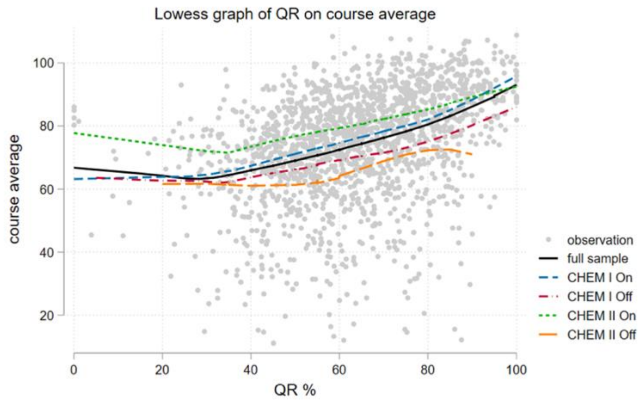

Figure 8. Course average vs. QL/QR percentage correct.

LASSO regression is not normally used for inference, but it is possible to select certain variables of interest to estimate the standard errors for the inputs. In this case the MUST and QL/QR scores are the variables of interest. Cross-fit partialing-out functions by splitting the sample and using one sample to calculate the LASSO linear regression coefficients in the second. To avoid bias several samples, in this case 10, are drawn and the results are averaged [17,18]. Table 5 presents the results from the full sample as well as the Chemistry I & II on- and off-sequence subsamples. MUST and QL/QR coefficients are directly comparable. In each sample, the MUST outperforms QR as a predictor, but the QL/QR still contributes to predictability of the final course averages.

Table 5. Cross-fit partialing-out LASSO linear regression coefficients

	Full Sample	Chem I On	Chem I Off	Chem II On	Chem II Off
MUST %	0.195***	0.217***	0.209***	0.189***	0.178*
	(0.0199)	(0.0283)	(0.0405)	(0.0295)	(0.0755)
QL/QR %	0.158***	0.196***	0.112*	0.107**	0.160
	(0.0260)	(0.0412)	(0.0551)	(0.0343)	(0.0960)
Observations	1736	666	574	344	152

Robust standard errors are in parentheses; $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

Fig. 9 use a lowess smoother to visualize the difference in explanatory power by removing the noise and creating a smooth line to help visualize the relationship between the variables influence on the course average. The MUST is a better predictor of course average having a consistently linear relationship across observations. This indicates that on average a student who performs poorly on the MUST will tend to have a lower course average and those who perform well will have higher course averages.

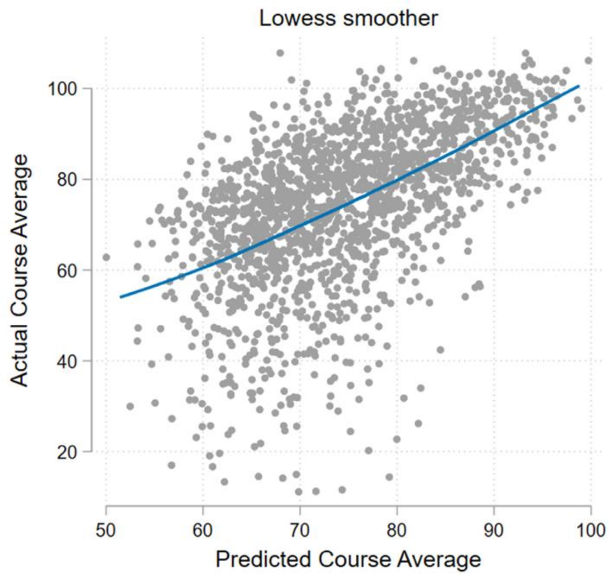

Figure 9**.** Actual vs. predicted course average showing a positive slope.

RESULTS AND DISCUSSION

Limitations

While the full sample is the most reliable model due to its sample size, most of the subsamples also work well in this case, except the Chem II off-sequence subsample whose estimates are likely not reliable (see Chem II off-sequence curved line in Fig. 8). This observation is consistent with Chem II off-sequence subsample being the lowest performing group overall and the group with the largest percentage of unsuccessful students (see Fig. 6). Reasons for students not succeeding are many from lack of academic preparation to emotional family situations. Without personal interviews this inquiry is not possible.

Conclusions

Rapid technological and social changes are creating a more interconnected world that is growing more diverse. We are preparing general chemistry students for global competence. Students' dependence on technology is hurting their quantitative literacy and reasoning abilities. Digital natives cannot make up for a lifetime of using technology, but can be provided opportunities in the classroom to solve some exercises without the calculator so that skills of estimating answers can be practiced.

Can you identify general chemistry students at the start of the semester who will struggle with the course? YES! If you can only give one diagnostic, the MUST is the better of the two diagnostic instruments (Fig. 10). Giving both MUST and QL/QR improves the chances of identifying about 10% more students who are at-risk of not succeeding in general chemistry. The more emphasis that is placed on QL/QR the better students will be prepared for this data-driven world. Chem II on-sequence students appear to be the best prepared to succeed. Using these students as the model, the more students' mental-math skills are honed, the more successful all students will be. Of the prepared students, 88.3% of Chem I on-sequence students and 90.5% of Chem II on-sequence students were successful. In this study, we drew inferences between procedural arithmetic and QL/QR skills from the results of two diagnostic instruments (Fig 10). Fig. 10 uses a concept map to illustrate how the diagnostic assessments' statistical values from Table 5 support the strong relationship between low scores on the assessments and failing to be successful in the course and vice versa. Using the MUST and the QL/QR diagnostics, about half of the students who are unsuccessful in Chem I and II present early warning signals that can be uncovered in a minimal amount of class time at the beginning of a semester.

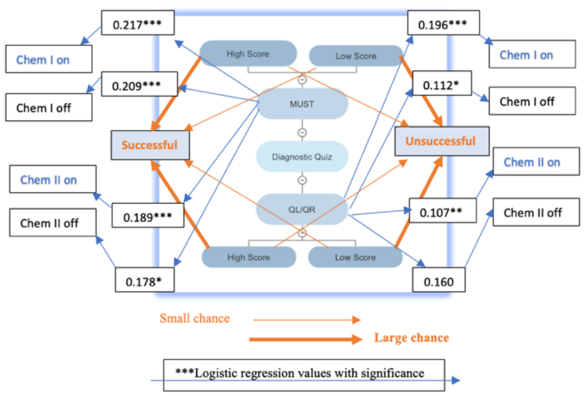

Figure 10. Concept map of LASSO linear regression coefficients on Chem 1 and II, on and off semesters.

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ACKNOWLEDGEMENTS

The authors thank all CER instructors for their participation in the Networking for Science Advancement team and their students who agreed to participate in these studies. Thank yous are also extended to the organizers of ACRICE 5 2022 for the invitation to share our data and results from the on-going research in Texas.

CHALLENGES AND OPPORTUNITIES IN CHEMISTRY EDUCATION - CULTIVATING MODELING AND SYSTEMS THINKING COMPETENCE

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ABSTRACT

Fostering students' modeling-based learning and systems thinking has been widely documented in areas of science education, in particular, in chemistry education. Students often learn scientific concepts in non-contextualized situations and with pieces of knowledge that appear as discrete knowledge of science. Making sense of science and using the knowledge and skills of science in practice have become a vital issue in school learning. This article will discuss the challenges we face in school teaching and learning and the opportunities and strategies that we can use to confront the challenges of cultivating students' scientific literacy. *[African Journal of Chemical Education—AJCE 13(2), June 2023]*

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INTRODUCTION

Scientists use models to represent their observation, thinking processes, as well as problem solving paths for developing hypothesis, theories, or generating descriptions and/or interpretations of a specific phenomenon. Scientist sometimes even make predictions of a scientific phenomenon when given necessary data based on the models they have built. Through constructing, assessing, and modifying internal or external representations, scientists contribute their knowledge to deepen the understanding of how science work in practice [1-4]. Scientists are not only aware of the potential of their models in shedding light on our understanding of the complexity of the scientific world and finding solutions for problems, but they are also aware of the limitations of models when available data and conditions are not robust enough to make generalization and prediction [5]. However, school teaching does not recognize the importance of model building and revision in science learning, students are not offered the opportunities to manipulate physical models or simulation to support their construction and revisions of models [1]. There is an emerging call in science education to cultivate students' literacy in models and modeling, and provide hands-on modeling opportunities. In such way, students will not learn chemistry as a collection of terminologies or discrete knowledge that have no clear impact on their lives.

More importantly, supporting students to recognize chemistry for the benefit of society and environment, systems thinking approach for chemistry education has been receiving increasing attention from researchers and practitioners in chemistry. These studies investigate how systems thinking in teaching and learning chemistry can be integrated (e.g., [6-8]) to emphasize the interdependence of components of dynamics systems and their interactions with other systems. In the 2011 review article titled "Key competencies in sustainability—a reference framework for academic program development" [9] synthesized a framework of sustainability-problem solving competence from existing literature, integrating five key competencies, namely, systems-thinking, anticipatory, normative, strategic, and interpersonal competence [10]. In their analysis of 272 publications between 1997-2020, they found that systems thinking is the most established competence in many projects. Thus, combining modeling-based learning with systems thinking sounds reasonable as both approaches aim for goal-oriented learning and treat science as a whole.

CHALLENGE 1: LACK OF UNDERSTANDING AND PRACTICE ON MODELING-BASED APPROACH

The modeling process is a process of developing physical objects or representations to describe, explain, and predict natural phenomena (e.g., [3, 11-14]). Through the modeling process, students can have an opportunity to build their own models, test their hypothesis, and collect data to support or refute hypothetical models of specific phenomena. Once their models are validated, the models can be applied on similar problems (near transfer) or used to understand or solve problems in other contexts (far transfer). However, if their models are inappropriate and invalid for explaining or predicting the scientific phenomenon, then they will have to revise their models based on the evidence collected and justify why and how the revisions are made. Sometimes, their "personal theories" of the mechanism of a phenomenon might need to be re-constructed completely to explain the data they have collected. To scientists, it might be called as scientific paradigm shift; for the students, it might imply a move toward a theory-like scientific model. The whole process of modeling intends to move students from concrete to abstract thinking, from single factor to multiple factors, and from individual components to relational connections of a scientific phenomenon. Thus, modeling practice is considered as a learning tool [14-15].

People's epistemological awareness about the purposes of modeling while conducting modeling activities has received quite a bit of attention in science learning (e.g., [16-19]). Researchers believe that the goal of modeling practices is to help students construct and evaluate knowledge as they engaged in learning activities. Thus, students' epistemological stances and epistemological awareness of model and modeling are related to how students develop and evaluate their models [20]. For example, [21] integrated previous research about students' epistemological awareness of model and modeling and stipulated the aspects of modeling competence in three levels (stances), that is, nature of models, multiple models, and testing models. Moreover, some researchers emphasized the criteria of good models from students' perspectives and provided the criteria for students to evaluate their model [22-23]. Emphasizing the discourse between a teacher and students in science learning and engaging students in modeling activities as a scientist are the core features of modeling practices (i.e., [24]). Thus, taking modeling practice as the epistemic practice not only moves research interests from students' epistemological beliefs to their engagement in epistemic practices [25] but also support students to consider modeling practices as a productive tool for understanding how the phenomenon operates [26].

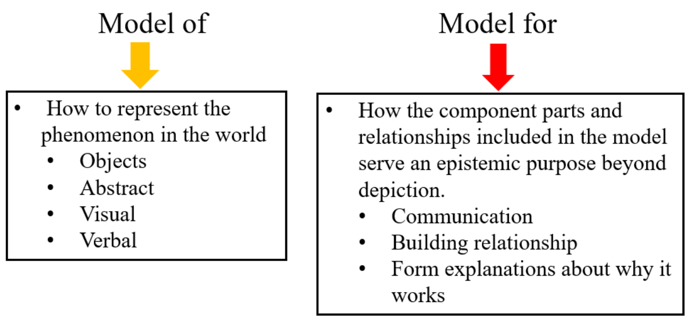
Many countries (e.g., Australia, Finland, Germany, Israel, Taiwan, and USA) are aware of the importance of developing students' understanding of nature of scientific models and modeling competence and included it in their K-12 curriculum standards/guidelines for sciences learning. Taking NGSS as an example, it stresses the role of models explicitly in each grade level, such as "creating a computational model to calculate the change in the energy of one component in a system when the change in energy of the other components(s) and energy flows in and out of the system are known for senior high schools (grades 9-12)" [27]. Building upon what the students already know from lower secondary school science and then moving toward advanced knowledge of science via modeling-based approach could support students to think of a scientific system as an interconnected model. As Next Generation Science Standards (NGSS) stated, engagement in modeling activities is critical in science learning. More importantly, students involving themselves in the practices of science bring themselves opportunities of appreciating the nature of science and developing better understanding of how any given practice contributes to the scientific enterprise. However, the problem is both students and teachers have limited understanding about what modeling is about, and what models' functions are in science learning and discoveries [1, 27].

To enhance students' competence in modeling practice, the emphasis on "*models for* shifts attention to how the component parts and relationships included in the model serve an epistemic purpose beyond depiction ([26], p. 51)" whereas the "models of" mainly on the representation of phenomenon or the reality. In other words, focusing more on the use of models for communication, the building of relationships among variables (components), the formation of explanations about why the phenomenon works, and the making of predictions of phenomena refer to *Model for* that is to "position students as responsible for knowledge construction and evaluation in science classrooms" ([26], p.57, See Figure 1). The *Model for* approach respects the epistemic purpose which we concur the essential nature of modeling practice needed in science learning.

To adopt a modeling-based approach, we conducted two types of activities, in chemistry classroom and in authentic context, to investigate its effectiveness on learning scientific concepts and developing modeling competence of secondary school students.

FIGURE 1.

The features of “model of” and “model for” (revised from [26])



OPPORTUNITY 1: PROMOTING MODELING-BASED ACTIVITIES

To support the development of meaningful understanding and generate explanatory models, it is important to engage students in purposeful knowledge construction work, to support students' making sense of scientific and systematic observation, to scaffold their descriptions and interpretation of phenomena with evidence, and finally, to use and revise models in science education classrooms [4, 15, 17, 24, 28, 29]. The unpacking of scientific theories into components and relations of a system is also crucial while conducting a modeling-based instruction. For instance, the Gas Law has five variables (pressure, volume, number of moles, temperature, and consistent figure) that form the PV=nRT formula, which shows their relationships in an ideal situation. Figure 2 shows how each factor relates to each other and how their relationships transform into a scientific theory.

Besides the simplified relations among variables depicted in Figure 2, [1] proposed a framework of modeling competence that includes three aspects, namely, models and modeling knowledge, practice (processes and products), and metacognitive knowledge of models and modeling. Each aspect has sub-categories describing the definition and scope of the aspect (See Figure 3). Among them, the details of the processes of modeling are described in Figure 4. Via the cyclic steps, namely developing, elaborating and evaluating, applying, and reconstructing models in the activities, students can learn about the roles models play in helping them understand the science phenomenon and how models function to achieve their goals in explaining and predicting the complex phenomenon. Below is a case using the modeling-based approach to introduce an electrical cell experiment and its concepts.

FIGURE 2.

The relationship of components and relations of a system (retrieve from: [50])

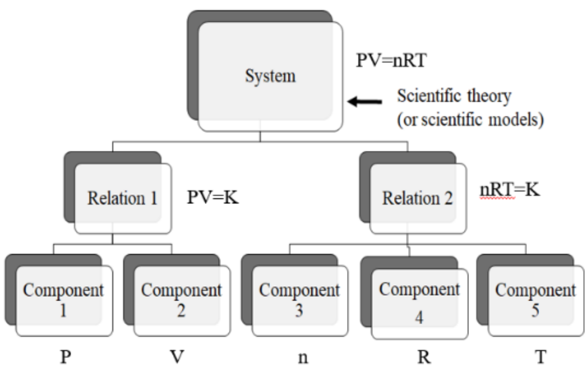


FIGURE 3

Framework of modeling competence (retrieve from: [1])

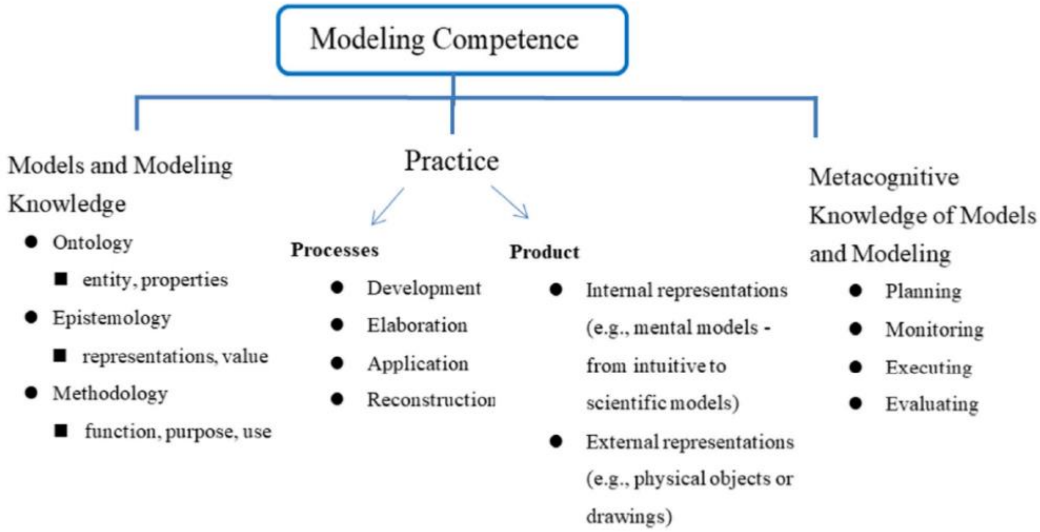
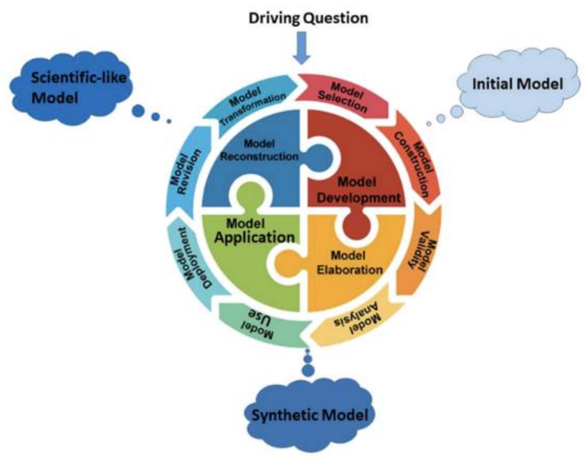


FIGURE 4

The DEAR cyclic model on modeling practice (retrieve from: [1])



CASE 1: MODELING-BASED CURRICULUM ON ELECTROCHEMICAL CELL WITH THE *DEAR* APPROACH

The Taiwanese curriculum guidelines on natural science have identified the electrochemical cell (EC) as a part of the learning content that should be introduced to students in middle school [41]. However, EC is a difficult topic for middle school students because of the abstract concepts and the dynamic processes, such as the direction of the electrons and the oxidation-reduction reaction [30-33]. Some research focuses on visualizing abstract concepts and the transformation among macroscopic, sub-microscopic, and symbolic representations [34]. Other research emphasizes the instruction guideline during students' learning activities, such as the inquiry-approach laboratory [35] and POE sequence [36]. Although substantial studies have been performed on the critical features (e.g., visualization and collaborative learning) that promote the understanding of science concepts, those of modeling-based approach are still critically lacking. EC is not only an integration of science concepts but also a productive model to explain or solve authentic problems, such as designing an EC with a higher voltage from a sustainability perspective [37]. Therefore, we should encourage students to develop, evaluate, and use their EC's model to make sense of the phenomenon.

We developed a four-week (8 lessons) modeling-based learning curriculum that involved a series of two unities about the EC. Each unity included hands-on activities (e.g., observing the phenomena and conducting the experiment) and minds-on activities (e.g., drawing the model and providing the explanation) to engage students in lessons. In addition, we designed the unities with the DEAR framework during learning activities and driving questions to address the compelling phenomenon.

Curriculum of the electrochemical cell

UNIT ONE: THE BASIC STRUCTURE AND PRINCIPLE OF THE ELECTROCHEMICAL CELL

The objective for unit one was to introduce the basic structure and principle of the EC in one week (two lessons). On the structure of EC, students can set up the electrochemical cell by understanding the components (e.g., electrode, electrolyte, salt bridge, and electric appliance) and their function in the EC, such as the Zinc pole being the negative pole and would release electrons. On the principle of the EC, students learned oxidation-reduction reactions and chemical reaction equations to explain how the electrochemical cell works from the microscopic perspective. Table 1 shows the design and the learning procedures of unit one.

During the model development stage, teachers guided students to select the components or models as prototypes to present their understanding of the phenomena via driving questions. As such, the teacher showed the fruit battery with the lighting LED and provided driving questions, such as why the LED would light up and what are the components of the fruit battery. To finalize the components of EC, teachers asked students to read the scientific history of the Galvanic cell and compare the components between the fruit battery and the Galvanic cell. After that, teachers demonstrated a Galvanic cell to show each component's function and the relationship between the components, such as the salt bridge connecting the two electrolytes with ions and the mass of the zinc pole decreases due to oxidation reaction.

Next, students would build a model of EC based on their experience, observation, or limited understanding. In the model evaluation stage, students can validate their model via a reliable resource or scientific principle, such as conducting an experiment to collect new data. In unity one, students read the textbook and manipulated the simulation to verify the prototype model. Students then drew the model from the microscopic perspective, and applied the principle of EC (e.g., the oxidation-reduction reactions and the flow of particles) to confirm the function and relationship of the components. For example, Zinc is more active than Copper (oxidation-reduction reaction), so the Zinc pole would release electrons to the Copper pole via the external circuit. Then, the Copper ion would accept the electrons and reduce to Copper. To balance the concentration of the ions in the EC, the positive and negative ions will move to the different electrolytes (the flow of particles).

Lastly, students applied the validated model to illustrate, explain or predict new phenomena in the model application stage. We asked students to explain why the fruit battery can provide power to light LEDs and which components are missing in the fruit battery. Some students would apply the original model and construct a mechanistic explanation. Others would find the salt bridge missing in the fruit battery and adjust the EC model to fit the new phenomena.

UNIT TWO: THE INTERACTION EFFECT OF THE CHEMICALS IN THE ELECTROCHEMICAL CELL

The learning tasks for unit two were twofold: (1) students would build a useful EC model via the experimental apparatus such as a beaker, U-tube, and wire. (2) Students would conduct the laboratory experiment to manipulate the concentration of electrolyte or the type of electrode and adjust the voltage of EC to find the interaction effect of the chemicals in the electrochemical cell. Take the Zn-Cu cell as an example, the higher the concentration of $CuSO_4$, the higher the voltage of the EC would be (Le Chatelier principle). Moreover, when students replace the Zinc pole with a Nickel pole, the voltage would decrease (oxidation-reduction reaction). We provided an explicit modeling process in the textbook and guided students with model-oriented prompts in unit two for over three weeks (6 lessons). For instance, we prompted students to justify their model with evidence, connect their model with the scientific principle, and ask students to present their model to other students.

At the beginning of the learning activities, students built concrete and functional ECs using the experimental apparatus based on their experiences and prior knowledge in the model development stage. Before students manipulated the factors (e.g., the concentration of electrolyte or the type of the electrode) to change the voltage, they predicted the outcome of the change and showed the value of the evidence via prompts (e.g., what evidence would support your model, or how would you get the evidence). Thus, students would reflect on the purpose of modeling practices as they shared their ideas with their peers.

In the model elaboration stage, students were asked to compare their experimental data with the theoretical data and validate the model with the scientific principle to validate their initial model. Then, they interpreted the information to confirm the causality about voltage. Teachers would ask students to justify their model, such as by asking “Do your data fit with the theoretical data and can you explain the relationships with the scientific principle?”

After that, students applied their understanding of the ES to explain the way of battery storage and draw the EC model on the whiteboard after a group discussion in the model application stage. Then, students shared their EC model and explanation during the whole class discussion. Teachers guided the students to integrate all the factors and built a consensus model based on other students' or teachers' suggestions. In other words, students validated their EC model based on their peers' ideas in the last learning activities.

TABLE 1

Modeling-based learning curriculum of the electrochemical cell in middle school

Lessons	Learning content	DEAR stages	Learning actives
Unit one: The basic structure and principle of the electrochemical cell			
Lesson 1	The components of the EC	D	Students *observe* the fruit battery to identify the components of EC.
	The function of the components	D	*Teachers demonstrate* the Galvanic cell, and students *reorganize* the prototype model into the initial model.
Lesson 2	The relationships among the components	D	
	The redox reaction and the flow of particles	E	*Students* read the textbook and manipulate the simulation to *validate* the initial model.
		A	*Students* apply the validated model to *explain* the new phenomena.
Unit two: The interaction effect of the chemicals in the electrochemical cell			
Lessons 1-2	The components of the EC	D	*Students* designed the experimental procedure and choose the martials.
Lessons 3-4	The factors affecting voltage	E	*Students* conducted *one of investigations, compared* the experimental data with the theoretical data and *validated* the model with the scientific theory.
Lessons 5-6	The redox reaction and Le Chatelier principle	A	*Each* group presented their explanation *with drawing* on the whiteboard.
		E	The teacher guides the students to build the *consensus model* based on peers' ideas.

Finding

Considering the different participants in units one and two, we used different statistical methods to examine the effectiveness of the MBL. In unit one, the paired *t-test* was conducted to evaluate students' conceptual understanding after MBL, and the scores of students' overall performance were significantly improved between the pretest (M = 25.67, SD = 7.25) and posttest (M = 67.27, SD =12.92) with the p < .001. Also, as shown in Table X, the results of the paired t-test showed the significant effect of the component t (23) = 13.40, $p < .001$, relationship t (23) = 7.32, $p < .001$, and system t (23) = 11.28, $p < .001$.

In unit two, we used the Wilcoxon signed-rank test to compare the pretest and posttest scores of the MBL. As shown in Table 2, the students demonstrated a significant difference between the overall means of the pretest and posttest ($M_{pretest}$ = 56.80, SD = 10.41, and $M_{posttest}$ = 71.84, SD = 13.01, Z = − 2.93, p = .003). Moreover, the categories of component and system significantly improved in the posttest (component: Z = − 2.32, p = .021; system: Z = − 2.94, p = .003). However, the category of relationship showed no significant improvement in the posttest (Z = − 0.21, p = .831). Those results suggest that students' understanding of electrochemical cells can improve via explicit modeling during modeling-based learning, especially in the categories of component and system.

TABLE 2

The Results of Unit One and Two of Students' Conceptual Understanding

	Pretest		Posttest			
Conceptual understanding	*M*	*SD*	*M*	*SD*	*t*	*p*
Unit one (*n* = 24)						
Overall	25.67	7.25	67.27	12.97	14.65	<.001
Component	14.73	5.63	36.17	4.32	13.40	<.001
Relationship	7.98	4.01	20.83	6.28	7.32	<.001
System	2.96	2.15	14.27	4.56	11.28	<.001
	Pretest		Posttest			
Conceptual understanding	*M*	*SD*	*M*	*SD*	*Z*	*p*
Unit two (*n* = 11)						
Overall	56.80	10.41	71.84	13.01	− 2.93	.003
Component	13.71	1.33	14.79	0.16	− 2.32	.021
Relationship	16.02	6.39	16.14	6.36	− 0.21	.831
System	27.07	6.77	40.91	8.68	− 2.94	.003

CHALLENGE 2: HOW TO MAKE SENSE OF SCIENCE KNOWLEDGE THROUGH AUTHENTIC LEARNING

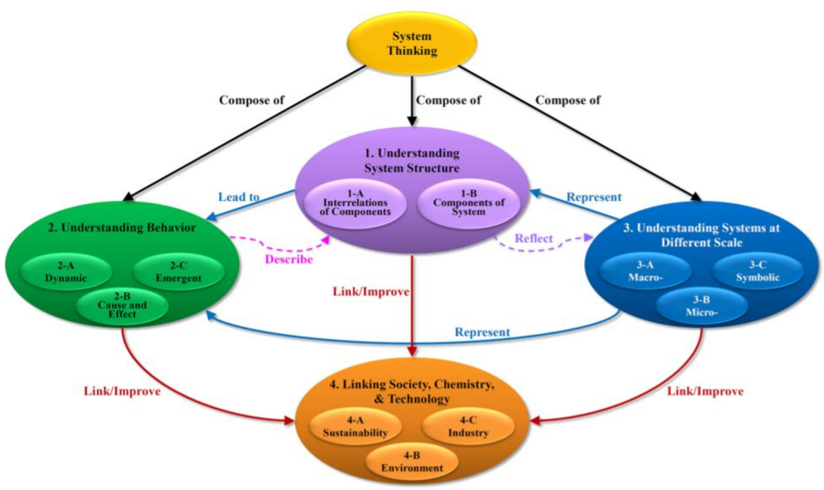
Based upon [38]'s analysis on PISA, they found that countries like Finland, Taiwan, Japan, Korea, and Germany, performed below OECD's average score on general interest in science, ways scientists design experiment, and what is required for scientific explanations, while the USA and Tunisia outperformed on these three aspects. Similarly, 15 years-old students from Japan, Korea, Taiwan expressed low agreement on "I generally have fun when I am learning science topics", "I am interested in learning science", and "I am happy doing science problem" and even below or barely equal to OECD average scores while students from Tunisia experienced enjoyment of learning sciences compared to the other countries. Their index of enjoyment of science (87, 91, 76 respectively for the statements addressed above) was much higher than the other countries' (OECD average score was 63, 63, and 43 respectively). How can we support students' performance in learning science while also developing their interest and motivation to learning sciences? How can we move students from factual knowledge learning to meaningful learning in science?

As models and modeling are considered integral parts of scientific literacy, educators need to introduce and engage students in authentic scientific inquiry. The goal-oriented approach in practice allows students to conceptualize why they are engaged in scientific activities and moves them from "doing the lesson" to "doing science".

In addition, according to NGSS, Crosscutting Concepts [CCCs] were identified, such as composition and property, cause and effect, systems, system models, energy, function, change, and interactions. Taiwan shares similar focus on the curriculum standards, moving science learning from reductionism to holistic, from disconnected/fragmented knowledge to linkage to their daily life. [39] advocated that the need of systems thinking is necessary to help students to understand system structure of a phenomena, to understand systems at different scales, to understand how "agent" behaves, and how knowledge of chemistry and technology with society are linked to make the world more sustainable (see Figure 4).

FIGURE 5

Framework of systems thinking (retrieve from: [39])



OPPORTUNITY 2: PROMOTING SYSTEMS THINKING APPROACH IN SECONDARY SCHOOL SCIENCE PRACTICE

Case 2. Authentic learning: Investigation of River Water Quality via Systems Thinking

Earth's surface is mainly covered by water, accounting for 75% of its total area. This precious resource is crucial in sustaining both human and ecological systems because it supports an extensive range of flora and fauna populations and their interactions with their surroundings. However, the availability of water for human consumption is limited (about 0.1%). Therefore, the United Nations [40] emphasized the availability and sustainable management of water for all people and identified clean water and sanitation as Sustainable Development Goals (SDGs).

The quality of water is a crucial issue in public healthcare and relates to the chemical, physical, and biological characteristics of water. Thus, building water quality models would require a holistic approach that would consider different situations in the complex system. Based on the requirement of science standards [41], we developed a curriculum about river water quality via modeling-based learning. In addition, we used the driving question (What is the quality of water in Keelung River that is near our school?) to guide students to engage in the learning activities. We also prompted students to consider water quality as a complex system by asking questions such as what are the factors that would influence water quality (structure), why did the fish in the Keelung River suddenly die in summer (behavior) and is it appropriate to use the death of aquatic biota to determine the quality of water (scale). Finally, to link the community to the environment, we organized a field trip to investigate the water quality of Keelung River and discussed the sustainable development of water resources.

Curriculum design

MODEL DEVELOPMENT STAGE

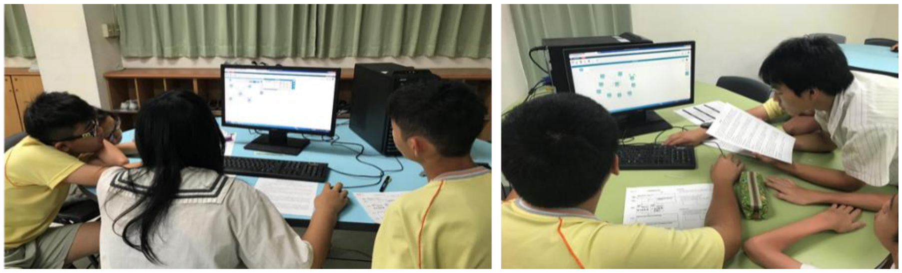
Water quality is a measure of how suitable water is for a particular use, such as drinking, or supporting aquatic life. The specific criteria for determining water quality would depend on the intended use of the water and the environmental regulations in place. Therefore, students should consider the specific situation to choose the factors of the water quality via the learning materials (e.g., news reports and popular scientific articles) and construct the model of water quality on SageModeler.

Scenario 1: Select the factors of the water quality. To engage students in learning activities, the teacher played news reports about a large number of fish that suddenly died in Keelung River near the students' community. Then, teachers posed the driving question to the students and asked students work in groups to provide several probable factors. For example, students believed that the death of the fish was caused by an increase in the temperature which decreased the amount of dissolved oxygen in the river. Students also suggested that eutrophication may have also caused the fishes' death because they smelled the stink when they walked by Keelung River. Looking at the students' responses, it is clear that these probable factors are based on students' life experiences and prior knowledge. Thus, the driving question would generate the connection between students and the social community.

Scenario 2: Develop a water quality model. Considering the students' understanding of the water quality, the teacher provided a popular scientific article that showed the measurement of water quality in the 20th century. After reading the article, some students agreed that the scientists used the type and population of aquatic species to determine the water quality. Others considered that the population of oysters is not the appropriate reference for water quality in this investigation because there are no oysters in Keelung River. The teacher prompted students: "if you are a scientist in the 21st century, how would you decide?" and encouraged students to share their ideas. Finally, students organized the factors of water quality based on their life experiences, prior knowledge, and the popular scientific article. As shown in Figure 6, students groups used a computational modeling tool called SageModeler (https://sagemodeler.concord.org) to present their model of water quality.

FIGURE 6

Student groups developed the model of water quality via SageModeler



Model elaboration stage

The measurement of water quality has improved significantly over time, and the parameters tested have expanded to include a wider range of contaminants. However, we could not replicate the entire experiment with all the indexes of water quality due to the limited experimental instruments available and limited scientific understanding among students. Therefore, students used popular science publications and a credible data source to validate their initial model. Then, the teacher and students went on a field trip to investigate the water quality of Keelung River.

Scenario 1: Validating the initial model. After students have shared their model, the conversation between the teacher and the students as follows.

Teacher: Do you need any tools to identify the factor?

Students: We can use the thermometer and the pH meter to measure the temperature and acidity of water.

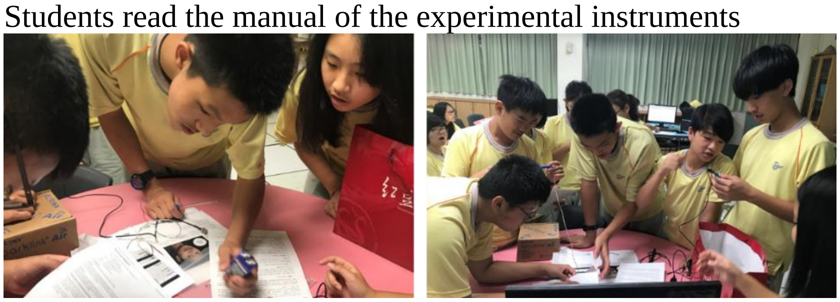
The teacher (agreed with this idea): How about the biochemical oxygen demand, conductivity, and turbidity shown in your model?

Considering the limited experimental instruments and scientific concepts, students obtained the tools and the tools' manuals. In this way, students learned the operational process of the tools and understood the scientific concepts of the specific factors (Figure 7). Then, students revised their model based on this investigation.

Meanwhile, the teacher asked students to justify their model: "How would you prove that your model can work?". Although the students' models were constructed based on scientific articles, it should be validated by various empirical resources. The Taipei environmental quality network (https://www.tldep.gov.taipei/EIACEP_EN/) provided the water quality index of the river and allowed individuals to download the data resources. Therefore, to validate their model, students could import the data into SageModeler to show the relationship among factors.

FIGURE 7

Students read the manual of the experimental instruments



Scenario 2: Conducting the field trip. To engage students in the field trip, the teacher planned to stop by seven sampling sites and organized the students into small groups (three or four students each). Before going on the field trip, each student was assigned a task (e.g., setting up the experimental instruments, collecting the sample, recording the data, and restoring the environment) (Figure 8.1 & 8.2) and made a device to test the water (Figure 8.2). In addition, students asked a person who was fishing near the sampling site, "Would you eat those fish?" to which the person responded, "No, many factories released wastewater upstream years ago. Even though the water quality is better now, I never eat these fish." It was an unexpected conversation between students and local residents and showed the value of the field trip. Finally, students uploaded and shared their data with their classmates.

FIGURE 8

Students recorded the data (3.1) and collected the sample (3.2)

(1) (2)

Model application stage

The water quality of Keelung River is pretty good and complies with regulations in Taiwan. Therefore, students did not only judge the water quality of the Keelung River via the model but also stated the reasons based on evidence, such as why they believed the water quality was good and which factors, they would add to the next field trip.

Scenario 1: Interpreting the data. All the students agreed that the water quality was good and provided sufficient evidence to support their claim based on the data collected from the field trip.

Teacher: Which factors would you add to the next field trip?

Student A: We deleted the type and population of aquatic species as the factors initially because we believed that the type and population of aquatic species are inaccurate. However, after this field trip, we think we can observe the population of aquatic plants as a factor because it is can be an indicator of eutrophication.

Student B: The fisherman mentioned the issue of industrial wastewater, and we should add the indicator of heavy metal.

Based on their field trip experience, students realized that there are many more factors at play when it comes to the maintenance of water quality.

Scenario 2: Reflecting on the sustainable development of water resources. From the system and system thinking perspective, the teacher guided students to see water quality as a system and understand the behavior, structure, and scale of water quality. In addition, the teacher introduced the Taipei environmental quality network to show how technology may support the government in managing water quality. In short, the field trip not only engaged students in the investigation but also provided more opportunities for students to reacquaint themselves with their community.

Findings

THE DEAR FRAMEWORK IS THE SCAFFOLD THAT SUPPORTED STUDENTS IN FIGURING OUT THE WATER QUALITY SYSTEM VIA MODELING PRACTICES.

The teacher used the DEAR framework as the scaffold to encourage students to participate in the learning activities. Moreover, the teacher posed the prompts to engage students in system thinking as they develop and use the water quality model. As Table 3 shows, the teacher provided the news article to provide facts (or behavior) about the water quality system and prompted students with questions like "What are the factors causing the death of fish?" in the model development stage. Students would identify the factors of the water quality system based on the facts (or behavior) of the system. In other words, the teacher supported students in describing the system structure based on the behavior of the system that indicated the features of system thinking (Table 3). From the system and systems thinking perspective, students considered the features of systems thinking and made the connection among those features in the model development and elaboration stages. After their field trip, students revised their model to link it to their community in the model application stage. Overall, the modeling practice is a teaching strategy that supports students in constructing concrete models from the system perspective.

TABLE 3

The Features of System Thinking in the Curriculum

DEAR stages	Teacher’s prompt	Features of system thinking
D	What are the factors causing the death of the fish?	Students described the *system structure* based on the *behavior of system*
	If you are a scientist in the 21st century, how to make a decision?	Structure shows the *behavior of system* based on the *scales of system*
E	Do you need any tools to detect the factor?	Structure shows the *system structure* based on the *scales of system*
	How would you prove that your model can work?	Students stated that the *system structure* would cause the *system's behavior* to change.
A	Which factors would you add to the next field trip?	Students revised the water quality system to *link to society*.

STUDENTS PERFORMED WELL ON INVESTIGATION PLANNING AND WERE HIGHLY MOTIVATED

We examined students’ competence in planning the investigation after the field trip, such as determining the quality of the seawater. In the study, students followed all the steps of the research processes and provided details of their purpose in each step (see Figure 9). Then, students used the computational modeling tool (SageModeler) to analyze the data and presented the relationship among the factors (system). In addition, students considered the various factors from a different perspective, such as environmental (green), physical (blue), and biological (orange) characteristics of seawater (see Figure 10). It is clear from the field trip that modeling-based learning can promote students' inquiry competence and provide students with more opportunities to practice system thinking.

Finally, most students showed high learning motivation and positive attitude toward the water quality curriculum. This result showed that middle school students can engage in complex problem-solving procedure and conduct investigations to make sense of the phenomenon from a systems perspective. Thus, curriculum designers and teachers should provide students with more opportunities to figure out the phenomenon and provide students with sufficient resources (e.g., learning scaffoldings and materials) to accomplish their learning goal.

FIGURE 9

Students' performance on planning the investigation

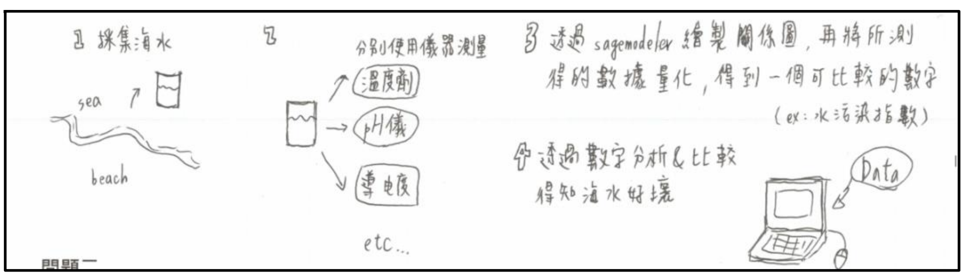
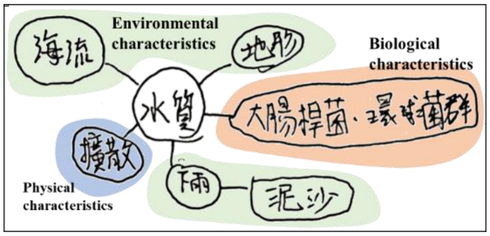


FIGURE 10

Students' model on the quality of seawater



CONCLUDING REMARKS AND IMPLICATIONS

Science teaching and learning have long been focusing on science content knowledge in the past. How systems thinking and reasoning through underlying factors and relationships of a specific and complex scientific phenomenon need to be emphasized in school learning [42]. Making linkages of such connections to a phenomenon would allow students to see the gaps or inconsistencies of their understanding and push them to identify additional or unrelated factors or relationships for the phenomenon [42]. Modeling practice also requires students to link factors of a specific phenomenon and develop appropriate models to describe, explain, or predict the phenomenon that is composed of various factors and relationships. Both share similarities of engaging students in active learning and being willing to self-regulate their construction and revision of their understanding of the interconnected knowledge of the science phenomenon.

From the cases, there are three facets that need to be highlighted.

Implementing modeling-based curriculum

Creating a modeling-based learning environment and curriculum, from designing and evaluating models to applying and reconstructing models, is not commonly integrated in school science [43-44]. In this article, the effectiveness of modeling-based activities has been evident from the data collected on our students' performance on content knowledge and their modeling competence in terms of their understanding of factors, relationships, and systems. We believe prompting students' understanding in an authentic context (Keelung River) and supporting their activities on understanding the relations of a system via questions like "*For what purpose, did you develop the model for Keelung River?*" proposed by [45] are promising. The questions can lead students to reflect upon what we have found and what might need to be reemphasized in future studies.

Although some researchers do not consider having sufficient content knowledge as necessary for conducting experiments, the authors believe that having basic knowledge and skills for conducting a meaningful science activity is a fundamental requirement. To reduce the burden of students, unpacking modeling-based tasks and being familiar with processes of modeling should be emphasized in teacher professional development. We were aware that epistemic practice approach was implicitly included in this study to make modeling-based approach more powerful and meaningful to both teachers and students. Future studies should explicitly take epistemic considerations into consideration when designing the curriculum [24].

Systems thinking as an instructional and learning tool

Helping students to understand the content knowledge and experimental skills of chemistry is important in school chemistry practice. More importantly, guiding students to recognize chemistry's contribution to sustainability and to embrace the integration of different scientific disciplines for keeping the Earth clean are critical to chemistry education. Researchers have a consensus about the nature of Systems Thinking, where a system is considered as a whole, not just a collection of parts [46]. In our study, we took students on a field trip to investigate Keelung River's water quality. The river was close to the school and the topic is highly relevant to their lives. Involving students in such an authentic activity and bringing their attention to how their chemistry knowledge and inquiry skills can be linked in learning about their environment is both appealing to students and helpful to student learning.

Teachers' competence on modeling-based approach

Finding an appropriate topic related to students' daily life and adopting modeling-based approach in the curriculum are still not widely implemented [19, 47. 48]. This might be due to teachers' lack of knowledge and experience in conducting modeling-based activities. Moreover, teachers also lacked sufficient knowledge and experiences about modeling-based approach [49].

Finally, we would like to use the following proverb proposed by Xun Zi (a Chinese philosopher, 316-235 or 237 B.C.) to highlight the importance of hands-on, minds-on, and engagement in science learning.

I hear I forget (Tell me and I will forget)
I see I remember (Show me and I will remember)
I do I understand (Involve me and I will understand) **(Xun Zi)**

Limitations

Although this study has shown that the students' performances significantly improved in understanding scientific principles and the holistic consideration with systems thinking via MBL, it was unclear whether or not the effect can last a long period of time. A longitudinal study should be carried out. Meanwhile, we noticed that it was a challenge for students to conduct this complex experiment because of the multiple variables were involved. To enhance students' competence on conducting such an experiment, we might need to train the teachers to unpack the task to small tasks so the students can achieve the learning goals gradually. Furthermore, we did not collect the discourse among the teacher and students to understand how the teacher guided the students to complete their tasks and how the teacher promoted the students to develop systems thinking of the phenomenon, there is a need to design research method to collect such data in order to balance the effectiveness and efficiency of MBL

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