Human Behavior, Development and Society
ISSN 2651-1762, Vol 21 No 1, March 2020

The Effects of Using Particulate Diagrams on High School Students' Conceptual Understanding of Stoichiometry

Faridah Lausin[1] and Jimmy Kijai, Asia-Pacific International University

Date Received: 6 November 2019 Revised: 16 February 2020 Accepted: 19 February 2020

Abstract

The lack of a conceptual understanding of stoichiometry among high school students is a valid concern because it impedes students' problem-solving ability, which is a significant predictor of performance in college chemistry. In this study the effects of a visual-based pedagogical approach was investigated on the understanding of four concepts of stoichiometry among tenth-grade chemistry students at an international high school in Thailand. The approach involves the systematic use of particulate diagrams in the instruction of stoichiometry in a real classroom setting. The study further examined the attitudes of the students towards the approach. Conducted using a one-group pre-test/post-test design, data for the study were collected using a conceptual stoichiometry test and an attitude questionnaire. Analyses of the test data indicated that the approach had a significantly positive effect on the students' conceptual understanding of stoichiometry, and they generally had a favorable attitude towards it.

Keywords: *Stoichiometry, conceptual understanding, particulate diagrams, pedagogical model*

Introduction

Stoichiometry problem-solving can pose challenges to high school chemistry students. From an analysis of student responses at Adventist International Mission School (AIMS), Muak Lek, Thailand to a variety of stoichiometric questions, it was noted that the primary source of these challenges was students' minimal or complete lack of conceptual understanding of stoichiometry. AIMS students appeared to have misconceptions regarding some stoichiometry concepts, including the concepts of mole, representative particles, mole ratio, theoretical yield, and limiting reagent. Their inadequate understanding of these concepts impeded their ability to solve stoichiometry problems successfully. Although studies have shown that the use of particle diagrams can effectively improve students' conceptual understanding of stoichiometry, this visual tool has not been applied systematically and extensively in AIMS chemistry classes, and its impact specifically on AIMS students' conceptual understanding of stoichiometry had not been explored.

Purpose of the Study

The purpose of this study was to investigate the effects of using particle diagrams (also called particulate diagrams) on AIMS high school students' conceptual understanding of stoichiometry, specifically on the concepts of representative particles, mole ratio, limiting reagent, and theoretical yield. In this study, a companion booklet entitled "Thinking the Particulate Way!" was designed and used as complementary material in lessons related to concepts of stoichiometry. At the end of the series of lessons, its effects on students' conceptual understanding of stoichiometry and their attitudes towards its use in learning stoichiometry were examined.

Literature Review

[1] Author's email address: ida@aims.ac.th

This paper was presented at the 7th International Scholar's Conference held on October 28–29, 2019 at Universitas Advent Indonesia, and selected for publication in HBDS.

Stoichiometry

Stoichiometry is a branch of chemistry that deals with calculations of the quantities of substances involved in chemical changes or chemical reactions (Wilbraham, Staley, Matta, & Waterman 2017). The word *stoichiometry* is derived from the Greek words: *stoicheion* (meaning "element") and *metron* (meaning "to measure") (Goldberg, 2015). Though the translation from Greek to English seems to imply that only chemical elements are involved and measured, very often chemical compounds are involved and measured in chemical reactions.

Stoichiometry calculations deal with the quantities of chemical elements, or compounds present, before undergoing a chemical change (reactants), and the chemical elements or compounds produced after the chemical change (products). These quantities are measured in terms of mass, volume, number of moles, and number of representative particles.

Both students and teachers find stoichiometry to be one of the most challenging topics in chemistry. Evaluation of senior secondary school chemistry syllabi indicates that students and teachers find the module on stoichiometry problematic (Seetso & Taiwo, 2005; Shadreck & Enunuwe, 2018). Even after alternative approaches for teaching stoichiometry are developed, students and teachers may still regard the topic as being complicated and unmotivating (Fach, Boer & Parchmann, 2007). Interviews with high school chemistry instructors revealed responses that were overwhelmingly similar, in that they found teaching stoichiometry challenging. Students' reactions toward learning about the concepts of stoichiometry were ones of fear and apprehension (Bridges, 2015) and discouragment (Schmidt & Jignéus, 2003).

Dahsah and Coll (2007) reported that even after major national curriculum reforms, Thai Grade 10 and 11 students who participated in a survey demonstrated less than the acceptable level of understanding concepts related to stoichiometry. The Thai students' responses also suggested that they resorted to the use of algorithms with little knowledge of the underlying concepts. Findings from a study involving 867 twelfth-grade Indonesian students showed that, in general, Indonesian students were more successful in answering questions that were algorithmically based, and found no strong positive correlations between student performance on conceptual questions and algorithmic questions (Agung & Schwartz, 2007). These studies suggest that students who do not grasp the chemistry concepts behind a problem sufficiently tend to use algorithmic methods. They merely use a memorized formula, manipulate the equation, and plug numbers in it until they fit.

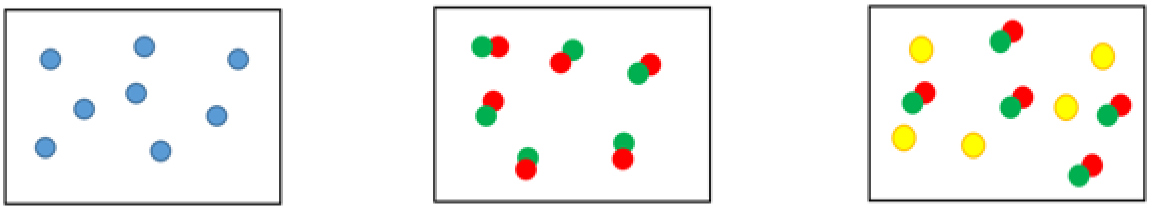
What makes stoichiometry so challenging to learn and understand is that the macroscopic features of chemical reactions, on which stoichiometry is primarily based, are emergent properties resulting from actions at the atomic or molecular levels (Cheng & Gilbert, 2014). These submicroscopic actions operate on a non-human scale and are unable to be directly manipulated or experienced. Therefore, developing an intuition for connecting these macroscopic features with submicroscopic interactions is difficult (Rahayu & Kita, 2009). Still another learning challenge is mastery of the representational system of symbols, formulas, equations, and mathematical manipulations used to describe and explain these unseen submicroscopic interactions that give rise to macroscopic features. Expert chemists move freely among these three levels as they pursue their work, including that of instruction (Johnstone, 2000). However, students, whose knowledge framework is rudimentary at best, have great difficulty understanding their teachers when explanations move away from the macroscopic level with which they have everyday experience. Effective stoichiometric instruction should promote student development of cognitive connections among macroscopic, submicroscopic, and representational aspects of stoichiometry.

Bridges (2015, p. 9) suggested that teachers need to be "knowledgeable, creative, and resourceful" in helping their students to learn stoichiometry. In recent years a number of alternative approaches for teaching this unit of chemistry have been developed. In Germany, a set of stepped supporting tools was implemented to help grade 9 students working on stoichiometric problems (Fach, Boer, & Parchmann, 2007). A study of 96 Indonesian students reported that macro–submicro–symbolic teaching, which employed multiple representations, could enhance student mental models and understanding of chemical reactions effectively, which is the basis for solving stoichiometric problems (Sunyono, Yuanita, & Ibrahim, 2015). Inquiry-based lessons, using particulate level models, may produce statistically significant improvement in grade 11 and 12 students' conceptual understanding of stoichiometry, even though there are variations in the intervention delivery (Kimberlin & Yezierski, 2016). An instructional model that incorporates definitions, computer-generated visuals at the submicroscopic level, and physical samples of various substances at the macroscopic level seems to improve students' conceptions of pure substances and mixtures (Sanger, 2000). These studies suggest that an understanding of the submicroscopic composition of chemical elements and/or compounds that make up the reacting and resulting substances in chemical reactions is an essential prerequisite to interpreting and solving stoichiometric problems.

The studies cited above indicate that a more visual pedagogical approach to teaching stoichiometry effectively could advance student conceptual understanding. Consequently, the Advanced Placement Chemistry curriculum was redesigned to include learning objectives that contain references to particulate representations of chemical phenomena (College Board, 2014). However, the shift in emphasis toward conceptual understanding using particulate images presents a real challenge for many chemistry teachers, because most of them have had limited exposure to particulate ideas before teaching chemistry, including during their high school years. Therefore, translating the recommendations for using particulate representations into teaching practices can be a daunting task. The scarcity of classroom-ready lessons or supplementary materials based primarily on particulate descriptions further compounds the challenge. From my own experience as a chemistry teacher, I observed that in high school chemistry textbooks, particle diagrams were used sparingly and sporadically as concept illustrations and as summative assessment items. Very few chemistry textbooks make extensive use of particle representations, and they are not accessible by all teachers. In their action research, Kimberlin and Yezierski (2016) designed and provided evidence for the effectiveness of two particulate level inquiry-based lessons. Unfortunately, these lessons could not be accessed online. Without classroom-ready and easily accessible materials, recommendations to incorporate particulate ideas in stoichiometry lessons create gaps in the literature.

Particle Diagrams

A particle diagram is a model that usually describes the arrangement and movement of particles in a substance. The particles are represented as circles that are either drawn individually or in groups of two or more, depending on what substance they constitute. In most science lessons, the diagram is used to explain the physical properties of solids, liquids, and gases. However, in stoichiometry, it is used to show the composition of substances involved in chemical reactions. It shows the number and types of particles that make up the reactants and products in chemical reactions. Examples of particle diagrams representing an element, a compound, and a mixture are shown below.



(a) Element (b) Compound (c) Mixture

Figure 1. Examples of Particle Diagrams

Methodology

Research Questions

The following questions were used as guides in the study.

Research Question 1: To what extent does the use of particle diagrams affect students' conceptual understanding of representative particles, mole ratio, limiting reagent, and theoretical yield?

Research Question 2. What are the students' attitudes towards the use of particle diagrams?

Research Design

The study employed a one-group pre-test post-test design (or paired-sample design). This design involved measuring conceptual understanding of stoichiometry in one group of students (grade 10) once before the treatment was implemented (pre-test), and once after it was implemented (post-test). Conclusions about the treatment's effects were formulated based on the difference between the pre-test and post-test data.

This design was adopted for several important reasons. First, this design allowed the study to be done in a real classroom setting, within a single class without having to separate students, and during school hours without disrupting the smooth running of any classes or school programs. Second, the treatment itself could be easily incorporated into the chemistry lessons without compromising real learning time for the students. A third reason was that the researcher had no control over the number of students who enrolled in General Chemistry class, and since the number was small (13 students), it was more feasible to adopt a one-group design.

Treatment Conditions

The treatment engaged students in simple, non-intrusive activities compiled in a booklet entitled *Thinking the Particulate Way*. The booklet contains 54 particle diagrams (also called particulate diagrams, or submicroscopic diagrams) related to topics and concepts of stoichiometry. The method of instruction for the stoichiometry unit traditionally included the interactive lecture method, modeling problem-solving, peer coaching, laboratory activities, and a very minimal use of particulate diagrams drawn on the whiteboard and shown on PowerPoint slides. In this treatment-added approach, the same strategies were used, but with the integration of information and exercises contained in the *Thinking the Particulate Way* booklet wherever and whenever they were relevant in the lessons. This booklet provided supplementary materials that allowed students ample opportunities to examine the submicroscopic basis of concepts related to stoichiometry, specifically the concepts of representative particles, mole ratio, limiting reagent, and theoretical yield.

The booklet was divided into four sections. Each section included a topic and one stoichiometry concept that was related to the study.

Population and Sample

The sample for this study was thirteen 10^{th} grade students who enrolled in the General Chemistry class for the academic year 2018–19 at AIMS. The sample was selected using a non-random, convenience sampling technique. The researcher sampled 13 tenth-grade chemistry students who were conveniently available and happened to be her students at the time of the study. With this sampling technique, it was not possible to specify the target population from which this sample was drawn. However, generalizability was not a concern because the interest was only in discovering the effects of a pedagogical approach on a specific group of individuals at AIMS to whom the results were relevant.

Instrumentation: Conceptual Stoichiometry Test (CST) Pre-test and Post-test

To determine the effects of the use of particle diagrams on students' conceptual understanding of stoichiometry, an improved version of a published instrument, called the Conceptual Stoichiometry Test (CST), was used. It was designed by Wood and Breyfogle (2006) and improved by

Kimberly and Yezierski (2016). Stoichiometric concepts addressed and measured by the 10-item test were: a) Representative Particles, b) Mole Ratio, c) Limiting Reagent, and d) Theoretical Yield.

The CST test was piloted with nine Grade 10 students enrolled in Physical Science class at AIMS. Apart from question reorganization, there was no need to change other aspects of the test after the pilot test.

Attitudes Towards the Use of Particle Diagrams Questionaire

A 10-item Attitude Towards Use of Particle Diagrams (ATPD) questionnaire was administered to students at the end of the stoichiometry unit to determine their attitudes to the use of particle diagrams, and whether or not these diagrams helped them understand stochiometric concepts. The researcher developed the 12-item questionnaire. Each item was rated on a Likert scale using five response categories: Strongly Agree, Agree, Not Sure, Disagree, and Strongly Disagree.

A pilot study was carried out for the questionnaire in which 10 twelfth-grade students were the respondents. The results suggested that no changes were necessary in the questionnaire.

Data Collection and Analysis

The researcher applied two data collection techniques—pre-test/post-test, and a survey questionnaire. The pre-test was administered to participants in one class period before their lessons on the Mole, chemical reactions, and stoichiometry. During the treatment period, chemistry classes continued as scheduled, and the *Thinking the Particulate Way* companion booklet was used in all of the chemistry lessons as a source of content knowledge and illustrations, for explanation and reinforcement of concepts, as well as for assessments. After the approximately five-week duration, the participants took the post-test and completed the questionnaire.

Data collected from the Conceptual Stoichiometry Test (CST) were analyzed using a paired-sample (correlated) t-test. Data collected from the Attitude Towards the Use of Particle Diagrams (ATPD) questionnaire were analyzed using descriptive statistics in the forms of means, standard deviations, and percentages.

Results

Results of Paired-samples t-test

Analysis of the participants' pre- and post-test mean scores on the four stoichiometry concepts was carried out using SPSS. Table 1 displays the descriptive statistics for the pre- and post-test conditions. While it appears that the participants performed differently under the pre-test and post-test conditions, further information in the form of inferential statistics is needed to determine whether there is any significant difference between participants' pre-test and post-test means on all four concepts.

Table 1. Paired Samples Statistics of Pre-/Post-test Mean Scores on Four Concepts of Stoichiometry

	Concepts Assessed	Mean	*N*	Std. Deviation	Std. Error Mean
Pair 1	Representative Particle Pre-test	7.46	13	2.73	0.76
	Representative Particle Post-test	11.00	13	2.38	0.66
Pair 2	Mole Ratio Pre-test	16.31	13	3.68	1.02
	Mole Ratio Post-test	18.62	13	2.36	0.66
Pair 3	Limiting Reagent Pre-test	5.77	13	1.42	0.39
	Limiting Reagent Post-test	7.31	13	2.06	0.57
Pair 4	Theoretical Yield Pre-test	5.77	13	1.42	0.39
	Theoretical Yield Post-test	7.31	13	2.06	0.57

A paired-samples t-test was conducted to determine whether there was a statistically significant difference in the pre-test and post-test mean scores of each of the four concepts of stoichiometry listed in research question 1. Table 2 (following page) displays the results of the paired sample t-test.

Table 2 shows that for all the concepts (pairs 1–4), the *p* (probability) value is substantially smaller than the specified value of .05, which means there is a highly significant difference between the pre-test and post-test scores. Combining the information from Table 1 and Table 2, the results of the analysis were as follows.

Table 2. Paired Samples t-test Analysis of Pre/Post-test Mean Scores on Four Concepts of Stoichiometry

	Paired Differences					t	df	Sig. (2-tailed)
	Mean	Std. Deviation	Std. Error Mean	90% Confidence Interval of Difference				
				Lower	Upper			
Pair 1 RepPart Pre - Post	-3.538	2.295	.637	-4.926	-2.151	-5.558	12	.000
Pair 2 MolRatio Pre - Post	-2.308	2.394	.664	-3.754	-.862	-3.476	12	.005
Pair 3 LimAgent Pre - Post	-1.538	1.713	.475	-2.574	-.503	-3.237	12	.007
Pair 1 TheoYield Pre - Post	-1.538	1.713	.475	-2.574	-.503	-3.237	12	.007

For the concept of Representative Particles (Pair 1), there was a statistically significant increase in pre-test scores prior to intervention (M = 7.46, SD = 2.73) to post-test scores after intervention (M = 11.00, SD = 2.38), t (12) = -5.558, p < .000 (two-tailed). The mean increase in post-test scores was 2.31, with a 95% confidence interval ranging from -4.93 to -2.15.

For the concept of Mole Ratio (Pair 2), there was a statistically significant increase in pre-test scores prior to intervention (M = 16.31, SD = 3.68) to post-test scores after intervention (M = 18.62, SD = 2.36), t (12) = -3.476, p < .005 (two-tailed). The mean increase in post-test scores was 3.54, with a 95% confidence interval ranging from -3.75 to -0.86.

For each of the concepts of Limiting Reagent and Theoretical Yield, there was a statistically significant increase in pre-test scores prior to intervention (M = 5.77, SD = 1.42) to post-test scores after intervention (M = 7.31, SD = 2.06), t (12) = -3.237, p < .007 (two-tailed). The mean increase in post-test scores was 1.54 with a 95% confidence interval ranging from -2.57 to -0.50. Although the results presented above tell us that the difference obtained in each concept pair was significant, it does not tell us about the magnitude of the intervention's effect.

Table 3 shows that the treatment had the following size effects on these respective concepts: 1.54 on Representative Particles, .96 on Mole Ratio, .90 on Limiting Reagent, and .90 on Theoretical Yield. The effect size was calculated using Cohen's *d*, which shows standardized differences between two means. An effect size of $d \le .20$ is considered "Small", a *d* between .20 and .79 is considered "Medium", and $d \ge .80$ is considered "Large" (Warner, 2013). Thus, we can conclude that the treatment had a large effect on the differences in CST scores for each concept obtained before and after the intervention.

Table 3. Cohen's *d* Results for Size Effect

Number	Concept	Size Effect	Interpretation
1	Representative Particles	1.54	Large
2	Mole Ratio	.96	Large
3	Limiting Reagent	.90	Large
4	Theoretical Yield	.90	Large

In short, the use of particle diagrams in the instruction of stochiometry significantly improved AIMS students' understanding of the concepts of representative particles, mole ratio, limiting reagent, and theoretical yield.

Analysis and Interpretation of ATPD Survey Results

A total of 13 survey forms were distributed, and all were completed and used for computations. Results show that the responses most frequently selected by the participants were Strongly Agree (41.0%), followed by Agree (37.2%) and Not Sure (16.7%). The responses least frequently selected were Disagree (3.8%) and Strongly Disagree (1.3%).

The results of the questionnaire were further analyzed by concept (Table 4). More than 80% of the participants responded with Agree and Strongly Agree, and scored between 4–5 on a 5-point Likert scale on the concept of Representative Particles. The results suggest that the majority of the participants agreed that the use of particle diagrams helped develop an understanding of this concept. By contrast, the lowest participant scores were for the concept of Theoretical Yield, but the remainder were high, which suggested that the majority of the participants agreed that the use of particle diagrams helped develop an understanding of these concepts.

Table 4. Descriptive Statistics for Concepts of Representative Particles, Mole Ratio, Limiting Reagent, and Theoretical Yield

	Statement	*M*	*SD*	%
	Representative Particles			
1.	Particle diagrams help me visualize the particles that make up compounds, mixtures, and elements	4.62	0.51	100
2.	Particle diagrams help me differentiate among atoms, molecules, ions, and combinations of these	4.46	0.78	84.6
3.	Particle diagrams help me understand what happens to the particles of reactants during chemical reactions	4.38	0.65	92.3
	Mole Ratio			
4.	Particle diagrams help me understand what the coefficients in balanced chemical equations represent	4.23	1.01	76.9
5.	Particle diagrams help me determine how many of each kind of atom takes part in a chemical reaction in the lowest whole number ratio	4.15	0.69	84.6
6.	Particle diagrams help me relate coefficients to mole ratio	3.69	0.86	61.6
7.	Particle diagrams help me determine the amounts of substances needed or produced in a chemical reaction	4.54	0.52	100
	Limiting Agent			
8.	Particle diagrams show that in some chemical reactions, reactants are not necessarily all used up	4.62	0.65	92.3
9.	Particle diagrams help me identify the reactants that is all used up first (limiting reagent)	4.46	0.66	92.3
10.	Particle diagrams help me identify the reactant that is NOT all used up (excess reagent)	4.31	0.75	85.6
	Theoretical Yield			
11.	Particle diagrams help me to understand the difference between theoretical and actual yield	3.15	0.99	46.2
12.	Particle diagrams help me identify which reactant determines the theoretical yield	3.08	1.04	30.8

From 85.6% to 92.3% of the participants responded with Agree and Strongly Agree on the concept of Limiting Reagent, which suggested that the majority of participants agreed that use of particle diagrams helped develop an understanding of this concept. Finally, only 30.8% to 46.2% of the participants responded with Agree and Strongly Agree on the concept of Theoretical Yield. These

results indicate that less than half of the participants agreed that use of particle diagrams helped develop an understanding of this concept.

The results of the ATPD questionnaire indicate that generally the participants demonstrated a favorable attitude towards use of particle diagrams in the instruction of stoichiometry. The majority of participating AIMS students agreed that use of particle diagrams helped them develop an understanding of the concepts of representative particles, mole ratio, and limiting reagent.

Reliability analysis was carried out on the ATPD scale. Cronbach's alpha shows the ATPD questionnaire possessed an acceptable internal consistency, $\alpha = .80$. This result indicates that the 12 items in the questionnaire are highly interrelated and reliably measure the underlying construct (Pallant, 2011).

Discussion

Studies have revealed that most high school chemistry students lack the conceptual understanding of stoichiometry necessary to answer questions correctly (Dahsah & Coll, 2007; Saltan & Tzougraki, 2011; Kimberlin & Yezierski, 2016; Shadreck & Enunuwe, 2018). Studies have also found that an understanding of the submicroscopic composition of chemical elements and/or compounds that make up the reacting and resulting substances in chemical reactions is an essential prerequisite to interpreting and solving all stoichiometric problems, especially conceptual ones (Davidowitz & Chittleborough, 2009; Jaber & Boujaoude, 2012; Sujak & Daniel, 2017. In this study, the submicroscopic composition of matter substances was represented by particle diagrams. Students' responses to the use of particle diagrams matched with what was already described in the literature, and confirmed the positive effects of using particulate models to enhance understanding of chemistry concepts.

Findings from this study can contribute to the local learning community in the following ways. The findings should encourage science educators to explore and adapt research-based pedagogical recommendations, and to verify their effectiveness on the learning of their students in their school settings.

The results of the study will help AIMS science teachers evaluate the impact of using particle diagrams in developing students' conceptual understanding of stoichiometry. They also will help teachers establish the extent to which particulate ideas should be incorporated into instruction to maximize concept attainment while avoiding cognitive overloading. Therefore, this study can help teachers develop new and specific strategies for enhancing conceptual learning in chemistry.

This study also encouraged students to approach stoichiometric problems from a particulate perspective. Training students to think "in a particulate way" will build a conceptual foundation not only for stoichiometry, but also for other high school chemistry topics, and will be beneficial for more advanced studies of the subject. This study can also help students rectify their misconceptions about some concepts of stoichiometry. This study could also help students develop appreciation and preference for more in-depth, conceptual understanding, rather than superficial learning.

The findings of this study add modestly to the body of literature on intervention stragegies in the teaching of chemistry, specifically stoichiometry. Visual-based conceptual approaches to teaching chemistry have been the primary trend, and they are likely to keep being used. Simple interventions such as the incorporation of particle diagrams in chemistry instruction can be the basis or beginning for more assertive, sophisticated, or elaborate pedagogies that support or enforce progressive conceptual understanding. Using particle diagrams could be an effective way to help students build conceptual understanding in a more elaborate way than this study has been able to demonstrate.

Limitations

They are a few limitations to the study. The first is that the research focused on a small population sample of only 13 high school students enrolled in chemistry class at one international school. The second limitation is that it involved only one chemistry teacher. Hence, the results of the study will have limited generalizability across students, teachers, and schools.

On account of the sample size, there was a reduced ability to detect the actual statistical differences between students' conceptual understanding before and after use of particle diagrams. Moreover, the use of only one group in the study's pre-test/post-test design could have compromised its internal validity.

Despite these limitations, the data collected can be useful for designing more extensive confirmatory studies or similar studies at other high schools in Thailand in the future.

Conclusion

From the results of the inferential analysis, the use of particle diagrams was found useful in the instruction of stoichiometry. It leads to a better understanding of the concepts of representative particles, mole ratio, limiting reagent, and theoretical yield. The attitudes of the students towards the use of particle diagrams in stoichiometry instruction indicated that all students in the cohort assessed found the diagrams helpful in enhancing their understanding of the concepts of representative particles, mole ratio, and limiting reagent, but not helpful in improving their understanding of the concept of theoretical yield.

References

Agung, S., & Schwartz, M. (2007). Students' understanding of conservation of matter, stoichiometry and balancing equations in Indonesia. *International Journal of Science Education, 29*(13), 1679–1702. doi:10.1080/09500690601089927

Bridges, C. (2015). *Experiences teaching stoichiometry to students in grades 10 and 11* (Doctoral dissertation, Walden University, United States). Retrieved from http://scholarworks.waldenu.edu/cgi/viewcontent.cgi?article=1290&context=dissertations

Cheng, M., & Gilbert, J. (2014). Teaching stoichiometry with particulate diagrams – Linking macro phenomena and chemical equations. In B. Eilam, & J. Gilbert (Eds.), *Science teachers' use of visual representations* (pp. 123–143). doi: 10.1007/978-3-319-06526-7_6

College Board. (2014). *AP chemistry course and exam description* (revised ed.). New York, NY: The College Board. Retrieved from https://secure-media.collegeboard.org/digitalServices/pdf/ap/ap-chemistry-course-and-exam-description.pdf

Dahsah, C., & Coll, R. (2007). Thai grade 10 and 11 students' conceptual understanding and ability to solve stoichiometry problems. *Research in Science & Technological Education, 25*(2), 227–241. doi:10.1080/02635140701250808

Davidowitz, B. & Chittleborough, G. (2009). Linking the macroscopic and sub-microscopic levels: diagrams. In J. Gilbert & D. Treagust (Eds.), *Multiple representations in chemical education* (pp. 169–191). Dordrecht, Netherlands, Springer. doi: 10.1007/978-1-4020-8872-8_9

Fach, M., Boer, T., & Parchmann, I. (2007). Results of an interview study as basis for the development of stepped supporting tools for stoichiometric problems. *Chemistry Education Research and Practice, 8*(1), 13–31. doi:10.1039/b6rp90017h

Goldberg, D. (2015). *Fundamentals of Chemistry* (5th ed.). New York, NY: McGraw-Hill Education.

Jaber, L., & Boujaoude, S. (2012). A macro–micro–symbolic teaching to promote relational understanding of chemical reactions. *International Journal of Science Education, 34*(7), 973–998. doi: 10.1080/09500693.2011.569959

Johnstone, A. (2000). Teaching of chemistry – Logical or psychological? *Chemistry Education Research and Practice 1*(1), 9–15. doi: 10.1039/a9rp90001b

Kimberlin, S., & Yezierski, E. (2016). Effectiveness of inquiry-based lessons using particulate level models to develop high school students' understanding of conceptual stoichiometry. *Journal of Chemical Education*, *93*(6), 1002–1009. doi:10.1021/acs.jchemed.5b01010

Pallant, J. (2011). *SPSS survival manual: A step by step guide to data analysis using the SPSS program* (4th ed.). Crows Nest, NSW: Allen & Unwin.

Rahayu, S., & Kita, M. (2009). An analysis of Indonesian and Japanese students' understandings of macroscopic and submicroscopic levels of representing matter and its changes. *International Journal of Science and Mathematics Education*, *8*(4), 667–688. doi: 10.1007/s10763-009-9180-0

Salta, K., & Tzougraki, C. (2011). Conceptual versus algorithmic problem-solving: Focusing on problems dealing with conservation of matter in chemistry. *Research in Science Education, 41*(4), 587–609. doi: 10.1007/s11165-010-9181-6

Sanger, M. (2000). Using particulate drawings to determine and improve students' conceptions of pure substances and mixtures. *Journal of Chemical Education, 77*(6), 762. doi:10.1021/ed077p762

Schmidt, H., & Jignéus, C. (2003). Students´ strategies in solving algorithmic stoichiometry problems. *Chemistry Education Research and Practice*, *4*(3), 305–317. doi: 10.1039/b3rp90018e

Seetso, I., & Taiwo, A. (2005). An evaluation of Bostswana senior secondary school chemistry syllabus. *Journal of Baltic Science Education, 2*(8), 5–14. Retrieved from http://oaji.net/articles/2016/987-1481284752.pdf

Shadreck, M., & Enunuwe, O. (2018). Recurrent difficulties: Stoichiometry problem-solving. *African Journal of Educational Studies in Mathematics and Sciences*, *14*, 25–31. Retrieved from https://www.ajol.info/ index.php/ajesms/article/viewFile/173393/162796

Sujak, K., & Daniel, E. (2017). Understanding of macroscopic, microscopic and symbolic representations among Form Four students in solving stoichiometric problems. *Malaysian Online Journal of Educational Sciences, 5*(3), 83–96. Retrieved from https://files.eric.ed.gov/fulltext/EJ1150426.pdf

Sunyono; Yuanita, L., & Ibrahim, M. (2015). Mental models of students on stoichiometry concept in learning by method based on multiple representation. *The Online Jouranl of New Horizons in Education, 5*(2), 30–45. Retrieved from http://www.tojned.net/journals/tojned/articles/v05i02/ v05i02-05.pdf

Warner, R. (2013). Applied statistics: From bivariate to multivariate techniques (2nd Ed.). Los Angeles, CA: Sage Publications, Inc.

Wilbraham, A., Staley, D., Matta, M., & Waterman, E. (2017). *Pearson chemistry*. Boston, MA: Pearson.

Wood, C. & Breyfogle, B. (2006). Interactive demonstrations for mole ratios and limiting reagents. *Journal of Chemical Education 83*(5), 741−746. doi.org/10.1021/ed083p741