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SMALL-SCALE AND SMARTPHONE-BASED COLORIMETRIC EXPERIMENTS TO ENHANCE GRADE-11 STUDENTS' CONCEPTUAL UNDERSTANDING OF CHEMICAL EQUILIBRIUM

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ABSTRACT

This study aimed to examine the conceptual understanding of chemical equilibrium among 11th-grade students using the 5E inquiry learning framework, in which the students were requested to conduct small-scale experiments on chemical equilibrium and factors influencing the equilibrium and the smartphone-based colorimetric determination of Kc. The data collection included two instruments: a two-tier diagnostic conceptual test with the reliability (KR20) of 0.82 and a semi-structured interview form. Thirty-one students participated in three 2-h 5E learning sessions, totaling 6 h. A paired-samples t-test revealed that the post-conceptual test scores (mean 31.46, standard deviation 6.82, 69.91%) were significantly higher than the pretest scores (mean 11.85, standard deviation 10.80, 26.33%) at a significance level of 0.05, with a normalized gain of 0.59, indicating a medium improvement. Most students progressed from the less accurate category, Partial Understanding with Specific Misunderstanding (PMU, 42.39%), to a more precise category, Partial Understanding (45.38%). Semi-structured interviews suggested that the 5E inquiry approach, using small-scale and smartphone-based colorimetric experiments, was engaging and effective in improving students' conceptual understanding. This intervention helped students shift their understanding of chemical reactions toward more accurate categories.

Keywords: chemical equilibrium; equilibrium constant; colorimetric analysis; small-scale experiment; high school chemistry

INTRODUCTION

Chemical equilibrium is when the forward and reverse reaction rates are equal. This equilibrium reflects a dynamic process, wherein the concentrations of reactants and products remain unchanged despite the ongoing conversion between them (Chang & Overby, 2021). The topic of chemical equilibrium, particularly the equilibrium constant (K_c), is considered one of the most challenging areas in chemistry because of the various factors that can influence equilibrium and the associated mathematical calculations (Akın & Uzuntiryaki-Kondakci, 2018; Bernal-Ballen & Ladino-Ospina, 2019; Prokša et al., 2018; Syahmani et al., 2023). It also necessitates understanding of the macroscopic, microscopic, and symbolic aspects (Prokša et al., 2018) and the dynamic nature of equilibrium articulated by Le Chatelier's principle (Costa & dos Santos, 2022). Many students nationwide face these challenges, as demonstrated in previous studies (Andriani et al., 2021; Bernal-Ballen & Ladino-Ospina, 2019; Muhsin & Laksono, 2023; Prokša et al.,

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2018; Rahmawati et al., 2022; Tarng et al., 2022; Rusli et al., 2024). The equilibrium constant (K_c) is the ratio of the equilibrium concentrations of the products to those of the reactants, with each concentration increased to the power of its relating stoichiometric coefficient (Chang & Overby, 2021).

Several practical activities have been developed to enhance students' learning outcomes on chemical equilibrium, including hands-on activities (Bindel, 2012), analogies (Yildirim et al., 2013), demonstrations (Eilks & Gulacar, 2016), and laboratory experiments (Campbell et al., 2017; Kajornklin et al., 2020); problem-based learning (Rusli et al., 2024); simulation (Rahmawati et al., 2022); and augmented reality (Tarng et al., 2022). However, many of these activities have the drawback of being conducted on a traditional scale, often requiring high costs and specialized scientific instruments, which makes them unsuitable for high school classrooms. Laboratory experiments are particularly recognized as one of the most effective methods for promoting visualization and conceptualization of this topic and increasing student engagement. While many laboratory experiments can enhance students' conceptual understanding of equilibrium, they are frequently impractical in the educational contexts of school to college levels because of the limited access to high-cost scientific instruments (Kajornklin et al., 2020; Namwong et al., 2018; Jovero & Picardal, 2022). Therefore, there is a strong need for alternative experiments that utilize inexpensive materials, require a quick setup, and are easy to conduct.

Recently, a low-cost, rapid method for fabricating paper towel-based experimental devices (PTEDs) has been introduced to illustrate the factors influencing chemical equilibrium. This method allows observing the color changes between pink and blue in the cobalt(II) complex reaction with the naked eye on a single sheet of PTEDs (Kajornklin et al., 2020). Additionally, the color intensity of the digital images captured from various areas of the PTEDs can be converted into concentrations of the reaction species using ImageJ or other image-processing software. The reaction's K_c can then be calculated as the ratio of the equilibrium concentrations of the products to those of the reactants.

The complex formation of thiocyanate ions with iron(III) is commonly used to demonstrate how to determine the K_c for this reaction considering the availability of reagents and the simplicity of observing color changes (Nyasulu & Barlag, 2010; Armenta et al., 2020). The reported K_c values for this reaction range from 98 to 146 M^{-1} (Nyasulu & Barlag, 2010). The equilibrium reaction of the iron(III)–thiocyanate complex and its corresponding K_c equation are illustrated in Figure. 1.

	$Fe^{3+}(aq)$ +	$SCN^{-}(aq)$ ⇆	$[FeSCN]^{2+}(aq)$
Solution color :	pale yellow	colorless	blood-red
[initial] :	x	y	-
[change] :	- z	- z	z
[equilibrium] :	x- z	y − z	z

$$K_C = \frac{[FeSCN]^{2+}}{[Fe^{2+}][SCN^{-}]} = \frac{z}{(x - z)(y - z)}$$

Figure 1. Equilibrium Equation of Iron(III)–thiocyanate and its K_c Calculation [2]

Building on previous studies that utilized PTEDs and paper-based analytical devices (PADs) (Namwong et al., 2018; Kajornklin et al., 2020), we analyzed the digital images of these devices captured with readily available smartphone cameras using ImageJ, an image-processing software. This analysis focused on color intensity to convert it into concentrations of chemical reaction species. We adapted these methods to suit high school classroom contexts better, emphasizing time efficiency, ease of operation, and the potential for equipment reuse. This study introduces an alternative, portable, and time-efficient method for investigating chemical equilibrium and the factors influencing equilibrium as a small-scale experiment on a single well plate. In addition, we also introduce a smartphone-based colorimetric method that determines the K_c of the thiocyanatoiron(III) complex ion using a single well plate. This approach employs colorimetric (or color intensity) analysis of smartphone-captured images. This small-scale, environmentally friendly method produces reproducible, quantitative data by utilizing low-cost, readily available materials, including a smartphone, a light control box (instead of a spectrophotometer), and a white well plate (instead of test tubes and cuvettes). It can be effectively used to explore the principles of chemical equilibrium, including K_c, in chemistry classrooms from high school to college. We evaluated the effectiveness of our method in enhancing students' learning by investigating the students' conceptual understanding of chemical equilibrium after participating in small-scale and smartphone-based colorimetric experiments, as outlined by Supasorn et al. (2018), and utilizing the 5E inquiry learning approach (Bybee, 2014; Ong et al., 2020; Asrizal et al., 2022; Wikara et al., 2022; Joswick & Hulings, 2024). Within this context, we posed the following research questions: (1) How do students' conceptual understanding scores change after they complete the small-scale and smartphone-based colorimetric experiments related to chemical equilibrium? (2) How do the distributions of students across each conceptual understanding category change after they complete the small-scale and smartphone-based colorimetric experiments related to chemical equilibrium?

METHODS

This study followed a mixed-methods research approach that involves collecting, analyzing, and integrating quantitative and qualitative approaches to comprehensively understand the research problem (Creswell & Creswell, 2022). This convergent parallel study employed a one-group pretest/posttest design to gather quantitative data. At the same time, semi-structured interviews were conducted to collect qualitative data that complemented the quantitative findings. Before data collection, ethical approval for human research was obtained under the code UBU-REC-07/2563 from the Ubon Ratchathani University Research Ethics Committee (2020).

Thirty-one 11th-grade students from a regular (non-gifted) classroom at a large high school in Ubon Ratchathani, Thailand, were selected as the study participants. The selection process was conducted with the prior approval of the school principal and the chemistry instructor during the first semester of the 2020 academic year (June to September). All participants provided informed consent and agreed to the study's findings and publication, ensuring their conceptual test data was used anonymously.

The treatment tool of this study comprised three 2-h inquiry learning activities: (1) a small-scale experiment of the chemical equilibrium of Fe^{3+}(aq) and SCN^-(aq) and factors affecting its equilibrium; (2) smartphone-based colorimetric determination of K_c for Fe^{3+}(aq) and SCN^-(aq) equilibrium; and (3) chemical equilibrium of NO_2(g) and N_2O_4(g) and factors affecting its equilibrium (Table 1).

Table 1. Key Learning Activities in each Lesson Plan

Learning Plan	Key Activities
1. Chemical equilibrium of Fe^{3+}(aq) and SCN^-(aq) and factors affecting its equilibrium	Small-scale experiment on a well plate Particulate activity using a magnetic whiteboard and colored magnets
2. Smartphone-based colorimetric determination of K_c for Fe^{3+}(aq) and SCN^-(aq) equilibrium	Smartphone-based colorimetric determination of K_c Particulate activity using a magnetic whiteboard and colored magnets
3. Chemical equilibrium of NO_2(g) and N_2O_4(g) and factors affecting its equilibrium	Small-scale experiment in a syringe Particulate activity using a magnetic whiteboard and colored magnets

Our leading equipment set was used for the smartphone-based colorimetric determination of equilibrium constant (K_c), white acrylic 20-well plates, autopipettes, and UV–visible spectrophotometers. The chemicals used in this experiment included aqueous nitric (HNO_3) solution, iron(III) nitrate nonahydrate ($Fe(NO_3)_3$•$9H_2O$), and potassium thiocyanate (KSCN). Nitric acid is corrosive and can cause skin, eye, and respiratory system irritation. Iron(III) nitrate nonahydrate may cause skin, respiratory, and severe eye irritation. Potassium thiocyanate is harmful if swallowed, inhaled, or absorbed through the skin. All aqueous solutions were freshly prepared, including 0.05 M HNO_3, 0.05 M $Fe(NO_3)_3$ in 0.05 M HNO_3, and 0.005 M KSCN.

To create the calibration plots for determining the concentrations of $[Fe(SCN)]^{2+}$, specific volumes of the 0.05 M $Fe(NO_3)_3$, 0.005 M KSCN, and 0.05 M HNO_3 solutions were transferred to a 20-well plate using an autopipette, as shown in Fig. 2(a) and Appendix I.

After the reactions reached their equilibrium, a whole picture of a reaction well plate was captured using a smartphone (iPhone 6s Plus) under a light control box (Fig. 2(b)). After the UV–visible spectrophotometer was calibrated using distilled water, the solution applied to Well No. 3 was transferred into a cuvette to be scanned in a wavelength range of 400–700 nm for a lambda max (λ_{max} = 460 nm). This λ_{max} was used for the absorbance measurements for the remaining solutions. The calibration plot from the UV–visible spectrophotometric method is shown in Figure 2(c).

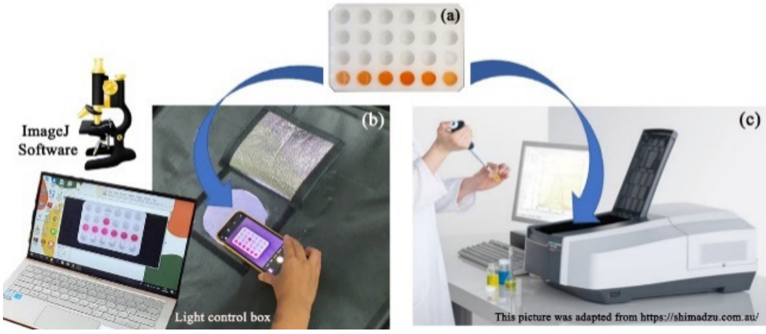

Figure 2. Experiment on the White Acrylic Well Plates (a), Determination of Kc by the alternative Colorimetric Analysis Method Using a Smartphone and a Light Control Box (b), and Standard UV–vis Spectrophotometry (c)

The digital images captured by a smartphone were analyzed in terms of the blue color intensity (B) using the ImageJ image-processing software (Fig. 2(b)). Since the equilibrium solutions are in red tone color, the blue (B) channel was preferred for the color intensity analysis. After each well of the standard solution was processed in terms of the blue color intensity, the calibration plots of the $-\log[Fe(SCN)]^{2+}$ concentration versus the blue color intensity from the colorimetric analysis of the images captured by the iPhone 6s Plus were generated (*Appendix II(a)*). On the contrary, the calibration plot of the $[Fe(SCN)]^{2+}$ concentration versus absorbance from the UV–visible spectrophotometric method was also generated, as shown in *Appendix II(b)*.

To determine the K_c of the iron(III)–thiocyanate reaction using equilibrium solutions by colorimetric and UV–vis methods, the other set of solutions was prepared and referred to as equilibrium solutions. A whole picture of a reaction well plate was captured using the iPhone 6s Plus under a light control box and analyzed using ImageJ and then compared with the calibration curve in Appendix II(a). At the same time, the absorbance measured by the UV–visible spectrophotometric method (λ_{max} of 460 nm) was compared with the calibration curve in Appendix II(b). The concentrations of $[Fe(SCN)]^{2+}$ and K_c of the iron(III)–thiocyanate reaction from these methods were 143.86 ± 1.37, 143.53 ± 1.31, and 142.96 ± 1.17, respectively (Appendix IV), which were in the range reported in previous studies (Nyasulu & Barlag, 2011). The paired-samples t-test analysis indicated that each pair of K_c obtained from the colorimetric analysis of the image captured by a smartphone and from the standard UV–visible spectrophotometric method did not have a statistically significant difference at the 95% confidence level ($p < 0.05$). This means that the proposed alternative colorimetric analysis is as effective as the standard UV–visible spectrophotometric method.

This study utilized a conceptual test on chemical equilibrium as its primary data collection tool. The method was reviewed and validated by two senior chemistry professors and a professor of chemistry education. The test comprised 15 two-tier diagnostic items, with some questions newly developed and others adapted from the chemical equilibrium concept test by Tamuang et al. (2017). The test covered seven items on the concepts of chemical equilibrium (questions 1–7) and eight items on factors affecting chemical equilibrium (questions 8–15). In the first tier, students were asked to select their answers, while in the second tier, they were required to explain their reasoning (Figure 3). The Simple Item Analysis software was used to calculate the difficulty index (P), discrimination index (r), and reliability. The difficulty index (P) for individual items ranged from 0.20 to 0.80, while the discrimination index (r) ranged from 0.27 to 1.00. In addition, the test's overall reliability, calculated using the Kuder–Richardson Formula 20 (KR20), was 0.82. Additionally, a scoring rubric was created for each item, consisting of two to four codes based on the number of subconcepts involved.

Q1: Consider the following reaction:

$Fe^{3+}(aq)$ + $SCN^{-}(aq)$ ⇆ $[FeSCN]^{2+}(aq)$ + Heat
Light Yellow — Colorless — Maroon

Supporting reactions: $Fe^{3+}(aq) + PO_4^{3-}(aq) \leftrightarrows FePO_4(s)$

$SCN^{-}(aq) + Ag^{+}(aq) \leftrightarrows Ag(SCN)(s)$

What change will turn the reaction color of the equilibrium between $Fe^{3+}(aq)$ and $SCN^{-}(aq)$ to maroon (darker)?

Which statement is correct?

A. Increase the concentration of $[FeSCN]^{2+}(aq)$.

<u>B. Decrease the reaction temperature.</u>

C. Add $PO_4^{3-}(aq)$ to the reaction.

Because (together with drawing, if applicable)..............................

....

……..

Subconcept	Code	Point
The choice selection is correct.	Choice(✓/×)	1.00/0.00
The reaction is exothermic or PO_4^{3-} is a reaction retarder.	A (✓/×)	0.75/0.00
When the temperature is decreased, the equilibrium will shift in the forward direction (or when the temperature is increased, the equilibrium will shift in the backward direction).	B (✓/×)	0.75/0.00
When the equilibrium shifts in the forward direction, the reaction color will be darker (or when the equilibrium shifts in the backward direction, the reaction color will be lighter).	C (✓/×)	0.50/0.00

Figure 3. Example of the Conceptual Test Item

The pre-conceptual test on chemical equilibrium took students 1 h to complete before the intervention. Afterward, groups of four to six students participated in three 2-h inquiry-based learning activities focused on chemical equilibrium (Figure 4).

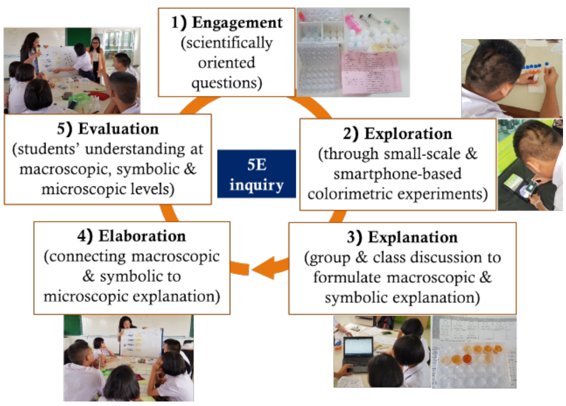

Figure 4. Implementation of the Smartphone-based Colorimetric Experiments through 5E Inquiry Learning

These activities were performed in a typical classroom context (Figure 5). The 5E inquiry learning cycle provided the foundation for each experiment's lesson plan (Bybee, 2014; Ong et al., 2020; Joswick & Hulings, 2024) and was adapted by Supasorn et al. (2022), as shown in Table 1.

Figure 5. Students Experimenting to Determine K_c Using the Colorimetric Analysis

The post-conceptual test took the students another hour to complete immediately after the intervention. Note that the pre- and posttest exam item selections and questions were rearranged.

The pre- and post-conceptual test results were evaluated based on specific scoring criteria. A score of 1.00 was awarded for each correct answer in the first tier. In the second tier, justifications or explanations were scored 0.50, 0.75, or 1.00 depending on the number of subconcepts addressed according to the grading rubric, with a maximum of 2.00 points per item. Each item had a total possible score of 3.00 points, and the entire exam had a maximum score of 45. Three chemistry experts agreed upon the grading method. The student responses from both tiers were categorized into five groups following a modified criterion from Supasorn et al. (2022). The categories were as follows: Good Understanding (GU), Partial Understanding (PU), Partial Understanding with Misconceptions (PMU), Misunderstanding (MU), and No Understanding (NU) (Table 2). If no explanation was provided in the second tier, the response was classified as "No Response: NR."

Table 2. Rubrics for Conceptual Categorization and Scoring in each Item of the Conceptual Test

Categories	Scoring Guideline		
	Choice	Reason (Subconcepts)	Point*
GU	✓	All subconcepts are correct.	3.00
PU	✓	Some (not all) subconcepts are correct, but not incorrect.	0.50–2.50
PMU	✓	Some subconcepts are correct, and some are incorrect.	1.50–2.50
	✓	All or some subconcepts are incorrect.	1.00
	x	All subconcepts are correct.	2.00
	x	Some (not all) subconcepts are correct, but not incorrect.	0.50–1.50
	x	Some subconcepts are correct, and some are incorrect.	0.50–1.50
MU	x	All or some subconcepts are incorrect.	0.00
NU	x	No information corresponds to any of the subconcepts.	0.00
NR	✓	No response.	1.00
	x	No response.	0.00

*The number of subconcepts for each item varies, but the available score is 3.00 points.

Additionally, the %actual gain and the normalized gain or <g> were used to calculate the learning gains of the students (Christman et al., 2024):

%actual gain = %Posttest – %Pretest
<g> = (%Posttest – %Pretest)/(100 – %Pretest)

RESULTS AND DISCUSSION

The study results were organized into three main parts: 1) students' pre- and post-conceptual test scores; 2) categories of students' conceptual understanding before and after the tests; and 3) gains and conceptual categories. The final sections incorporated insights from the semi-structured interviews, highlighting intriguing examples.

The conceptual test covered two subtopics: chemical equilibrium and factors affecting equilibrium ("factors"). Table 3 reveals that students achieved an overall mean pretest score of 10.80 (26.33%) and an overall mean posttest score of 31.46 (69.91%). Their actual gain was 43.58%, with a normalized gain (<g>) of 0.59, indicating a medium improvement. A paired-samples t-test confirmed that the posttest scores were significantly higher than the pretest scores at a 0.05 significance level. Although the posttest score (69.91%) fell below expectations, it is important to note that the participants were from a regular classroom, consisting mostly of medium- to low-achieving students, rather than high achievers. Considering their prior performance, the posttest scores and gains were deemed satisfactory. For the two subtopics, the pretest, posttest, and <g> scores were as follows: for chemical equilibrium, 5.34 (25.42%), 14.19 (67.59%), and 0.57; and for factors affecting equilibrium, 6.51 (27.12%), 17.27 (71.94%), and 0.62. Paired-samples t-tests indicated that the differences between pretest and posttest mean scores were statistically significant for the overall scores and for both subtopics.

Table 3. Students' Scores from the Conceptual Test of Chemical Equilibrium

Tiers	Available	Pretest			Posttest			Gain		T
		Mean	S.D.	%	Mean	S.D.	%	%	<g>	
Equilibrium	21.00	5.34	4.78	25.42	14.19	3.27	67.59	42.17	0.57	7.827*
Factors	24.00	6.51	6.24	27.12	17.27	3.98	71.94	44.83	0.62	7.611*
Total	45.00	11.85	10.80	26.33	31.46	6.82	69.91	43.58	0.59	7.890*

*Statistically different at the sig. level of 0.05.

The percentages of students who fell into each conceptual category on the pre- and post-conceptual exams are shown in Table 4. Before the intervention, the percentages of students in the categories of GU, PU, PMU, MU, and NU were 0.00, 8.39, 42.37, 25.38, and 12.90, respectively, with 10.97% of students not responding in the reason tier (NR). For both subtopics, most students (over 40%) were classified under the PMU category. Following the intervention, the percentages for these categories changed to 19.35, 45.38, 28.17, 7.10, and 0.00, respectively, with no students remaining in the NR group. Over 45% of the students progressed to the more accurate conceptual category, PU, across both subtopics.

Table 4. Percentages of Students Placed in the Conceptual Categories of the Chemical Equilibrium

Subconcept	Percentage of Students					
	GU	PU	PMU	MU	NU	NR
Chemical equilibrium						
Pretest	0.00	6.45	47.00	22.12	13.82	10.60
Posttest	20.74	45.16	26.73	7.37	0.00	0.00
Change*	20.74	38.71	−20.28	−14.75	−13.82	−10.60
Factors affecting equilibrium						
Pretest	0.00	10.08	38.31	28.23	12.10	11.29
Posttest	18.15	45.56	29.44	6.85	0.00	0.00
Change*	18.15	35.48	−8.87	−21.37	−12.10	−11.29
Total						
Pretest	0.00	8.39	42.37	25.38	12.90	10.97
Posttest	19.35	45.38	28.17	7.10	0.00	0.00
Change*	19.35	36.99	−14.19	−18.28	−12.90	−10.97

*The minus sign (−) indicates changes in a decreasing manner.

After the intervention, the percentages of the students resenting lower conceptual understanding (PMU, MU, and NU) decreased, while those in categories indicating a higher conceptual accuracy (GU and PU) increased. This change was attributed to the implementation of the small-scale chemical equilibrium experiment and the smartphone-based colorimetric determination of K_c, which allowed the students to engage in the experiment actively, thereby enhancing their conceptual understanding (Tamuang et al., 2017; Kajornklin et al., 2020). Combining these methods proved effective in helping the students shift from an inaccurate to an accurate conceptual understanding of chemical equilibrium. However, only 19% of the students achieved the highest category, GU. Despite some students remaining in the MU category (7.10%) and none in the NU category, this outcome was still considered satisfactory.

Taştan Kırık and Boz (2012) explained that misconceptions can be difficult to address, even after active learning experiences. This was why some students continued to be classified in the PMU and MU categories. If these misconceptions are overlooked, they may hinder students' future learning. For example, in Thai schools and some other countries, chemical equilibrium is typically taught after the concept of reaction rates, making a solid understanding of the reaction rates essential. Consequently, if students do not fully grasp the reaction rates, their understanding of chemical equilibrium will likely be flawed.

Students' normalized gain, or <g>, and conceptual categories were also examined for each of the 15 questions in the conceptual test of chemical equilibrium (Figure 6 and 7; see *Appendix A2*).

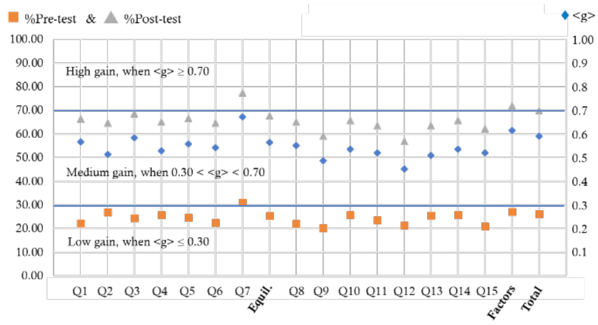

Figure 6. Percentages of the Pre- and Posttest Scores (left scale) and Normalized Gain or <g> (correct scale) for each Question in the Conceptual Test of Chemical Equilibrium

The percentages of students placed in the GU and PU categories, along with the mean posttest score and <g> for the chemical equilibrium topic, were higher compared to those for the topic of factors affecting equilibrium. This discrepancy was attributed to the lower complexity of the chemical equilibrium concept compared to the factors affecting equilibrium, which involved various elements, such as reactant and product concentrations, total pressure or volume, and temperature, which each uniquely influence chemical equilibrium (Kajornklin et al., 2020).

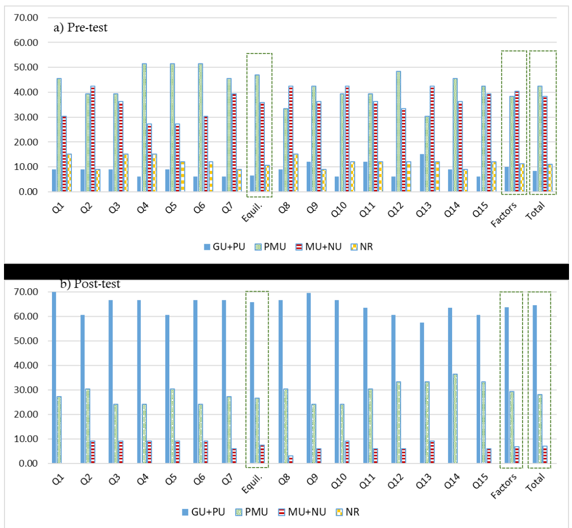

Figure 7. Percentages of the Students in each Conceptual Category in the a) pre- and b) post-conceptual Tests of Chemical Equilibrium

Furthermore, insights from the interviews regarding chemical equilibrium also supported this explanation and were aligned with those in the previous findings (Kajornklin et al., 2020; Tamuang et al., 2017), indicating that the factors affecting equilibrium were perceived as the most challenging topic within the chemical equilibrium subtopics.

Student A was classified as having Partial Understanding with Specific Misunderstanding (PMU) before the intervention because she demonstrated a limited understanding by stating,

"Chemical equilibrium is when the amounts of reactants and products stay constant, but this only happens in a closed system."

After the intervention, she progressed to the GU category, articulating a more transparent comprehension as follows:

"Chemical equilibrium presents when the rates of the forward and reverse reactions are the same or when the concentrations of both reactants and products are steady. Equilibrium can occur in closed and open systems, but there must not be gas in the reaction species if the reaction occurs in an open system."

Student B was initially categorized as MU because she held the specific misconception that:

"Chemical equilibrium is the state where the concentrations of both reactants and products are equal."

After the intervention, she moved to the PU category, showing partial understanding by stating,

"Chemical equilibrium is the state where the concentrations of both reactants and products are steady, though they do not have to be equal."

Student C was classified as NU before the intervention because he could not define chemical equilibrium. However, after the intervention, he advanced to PMU by expressing a partial understanding with a specific misunderstanding:

"Chemical equilibrium is the state where the rates of the forward and reverse reactions are equal, but it occurs only in a closed system."

Student D also started in the NU category because she did not understand chemical equilibrium. After the intervention, she moved to the MU category, expressing a specific misunderstanding by saying the following:

"Chemical equilibrium is when the concentrations of both reactants and products are equal, and the reaction must be irreversible."

The students were also interviewed with the additional question, "If you owned a plant producing ammonia gas through the Haber-Bosch process, what would you do to increase its productivity?" Their responses varied.

Before the intervention, Student A incorrectly stated, "Increasing the reaction temperature will increase the productivity of all reactions." However, after the intervention, she correctly explained that "decreasing the reaction temperature will increase productivity since the Haber-Bosch process is exothermic."

Student B initially responded incorrectly, saying, "Increasing the reaction pressure will increase the productivity of gas reactions." After the intervention, he provided a partially correct response, saying, "Decreasing the reaction temperature will increase productivity since some reactions perform better at lower temperatures."

The question that showed the most significant improvement was Q7, which focused on chemical equilibrium. In contrast, Q12, which addressed the factors affecting equilibrium, had the lowest performance, in alignment with the gains and percentages of students in the more accurate categories for these subtopics. Q7 was relatively straightforward; students could derive the K_c formula from the provided chemical reaction and easily calculate the K_c value. In contrast, answering the more complex question Q12 required understanding how Cl^- can form a precipitate in the presence of Ag^+. If Ag^+ is filled to the reaction, the Cl^- concentration (a reactant) decreases as some Cl^- forms a precipitate with Ag^+. Consequently, the reaction shifts backward, favoring the pink color. Misinterpreting this scenario prevents students from answering the question correctly.

This study provides implications for chemistry teachers, highlighting that while inquiry-based experiments can support students' progression from lower to higher conceptual understanding, they may not fully resolve misconceptions. To bridge this gap, teachers might consider integrating chemistry experiments, small-scale experiments (Listyarini et al., 2019), or experimental kits (Sharif et al., 2021) with visualization tools that help students connect observable macroscopic results and symbolic or chemical equation representations with abstract microscopic concepts. Incorporating these tools within the 5E inquiry framework can enhance students' comprehension at each phase of the learning process, engaging them through hands-on activities designed to spark curiosity and deepen their learning (Kibga et al., 2021; Ouahi et al., 2024). We recommend that future research should explore students' conceptual understanding, mental models, and science competencies as key study variables to help assess the effectiveness of small-scale and smartphone-based colorimetric experiments in enhancing both students' conceptual understanding and their science competencies in relation to chemistry concepts.

CONCLUSION

This study confirmed that using small-scale experiments on chemical equilibrium and the smartphone-based colorimetric determination of K_c through the 5E inquiry learning approach will successfully enhance students' understanding of the related concepts. The normalized gain between the pre- and post-conceptual tests indicated a moderate improvement in conceptual understanding. A paired-samples *t*-test revealed that the post-conceptual test scores were significantly higher than the pre-conceptual test scores with a 0.05 significance level. Before the intervention, most students fell into the PMU category, and none was classified as having GU. After the intervention, most students advanced to the PU category, and no students remained in the NU category. However, some misconceptions persisted because of the resistance to changing existing misunderstandings. The common misconceptions observed in the posttest included the following: equilibrium occurs only in a closed system; the concentrations of reactants and products are equal at equilibrium; increasing the temperature boosts productivity for all reactions; increasing the pressure raises productivity for all gas reactions; and confusion between the effects of temperature changes on endothermic and exothermic reactions.

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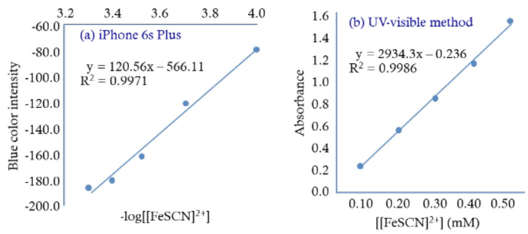
APPENDIX

Appendix I. Volumes and Concentrations of Calibration Solutions

Well no.	Volume (µL)				Initial Concentration (M)	
	0.05 M $Fe(NO_3)_3$	0.005 M KSCN	0.05 M HNO_3	Total	$Fe(NO_3)_3$	KSCN
Blank	300	0	900	1,200	1.25 x 10^{-2}	-
1	300	24	876	1,200	1.25 x 10^{-2}	1.00 x 10^{-5}
2	300	48	852	1,200	1.25 x 10^{-2}	2.00 x 10^{-5}
3	300	72	828	1,200	1.25 x 10^{-2}	3.00 x 10^{-5}
4	300	96	804	1,200	1.25 x 10^{-2}	4.00 x 10^{-5}
5	300	120	780	1,200	1.25 x 10^{-2}	5.00 x 10^{-5}

Appendix II. Calibration Plots of $[Fe(SCN)]^{2+}$ from Colorimetric Method Using Images Captured by iPhone 6s Plus (a) and UV-Vis Spectrophotometric Method (b)



Appendix III. Volumes and Concentrations of Equilibrium Solutions for the Determination of K_c Colorimetric and UV-Vis Methods

Well no.	Volume (µL)				Initial Concentration (mM)	
	0.05 M $Fe(NO_3)_3$	0.005 M KSCN	0.05 M HNO_3	Total	$Fe(NO_3)_3$	KSCN
Blank	600	0	600	1,200	2.50	-
1	600	60	540	1,200	2.50	0.25
2	600	120	480	1,200	2.50	0.50
3	600	240	360	1,200	2.50	1.00
4	600	360	240	1,200	2.50	1.50
5	600	480	120	1,200	2.50	2.00

Appendix IV. Concentration (M) of $[Fe(SCN)]^{2+}$ at Equilibrium and Equilibrium Constant or K_c by Colorimetric and UV-vis Methods

No.	Colorimetric Method (iPhone 6s Plus)			UV-visible Method		
	Int.	$[[Fe(SCN)]^{2+}]$ (mM)	K_c (M^{-1})	Abs.	$[[Fe(SCN)]^{2+}]$ (mM)	K_c (M^{-1})
1	-61.3	0.065	144.2	0.1664	0.065	143.5
2	-96.8	0.128	145.1	0.3495	0.127	143.7
3	-130.8	0.245	143.95	0.6896	0.243	142.3
4	-150.2	0.355	144.5	1.0156	0.354	144.0
5	-162.6	0.450	141.5	1.2945	0.449	141.2
	-	-	143.9	-	-	143.0
S.D.	-	-	1.37	-	-	1.17

Int. stands for "Intensity" and Abs. stands for "Absorbance"