# 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].

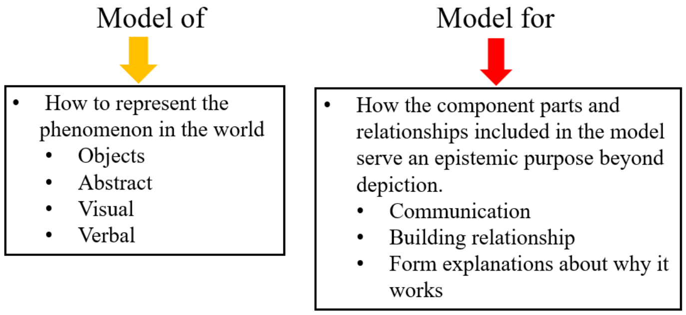
Many countries (e.g., Australia, Finland, Germany, Israel, Taiwan, and USA) are aware of the importance of developing students' understanding of nature of scientific models and modeling competence and included it in their K-12 curriculum standards/guidelines for sciences learning. Taking NGSS as an example, 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])



Model of

- How to represent the phenomenon in the world
  - Objects
  - Abstract
  - Visual
  - Verbal

Model for

- How the component parts and relationships included in the model serve an epistemic purpose beyond depiction.
  - Communication
  - Building relationship
  - Form explanations about why it works

## 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])

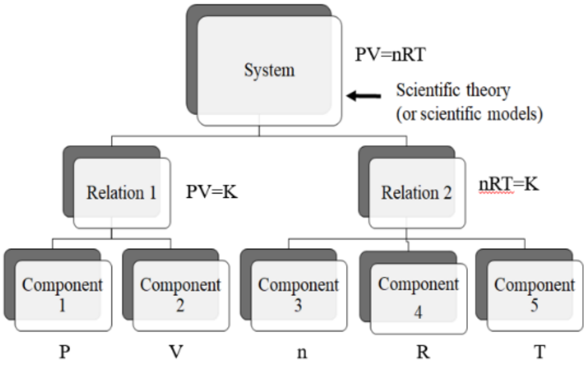


FIGURE 3

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

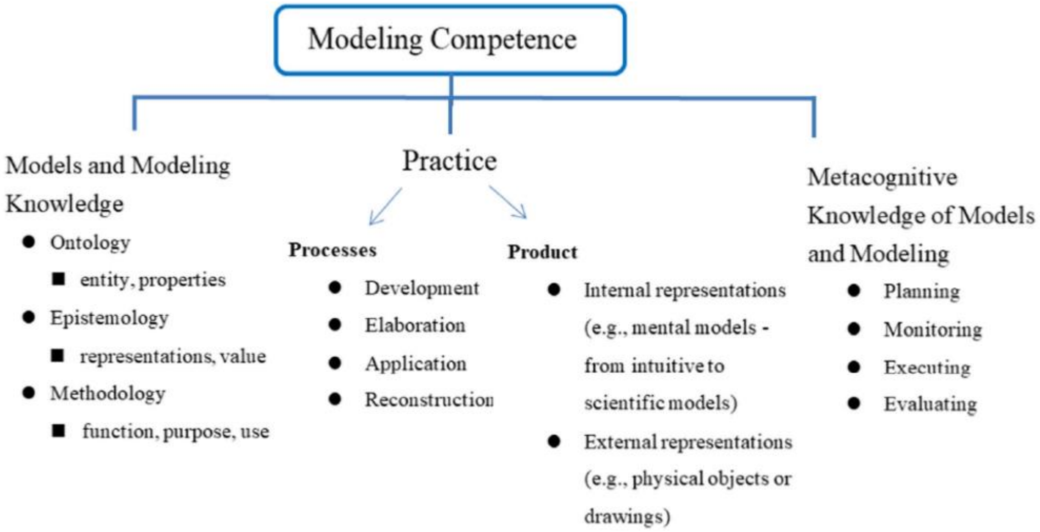
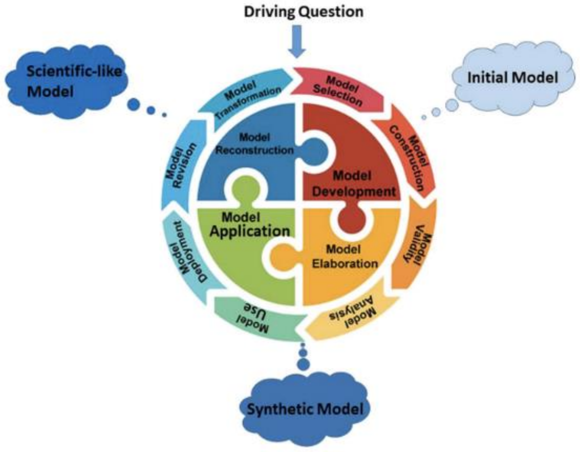


FIGURE 4

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

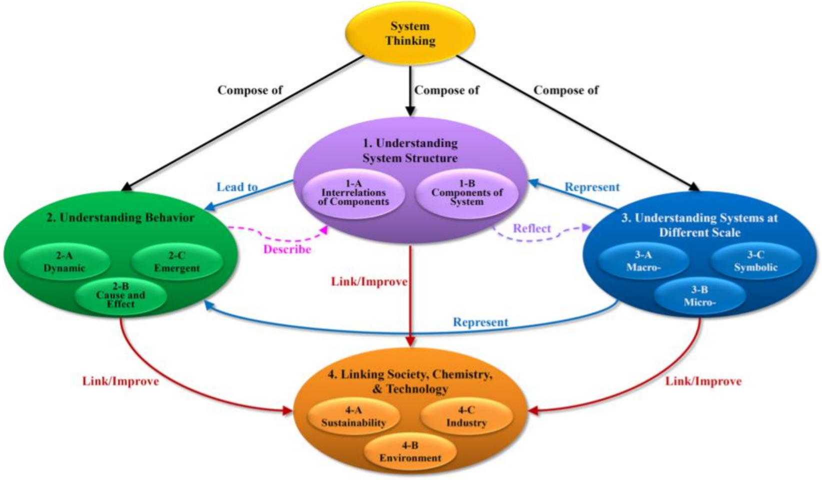
Based upon [38]'s analysis on PISA, they found that countries like Finland, Taiwan, Japan, Korea, and Germany, performed below OECD's average score on general interest in science, ways scientists design experiment, and what is required for scientific explanations, while the USA and Tunisia outperformed 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

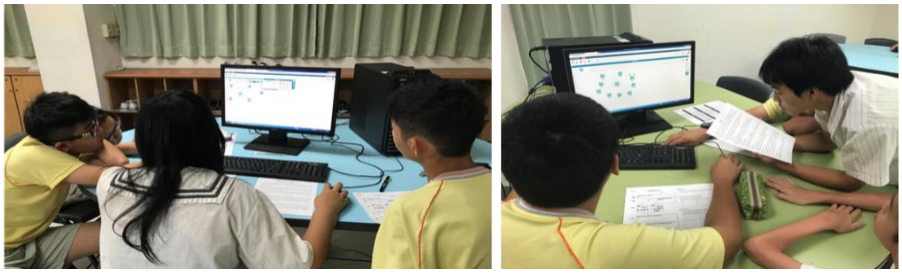
Water quality is a measure of how suitable water is for a particular use, such as drinking, or supporting aquatic life. The specific criteria for determining water quality would depend on the intended use of the water and the environmental regulations in place. Therefore, students should consider the 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

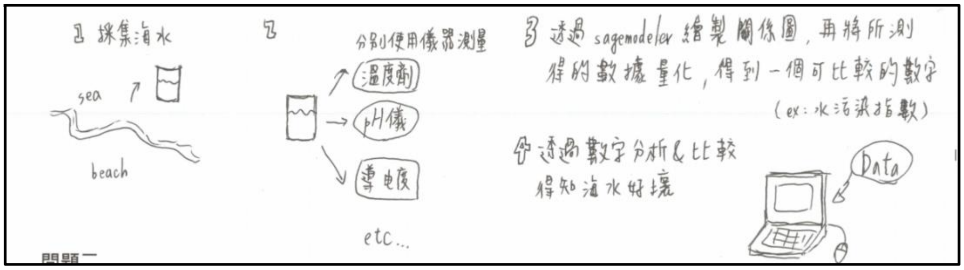
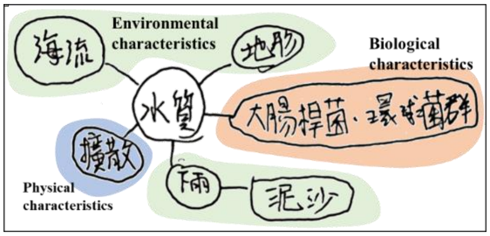


FIGURE 10

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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