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Design and Validation of a Virtual Chemical Laboratory—An Example of Natural Science in Elementary Education

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Featured Application: Virtual chemical laboratory system based on augmented reality.

Abstract: In the natural science curriculum, chemistry is a very important domain. However, when conducting chemistry experiments, safety issues need to be taken seriously, and excessive material waste may be caused during the experiment. Based on the 11-year-old student science curriculum, this paper proposed a virtual chemistry laboratory, which was designed by combining a virtual experiment application with physical teaching materials. The virtual experiment application was a virtual experiment laboratory environment created by using selected experimental equipment cards in combination with augmented reality (AR) technology. The physical teaching materials included all virtual equipment required for experiment units. Each piece of equipment had corresponding cards for learners to choose from and utilize in specific experimental operations. It was hoped that students were able to achieve the desired learning effectiveness of experimental teaching while reducing the waste of experimental materials through the virtual experimental environment. This study employed the quasi-experimental and questionnaire survey methods to evaluate both learning effectiveness and learning motivation. Eighty-one students and eight elementary school teachers were surveyed as research subjects. The experimental results revealed that significant differences in learning effectiveness existed between the experimental group and control group, indicating that the application of AR technology to teaching substantively helped enhance students' learning effectiveness and motivation. In addition, the results of the teacher questionnaire demonstrated that the virtual chemistry laboratory proposed in this study could effectively assist with classroom teaching.

Keywords: virtual chemistry laboratory; learning motivation; learning effectiveness; augmented reality

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1. Introduction

Over the past few decades, chemistry has been regarded as a very difficult subject, as its abstract concepts are hard to teach and difficult to be learned using an intuitive perspective. This has given rise to difficulties in learning. Serious misunderstandings arise when students learn using their existing concepts and views [1,2]. In fact, many abstract concepts are key in learning chemistry and other science subjects [3]. If students have no adequate grasp of these fundamental concepts, they cannot understand more difficult theories [4]. The Natural Science and Living Technology Curriculum in elementary schools involves multiple concepts. For example, the differences between many aqueous solutions cannot be distinguished intuitively; accordingly, students may develop misconceptions due to inadequate knowledge of different properties [5]. In traditional didactic teaching, teachers impart knowledge of many colorless and odorless gases only through textbooks. This is likely to result in rote memorization rather than true understanding on the part of students [6]. The experimental curriculum has been viewed as having great importance in helping students grasp difficult concepts through hands-on practice.

In addition to learning fundamental knowledge in the classroom, experimental operation is also a critical part of the chemistry curriculum. In [7], by Rusek et al., the findings of a questionnaire survey targeting 466 Czechoslovak primary school teachers showed that experiments play a pivotal role in education; however, in actuality, the proportion of teachers implementing the experimental curriculum remained low. Wieman [8] advocated for maintaining enthusiasm for experimental curriculum activities and practicing the acquired knowledge through the process of experiments. Experimental curriculum activities can not only cultivate students' logical thinking skills but also increase their problem-solving abilities [9]. To enable its students to understand course concepts, the Polytechnic University of Milan (Politecnico di Milano) specifically designed a laboratory to provide them with a good experimental environment for conducting experiments [10].

Safety considerations play a significant role in determining whether the experimental curriculum can be implemented. While engaging in chemistry experiment activities, students remain deficient in their perception and attitude toward experimental safety [11]. For example, in 2001, in an elementary school in Taichung City, Taiwan, an accident happened as a result of improper experimental operation. During the experiment process, all of the materials were mixed in an empty bottle, and carbon dioxide produced therein instantaneously exploded, injuring three students [12]. In 2020, four children in a primary school in Jiangsu, China sustained serious burns as a result of improper experimental operation. During the experiment, alcohol was mistakenly added to a lit alcohol burner/lamp, which caused an instantaneous explosion [13]. In fact, the danger latent in various kinds of glass equipment in laboratories is often overlooked by students and teachers [14].

In recent years, school laboratory accidents have happened frequently. For instance, according to the analysis of the major school laboratory accidents from 2011 to 2016 released by Taiwan's Ministry of Education [15], among the 77 accidents that occurred in these five years in Taiwan, the top 2 accidents with the highest percentages were fire and cut injuries. According to the 2017/2018 survey of school laboratory accidents by the Hong Kong Education Bureau [16], there was a total of 287 laboratory accidents, 36% of which were cuts caused by such glass equipment as test tubes, beakers and catheters, and 50% were burns resulting from touching the source of fire while handling tripods, pliers or alcohol burners. In 2020, a laboratory explosion incident happened in the Chemistry Department of the University of Pennsylvania in the USA. Due to students' improper manipulation, the machine tools in the laboratory gave off sparks, which ignited volatile gases, thereby causing an explosion [17]. The above literature indicates that accidents will happen to students in different regions and of different grades during the process of experiment operations at school laboratories, as shown in Table 1.

Table 1. Laboratory accidents in different places in recent years.

Institute	Year	Nation/Area	Grade	Factors Causing Dangerous Incidents
Taichung City Government Information Bureau	2001	Taiwan	Elementary School	Explosion caused by carbon dioxide
Ministry of Education	2018	Taiwan	High School	Fires and cut injuries
Education Bureau	2018	Hong Kong	Secondary School	Glass cuts and fire burns
Qianjie Elementary School	2020	China	Elementary School	Instantaneous explosion caused by alcohol
University of Pennsylvania	2020	USA	University	Explosion caused by volatile gases

Alternatively, the materials used in the process of chemistry experiments resulted in a lot of waste after experiments. Many people have begun to discuss the issue of excessive material waste in experiments in recent years, as environmental awareness has grown both within and outside Taiwan. According to the feedback of a teacher questionnaire survey, Yang [18] concluded that the amount of materials used in the process of experiments should be reduced, while alternative experiments that are eco-friendly should be developed to replace experiments in traditional teaching. Take the aqueous solution unit in the elementary school Natural Science and Living Technology Curriculum domain as an example. In the electrical conductivity experiment of aqueous solutions, the electric wires and aqueous solutions used cannot be reused [19]. In the acidity and alkalinity experiment of aqueous solutions, a set of litmus paper has to be used for testing each solution, which results in excessive waste of materials [20]. Thus, reducing the use and waste of consumable materials in the process of chemistry experiments is also an issue worth investigating and studying.

In the 1990s, Zhang [21] defined learning motivation as an inner psychological process which teachers can stimulate in students to engage in a learning activity, continue and direct the activity toward the objectives set by the teachers in their instruction. Literature [22] highlighted that in the process of teaching, good learning motivation will affect the learning strategy of learners, which, in turn, will raise the significance of learning effectiveness. However, in traditional teaching methods, often due to curriculum schedules and safety of experiments, teachers will teach simply by showing pictures or playing videos. Students' learning motivation may suffer as a result of such methods. Further literature [23,24] also highlighted that most science subjects focus too much on the transmission of knowledge while overlooking whether this could enhance students' interest and motivation. As learning motivation is critical to the depth of understanding curriculum contents [25], enabling students to maintain high interest and learning motivation in learning the science curriculum are important educational goals.

With the flourishing development of information technology in recent years, mobile devices such as smartphones have become increasingly popular in an individual's daily life. The technological development of these mobile devices has contributed to the introduction of augmented reality (AR) technology into the educational domain; the concept of augmented reality has immensely impacted teaching methods and curriculum content design in recent years. Many people have proposed applying AR in the curriculum so as to add more fun and interaction to it, thereby increasing students' learning motivation and enhancing their learning effectiveness. The related examples of AR application are shown in Table 2.

In summary, the above examples of applying AR technologies to the education domain show that the use of AR methods in teaching not only makes curriculum design more innovative and attractive but also increases students' learning motivation with higher levels of fun and interactivity, thereby enhancing their learning effectiveness. If experiments are needed in the curriculum as a means of assisted teaching, AR is also very suitable for experimental teaching, as the virtual laboratory can solve the safety problem and allow learners to actually operate different types of experiments through a micro perspective.

Based on the above literature review, AR could significantly enhance both the learning motivation and effectiveness of students. Thus, this study designed experiments targeting the 11-year-old student Natural Science and Living Technology Curriculum. Through the virtual chemistry laboratory, students could avoid the dangers resulting from their erroneous operation and reduce the waste of experimental materials. Students were provided with a pre-class exercise and post-class review so as to increase their learning motivation and enhance their learning effectiveness in relation to the curriculum. Further, this study also aimed at increasing the willingness of teachers to use the virtual chemistry laboratory in their class so as to lower the pressure of preparing for experimental lessons. This study put forth an experimental teaching method using AR and compared it with traditional experimental teaching methods. Three main contributions of the study are listed below:

1. With respect to equipment, the proposed teaching method lowers the cost of equipment needed for chemistry experimental teaching through smartphones and cards.

2. With respect to environmental protection, the proposed teaching method implements the idea of green chemistry experiments, reducing the use of consumable materials and production of waste.
3. With respect to safety, the proposed teaching method avoids dangers that may happen due to erroneous operation in the process of chemistry experiments.

Table 2. Examples of application of AR to different educational domains.

Reference	Year	Characteristics
[26]	2009	Using AR to assist students in their English learning by using novel methods to stimulate learning
[27]	2013	Enabling students to understand the abstract electromagnetic force unit through the method of AR simulation
[28]	2017	Assisting students in performing robotics programming through using AR in combination with smart glasses
[29]	2017	Analyzing teaching methods using virtual laboratories, as compared to those using traditional ones, which can transform the future learning method of students
[30]	2018	Conducting experiments with the assistance of the method of AR in conjunction with physical chemistry equipment
[31]	2018	Visualizing chemical molecular models by displaying them on labelled cards to help students learn chemistry more clearly
[32]	2018	Enabling users to understand laboratory safety rules with mixed reality technology through smart glasses
[33]	2018	Comparing the effectiveness of spatial memory training between AR and virtual reality (VR) in a control-room scenario to evaluate the impact of AR and VR training on short-term and long-term memory. The results show that VR training is better than AR in short-term memory, and AR training is better than VR in long-term memory
[34]	2021	Visualizing 3D piano performance animations for both hands based on the input MIDI file, which contains the time sequences of different keys
[35]	2021	Using collaborative AR to extend the concept of the touring of painting art exhibitions towards collecting itinerary and interaction analytics

The research results revealed that in the learning of the Natural Science and Living Technology Curriculum, the group operating virtual experiments and that conducting traditional experiments reached statistically significant difference in their extent of progress. The experimental group achieved greater progress than the control group, indicating that the application of AR to teaching was indeed helpful to learning. As per responses shared in the questionnaire, students showed high levels of satisfaction with regard to the use of AR in learning, thereby indicating that AR was helpful in strengthening their learning motivation. Teachers also showed high levels of acceptance regarding the application of AR to teaching, demonstrating that virtual chemistry laboratory could effectively assist teachers in their classroom instruction.

2. Research Method

Figure 1 shows the research framework diagram of this study. We proposed a teaching system that was designed in accordance with the experiments in the 11-year-old student Natural Science and Living Technology Curriculum, and evaluated the learning effectiveness of students using this system through the quasi-experimental and questionnaire survey methods. Further, this study also invited several elementary school teachers to personally take part in virtual chemistry experiments, and conducted the survey according to their opinions. After the experiment, we performed an analysis of the collected test papers and questionnaires. Further explanations are provided below regarding the research subjects, curriculum planning, research design, experimental procedures, and research tools. The virtual chemistry laboratory will be introduced in detail in the next section.

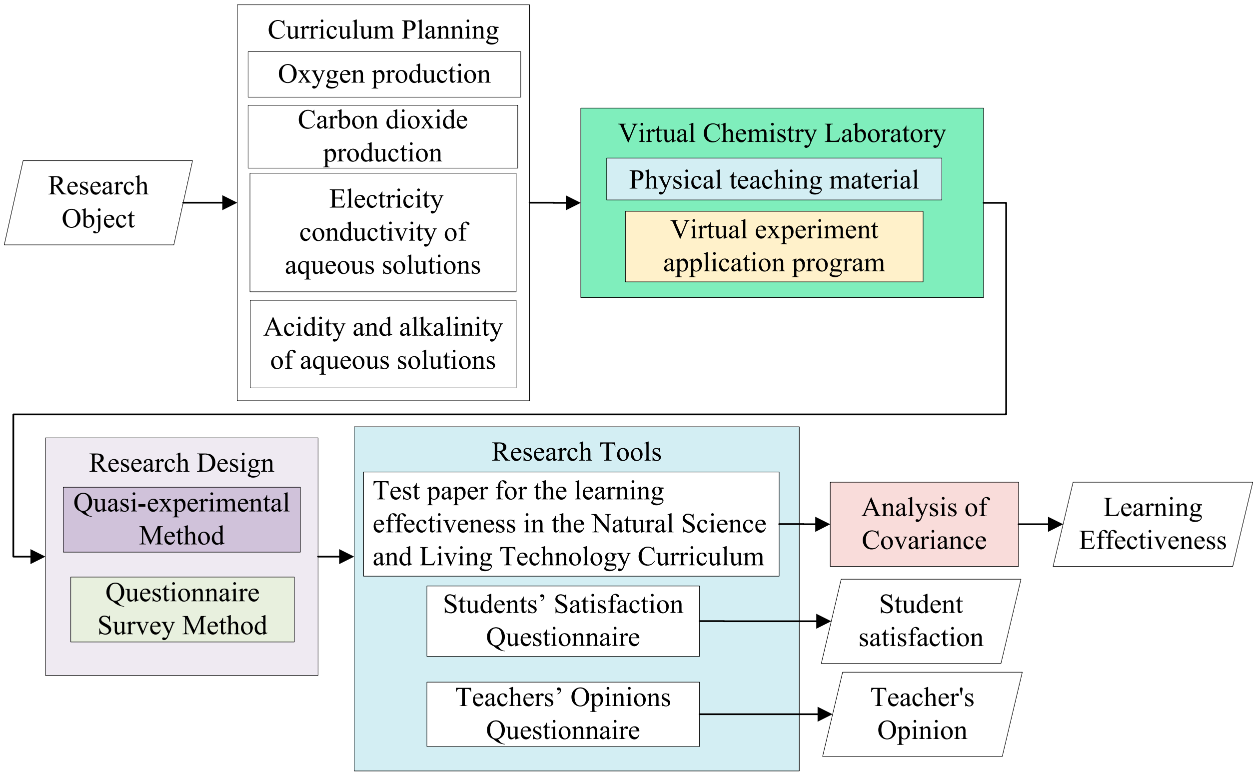


Figure 1. Architecture of the research method used in this study.

2.1. *Research Subjects*

The research subjects of this study were 11-year-old students, and the place of the experiment was an elementary school in Yunlin County. The study considered 11-year-old students as its research samples, with a total of 81 research participants. Additionally, an opinion survey was conducted on eight teachers. The number of people allotted to each group of the experimental teaching is shown in Table 3, with 41 students in the experimental group and 40 in the control group. The experimental group used the virtual chemistry laboratory when conducting experiments, while the control group conducted traditional experiments.

Table 3. Group number in this study.

Group	11-Year-Old Students
Control Group	40
Experiment Group	41

2.2. *Curriculum Planning*

This study hoped that through different experimental methods, students could use new experiential ways to conduct experiments under the premise of safety, thereby understanding the related concepts in the Natural Science and Living Technology Curriculum. Therefore, this study designed a virtual chemistry laboratory that combined technology, educational goals, and experiments. Its learning objectives and contents are given in detail below.

2.2.1. Learning Objectives

In the 2019 curriculum guidelines for the 12-Year Basic Education, the learning domain of the 11-year-old student Natural Science and Living Technology Curriculum includes experiments of three units, as shown in Figure 2. Among these three, the unit of air and combustion involves the production of oxygen and carbon dioxide. As oxygen is comburent, students may touch the source of fire during experimental operation, and accordingly cause an explosion. In the making of carbon dioxide, it is necessary to mix different materials in an air-tight container, which may cause an explosion [12,13].

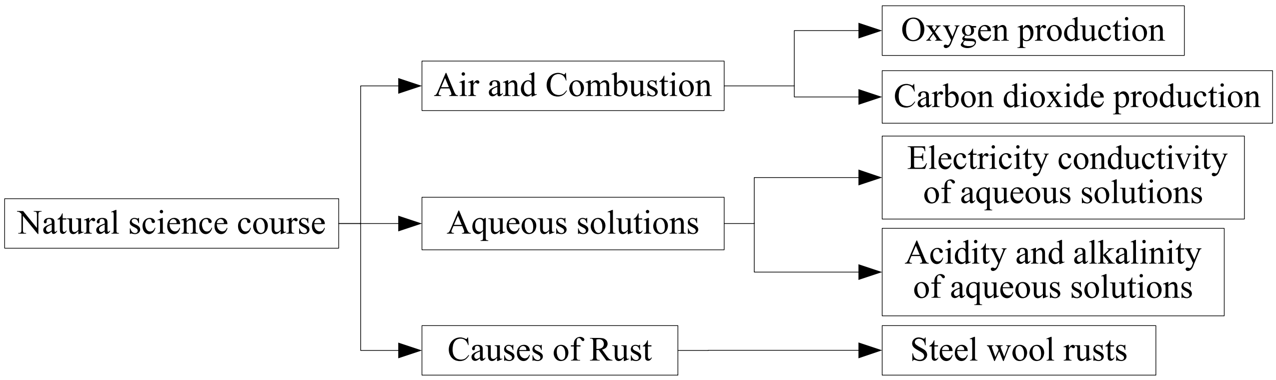


Figure 2. Knowledge framework of related concepts in natural science courses.

Alternatively, the aqueous solutions unit includes two experiments; one on their electrical conductivity, and the other on their acidity and alkalinity. In the process of these two experiments, it is necessary to perform reaction tests between experimental equipment and several kinds of aqueous solutions. To ensure the precision of the experiment, used electric wires, aqueous solutions and litmus paper cannot be reused. The use of excessive materials leads to waste. The unit on the causes of rusting contains a rusting steel wool experiment, which only requires steel wool and a single solution as experimental materials. The steel wool soaked with solution is compared with an unsoaked one. The solution is then allowed to stand for a period of time, after which students observe their respective reaction results. In the process, relatively little consideration is given to safety and environmental protection.

A previous study [36] found in a survey on elementary school science teachers regarding the current situation of science classrooms in elementary schools that inadequate fire equipment in elementary school laboratories is a cause of concern about the safety of students. Coupled with the excessive waste of materials in the experimental process, this has caused laboratories to become the blind spot for safety and environmental protection in school campuses. Hence, the emphasis on the planning of learning objectives in this study was designed according to the following four considerations:

1. To design virtual experiments with safety concerns
2. To design virtual experiments involving limited waste of excessive materials
3. To cultivate thinking and problem-solving abilities from experiments
4. To foster interest in scientific inquiry from experiments

2.2.2. Learning Contents

According to the planning of learning objectives, this study chose the experiments of two units, namely, air and combustion and aqueous solutions, designing them as virtual experiments. The five parts of the experimental curriculum planning, viz., theme, unit experiment, learning objectives, learning content, and factors of safety and environmental protection are shown in Table 4.

Table 4. Planning table of Natural Science and Living Technology Curriculum experimental curriculum.

Theme	Unit Experiment	Learning Objectives	Learning Content	Safety or Environmental Protection Factor
Air and Combustion	Oxygen production	Learn how to produce oxygen and examine its properties	Investigate what reaction oxygen and fire will produce	Instantaneous explosion
	Carbon dioxide production	Learn how to produce carbon dioxide and examine its properties	Investigate which materials, when mixed together, will produce carbon dioxide	Instantaneous explosion
Aqueous solutions	Electricity conductivity of aqueous solutions	To know that different aqueous solutions have different electrical conductivity	Test whether different aqueous solutions can conduct electricity through battery-operated light bulbs	Waste of materials
	Acidity and alkalinity of aqueous solutions	Understand color changes of litmus paper in aqueous solutions with different acidity and alkalinity	Distinguish the acidity and alkalinity of different aqueous solutions and test them with litmus paper	Waste of materials

2.3. Research Design

This section was divided into two parts. The quasi-experimental research method and questionnaire survey method were employed, with the aim to investigate the effects of different methods of experimental teaching on the learning effectiveness of 11-year-old students in the Natural Science and Living Technology Curriculum, and the level of satisfaction of the experimental group students and teachers after using the virtual chemistry laboratory. The research design of this study is described below.

2.3.1. Quasi-Experimental Method

By the research definition of this study, as there was no way to achieve complete random assignment in the experimental design, a quasi-experimental method was adopted. However, as such a method cannot develop an ideal and real experiment with other disturbances excluded, a method of statistical control was used. The commonest analytical method in statistical control is the analysis of covariance, which is divided into three variables, namely the independent variable, covariate variable, and dependent variable. The independent variable of this study was different methods of experimental teaching, which could be divided into experimental and control groups. The dependent variable was the post-test scores of learning effectiveness, while the covariate variable was the pre-test scores of learning effectiveness.

2.3.2. Questionnaire Survey Method

This study adopted the students' satisfaction questionnaire and teachers' opinions questionnaire as the experimental questionnaires. The former was for surveying the level of satisfaction of the experimental group students with the way of learning under the virtual chemistry laboratory. The teachers' opinions questionnaire was for surveying their opinions after using the virtual chemistry laboratory.

2.4. Experimental Procedure

The experimental procedure of this study is shown in Figure 3, which was mainly divided into three stages, namely pre-test, experimental curriculum activities, and post-test. The research samples were 81 participating students, who were divided into experimental and control groups. The former conducted the virtual experiment, while the latter, traditional ones. The time of the experiment of this study totaled 80 min.

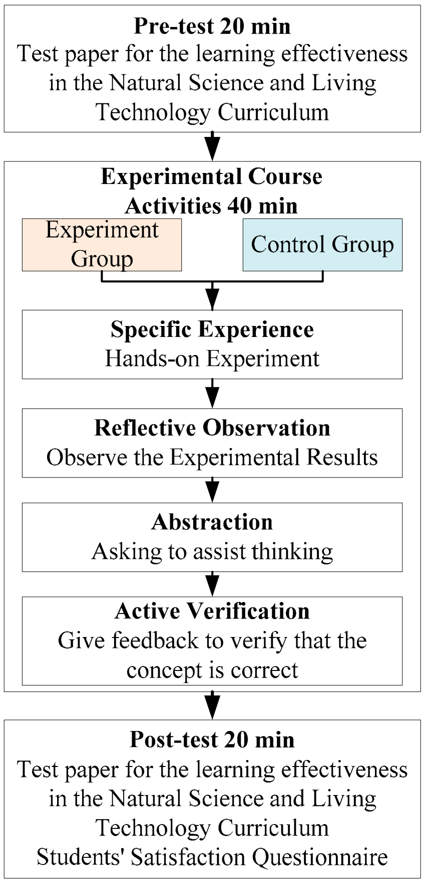


Figure 3. Flow chart of the experimental activity in this study.

2.5. Research Tools

In this experimental teaching, three research tools were used: the test paper for the learning effectiveness in the Natural Science and Living Technology Curriculum, the student satisfaction questionnaire, and the teacher opinions questionnaire, which are all described below.

2.5.1. Test Paper for the Learning Effectiveness in the Natural Science and Living Technology Curriculum

The test paper for learning effectiveness in the Natural Science and Living Technology Curriculum of this study was administered before the experimental teaching. Its aim was to understand students' knowledge of the concepts in the Natural Science and Living Technology Curriculum before and after the experimental teaching. The scope of the content of the test paper revolved around the units of air and combustion and aqueous solutions. The question types included multiple-choice questions of three difficulty levels: high, medium, and low, with a total of 20 questions, including 10 low-level questions, 5 medium-level questions, and 5 high-level questions. The analysis of covariance was used to analyze learning effectiveness.

2.5.2. Student Satisfaction Questionnaire

The student satisfaction questionnaire of this study was administered after the experimental teaching, with the aim to analyze the level of students' acceptance of integrating the virtual chemistry laboratory into experimental curriculum activities, and their opinions and suggestions in relation to learning. The design of the questionnaire adopted the form of a five-point Likert scale, and descriptive statistics were used to present the survey results. The questionnaire was developed by the researcher with references taken from related questionnaires of other researchers and further adaptations made [37–39].

2.5.3. Teacher Opinions Questionnaire

The teacher opinions questionnaire was administered after the experimental teaching, with the aim to analyze what the teachers thought about integrating the virtual chemistry laboratory into the experimental curriculum activities, and their opinions and suggestions in relation to teaching. The design of the questionnaire adopted the form of a five-point Likert scale, and descriptive statistics were used to present the survey results. The questionnaire was developed by the researcher with references taken from related questionnaires of other researchers and further adaptations made [38,40].

3. The Proposed Design of Virtual Chemical Laboratory

This study developed a virtual chemistry laboratory, which was based on AR technology to provide a teaching method different from the traditional chemistry experiments, aiming to help students benefit from active learning with teachers undertaking the role of facilitators. Figure 4 is the schematic diagram of teaching methods of traditional chemistry experiments and the proposed virtual chemistry experiment. Figure 4a is the schematic diagram of the teaching method of traditional chemistry experiment. The teacher primarily explains and demonstrates the experimental steps, while students replicate the demonstrated steps while conducting the experiment. After the experiment, the waste produced in the experimental process has to be cleaned. Such a traditional teaching method not only wastes resources but also has the problem of personal safety when dangerous experiments are conducted. Figure 4b is a schematic diagram of the teaching method of the proposed virtual chemistry laboratory, where experiments are conducted and chemical reactions are simulated through AR approaches to provide students with experience similar to actual experiments. Further, virtual experiments allow students to repeat the experiments. Aside from avoiding waste and wasting resources, virtual experiments can eliminate concerns regarding the occurrence of dangerous incidents due to erroneous operation in hazardous experiments, thereby enabling students to understand which dangerous reactions will occur as a result of erroneous operation.

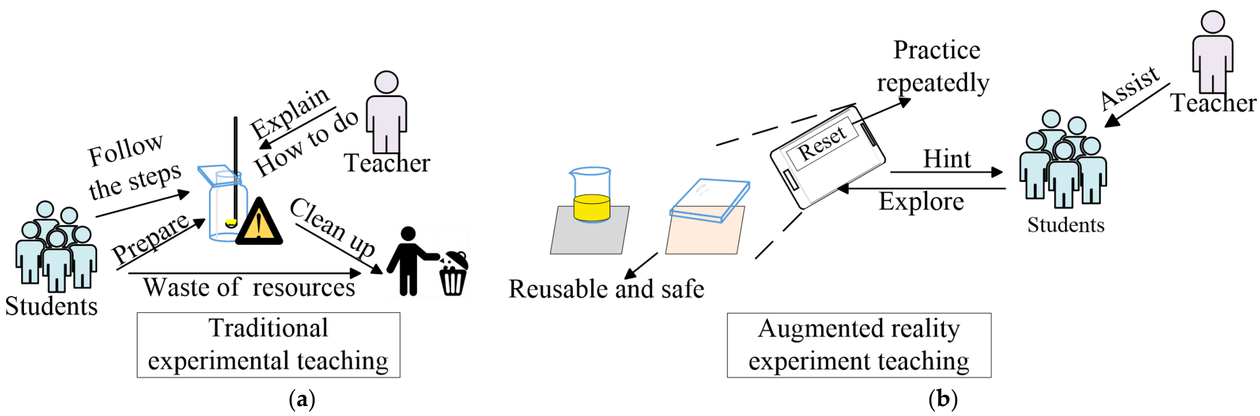


Figure 4. Comparison of two teaching methods: (**a**) teaching method of traditional chemistry experiments, (**b**) teaching method of the proposed virtual chemistry laboratory.

3.1. The Proposed Virtual Chemistry Laboratory

This section explains the idea and operational concept of the virtual chemistry laboratory design, whose framework diagram is represented in Figure 5. This teaching system was made up of three parts, namely, Android App, AR and the physical teaching materials bank. Users could enhance their sense of experience through the virtual chemical reactions in an actual scene by operating AR chemistry experiments. It was hoped that consistency with traditional chemistry experiments was retained during the process of user operations, with the element of interactivity added.

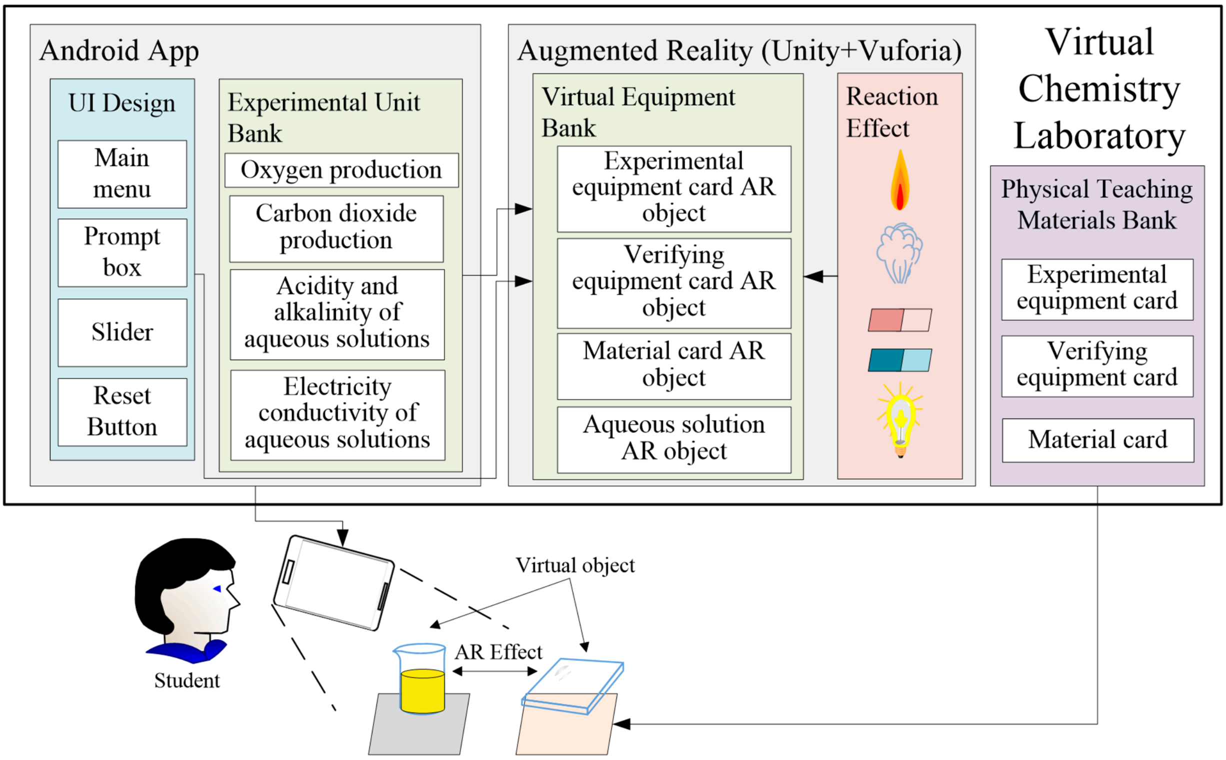


Figure 5. Architecture of the proposed virtual chemistry laboratory.

3.1.1. Android App

An Android App was used to execute the operational interface of the proposed teaching system, which was provided for students to use in their mobile devices. It contained two parts, namely, the experimental unit bank and user interface (UI) design. The experimental unit bank was made up of several experimental units and accessed from the application, and learners could choose by themselves the experimental unit they would like to learn. After making the selection, a scene switch would appear on the smartphone screen, switching the experimental scene to the corresponding unit, and this made learning several experiments possible.

For the UI design, students could see several experimental units and descriptions of their experiments. In the process of the experiment, when learners encountered something they did not understand, they could click the hint button, and a prompt box would appear to guide them to operate the experiment. By manipulating the slider component, learners could freely add the required solution dosage for different experiments. If users failed in an experiment operation or wished to re-experience the experimental activities after finishing an experiment, they could repeat the operation through the reset button.

3.1.2. Augmented Reality (AR)

AR was an important function of the proposed virtual chemistry laboratory. It included two parts, namely, a virtual equipment bank and reaction effects, which were used to present various kinds of chemical reactions needed for the virtual chemistry experiments. The virtual equipment bank provided every simulated virtual object, including the virtual objects of experimental equipment cards, materials cards, verifying equipment cards and aqueous solutions, for matching various cards in the physical teaching materials bank. In the experimental process, students were required to pick the cards they needed from the physical teaching materials bank, and when they identified them with their smartphones, the corresponding virtual objects could be displayed. The reaction effects were to enable the students to understand the chemical reactions in the experimental process in the process of operating virtual chemistry experiments. Thus, to make the reaction effects of virtual experiments identical to actual situations, we designed several kinds of reaction effects according to the needs of different experiments, such as flame ignition, bubble generation, color changes of litmus paper, and light bulbs lighting up. Note that we used Unity and Vuforia engines to develop the virtual objects, reaction effects, and pose tracking functions required in the AR environment.

3.1.3. Physical Teaching Materials Bank

According to the above-mentioned curriculum planning, this study designed four experimental units. All devices needed for each unit would have their corresponding cards. According to the needs of the experiments, the collision between the experimental cards could attain the function of equipment assembly, while the collision between experimental equipment and materials cards could produce the effect of adding materials. Finally, through verifying equipment cards, the chemical reactions of each experiment could be understood so as to examine whether the experiments were correct. The functions designed for various kinds of cards are shown in Table 5.

Table 5. Card designs and function descriptions.

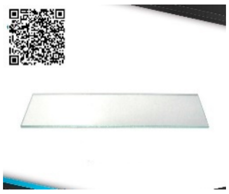
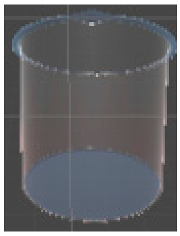
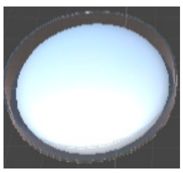
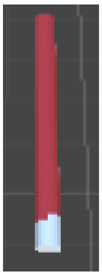
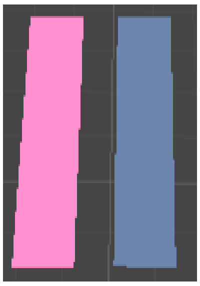
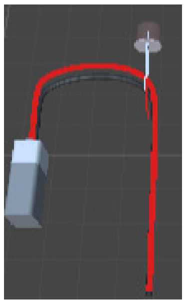
Card Type	**Physical Teaching Material**				**Function Description**
Experimental equipment card					
Name	Wide mouth bottle	Glass	Beaker	Dropper	Equipment Assembly
AR object					
Material card					
Name	Enoki mushroom		Baking soda		Addition of material
AR object					

Table 5. *Cont.*

Card Type	Physical Teaching Material				Function Description
Verifying equipment card					
Name	Incense	Candle	Litmus paper	Battery bulb group	Displaying chemical reaction
AR object					

3.2. Operation Procedures

Table 6 shows the operational procedures of all experimental units. Students had to conduct the experimental operation in accordance with these procedures, and at the end, the AR reaction effects could be used to determine whether the experiments were correctly conducted. Table 7 shows the screen of actual operation and descriptions of the steps of the experiment of the oxygen production unit. It contained five steps.

Table 6. Operational concepts of each experimental unit.

Experimental Unit	Operational Procedure	Related Chemical Reaction
Oxygen production	Prepare a wide-mouth bottle → Add hydrogen peroxide to the bottle → Add enoki mushrooms → Cover the bottle with a glass plate → Place incense sticks in the wide-mouth bottle to verify the comburent phenomenon	1. The gas produced by adding too little solution is insufficient to set the incense sticks on fire 2. Under standard condition, the incense sticks will be lit and burn 3. The gas produced by adding too much solution will render the incense sticks to burn more vigorously than under standard conditions
Carbon dioxide production	Prepare a wide-mouth bottle → Add vinegar to the bottle → Add baking soda → Cover the bottle with a glass plate → Place a candle over the wide-mouth bottle to verify the phenomenon of inhibiting combustion	1. The gas produced by adding too little solution is insufficient to extinguish the candle 2. Under standard conditions, the candle will go out 3. The bubble produced resulting from the reaction of adding too much solution will spill over the container, making it impossible to continue the experiment
Acidity and alkalinity of aqueous solutions	Prepare a beaker → Add solution to the beaker → Use a dropper to suck up the solution → Place the solution sucked up by the dropper on a piece of litmus paper → Verify the acidity and alkalinity of the solution	1. Neutral solution → No change in the color of the litmus paper 2. Acidic solution → No change in the color of red litmus paper, the blue turns red 3. Alkaline solution → Red litmus paper turns blue; the blue remains unchanged

Table 6. *Cont.*

Experimental Unit	Operational Procedure	Related Chemical Reaction
Electrical conductivity of aqueous solutions	Prepare a beaker → Add solution to the beaker → Place a set of battery-operated light bulbs in the solution → Verify whether the solution has electrical conductivity	1. Solutions possessing conductivity → light bulbs will light up 2. Solutions possessing no electrical conductivity → light bulbs will not light up

Table 7. Steps of operating the oxygen production experiment.

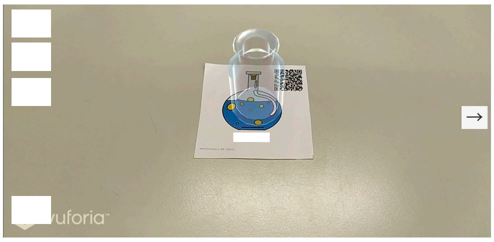
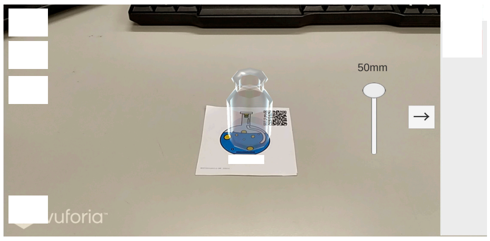
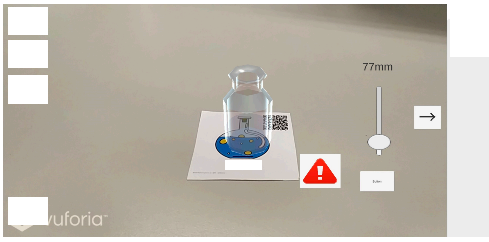
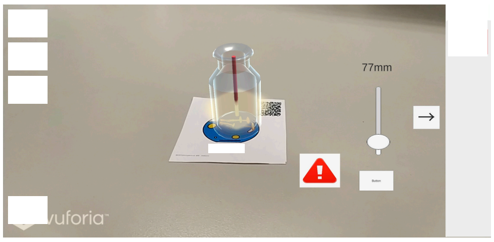
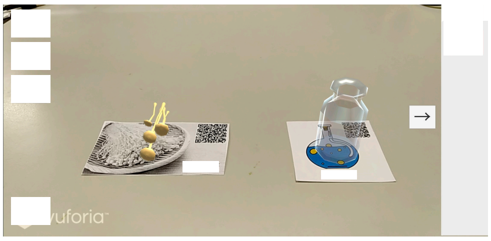
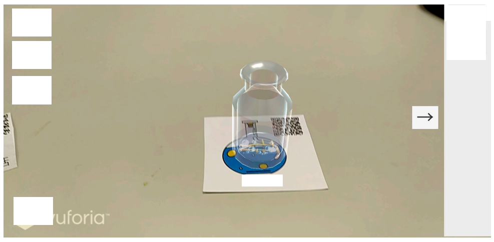
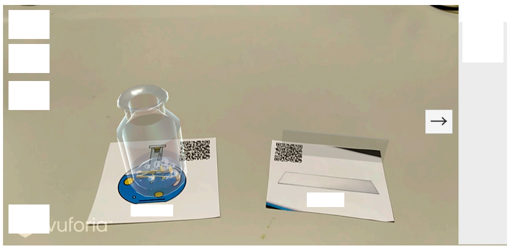
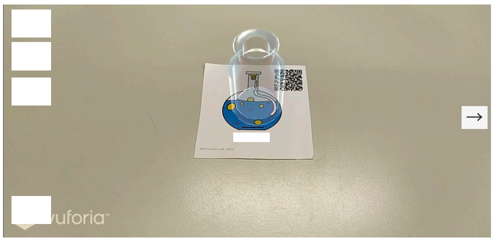
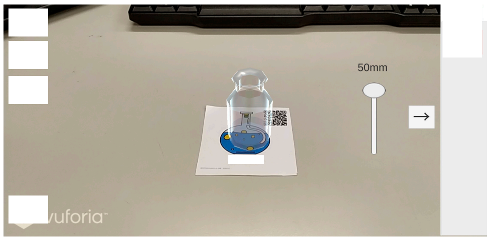
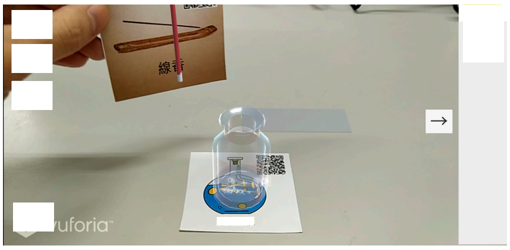
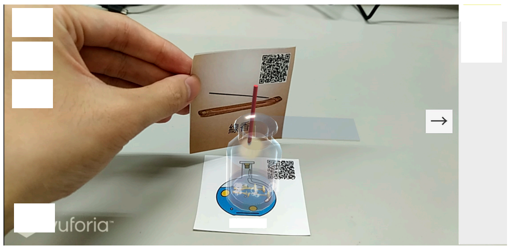
Step 1	 
Screen description	Take the experimental equipment card of the wide mouth beaker, and click the right arrow on the right side of the screen to choose the solution to be added.
Step 2	 
Screen description	If the user adds excessive amounts of solution, there will be a warning and animation to remind her/him.
Step 3	 
Screen description	Take the enoki mushroom card and add it to the experimental equipment card of the wide mouth bottle, and then observe the phenomenon of oxygen generation.
Step 4	 
Screen description	Take and then place the experimental equipment card of the glass plate over the experimental equipment card of the wide mouth bottle.

Table 7. *Cont.*

Step 1		
Step 5		
Screen description	Take and place the verifying equipment card of the incense sticks in the experimental equipment card of the wide-mouth bottle, and then observe the comburent phenomenon.	

Step 1: Prepare the equipment cards needed for the experiment.
Step 2: Add the aqueous solutions needed for this experiment; in this step, warning signs would appear to remind the students not to add excessive solution volumes.
Step 3: Use the materials cards to add the materials for producing oxygen; in this experiment, enoki mushrooms were used.
Step 4: Cover the wide-mouth bottle with glass plate equipment and wait for oxygen to be produced.
Step 5: Use the verifying equipment card of incense sticks to test the comburent phenomenon of oxygen. The more oxygen produced, the more obvious the comburent phenomenon of the incense sticks.

Note that interested readers can refer to the following four online videos to watch the demonstration of each virtual experiment listed in Table 6:

Video of oxygen production—https://youtu.be/sjMqkrDD-vA (accessed on 24 October 2021).

Video of carbon dioxide production—https://youtu.be/AEjhQvwQI4g (accessed on 24 October 2021).

Video of acidity and alkalinity of aqueous solutions—https://youtu.be/eCyZ8sp-Wss (accessed on 24 October 2021).

Video of electrical conductivity of aqueous solutions—https://youtu.be/vn_Qb444uHU (accessed on 24 October 2021).

4. Results

This section investigates the experimental results using different teaching methods, including the difference in learning effectiveness of 11-year-old student in the Natural Science and Living Technology Curriculum. It also sought to understand the opinions and views of the students and teachers in the experimental group on the virtual chemistry laboratory through the students' satisfaction and teachers' opinions questionnaires. The survey results were analyzed and discussed. An analysis was performed on the collected experimental data using the SPSS 20 statistical software. A detailed explanation of analytical methods is given below.

4.1. Learning Effectiveness

This study aimed to investigate the effects of applying the virtual chemistry laboratory to the Natural Science and Living Technology Curriculum on 11-year-old students. This was done by administering a learning effectiveness pre-test before the implementation of the curriculum activities and a post-test right after the completion of curriculum experimental activities. The differences in the influences the varied experimental teaching methods had on the two groups were analyzed.

4.1.1. Test of Homogeneity of Within-Group Regression Coefficient

First, before performing the covariance analysis, it was necessary to conduct a test of homogeneity of regression slope, thereby examining the interaction effect between the covariate variable and dependent variable in each group with regression analysis. If the effects accorded with the hypothesis of the covariance analysis, which was the homogeneity of within-group regression coefficients, the subsequent covariance analysis could then be conducted. The test results of the test of homogeneity of regression coefficients of this study are shown in Table 8.

Table 8. Test of homogeneity of within-group regression coefficients.

Source of Change	Sum of Squared Deviation from the Mean	Degree of Freedom	Mean Sum of Squares	F-Test	*p*-Significance
Pre-test results	6859.834	1	6859.834	279.385	0.000
Group	37.443	1	37.443	1.525	0.221
Interaction effect(pre-test results × group)	23.714	1	23.714	0.966	0.329
Error	1890.607	77	24.553		

The analysis results showed that the test of homogeneity of the learning effectiveness tests under different methods of experimental teaching did not reach the significance level of 0.05. The F-value was 0.966, while the p-value was 0.329 > 0.05. Therefore, the result accorded with the hypothesis of the covariance analysis's test of regression coefficient homogeneity.

4.1.2. Comparison of the Differences in Learning Outcomes

The descriptive statistics of the pre- and post-tests of different groups were shown in Table 9. The mean score and standard deviation of the control group in the pre-test were 80.875 and 10.794 respectively, while those of the experimental group were 82.195 and 9.490 respectively. The mean score and standard deviation of the control group in the post-test were 83.000 and 11.367 respectively, while those of the experimental group were 86.585 and 9.901 respectively. Note that, since most of the test questions are low-level questions, the difference in the mean of the corresponding pre-test and post-test scores is relatively small.

Table 9. Summary table of descriptive statistics.

Group	Source of Change	Mean	Standard Deviation	Number of People
Control group	Pre-test	80.875	10.794	40
	Post-test	83.000	11.367	40
Experimental group	Pre-test	82.195	9.490	41
	Post-test	86.585	9.901	41

The results of the covariance analysis were shown in Table 10. The differences between the two groups were significant (F-value = 4.565, p-value = 0.036 < 0.05). The experimental group outperformed the control group in the post-test, indicating that there would be significant differences in the scores on the post-test learning effectiveness among students as a result of different methods of experimental teaching. It was deduced from Table 11 that the mean of the control group was 83.621 after adjustment, while that of the experimental group was 85.979 after adjustment. The mean of the experimental group in the post-test was higher than that of the control group in the same test; such results indicated that the experimental group, compared with the control group, was better in relation to student learning outcomes.

Table 10. Summary table of covariance analysis.

Source of Change	Type III Sum of Squares	Degree of Freedom	Mean Sum of Squares	F-Test	p-Significance
Group in the experiment	112.046	1	112.046	4.565	0.036 *
Pre-test result	7047.630	1	7047.630	287.159	0.000
Error	1914.321	78	24.543	-	-

* $p < 0.05$.

Table 11. Marginal mean and standard error.

Group	Mean	Standard Error	95% Confidence Interval	
			Lower Limit	Upper Limit
Control group	83.621	0.784	82.060	85.183
Experimental group	85.979	0.775	84.437	87.521

4.2. Survey on Students' Satisfaction

The student satisfaction questionnaire of this study was administered after the experimental teaching, which was used to analyze the level of experimental group students' acceptance of integrating the virtual chemistry laboratory into the experimental curriculum activities, and their opinions and suggestions in relation to learning. The internal consistency reliability of this student satisfaction questionnaire reached 0.988.

The statistical results in Table 12 are divided into three parts. The first part covers Questions 1–5. The results indicated that the mean score of satisfaction with the virtual chemistry laboratory was 4.19, indicating that in general, users had high levels of satisfaction with using the virtual chemistry laboratory proposed in this paper. This result was seen in areas including the design of physical teaching materials, convenience of operation, clear and concise instructions, and conducting the virtual experiment with a teaching method that made use of smartphones in conjunction with AR. The second part includes Questions 6–10, which assessed the feeling about operating an experiment through the virtual chemistry laboratory, and had a mean score of 4.24. This result showed that users preferred the method of teaching with the aid of AR in the classroom; further, such method enabled users to stay focused on the experiment and comprehend its process more easily, thereby assisting in their learning process. Users also expressed hope that the teaching methods appropriate for using AR could be applied to other curricula. Part 3 includes Questions 11–19, which were to evaluate whether the unit content designed in relation to the proposed virtual chemistry laboratory conformed to the planning of the curriculum. In the entire process of the virtual experiment, the real chemical reactions clearly enabled users to understand various aspects of each unit, viz. definition, nature and application.

Table 12. Students' satisfaction questionnaire.

No.	Item Content	Mean Value	Standard Deviation	No. of People
1	I feel that identifying picture cards using smartphones is helpful.	4.07	0.848	41
2	I feel that it is very convenient to operate the AR-based teaching method through smartphones.	4.12	0.872	41
3	The steps of operating the AR-based teaching method are simple and clear.	4.17	0.919	41
4	I feel that the AR-based teaching method can attract my attention.	4.32	0.820	41
5	I like the method of learning through the AR-based teaching method.	4.29	0.814	41
6	I feel that operating experiments through the AR-based teaching method will enliven the curriculum.	4.29	0.716	41
7	I feel that operating experiments through the AR-based teaching method makes me more focused on learning.	4.20	0.679	41
8	I feel that operating experiments through the AR-based teaching method helps me learn the curriculum of the natural science domain more easily.	4.17	0.803	41
9	I feel that operating experiments through the AR-based teaching method helps me understand the process of natural science experiments more easily.	4.17	0.771	41
10	I hope the AR-based teaching method can also be applied to other learning domains.	4.41	0.836	41
11	The teaching method for air and combustion enabled me to understand whether oxygen can help support the combustion of substances.	4.22	0.909	41
12	The teaching method for air and combustion helped me understand how to produce oxygen and examine its properties.	4.34	0.794	41
13	The teaching method for air and combustion helped me learn the uses of oxygen.	4.24	0.799	41
14	The teaching method for air and combustion helped me understand that carbon dioxide cannot support the combustion of substances.	4.39	0.737	41
15	The teaching method for air and combustion helped me understand how to produce carbon dioxide and examine its properties.	4.24	0.734	41
16	The teaching method for air and combustion helped me learn the uses of carbon dioxide.	4.22	0.759	41
17	The teaching method for aqueous solutions helped me learn what litmus paper is and how to use it.	4.34	0.762	41
18	The teaching method for aqueous solutions enabled me to understand that we use litmus paper to test the properties of aqueous solutions.	4.24	0.830	41
19	The teaching method for aqueous solutions enabled me to know that some aqueous solutions possess electrical conductivity.	4.32	0.722	41

4.3. Survey on Teachers' Opinions

The teacher opinions questionnaire for this study was administered following the experimental teaching, with the goal of analyzing how the teachers felt about incorporating the virtual chemistry laboratory into experimental curriculum activities, and their opinions and suggestions in relation to teaching. The internal consistency reliability of this questionnaire was 0.703.

According to the statistical results of the teacher opinions questionnaire in Table 13, the teachers considered that current teaching materials (such as pictures and videos) and actual number of hands-on experimental courses are inadequate for the teaching curriculum. They also considered that this virtual chemistry laboratory is in line with the objectives of the curriculum design, which can greatly shorten teachers' lesson preparation time. Through the virtual chemistry laboratory, experiments can be conducted in a simple, clear, and safe manner. Using various teaching methods, teachers can more effectively impart knowledge about curriculum content. Further, this virtual chemistry laboratory enables students to concentrate more in class, strengthen their learning motivation, and enhance their learning effectiveness.

Table 13. Teacher opinions questionnaire.

No.	Item Content	Median	No. of People
1	I think the AR-based teaching method is in line with the objectives of the current curriculum design.	4	8
2	I think the number of times students are actually conducting experiments is not enough.	4	8
3	I think learning through the AR-based teaching method can increase students' concentration with respect to the curriculum.	4	8
4	I think traditional teaching materials like pictures or videos are enough to enable students to understand [natural science] knowledge.	2	8
5	I think using the AR-based teaching method can enhance students' learning outcomes.	4	8
6	I think the AR-based teaching method is much safer compared with traditional experiments.	4	8
7	I think the AR teaching method can shorten my lesson preparation time.	4	8
8	I think the AR-based teaching method can strengthen students' learning motivation.	4	8
9	I will incorporate the AR-based teaching method in my teaching plan.	4	8
10	I think the effects of AR-based teaching method are better than those of traditional teaching materials.	3	8
11	I am willing to use AR-based teaching method in my class.	4	8
12	I think the AR-based teaching method can present different teaching methods.	5	8
13	I think the AR-based teaching method is helpful to teachers in more effectively imparting the content of the curriculum.	4	8
14	I think the AR-based teaching method is simple and clear in operational terms.	3.5	8

5. Conclusions and Future Work

This study has put forth a teaching system based on a virtual chemistry laboratory, which makes use of AR technology to implement virtual chemistry experimental teaching. The proposed teaching system framework is divided into two parts, namely, physical teaching materials and virtual experiment application. The physical teaching materials include all devices needed for the virtual chemistry experiments. Users may choose the required experimental cards according to the experimental units, in lieu of actual chemistry experimental equipment and consumable materials. The AR technology-based virtual experiment application is to conduct experiments, which are part of the curriculum objectives, thereby allowing users to perform virtual experiments through physical teaching materials and smartphones. The experimental results clearly demonstrated that with respect to learning outcomes, the experimental group students' learning effectiveness reached a significant difference when compared to the control group, indicating that the AR-based teaching method can effectively enhance student performance. With respect to the survey on satisfaction, students in general showed high levels of satisfaction, thereby concluding that AR is helpful in strengthening students' learning motivation. With regard to the survey on teachers' opinions, in general, the teachers showed high levels of acceptance, indicating that virtual chemistry laboratory can effectively assist teachers with classroom instructions.

In terms of future work, we plan to add a multiplayer connection system to the study's virtual chemistry laboratory, so that students may conduct multiplayer experimental activities in different groups. In this way, teachers can timely observe their students operating experiments on different mobile devices and provide guidance and opinions. However, for such a practice, connection stability will undoubtedly be a major challenge. Therefore, maintaining connection stability in the experimental process is also one of the significant directions for future research.

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