Effects of Developing an Interactive AR Plant Structure Experiment System for Elementary Natural Science Course

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***Abstract*—Scientific inquiry stands as a cornerstone in elementary education. Traditional natural science teaching, bolstered by experiments, enhances students' conceptual understanding, boosting their learning motivation and effectiveness. Nonetheless, some conventional natural science experiments are time-consuming, potentially diminishing students' learning outcomes by causing unnecessary waits or truncating classroom time. With the advent of augmented reality (AR) technology, there is an opportunity to seamlessly blend virtual digital resources within physical classrooms. This fusion can increase the efficiency of natural science experiments while diminishing associated risks. In response, this study introduced an AR-based interactive plant structure experiment system into an elementary natural science course's plant anatomy unit, aiming to assess its impact on student learning achievements. Employing a quasi-experimental design, the study had one group undergo traditional classroom teaching for basic plant anatomy knowledge, followed by the AR system for plant structure experiments. Conversely, a control group utilized traditional teaching and experimental methods throughout. The findings revealed no significant disparities in learning achievements between the groups. However, the AR system effectively curtailed experiment waiting times and reduced the risk of experimental failures.**

***Keywords*—natural science education, plant science experiment, experimental education, augmented reality, quality education**

I. Introduction

Science originates from humans' curiosity about and needs related to the phenomena and changes in the surrounding environment. By observing the various phenomena and changes in nature, students' curiosity about science is aroused, leading them to explore actively. Natural science education is also the core of sustainable development, cultivating students' scientific literacy, enhancing their adaptability to the environment, and improving their problem-solving skills [1]. In the 12-year Basic Education Curriculum Guidelines issued by the Ministry of Education in Taiwan, natural science is structured through interdisciplinary integration at the elementary education level, connecting with life curriculum and laying the foundation for learning attitudes and interests in natural science curriculum, which is the enlightenment stage for cultivating scientific literacy [2]. Scientific inquiry is one of the important goals of education today.

In traditional natural science education, teachers often use lecture-based teaching to impart basic knowledge concepts to students [3]. However, there are also many natural science experiments that allow students to actively participate and observe. During experiments, students take the initiative to explore while teachers assist and guide them in observation and recording. Through experimentation, students can deepen their knowledge and understanding of science concepts [4], and their interest in learning science increases [2, 5]. In order to help students acquire the necessary skills in learning activities, including critical thinking, problem-solving, collaboration and leadership, adaptability, communication, innovation, data collection, and analysis [6], and to achieve the goal of scientific inquiry, the spirit and methods of exploration and practical application should be emphasized in every stage of natural science education. Therefore, the presence of experiments in the natural science curriculum is essential.

The elementary school stage is a golden age of curiosity and is very suitable for scientific exploration and teaching [7]. In addition to correcting misconceptions, eliminating knowledge gaps, and generating new knowledge, the curiosity for learning drives students to learn new knowledge, creates the pleasure of thinking, and enables them to perceive new problems [8]. Many units in the natural curriculum of elementary school include experiments, such as experiments on plant structure, recognizing magnetism, air flow, temperature and dissolution, buoyancy, capillary phenomena, siphon phenomena, and light, among others. Through experimental operations, students can learn by doing, understand the knowledge concepts of each unit through observation, and analyze data by recording results. However, the time required for each experiment varies. Most natural science experiments can yield immediate results, such as experiments on light refraction and reflection, buoyancy, and air flow, among others. However, some experiments require waiting time, such as those involving plant structure. In Taiwan, the experiment designed to observe plant structure involves placing celery in red ink to observe its transpiration and nutrient transport modes. It is a simple and necessary experiment, but the waiting time for the results may not fit within one class period. Additionally, there is still a risk of failure with this experiment, even though it is simple.

Based on the above, traditional natural science experiments often take too long for students to wait for results or for the class time to accommodate, which can have a negative impact on students' learning outcomes [9]. In recent years, the flourishing development of Augmented Reality (AR) technology can effectively integrate virtual digital resources into physical classrooms, and increase the

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efficiency of natural science experiments while reducing associated risks through the integration of virtual and real elements [10]. Moreover, considering that the Ministry of Education in Taiwan has successfully promoted the One-Tablet-Per-Student initiative in elementary schools, every elementary student now has access to a mobile device capable of running AR applications [11, 12]. Therefore, this study developed an interactive plant structure experiment system based on AR technology, and integrated the proposed system into the plant structure unit experiment of the elementary school natural science course to evaluate its impact on student learning achievements. To evaluate the impact of the proposed system integrated into the plant structure unit experiment of the elementary school natural science course on student learning achievements, this study plans an experiment to investigate the following research questions.

1) Do students who learn the plant structure unit in the elementary school natural science course using the system proposed by this study achieve the same learning outcomes as students taught through traditional teaching methods?
2) Do both high-motivated and low-motivated students who use the system proposed by this study to learn the plant structure unit in the elementary school natural science course achieve the same learning outcomes as their respective counterparts who are taught using the traditional teaching approach?
3) Do low-motivated students who use the system proposed by this study to learn the plant structure unit in the elementary school natural science course achieve the same learning outcomes as high-motivated students who use the same approach?

II. Literature Review

A. The Application of Augmented Reality in Education

Augmented reality (AR) technology has gradually been integrated into various aspects of daily life, introducing innovative interactive modes to the entertainment industry, commercial advertising, digital learning, and other areas [13]. According to Milgram and Kishino's [14] proposed "real-virtual continuum" system, reality and virtual environments are viewed as a continuous region, with one side being the purely real environment and the other side being the purely virtual environment. The middle area represents the mixed reality (MR) where the real and virtual environments coexist simultaneously [14]. The part of the MR environment closer to the real environment is called AR, while the part closer to the virtual environment is called augmented virtuality (AV). Azuma [15] believes that an AR environment must have three elements: the ability to combine virtual and real objects in the same interface or space, real-time interaction, and the virtual objects existing in real 3D space and being interactive with the user. Pence [16] further categorizes AR into two usage modes: marker-based and markerless. Marker-based AR requires users to scan marked objects with AR information using devices to obtain virtual information. The markers can be pictures or objects. On the other hand, markerless AR provides AR information based on the user's location using the GPS function of mobile devices [16] or through natural feature recognition and establishing corresponding relationships [17]. In summary, AR technology combines virtual objects with real scenes, allowing virtual objects to interact with users in real-time [18].

With the emergence of mobile devices and the increasing maturity of AR technology, the feasibility of applying AR technology in the education field has been greatly improved [19]. The teaching method incorporating AR has also been applied in many educational fields [20]. Lai and Chang [21] used AR in English learning, dividing two first-grade classes in elementary school into an experimental group and a control group. The experimental group used an AR application for learning, while the control group learned English vocabulary through traditional methods. The results showed that incorporating AR into English vocabulary learning can significantly improve students' learning motivation and academic performance. Tsai *et al*. [22] used AR technology in chemistry experiments in elementary school. This method not only ensures the safety of experiments, but also avoids the waste of experiment materials. Students can also easily observe the results of experiments, and the research results indicate that teaching methods using AR for chemistry experiments can effectively improve students' learning performance.

Chen *et al*. [23] used an AR-assisted learning system to teach literature characters in Chinese language, and the results showed that this learning system helped students improve their learning effectiveness and also stimulated positive learning motivation and interest. Hsu [24] utilized an Augmented Reality (AR) application that incorporated the eight planets to teach sixth-grade students. The study's findings indicated that the students exhibited a high acceptance of the AR technology, and the integration of AR into astronomy education, specifically regarding the eight planets, contributed to enhancing students' learning motivation. Cai and Meng [25] pointed out the advantages of applying AR in education, including breaking through spatial or temporal limitations by overlapping virtual images and real situations to enhance the user's sense of presence [22, 24]; increasing the concreteness and interactivity of teaching materials, and the real-time interaction function can help students focus on learning [21]; presenting flat images and three-dimensional objects and providing simulated environments with multiple sensory stimuli can help students learn abstract knowledge concepts [25]. In addition to convenience, teaching tools combined with AR technology can also achieve the goal of adaptive teaching, providing opportunities for students to practice repeatedly and receive immediate feedback according to their own learning pace, thereby enhancing their learning motivation [26] and promoting their learning achievements [27].

Regarding the application of AR in natural science education, Atmojo *et al*. [28] applied augmented reality as a teaching tool in the natural science curriculum of elementary schools. The experimental subjects were sixth-grade students from six elementary schools. The results showed that this method can effectively improve the quality of elementary school natural science learning. AR technology can help students understand the content of teaching materials, and learning activities can be conducted in an interesting way, thus enhancing students' learning effectiveness. Hsu *et al*. [29] suggested that learning with AR can significantly enhance students' motivation and learning outcomes in biology [29]. Chien *et al*. [30] integrated AR technology into the plant observation activities of third-grade elementary school students. The students' learning outcomes were measured using Bloom's taxonomy. The results showed that students in the experimental group who observed plants through AR had significantly better understanding in conceptual analysis and leaf arrangement recognition compared to the control group. AR-based materials can significantly enhance students' higher-order cognitive abilities, enabling them to effectively construct knowledge. Weng *et al*. [31] redesigned the food biotechnology unit in junior high school biology textbooks by integrating AR technology. They used a quasi-experimental pretest-posttest design and collected student feedback on the AR-enhanced books. The results indicated that using AR technology can improve students' learning outcomes in analytical aspects as well as their attitudes toward learning biology. Students' feedback mentioned that AR can effectively promote their biology learning.

B. Integration of Information Technology in Natural Science Education

One of the goals of teaching natural science is to cultivate students' scientific literacy, which includes skills such as observation, applying numerical measurements, reasoning, controlling variables, and more. However, in the classroom, teachers are often limited by factors such as time, space, and the difficulty of observation, which can make it challenging to develop students' scientific literacy skills through hands-on experiments or field observations. Therefore, integrating information technology into teaching is crucial for natural science education. There are many ways to integrate information technology into natural science education, such as changing traditional textbooks into interactive e-books. This not only provides information through multimedia but also guides students to observe and ask questions, enhancing their higher-order thinking skills [32]. Another way is to use interactive animated media to aid teaching [33], making it easier for students to understand the content of the material and facilitating the transmission of knowledge. Additionally, developing natural science comic learning media as supplementary materials can make the learning process more interesting and engaging for students [34]. Moreover, natural science encompasses many abstract knowledge concepts [35], and integrating information technology into natural science education can enrich students' learning environment, enhance teaching quality, and increase students' interest and motivation to learn. AR technology is an excellent auxiliary tool for teaching abstract subjects [36].

Lo *et al*. [37] developed an AR application combined with innovative teaching materials for natural science exploration activities for primary school students. The learning content focused on the feeding ecology of butterflies, using the AR application to observe nature, teach students about environmental protection concepts, and familiarize them with common natural organisms. Hsu [38] used the fourth-grade natural science curriculum "Light Bulb On" as the theme, which included understanding wires, light bulbs, batteries, and the concept of simple circuit series and parallel connections. Through the use of AR applications combined with graphic cards, students can design circuits more easily, observe the brightness of light bulbs, and improve their learning motivation. Chang and Hwang [39] focused on the concept of electromagnetics and developed a flipped learning system combined with AR technology. Students learned the principle of electromagnetic iron through videos before class and previewed the experimental content and process. During the experimental course, the system guided students to operate the experiment through the function of AR [40]. The use of animations to display the direction of electric current and magnetic field made it easier for students to understand abstract concepts. The research results showed that with the assistance of AR technology, students' learning achievements, motivation, and self-efficacy were significantly improved. Chemical reactions between molecules are quite abstract concepts for primary school students [41]. Through the use of AR technology to simulate the chemical interactions between atoms and molecules to produce new chemical substances, this method not only avoids safety issues such as toxic gases or fires that may arise from chemical experiments but also saves the cost of purchasing chemical materials.

In natural science education, abstract concepts are often used to explain natural phenomena. AR technology can be applied to science experiments by combining virtual objects with real scenes and providing real-time interaction, creating different learning experiences that can enhance student engagement and motivation [42]. Additionally, AR technology can simulate phenomena that are difficult or impossible to observe with the naked eye, making abstract concepts more visual and easier for students to understand [43]. By simulating experiments with safety concerns, AR can provide a safe learning environment. AR technology is a fun and effective way of learning that can not only stimulate student interest but also save time and space, improve student motivation and focus, reduce cognitive load, and enhance learning outcomes [44, 45].

III. AR Interactive Plant Structure Experiment System

This study developed an AR interactive plant structure experiment system that incorporates the experiment on how plants absorb water in the natural science unit of fifth-grade elementary school. The system architecture is shown in Fig. 1, utilizing the Android operating system as the core, the Unity 3D engine as the foundation, and the Vuforia software development kit (SDK) for AR technology development. The native Android application can be directly installed on an Android mobile device. By utilizing the device's camera, the system can recognize scanned objects and generate virtual objects and interactive behaviors. These virtual elements are then seamlessly integrated into the real-world scene captured by the camera. This application aims to guide students in conducting interactive experiments and encourages their active participation.

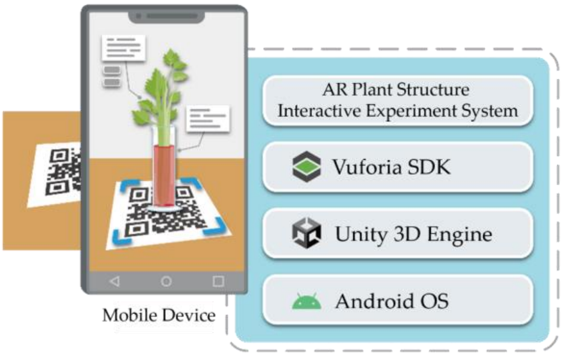

Fig. 1. Architecture of AR interactive plant structure experiment system.

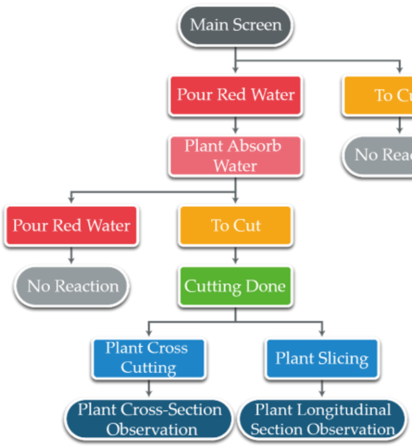

Fig. 2. Operation procedures for the AR plant structure interactive experimental system.

In order to support the plant structure experiment, this system designs a series of scenes and interactive content for students to fully engage with, as shown in Fig. 2. The relevant teaching content presented in the system is based on the curriculum outlined in Taiwanese elementary school textbooks and has been reviewed by three elementary school teachers with over 10 years of experience teaching natural science courses. Students use an Android mobile device to execute the system and activate the camera function, which then enters the main screen of the system. A virtual teacher guides students through the experiment. When students use the mobile device to scan the prepared QR code for the experiment in the real environment, the system begins to detect and recognize objects. The system then generates virtual equipment and scenes to be presented in the real environment image captured by the mobile device, achieving the effect of AR, as shown in Fig. 3. The virtual teacher sets the tasks that students need to complete in each experimental scene. During the virtual reality interaction experiment process using the system, students can operate virtual equipment according to the experimental needs, complete the experimental tasks, and observe the experimental results. If the experimental operation procedure is incorrect, the system allows students to repeat the steps. When the experimental operation procedure is correct, the virtual teacher guides students to enter the next experimental scene. During each experimental step, students can observe the experimental results clearly from 360 degrees as the system is based on the Unity 3D engine. In addition, the system provides an experimental record function for students to record the experimental process at any time.

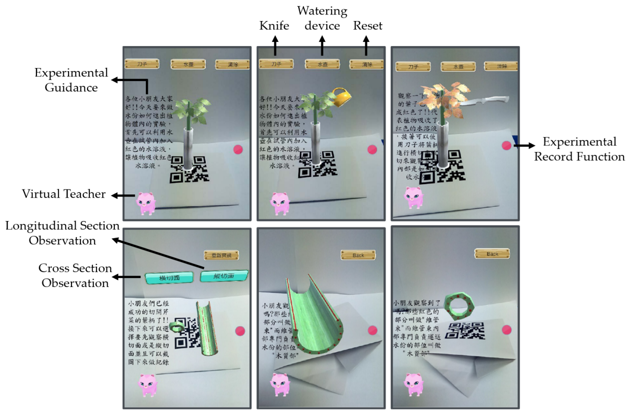

Fig. 3. Operational interface of AR interactive experiment system for plant structures.

IV. Experiment

A. Experimental Design

In order to evaluate the impact of the proposed system on students' plant structure experiments, this study implements a quasi-experimental design in the natural science course of elementary school. The teaching material is the second chapter, "Structure and Function of Plants," in the first semester of the fifth grade of elementary school, combined with the experiment on how plants absorb water. The teaching duration is three weeks, and the participants include two classes (32 students) and one teacher. One class of 16 students is the experimental group, which uses traditional classroom teaching for plant structure basic knowledge learning in the traditional classroom, and utilizes the AR interactive plant structure experimental system for plant structure experiments in the natural science laboratory. The other class of 16 students is the control group, which uses traditional classroom teaching for plant structure basic knowledge learning in the traditional classroom, and employs traditional experimental methods for plant structure experiments in the natural science laboratory. The aforementioned traditional classroom teaching refers to the teacher providing students with relevant basic knowledge instruction in a traditional classroom, while the traditional experimental methods refer to the teacher guiding students in the natural science laboratory using experimental materials to conduct plant structure experiments.

B. Instrument

To evaluate the effectiveness of the intervention, this study analyzed data collected from a prior knowledge test, a learning achievement test, and questionnaires measuring learning motivation and technology acceptance. Due to the constraints of the course, the prior knowledge test was based on the final exam of the natural science domain in the second semester of the fourth grade of elementary school. The learning achievement test was designed based on the learning objectives of commercial reference books, lecture notes, and assessments, and was reviewed and evaluated by three experts to ensure content validity. These three experts are elementary school natural science teachers, each with ten years of teaching experience. After review and modification, the learning achievement test used in this study consisted of 10 questions, with a full score of 100 for both the prior knowledge test and the learning achievement test.

In order to evaluate the impact of students' learning motivation and attitudes on the learning achievement of the plant structure experiment integrated with the system proposed in this study, the Intrinsic Motivation Scale (IMS) of the Motivated Strategies for Learning Questionnaire (MSLQ) was used [46]. The IMS is primarily used to assess students' goals, beliefs, and interests regarding the importance and interest of the teaching activities in this study. The IMS dimension of the MSLQ has been widely used in literature to demonstrate students' learning motivation in information technology-assisted teaching activities [47–49]. The scale consists of 9 questions, and the scoring is based on a 7-point Likert scale.

C. Procedure

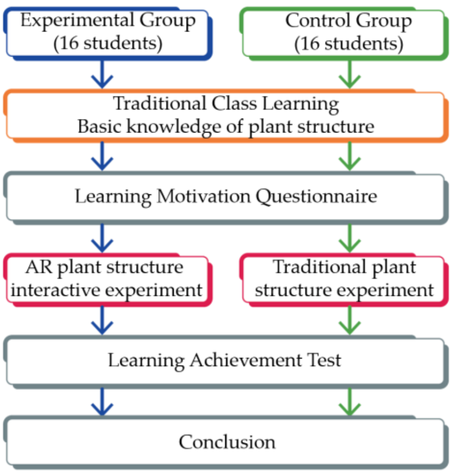

Fig. 4. Experimental procedure.

Fig. 4 illustrates the experimental process of this study. Prior to the formal plant structure experiment, the teacher arranged for both the experimental and control groups to learn the basic knowledge of plant structure in a traditional classroom setting. Both groups were then invited to fill out a Motivated Strategies for Learning Questionnaire to measure their learning motivation before participating in the plant structure experiment. After completing the basic learning and questionnaire, both groups of students conducted the plant structure experiment, with the teacher providing instructions for both groups. The control group conducted the experiment using traditional methods, while the experimental group used the AR interactive plant structure experiment system. Both groups of students worked in pairs to conduct the experiment. Due to time constraints in the semester, the control group students were unable to wait for the plants to absorb water, so the teacher provided an equal number of pre-absorbed plants for them to complete the experiment procedure and then observe plant water absorption. The experimental group students used the AR interactive plant structure experiment system to conduct the plant water absorption experiment procedure and observe the process. After completing all teaching and experimental activities, both groups of students took a learning achievement test to complete the experiment.

V. Results

Based on the experimental design and measured data, this study analyzed and explored the impact of integrating the proposed system into the plant structure experiment conducted in the natural science course on student learning from aspects such as learning achievement and learning motivation.

A. Analysis of Learning Achievement

This analysis was conducted to evaluate the impact of integrating the plant structure experiment into the natural science course on student learning achievement. To assess whether there were differences in prior knowledge between the experimental and control groups before participating in the experiment, this study analyzed the final exam scores of the two groups of fourth-grade elementary school students in the natural science domain. The experimental group had a mean score of 89.06 with a standard deviation of 8.66, while the control group had an average score of 87.13 with a standard deviation of 10.86. Due to the small sample size in this study, a Mann-Whitney U test was conducted to examine whether there were significant differences in prior knowledge between the two groups, and the results showed no significant difference in prior knowledge in the natural science domain between the experimental and control groups, as shown in Table 1. The results indicate that the two groups had equivalent prior knowledge before participating in the instructional experiment activities.

Table 1. Mann-Whitney U test on prior knowledge levels between experimental and control groups

Group	N	Mean Rank	Sum of Ranks	*U*	*p*
Experimental Group	16	17.16	274.50	117.500	0.696
Control Group	16	15.84	253.50		

To further investigate the impact on student learning achievement, this study used one-way analysis of covariance (ANCOVA) as the analytical method for learning achievement outcomes. This was done to eliminate the influence of students' prior knowledge in the natural science domain on learning achievement outcomes. The student learning achievement test results were set as the dependent variable, while the fourth-grade students' natural science domain final exam scores in the second semester of elementary school were set as the covariate. The assumption of homogeneity of the regression slope ($F = 3.976$, $p > 0.05$) was not violated. Next, the homogeneity of variance was assessed by Levene's test, which showed that the within-group variances were considered equal ($F = 0.003$, $p > 0.05$). This indicates that the ANCOVA was suitable to perform. Table 2 presents the results of the one-way ANCOVA analysis of learning achievement test scores for the experimental and control groups. The adjusted mean and standard error for the experimental group were 77.5 and 19.15, respectively, while for the control group, they were 80.63 and 20.48, respectively. The analysis results indicated no significant difference between the adjusted learning achievement test scores of the experimental and control groups ($F(1,29) = 0.860$, $p = 0.361 > 0.05$). This result suggests that the system proposed in this study, which was integrated into the natural science course and focuses on plant structure, has the same effect on student learning achievement as traditional teaching experiments.

Table 2. One-way ANCOVA of learning achievement test results between the experimental and control groups

Group	N	M	SD	*F*	*p*
Experimental Group	16	77.5	19.15	0.860	0.361
Control Group	16	80.63	20.48		

B. Analysis of Learning Motivation

To assess whether there were differences in learning motivation between the control and experimental groups prior to participating in the experiment, this study analyzed the results of the learning motivation questionnaire completed by both groups. The experimental group had a mean score of 6.32 with a standard deviation of 0.53, while the control group had a mean score of 5.93 with a standard deviation of 0.82. Due to the small sample size in this study, a Mann-Whitney U test was conducted to determine whether there were significant differences in learning motivation between the two groups before the plant structure experiment. As shown in Table 3, the results showed no significant difference in learning motivation between the experimental and control groups.

Table 3. Mann-Whitney U test of learning motivation results between the experimental group and the control group

Group	N	Mean Rank	Sum of Ranks	*U*	*p*
Experimental Group	16	17.78	284.50	107.500	0.445
Control Group	16	15.22	243.50		

To further explore the influence of different learning motivations on learning achievement among students in the experimental and control groups, this study classified them into high and low learning motivation groups based on their rankings in the learning motivation scale. The study then analyzed the effects of high and low learning motivation on learning achievement for both groups of students.

1) Analysis of learning achievement for high-motivated students in the experimental and control groups

To evaluate whether there were differences in learning achievement between highly motivated students in the experimental and control groups under AR plant structure experimental and traditional experimental teaching modes, this study conducted a one-way ANCOVA analysis. The final exam scores of natural science in the fourth grade of the elementary school in the experimental and control groups with high learning motivation were set as covariates, and the post-test scores of learning achievement were set as dependent variables. The assumption of homogeneity of the regression slope ($F = 0.001$, $p > 0.05$) was not violated. Next, the homogeneity of variance was assessed by Levene's test, which showed that the within-group variances were considered equal ($F = 3.95$, $p > 0.05$). This indicates that the ANCOVA was suitable to perform. The analysis results showed no significant difference in the post-test scores of learning achievement between highly motivated students in the experimental and control groups ($F = 3.016$, $p = 0.106 > 0.05$) as shown in Table 4. This result indicates that the system proposed in this study integrated into the plant structure experiment of the natural science course had an equivalent effect on the learning achievement of highly motivated students compared to traditional experimental learning.

Table 4. One-way ANCOVA analysis of high-motivated students in the experimental and control groups

Group	N	M	SD	*F*	*p*
Experimental Group	8	67.5	20.53	3.016	0.106
Control Group	8	88.75	11.26		

2) Analysis of learning achievement for low learning motivation students in experimental and control groups

This study conducted a one-way analysis of covariance to evaluate differences in learning achievement between the experimental group and the control group of low-motivation students in AR plant structure experimental teaching and traditional experimental teaching modes. The final exam scores in the natural science domain of fourth-grade students in the experimental and control groups with low learning motivation were used as covariates, while the post-test scores of learning achievement served as the dependent variable. The assumption of homogeneity of the regression slope ($F = 1.875$, $p > 0.05$) was not violated. Next, the homogeneity of variance was assessed by Levene's test, which showed that the within-group variances were considered equal ($F = 1.123$, $p > 0.05$). This indicates that the ANCOVA was suitable to perform. The analysis results indicated no significant difference in post-test scores of learning achievement between the experimental group and the control group of low-motivation students ($F = 0.625$, $p = 0.443 > 0.05$), as shown in Table 5. This result suggests that the system proposed in this study, integrated into the natural science course of the plant structure experiments, has an equivalent effect on the learning achievement of low-motivation students as traditional teaching experiments.

Table 5. One-way ANCOVA analysis of the low learning motivation students in the experimental and control groups

Group	N	M	SD	*F*	*p*
Experimental Group	8	87.5	11.65	0.625	0.443
Control Group	8	72.5	24.93		

3) Analysis of learning achievement for high and low learning motivated students in the experimental group

To evaluate the learning achievements of high- and low-motivation students in the experimental group who received AR-based plant structure experimental teaching, a Mann-Whitney U test was conducted to examine whether there were significant differences in prior knowledge between the two groups. The results showed that there were no significant differences in prior knowledge in the natural science domain between high- and low-motivation students in the experimental group, as shown in Table 6.

Table 6. Mann-Whitney U test on prior knowledge levels between high and low learning motivated students in the experimental group

Group	N	Mean Rank	Sum of Ranks	*U*	*p*
High-Learning Motivation	8	7.69	61.50	25.500	0.505
Low-Learning Motivation	8	9.31	74.50		

The present study further analyzed the learning achievement scores using one-way ANCOVA, with the students' learning achievement test results as the dependent variable and their final exam scores in the natural domain in the fourth grade of elementary school as the covariate. The assumption of homogeneity of the regression slope (F = 2.730, $p > 0.05$) was not violated. Next, the homogeneity of variance was assessed by Levene's test, which showed that the within-group variances were considered equal (F = 3.290, $p > 0.05$). This indicates that the ANCOVA was suitable to perform. Table 7 presents the results of the one-way ANCOVA for the learning achievement test scores of the high and low learning motivation students in the experimental group. The adjusted mean and standard error for the high learning motivation group were 67.5 and 20.53, respectively, while those for the low learning motivation group were 87.5 and 11.65, respectively. The analysis results indicated a significant difference in the adjusted learning achievement test scores between the high- and low-motivation groups ($F(1,13) = 5.109$, $p = 0.042 < 0.05$), suggesting that the low learning motivation students performed better than the high learning motivation students in learning plant structure through the experimental teaching model proposed in this study.

Table 7. One-way ANCOVA analysis was conducted on the high and low learning motivation students in the experimental group

Group	**N**	**M**	**SD**	***F***	***p***
High-Learning Motivation	8	67.5	20.53	5.109*	0.042
Low-Learning Motivation	8	87.5	11.65		

* $p < 0.05$

VI. Discussion

Although the AR plant structure interactive experimental system developed in this study can contribute to the teaching of plant structure experiments in elementary natural science courses, relevant literature suggests that when teachers apply AR technology in teaching, they need to consider the following aspects that may affect student learning: (1) the multi-dimensional interactivity provided by AR systems, which may include many digital objects and more complex virtual interactions, can easily increase students' cognitive load [50]; (2) new technology integrated into teaching requires teachers to allocate sufficient time for students to familiarize themselves with the operation of new technology, and AR emphasizes the combination of virtual digital objects and scenes with real-world environments, which can easily confuse students in operation [51]; (3) systems developed using AR technology need to consider multi-user interactions to adapt to changes in teachers' and students' teaching needs; otherwise, it can easily affect teaching effectiveness [52]; (4) Since AR-based learning systems provide a virtual simulation learning environment, it is recommended that educators arrange field trips or experimental activities as supplementary learning. This allows students to personally experience and observe scientific phenomena in the real world [53], or through the display of physical models, allowing students to directly observe and touch to deepen their understanding of scientific phenomena. For scenes that are difficult to reproduce, sensory input generated by computers, including animations, sounds, GPS data, pictures, and visualizations, can be used to enhance or supplement the learning experience [54]; (5) Students using AR systems may easily ignore their surrounding physical space and focus only on the data presented on handheld devices. Additionally, students often focus on exchanging messages with each other, leaving little time for more important activities such as finding and analyzing data or sharing and discussing data with teammates. This distraction is caused by the large amount of data displayed in the learner's field of view, which can overload their perceptual and neural systems, leading to negative impacts [55]; (6) It is recommended to design clear and concise learning content, avoiding excessive visual and auditory stimuli to maintain students' attention [56]. Providing adequate breaks and intervals allows students to rest and recover their energy, preventing fatigue from prolonged use of AR technology [56]. In addition, the results of this study found that low-motivation students performed better in learning achievement than high-motivation students when using the AR system developed in this study for teaching plant structure experiments in elementary school natural science courses. Relevant research results indicate that AR can stimulate the learning motivation of low-motivation students and thereby improve their learning achievement [57]. Moreover, motivation is the intrinsic cognitive and emotional process that stimulates and sustains goal-directed actions and outcomes. Self-efficacy is a key element in motivating intrinsic motivation, which can be influenced by personal and environmental variables and affects individuals' choice, effort, persistence, and motivational outcomes [58]. Learning methods that integrate AR technology are more likely to capture students' attention [59]. During the learning process, students use metacognitive awareness to regulate their learning process, thereby generating learning motivation [60]. However, when students do not recognize the value of effort, higher autonomy in learning can actually reduce learning motivation, leading to lower achievement among initially high-motivation students [61]. As a result, low-motivation students may perform better than high-motivation students in their learning outcomes.

To enable teachers and students to navigate and utilize the features of the AR-based learning system, educators can establish a clear and precise training course, create instructional videos, or provide operation manuals to introduce the functions and usage of the AR learning system to teachers and students. For example, Mystakidis *et al*. [62] adopted a flipped classroom approach, allowing teachers to conduct self-learning through online seminars and to learn flexibly according to their personal schedules. Hu, Goh, & Lin [63] had students complete a simple application exercise at the beginning of AR learning activities. If students failed to get the correct answer after two attempts, the system would display the correct answer and related navigation instructions. This approach prevents students from checking the answers without attempting the questions and avoids learning frustration, allowing them to continue with the learning activities. Additionally, when using the AR-based learning system, there may be issues with system instability, such as the marker not being detected due to excessive or insufficient classroom lighting. Therefore, it is recommended to not only plan classroom layouts to provide sufficient activity space for students but also monitor lighting [64, 65]. Schools can establish technical support teams to resolve technical issues encountered by students and teachers when using the AR system [56]. Establishing smart campuses to provide real-time technical support services [66], and offering dedicated support personnel or emergency contact channels during learning activities to quickly address technical malfunctions [67]. Finally, to enable educators to adapt or develop assessment methods to accurately evaluate student learning outcomes and performance within the context of AR-based learning experiences, Bacca, Baldiris, Fabregat, Graf, & Kinshuk [68] suggest designing diverse assessment tools, including quizzes, task performance evaluations, portfolios, and peer assessments, to comprehensively assess students' learning outcomes in AR learning experiences. Additionally, they recommend creating assessment tools that measure students' skills, knowledge, and attitudes to provide a holistic evaluation of learning outcomes in AR-based learning [68]. Sahin & Yilmaz [69] used a scale developed by Küçük, Yilmaz, Baydas, and Göktaş in 2014 [70] to measure students' attitudes toward AR activities. The scale consists of 15 items reflecting three factors: satisfaction, anxiety, and willingness. Satisfaction is related to students' perceptions of the ease of use and usefulness of AR technology for learning. Willingness reflects students' desire to use the technology in the future. Higher levels of satisfaction and willingness are associated with more positive attitudes towards AR technology. Anxiety pertains to any concerns students may have about using AR technology. Higher levels of anxiety can negatively impact students' attitudes. The scale is rated on a 5-point Likert scale. Nikou *et al*. [71] developed a scale to assess teachers' integrated augmented reality competencies. Educators can use this scale for self-assessment of their AR competencies, while teacher professional development institutions and policymakers can use it to design AR training programs.

VII. CONCLUSIONS

This study developed an AR plant structure interactive experimental system using AR technology and integrated it into plant structure experiments in elementary school natural science courses. This allowed students to interact with the experiments using AR technology, reducing the waiting time for experimental results and improving the situation where traditional experiments are limited by course time and may affect student learning. The results showed that there was no significant difference in learning achievement between students who used the AR plant structure interactive experimental system and those who used traditional experimental teaching methods. Moreover, since the traditional "plants absorb water" experiment could not be completed within the scheduled experimental class during the same week, this demonstrates that the system also effectively reduced the waiting time for experiments and the risk of poor experimental results. This suggests that the AR plant structure interactive experimental system proposed in this study can be used as a learning tool for plant structure courses in elementary school natural science curriculum.

In summary, the main contribution of this study is to investigate the impact of integrating an AR-based plant structure interactive learning system into elementary school natural science curriculum on students' learning outcomes. However, the study is limited by the semester and class system in domestic elementary schools, which makes it difficult to randomly select students to participate in the experiment, and the small experimental scale is also a limitation. Therefore, future research should continue to apply the developed system in natural science experiments and consider the number of learning devices and the number of students participating in the course in large-scale teaching environments. In addition, the developed system in this study requires the use of mobile devices. This consideration can be improved as the policy of using tablets in schools in Taiwan continues to be promoted. In the future, this study will record students' experimental operation behaviors through the system and conduct an analysis of students' learning behaviors to explore the differences and impacts of learning behaviors on students with high/low learning motivation and achievement.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

All authors conducted the research and wrote the paper; Z.-J.J. and Y.-T.L. analyzed the data; Y.-C.L. and Y.-T.L. revised and edited the paper; all authors had approved the final version.

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