education sciences

MDPI

Article

Teaching Science Using Argumentation-Supported 5E-STEM, 5E-STEM, and Conventional Didactic Methods: Differences in the Learning Outcomes of Middle School Students

Vu Thi Ha [1,2,†], Le Hong Chung [1,†], Nguyen Van Hanh [1,*,†] and Bui Minh Hai [2]

1 School of Engineering Pedagogy, Hanoi University of Science and Technology, Hanoi City 100000, Vietnam
2 Department of Education Quality Assurance, National College for Education (Vietnam), Hanoi City 100000, Vietnam
* Correspondence: hanh.nguyenvan@hust.edu.vn
† These authors contributed equally to this work.

Abstract: 5E-based science, technology, engineering, and mathematics (5E-STEM) education is known to be one of the most used pedagogical models in STEM-oriented science courses for middle school students. However, the 5E model lacks a clear explanation of how STEM subjects are strongly linked in each of its operational "E". In this study, a novel approach was proposed with the use of the argumentation-supported 5E-STEM (A-5E-STEM) model in the science curriculum. The purpose of this study was to examine the differences in learning achievements, learning motivation, learning interest, and higher-order thinking skills of middle school students between teaching science using A-5E-STEM, 5E-STEM, and conventional didactic methods. A semi-experimental study with post-test only non-equivalent groups design was used. A "Separating Mixtures" unit in the 6th grade Natural Science curriculum was designed with A-5E-STEM and 5E-STEM model orientation. The participants were three 6th grade classes with a total of one hundred and twenty students at a public middle school in Hanoi City, Vietnam. The first experimental group was taught science using the A-5E-STEM model, the second experimental group was taught science using the 5E-STEM model, and a control group was taught the science unit with conventional didactic methods. A post-test was used to collect data on learning achievement, and questionnaires were used to collect data on learning motivation, interest, and higher-order thinking skills of middle school students in the science curriculum. The findings showed that the effect of teaching science using the A-5E-STEM model on learning achievement, motivation, interest, and higher-order thinking skills of middle school students was significantly superior to that of the 5E-STEM model and conventional didactic methods. Therefore, science teachers are expected to increase the use of the A-5E-STEM model in their related curriculum.

Keywords: integrated STEM; 5E-based STEM (5E-STEM); argumentation-supported 5E-STEM (A-5E-STEM); conventional didactic methods; learning outcomes; middle school students

Citation: Ha, V.T.; Chung, L.H.; Hanh, N.V.; Hai, B.M. Teaching Science Using Argumentation-Supported 5E-STEM, 5E-STEM, and Conventional Didactic Methods: Differences in the Learning Outcomes of Middle School Students. *Educ. Sci.* **2023**, *13*, 247. https://doi.org/10.3390/educsci13030247

Academic Editor: Yusuf F. Zakariya

Received: 2 January 2023
Revised: 23 February 2023
Accepted: 24 February 2023
Published: 26 February 2023

1. Introduction

The impetus for science, technology, engineering, and mathematics (STEM) education emerged from a concern for the decline in the number of students enrolled in STEM fields in higher and vocational education which provides a high-quality workforce for a nation's competitiveness and prosperity [1]. In K-12 schools, efforts to improve STEM teaching and learning have focused on interdisciplinary or integrated instruction, commonly referred to as "integrated STEM education", rather than a separate subject approach [2]. The integration of STEM education is achieved by creating interdisciplinary knowledge among STEM subjects in solving real-world problems [1]. It gives K-12 students an opportunity to make sense of the integrated world, rather than learning fragmentary pieces of knowledge and practicing it [3].

The rapid growth of integrated STEM education in K-12 schools is due to the interdisciplinary interactions among STEM subjects that can help students to improve many types of learning outcomes [4]. It is believed that using a real-world problem as a learning context can enhance the students' positive *motivation* for learning STEM content [5–7]. Integrating STEM subjects into a real-world problem can make the lesson more interesting and different, and make the learning process fun and active [4,8]. Engineering and technology provide a hands-on context in which students can test their own scientific knowledge and apply it to engineering design practices, and therefore, it can enhance their *higher-order thinking skills*, improve their *learning achievements*, and foster their *learning interest* in STEM subjects [2,5,9]. In short, with the use of integrated STEM education, real-world problems are not fragmented from the separate subjects which are taught in schools, thereby improving student learning outcomes [10].

Most integrated STEM courses are initiated from a formal curriculum where subjects are taught separately, followed by a description of the overlap of related subjects [11]. The K-12 science curriculum strongly encourages teachers to approach STEM-oriented science teaching in their courses. The 5E instructional model, a framework for guided-inquiry, is known to be one of the effective pedagogical models that is most commonly used in STEM-oriented science courses [12,13], commonly referred to as the 5E-based STEM (5E-STEM) model. The process of teaching science using the 5E-STEM model guides students through five phases: Engage (students' attention is drawn to the lesson), Explore (students explore the topic through various activities and experiments), Explain (students define and explain concepts related to the topic through in-class discussions), Elaborate (students transfer their current learning in different situations), and Evaluate (students' learning process and quality are evaluated), which are performed sequentially throughout the lesson implementation [12]. In other words, the 5E-STEM model describes a sequence of tasks carried out over time during the process of designing and implementing a STEM-oriented science course [13,14]. However, the 5E instructional model does not explain well how individual STEM subjects are integrated in each of its operational phases. In this context, a question arises as to 'how STEM knowledge is acquired by the students more effectively and efficiently during each phase of 5E-STEM practices'.

One of the effective ways to increase the interdisciplinary connection of STEM subjects is to use the Toulmin's argumentation model in science learning [13,15,16]. The Toulmin's argumentation model strongly advocates for engaging students in the development of problem-solving arguments using discussions and principles in STEM subjects [15]. Students integrate content from all four STEM subjects when they justify engineering design ideas and solutions [17]. Therefore, argumentation-supported STEM education is one potential model to help students integrate content and practices from all of the STEM disciplines through discussions [17]. There are findings that argumentation-supported STEM education can positively contribute to the success of student outcomes in the science curriculum [18,19]. In short, argumentation should be taken into consideration as one of the foundational practices for students to integrate knowledge and skills from all STEM subjects to solve real-world problems in integrated STEM units [17,18,20]. This gave us the novel idea of combining the argumentation-supported STEM and 5E-STEM education, which was named the argumentation-supported 5E-STEM (A-5E-STEM) model and then applied in a science curriculum to further enhance students' learning outcomes.

Therefore, the purpose of this study was to examine the differences in learing achievement, learning motivation, learning interest, and higher-order thinking skills of middle school students between teaching science using the A-5E-STEM model, 5E-STEM model, and conventional didactic methods.

2. Review of Related Literature

2.1. Teaching Science Using the 5E-STEM Model and Associated Outcomes of K-12 Student Learning in the Science Curriculum

By the 1980s, the evidence for the effectiveness of teaching science based on the 5E instructional model was clear, and it was considered the most widely used model for improving the K-12 science curriculum [21]. The positive consequence was that the 5E instructional model began to be widely applied to design science lesson plans or large-scale science programs [21]. Since its development, a large number of empirical studies on teaching science based on the 5E instructional model have revealed the positive effects of the 5E instructional model on students' learning outcomes [21,22]. In 2022, the findings from a systematic review of 74 empirical studies on the 5E instructional model in science education have revealed that the 5E model was enriched when used in combination with various processes [22]. In particular, it was the emergence of a new trend in which the phases of the 5E instructional model were enriched with STEM applications [22].

Examination of the studies in the related literature of teaching science using the 5E-STEM model and associated outcomes of K-12 student learning, reveiled that the 5E instructional model contributes positively to student learning success by enabling students to learn in a meaningful way [12,23,24]. More specifically, teaching using the 5E-STEM model applied to the 9th grade science curriculum showed a significant difference in students' learning achievements and creativity between the experimental and control groups, and in favor of the experimental group [12]. In another study, when a "marine science" course used the 5E-STEM model, the 9th grade students in the experimental group scored better in attention, relevance, and satisfaction of learning motivation than the control group using conventional didactic methods; students in the experimental group also scored higher in learning achievement than the control group [23]. In addition, using the 5E-STEM model in a 10th grade science curriculum showed a statistically significant difference in the students' critical thinking and reasoning skills between the STEM group and the conventional group [25,26]. Teaching using the 5E-STEM model applied to a 3rd grade science curriculum also showed a significant difference in the students' learning achievements [24]. Integrating the topic of nanotechnology into the science unit "Nanoscience" using the 5E-STEM model has enhanced the learning achievement and interest of K-12 students [27]. In short, the evidence from the existing studies suggests that teaching science using the 5E-STEM model has a positive effect on the learning achievement, learning motivation, learning interest, and higher-order thinking skills (critical thinking and reasoning skills, creativity, etc.) of K-12 students. However, we have not found any studies on teaching science using the 5E-STEM model where all learning outcomes were directly examined in a single study.

2.2. Teaching Science Using the Argumentation-Supported STEM Model and Associated Outcomes of K-12 Student Learning in the Science Curriculum

Argumentation is the production of a claim based on evidence, and to exchange ideas and provide justifications that make people accept the validity of the claim [19,28]. Argumentation-based learning is a learning approach in which students produce reasons for problem solving by providing evidence and by supporting their arguments with evidence [29]. It provides students with an in-depth and multifaceted way of thinking about a subject [29]. For this reason, some scholars have thought of combining argumentation-based learning and integrated STEM activities to assist students in their design ideas and decisions [29]. A study using the argumentation-supported STEM model in science education demonstrated that K-12 students integrated content from all four STEM disciplines when justifying engineering design ideas and solutions [17]. Thus, real-world problem solving is enhanced in the context of evidence by using the argumentation model, and evidence is scientifically characterized by STEM disciplines that students can acquire through activities and experiments. In the argumentation model, every argument always has three fundamental parts: the claim, the data, and the warrant [13].

- Claim: Opinions or explanations for the solution of the problem.
- Data: Events or observations used to support the claim.
- Warrant: These are the reasons why the data support the claim.

When examining the related literature, it is seen that the argumentation-supported STEM model has a positive effect on the learning outcomes of K-12 students in the science curriculum. More specifically, the integration of STEM subjects into Toulmin's argumentation model and applied to the 6th grade science curriculum increased students' learning achievements [13]. It was also reported that reflective thinking skills of middle school students developed with the integration of STEM subjects into Toulmin's argumentation model [13]. In another study, it was concluded that students' reflective thinking skills for problem solving and scientific creativity, and learning achievement were more developed in applications made by integrating STEM subjects into the argumentation model when applied to the 7th grade science curriculum [19]. However, a study using the argumentation-supported STEM model in science education reported that it had no effect on the development of reflective thinking skills among middle school students [18]. Therefore, these contradictory findings should be further investigated. In another study, it was observed that there was a positive change in favor of the experimental group for STEM learning motivation of middle school students with argument-based STEM activities [16]. In addition, argumentation-supported STEM activities applied to the design-technology course in the 8th grade curriculum were effective in improving the attitudes of the students towards STEM and their problem-solving skills [29]. In short, the argumentation-supported STEM model can be used to increase learning achievement, developing higher-order thinking skills (reflective thinking skills, problem-solving skills, creativity, etc.), and fostering learning interest and motivation of middle school students in the science curriculum.

2.3. The Combination of 5E-STEM and Argumentation-Supported STEM Models Applied in the Science Curriculum

When viewed in terms of strengths, it is seen that the 5E-STEM model focuses mainly on describing a sequence of hands-on experiences throughout the lesson time to guide students in solving real-world problems, while the argumentation-supported STEM model allows students to better integrate content from all STEM subjects by using evidence to justify design ideas and solutions. When examining the related literature, it was found that the 5E-STEM model has positive effects on learning achievement, motivation, interest, and higher-order thinking skills of K-12 students in the science curriculum; the argumentation-supported STEM model shows the same effects. This leads to the idea that the 5E-STEM model and the argumentation model can be combined to further enhance students' learning outcomes in the science curriculum.

With the idea of teaching science using the A-5E-STEM model in mind, 5E-STEM activities will lead students through the "E" learning phases of real-world problem solving in the science course, while Toulmin's argumentation model provides arguments for developing STEM knowledge in each phase of the 5E cycle. The combination of the 5E instructional model and Toulmin's argumentation model in a STEM-oriented science unit can be visualized as shown in Figure 1.

In Figure 1, there are three main tasks to be performed in the design of a science unit based on the A-5E-STEM model. The first task of designing a science unit using the A-5E-STEM model begins with defining an authentic problem situation; be it a school, local, regional, national, or global problem [14]. The authentic problem situation in a science unit using the A-5E-STEM model is considered "good" when it has a potential connection between STEM subjects and there are no immediately obvious solution or absolute solutions. The second task is to design learning content and hands-on experience activities for students in each "E", such as reading comprehension exercises, experiments, discussions, and investigations [14]. The final task is to use the argumentation model to enhance the integration of STEM subjects into each appropriate "E" phase. Authentic problem situations become the center of discussion for students to explore and connect the fields of science, technology, engineering, and math through developing arguments. Students construct knowledge by making a claim, providing evidence and facts to support the claim, and linking facts to the claim, in relation to the hands-on experiential activities of each phase of the 5E.

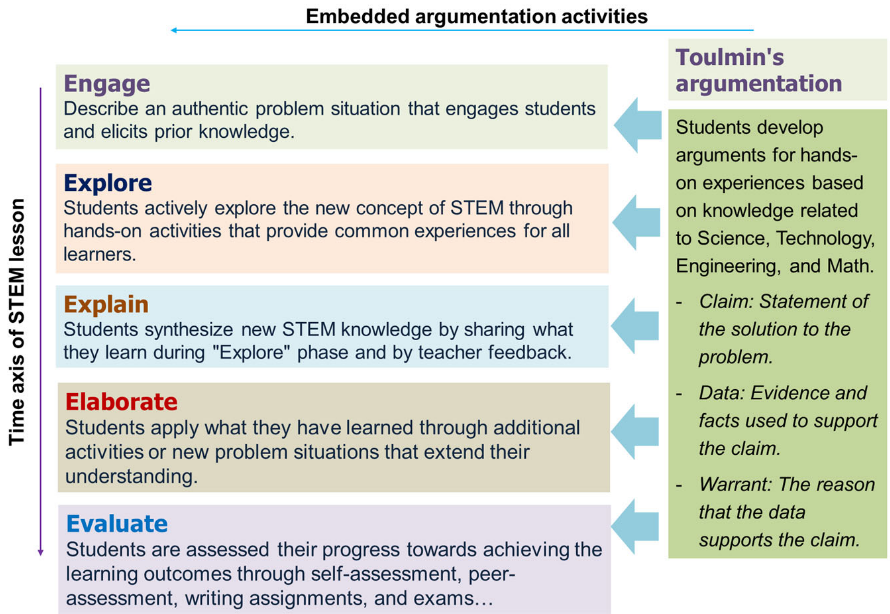

Figure 1. The combination of the 5E-STEM model and Toulmin's argumentation model.

2.4. Research Questions and Hypotheses

This study was guided by four research questions:

Research question 1 (RQ1): How did students' learning achievement differ between teaching science using A-5E-STEM, 5E-STEM, and conventional didactic methods?

Research question 2 (RQ2): How did students' learning motivation differ between teaching science using A-5E-STEM, 5E-STEM, and conventional didactic methods?

Research question 3 (RQ3): How did students' learning interest differ between teaching science using A-5E-STEM, 5E-STEM, and conventional didactic methods?

Research question 4 (RQ4): How did students' higher-order thinking skills differ between teaching science using A-5E-STEM, 5E-STEM, and conventional didactic methods?

There were four research hypotheses that predicted the outcomes of the research questions:

Hypothesis 1 (H1). *At least one of the observed means of students' learning achievement of the three groups of teaching science using A-5E-STEM, 5E-STEM, and conventional didactic methods was different.*

Hypothesis 2 (H2). *At least one of the observed means of students' learning motivation of the three groups of teaching science using A-5E-STEM, 5E-STEM, and conventional didactic methods was different.*

Hypothesis 3 (H3). *At least one of the observed means of students' learning interest of the three groups of teaching science using A-5E-STEM, 5E-STEM, and conventional didactic methods was different.*

Hypothesis 4 (H4). *At least one of the observed means of students' higher-order thinking skills of the three groups of teaching science using A-5E-STEM, 5E-STEM, and conventional didactic methods was different.*

When H1, H2, H3, or H4 were accepted, the following research hypotheses were examined.

Hypothesis 5 (H5). *The observed means of students' learning achievement of the three groups of teaching science using A-5E-STEM, 5E-STEM, and conventional didactic methods were all different*.

Hypothesis 6 (H6). *The observed means of students' learning motivation of the three groups of teaching science using A-5E-STEM, 5E-STEM, and conventional didactic methods were all different*.

Hypothesis 7 (H7). *The observed means of students' learning interest of the three groups of teaching science using A-5E-STEM, 5E-STEM, and conventional didactic methods were all different*.

Hypothesis 8 (H8). *The observed means of students' higher-order thinking skills of the three groups of teaching science using A-5E-STEM, 5E-STEM, and conventional didactic methods were all different*.

3. Methodology

3.1. Design

This was a semi-experimental study with post-test only non-equivalent groups design. A "Separating Mixtures" unit in the 6th grade Natural Science curriculum has been designed with A-5E-STEM and 5E-STEM model orientation. The first experimental group was taught science using the A-5E-STEM model, the second experimental group was taught science using the 5E-STEM model, and a control group was taught in the science unit with conventional didactic methods. Students in the experimental classes were divided into small groups (six students per group) and they solved problems together in the laboratory; while the control class received conventional didactic methods through reading, listening, and discussion related to the "Separating Mixtures" unit. All three classes were taught by the same teacher and for the same duration of 3 h in November 2022. A post-test was used to collect data on learning achievement, and questionnaires were used to collect data on learning motivation, learning interest, and higher-order thinking skills of the middle school students in the science curriculum.

3.2. Participants

A random sampling scenario of students was not possible because of the requirements of maintaining regular classes of public middle schools in Vietnam. Thus, this semi-experimental study used convenience sampling method. The participants were three 6th grade classes with a total of one hundred and twenty students at a public middle school—Le Ngoc Han Middle School in Hai Ba Trung District, Hanoi City, Vietnam. These three classes were selected because they met the following criteria: (1) they contained similar proportions of boys and girls, and (2) the same teacher was teaching the 6th grade Natural Science course. Class 6A3, with 40 students (21 boys and 19 girls), was selected as the first experimental group and received lessons inscience using the A-5E-STEM model. Class 6A4, with 40 students (18 boys and 22 girls), was selected as the second experimental group and received lessons in science using the 5E-STEM model. Class 6A11, with 40 students (19 boys and 21 girls), was selected as the control group. All the students were about 11 years old.

3.3. Experimental Units

The "Separating Mixtures" unit, which is the 17th unit of the 6th grade Natural Science curriculum, was taught to students in a total of three lesson hours based on the A-5E-STEM, 5E-STEM, and conventional didactic methods. The content of this unit is intended to introduce students to some simple concepts and methods of separating mixtures including filtration, evaporation, and liquid–liquid extraction.

Teaching "Separating Mixtures" using the A-5E-STEM model: The "Separating Mixtures" unit was redesigned with an A-5E-STEM orientation and aligned with the curriculum standards. The authentic problem-based STEM Lab activities titled "Separating Salt and

Sand: Can You Do That?" was introduced to students. The lesson plan of this STEM unit is shown in Figure 2.

Phase	Description	Argumentation activities
Engage	- Problem statement: How to separate salt and sand. - Students read the techniques of separating mixtures: filtration, extraction, and evaporation.	- Question: What ideas do you have for separating sand and salt? - Claim: "I can separate sand and salt water with a filter; Salt can be separated by evaporating water!" - Data: What properties of salt and sand allow you to separate them? - Warrant: Are you sure about your idea?
Explore	- Students study the operation of filter paper, and experimental materials/equipment. - Cooperative learning and hands-on task using experimental manipulations.	- Question: How many filter papers will your team use to separate the sand from the salt water? - Claim: "My team will use one, two or three filter papers to separate the sand from the salt water!" - Data: What makes you think such amount of filter paper should be used? - Warrant: Do you think that your filter will run well?
Explain	- Write a report. - Comment and explain the purity of salt and sand. - Calculation for productivity of salt and sand. -Share test results.	- Question: In your test results, did the salt and sand achieve the same purity and weight as the original? - Claim: "After the experiment, the purity and weight of salt and sand were not obtained as original!" - Data: Did the purity and weight of the salt and sand increase or decrease? Please explain more about that? - Warrant: Do you think there was still a small amount of salt mixed in the sand, and also a small amount of sand mixed in the salt?
Elaborate	- Discussion of practical tasks: separating salt from sea water, separating sugar from water, separating cooking oil and water, separating sand and sugar.	
Evaluate	- Writing assignments. - Students evaluate their suitability for a career as a chemist or chemical engineer.	- Question: What career are you interested in? - Claim: "I am interested in the career of chemist or chemical engineer or other to pursue a future career!" - Data: What do you understand about your chosen career? - Warrant: Are you sure about your career choice?

Figure 2. The lesson plan of the STEM unit "Separating Salt and Sand: Can You Do That?".

Teaching "Separating Mixtures" using the 5E-STEM model: This unit was also prepared by researchers and contained identical conditions to the "Separating Mixtures" unit using the A-5E-STEM in terms of science content, materials, duration, and form of instruction. Its lesson plan was the same as Figure 2, except that no argumentation activities were included.

Teaching "Separating Mixtures" using conventional didactic methods: This unit was taken from the existing lesson plans of teachers who teach the 6th grade Natural Science course at their school. This unit was teacher-centered, with the students sitting quietly, and listening attentively and passively, and the teachers acting as the primary source of scientific knowledge through lectures. Lectures were conducted in a traditional classroom environment with a blackboard and a multimedia projector.

3.4. Instruments

A post-test was used to collect data on learning achievement, and questionnaires were used to collect data on learning motivation, learning interest, and higher-order thinking skills of students in the 6th grade Natural Science course. Using SPSS software, the Cronbach's α was calculated to observe the reliability of the scales. A cut-off point of 0.7 of the α value reflects an acceptable internal consistency of the scale [30].

- *Learning achievement:* STEM education emphasizes the importance of integrating a large amount of content from individual STEM subjects to help students connect ideas across disciplines and to solve real-world problems. However, integrated STEM-oriented courses should also focus on learning goals and standards so as not to inadvertently reduce student performance in those subjects in the curriculum [31]. Therefore, a post-test for the students' learning achievement in the "Separating Mixtures" unit was developed based on the learning standards of the 6th grade Natural Science course in Vietnam (Appendix A). However, the learning of skills was not reflected in the test scores. Test scores were used as observed data for students' learning achievement in the "Separating Mixtures" unit.

- *Learning motivation:* Keller's ARCS model was used as the basis for developing a learning motivation questionnaire using a 5-point Likert-type scale. The questionnaire consists of four sub-groups including attention, relevance, confidence, and satisfaction. A total of 16 questions were developed to measure students' learning motivation in the "Separating Mixtures" unit. Cronbach's α reliability tests were used to measure the internal consistency of the overall questionnaire and each sub-group. The α values of attention, relevance, confidence, and satisfaction were 0.87, 0.78, 0.87, and 0.82, respectively, and the α value of the overall questionnaire was 0.94 (Table 1). Because all values were above 0.7, the internal consistency of the learning motivation questionnaire was acceptable.
- *Learning interest:* The three-dimensional model of students' learning interest proposed by [32] was used to build a questionnaire with three sub-groups including cognitive attention, learning emotion, and thinking activity, using a 5-point Likert-type scale. A total of 12 questions were developed to measure students' learning interest in the "Separating Mixtures" unit. The α values of cognitive attention, learning emotion, and thinking activity were 0.85, 0.88, and 0.87, respectively, and the α value of the overall questionnaire was 0.95 (Table 2). Because all values were above 0.7, the internal consistency of the learning interest questionnaire was acceptable.
- *Higher-order thinking skills:* The questionnaire measuring students' higher-order thinking skills developed by [33] was used and modified in this study. The questionnaire focused on three sub-groups including collaboration tendency, critical thinking awareness, and problem-solving tendency. A total of 12 questions were developed to measure students' higher-order thinking skills in the "Separating Mixtures" unit. The α values of collaboration tendency, critical thinking awareness, and problem-solving tendency were 0.86, 0.87, and 0.85, respectively, and the α value of the overall questionnaire was 0.94 (Table 3). Because all values were above 0.7, the internal consistency of the higher-order thinking skills questionnaire was acceptable.

Table 1. Reliability of the learning motivation questionnaire.

Code	Item	Cronbach's α
A	**Attention (A = A1 + A2 + A3 + A4)**	0.87
A1	The problem situation of the "Separating Mixtures" unit was attractive, interesting and challenging.	
A2	I was engrossed in the whole process of solving the problem of separating mixtures.	
A3	The hands-on activities in the "Separating Mixtures" unit were fun to do.	
A4	The discussion activities were very lively and active.	
R	**Relevance (R = R1 + R2 + R3 + R4)**	0.78
R1	Teaching content and activities were relevant to real life and personal experiences.	
R2	Teaching content and activities were related to using knowledge of many subjects, such as technology and math.	
R3	Teaching activities encouraged different ideas or solutions to the problem situation of separating mixtures.	
R4	I have seen careers related to the "Separating Mixtures" unit.	
C	**Confidence (C = C1 + C2 + C3 + C4)**	0.87
C1	I feel confident in solving any problem related to the separating mixtures, for example "separating sugar and sand".	
C2	I feel confident to offer ideas and solutions for separating mixtures, for example separating sugar and sand.	
C3	I feel confident that I can practice separating mixtures from my ideas and solutions.	
C4	I feel confident in discussing ideas and solutions to the problem situation of separating mixtures.	

Table 1. *Cont.*

Code	Item	Cronbach's α
S	**Satisfaction (S = S1 + S2 + S3 + S4)**	0.82
S1	I was satisfied with the problem situation and problem solving process.	
S2	I was satisfied with the knowledge gained.	
S3	I was satisfied with the practices of separating mixtures	
S4	I was satisfied with the discussion for separating mixtures.	
	Overall scale	0.94

Table 2. Reliability of the learning interest questionnaire.

Code	Item	Cronbach's α
CA	**Cognitive Attention (CA = CA1 + CA2 + CA3 + CA4)**	**0.85**
CA1	I paid more attention to this lesson than the previous lessons.	
CA2	I paid attention selectively to ideas and solutions that work for the problem of separating mixtures.	
CA3	I focused on listening, thinking rationally about the ideas and solutions in the discussions.	
CA4	I participated actively in the discussions.	
LE	**Learning Emotion (LE = LE1 + LE2 + LE3 + LE4)**	**0.88**
LE1	I enjoyed the problem situation in this lesson.	
LE2	I feel the lesson content was very useful.	
LE3	I enjoyed participating in hands-on activities.	
LE4	I enjoyed participating in discussion.	
TA	Thinking Activity (TA = TA1 + TA2 + TA3 + TA4)	**0.87**
TA1	I feel this lesson improved my reasoning and problem-solving skills.	
TA2	I was actively thinking about more efficient solutions to the problem situation of separating mixtures.	
TA3	I was interested in being able to use what I learned in one unit into another unit or course, such as technology, math.	
TA4	I was interested in learning about careers related to this lesson.	
	Overall scale	**0.95**

Table 3. Reliability of the higher-order thinking skills questionnaire.

Code	Item	Cronbach's α
CT	**Collaboration Tendency (CT = CT1 + CT2 + CT3 + CT4)**	0.86
CT1	I tried my best to complete the common task well.	
CT2	I cooperated actively to accomplish the common task.	
CT3	While working together with other students, I communicated well with them.	
CT4	The tasks were properly assigned to each member.	
CTA	**Critical Thinking Awareness (CTA = CTA1 + CTA2 + CTA3 + CTA4)**	0.87
CTA1	I pondered whether what I learned to be appropriate for the problem situation of separating mixtures.	
CTA2	I thought of other possible solutions to the problem situation of separating mixtures.	
CTA3	I considered the different opinions to determine a reasonable solution to the problem situation of separating mixtures.	
CTA4	I provided arguments for the plausibility of my solution in the problem situation of separating mixtures.	
PST	**Problem-Solving Tendency (PST = PST1 + PST2 + PST3 + PST4)**	0.85

Table 3. *Cont.*

Code	Item	Cronbach's α
PST1	I believe that I am capable of solving other problem situations of separating mixtures which I may encounter.	
PST2	I believe I can independently solve the problem situations of separating mixtures in this lesson.	
PST3	When encountering other problem situations, I am willing to face and solve them.	
PST4	I will always do my best to solve the problem which I may encounter.	
	Overall scale	0.94

3.5. Statistical Analysis

All collected data were analyzed using IBM SPSS v26.0 software. Means and standard errors were used to describe the scores on learning achievement, learning motivation, learning interest, and higher-order thinking skills of students. Statistical analyses were performed in two phases.

Phase 1: Unrelated one-way ANOVA analyses were used to examine H1, H2, H3, and H4. In the ANOVA analysis, the F-statistic is used to test the research hypotheses [34]. The observed F-value is compared with the critical F-value which is determined from the F Distribution Table by the degrees of freedom including column Df (between groups) and row Df (within individuals) [34]. In this study, ANOVA analyses were performed with 3 groups of students and a total of 120 students; accordingly, Df (between groups) = 3 − 1 = 2 and Df (within individuals) = 'number of objects'—Df (corrected total)—df (between groups) = 120 – 1 − 2 = 117. Looking at the F Distribution Table at column Df (between groups) = 2 and row Df (within individuals) = 117, we obtained a critical F-value of 3.07 (with a significance level of 0.05). Therefore, when the observed F-value was equal to or less than the critical F-value = 3.07 and the p-value was greater than 0.05, a research hypothesis was rejected. In contrast, when the observed F was greater than the critical F-value = 3.07 and the p-value was less than 0.05, a research hypothesis was accepted.

Phase 2: When the observed F-value was statistically significant, the One-Way ANOVA Post Hoc test using the LSD method was used to examine for H5, H6, H7, and H8. The LSD method was used because it allows finding the smallest significant difference between two means [35]. When the p-value was less than 0.05, a research hypothesis was accepted.

4. Results

4.1. RQ1: How Did Students' Learning Achievements Differ between Teaching Science Using A-5E-STEM, 5E-STEM, and Conventional Didactic Methods?

The measure of students' learning achievements was reflected through the test scores (using a 10-point scale) of the "Separating Mixtures" unit based on the learning objectives of the 6th grade Natural Science course. In SPSS, an unrelated one-way ANOVA was conducted to answer RQ 1. The results are presented in Table 4.

Table 4. ANOVA results for students' learning achievements.

Group	N	Mean	Std. Error	95% Confidence Interval (CI) for Mean	
				Lower	Upper
6A3 (A-5E-STEM)	40	7.938	0.2230	7.486	8.389
6A4 (5E-STEM)	40	7.125	0.2605	6.598	7.652
6A11 (Conventional Didactic)	40	5.463	0.2987	4.858	6.067
Total	120	6.842	0.1775	6.490	7.193
F = 23.085, p = 0.00					

The ANOVA results in showed that the p-value = 0.00 was less than the significance level of 0.05, and the value of the observed F = 23.085 was greater than the critical F = 3.07. Therefore, H1 was accepted. In other words, at least one of the observed means of the students' learning achievements differed between the three groups of teaching science using A-5E-STEM (mean = 7.938, 95% CI = 7.486 ÷ 8.389), 5E-STEM (mean = 7.125, 95% CI = 6.598 ÷ 7.652), and conventional didactic methods (mean = 5.463, 95% CI = 4.858 ÷ 6.067).

When the ANOVA F-statistic was statistically significant, an ANOVA Post-Hoc test was performed to compare pairs of the observed means of students' learning achievements (Table 5).

Table 5. ANOVA Post-Hoc test results for students' learning achievements.

(I) Groups	(J) Groups	Mean Difference (I − J)	Std. Error	Sig.	95% CI	
					Lower	Upper
6A3	6A4	0.8125	0.3713	0.031	0.077	1.548
6A3	6A11	2.4750	0.3713	0.000	1.740	3.210
6A4	6A11	1.6625	0.3713	0.000	0.927	2.398

As shown in Table 5, all p-values were less than 0.05 and all 95% confidence intervals did not cover the value '0′, indicating that H5 was accepted. In other words, the observed means of the students' learning achievements differed between the three groups of teaching science using A-5E-STEM (6A3 class), 5E-STEM (6A4 class), and conventional didactic methods (6A11 class). More specifically, teaching science using the 5E-STEM model significantly increased the observed means on students' learning achievements when compared to teaching using conventional didactic methods (mean difference = 1.6625, p = 0.00 [<0.05], 95% CI = 0.927 ÷ 2.398). When the argumentation model was combined with the 5E-STEM model, a new model "A-5E-STEM" further increased the observed means on students' learning achievements when compared to teaching using 5E-STEM (mean difference = 0.8125, p = 0.031 [<0.05], 95% CI = 0.077 ÷ 1.548). Thus, teaching science using the A-5E-STEM model has a positive effect on the learning achievements of middle school students in the science curriculum.

4.2. RQ2: How Did Students' Learning Motivation Differ between Teaching Science Using A-5E-STEM, 5E-STEM, and Conventional Didactic Methods?

Students' learning motivation was observed in four sub-groups including attention (with four observed items), relevance (with four observed items), confidence (with four observed items) and satisfaction (with four observed items). The scores of these sub-groups were calculated as the sum of its four observed items. Then, an unrelated one-way ANOVA was conducted to answer RQ2. The results are presented in Table 6.

Table 6. ANOVA results for students' learning motivation.

Observed Variable		Mean	Std. Error	95% CI for Mean		ANOVA
				Lower	Upper	
Attention	6A3	17.180	0.486	16.198	18.162	F = 31.044 p = 0.00
	6A4	14.150	0.188	13.770	14.530	
	6A11	12.025	0.614	10.782	13.268	
Relevance	6A3	16.928	0.470	15.977	17.880	F = 22.135 p = 0.00
	6A4	13.910	0.174	13.559	14.261	
	6A11	12.772	0.611	11.536	14.009	
Confidence	6A3	16.585	0.593	15.386	17.784	F = 12.826 p = 0.00
	6A4	13.875	0.193	13.484	14.266	
	6A11	12.622	0.756	11.094	14.150	
Satisfaction	6A3	17.360	0.454	16.443	18.278	F = 16.620 p = 0.00
	6A4	14.125	0.203	13.714	14.536	
	6A11	13.589	0.710	12.152	15.025	

Looking at the ANOVA results in Table 6, in all cases the *p*-values were less than 0.05, the observed F-values were greater than the critical F = 3.07, and all 95% confidence intervals did not cover the value "0". Therefore, H2 was accepted. In other words, at least one of the observed means of the students' learning motivation difered between the three groups of teaching science using A-5E-STEM (6A3 class), 5E-STEM (6A4 class), and conventional didactic methods (6A11 class). More specifically, it was the probability that the observed means of the students' learning motivation in group 6A3 (with A-5E-STEM) were greater than group 6A4 (with 5E-STEM), and in group 6A4 were greater than group 6A11 (with conventional didactic methods).

When the ANOVA F-statistics were statistically significant, an ANOVA Post-Hoc test was performed to compare pairs of the observed means of students' learning motivation (Table 7).

Table 7. ANOVA Post-Hoc test results for students' learning motivation.

Observed Variable	(I) Groups	(J) Groups	Mean Difference (I − J)	Std. Error	Sig.	95% CI	
						Lower	Upper
Attention	6A3	6A4	3.030	0.658	0.000	1.728	4.332
	6A3	6A11	5.155	0.658	0.000	3.853	6.457
	6A4	6A11	2.125	0.658	0.002	0.823	3.427
Relevance	6A3	6A4	3.018	0.646	0.000	1.740	4.297
	6A3	6A11	4.156	0.646	0.000	2.878	5.435
	6A4	6A11	1.138	0.646	0.081	−0.141	2.416
Confidence	6A3	6A4	2.710	0.800	0.001	1.126	4.294
	6A3	6A11	3.963	0.800	0.000	2.379	5.547
	6A4	6A11	1.253	0.800	0.120	−0.331	2.837
Satisfaction	6A3	6A4	3.235	0.708	0.000	1.833	4.637
	6A3	6A11	3.771	0.708	0.000	2.370	5.173
	6A4	6A11	0.536	0.708	0.450	−0.865	1.938

According to the results shown in Table 7, H6 was only accepted for the observed "attention" variable of the students' learning motivation because the *p*-values were less than 0.05 and all 95% confidence intervals did not cover the value '0'. This meant that the students' learning attention means of the three groups of teaching science using A-5E-STEM (6A3 class), 5E-STEM (6A4 class), and conventional didactic methods (6A11 class) were all different. More specifically, teaching science using the 5E-STEM model significantly increased the students' learning attention means when compared to teaching using conventional didactic methods (mean difference = 2.125, p = 0.002 [<0.05]; 95% CI = 0.823 ÷ 3.427). When the argumentation model was combined with the 5E-STEM model, a new model "A-5E-STEM" further increased students' learning attention means when compared to teaching using 5E-STEM (mean difference = 3.030, p = 0.00 [<0.05]; 95% CI = 1.728 ÷ 4.332). In short, the students' learning attention means in group 6A3 (with A-5E-STEM) were greater than group 6A4 (with 5E-STEM), and the means in group 6A4 were greater than group 6A11 (with conventional didactic methods).

In the remaining three observed variables of students' learning motivation including relevance, confidence, and satisfaction, H6 was rejected. When examining the comparison pairs of 6A3 and 6A4, and 6A3 and 6A11 in all cases, *p*-values < 0.05 and 95% confidence intervals not covering the value '0' showed that the observed means of learning relevance, learning confidence, and learning satisfaction of students in teaching science using the A-5E-STEM model were significantly greater than those in teaching science using the 5E-STEM model and conventional didactic methods. However, when examining the comparison pair of 6A4 and 6A11 in all cases, *p*-values > 0.05 and 95% CI covering the value '0' showed that the observed means on learning relevance, learning confidence, and learning satisfaction of students in teaching science using 5E-STEM were not different from those of students in teaching science using conventional didactic methods. Thus, teaching science using the A-5E-STEM model was particularly effective for developing the relevance, confidence, and satisfaction of students' learning motivation, whereas teaching science using the 5E-STEM model was not.

4.3. RQ3: How Did Students' Learning Interest Differ between Teaching Science Using A-5E-STEM, 5E-STEM, and Conventional Didactic Methods?

Students' learning interest was observed in three sub-groups including cognitive attention (with four observed items), learning emotion (with four observed items) and thinking activity (with four observed items). The scores of these sub-groups were calculated as the sum of its four observed items. Then, an unrelated one-way ANOVA was conducted to answer RQ3. The results are presented in Table 8.

Table 8. ANOVA results for students' learning interest.

Observed Variable		Mean	Std. Error	95% CI for Mean Lower	95% CI for Mean Upper	ANOVA
Cognitive Attention	6A3	17.350	0.363	16.617	18.083	F = 33.354 $p = 0.00$
	6A4	14.175	0.118	13.936	14.414	
	6A11	12.150	0.687	10.760	13.540	
Learning Emotion	6A3	17.975	0.417	17.132	18.818	F = 29.741 $p = 0.00$
	6A4	14.400	0.159	14.078	14.722	
	6A11	12.647	0.738	11.154	14.139	
Thinking Activity	6A3	17.325	0.398	16.521	18.129	F = 35.080 $p = 0.00$
	6A4	13.900	0.159	13.578	14.222	
	6A11	11.575	0.729	10.100	13.050	

Looking at the ANOVA results in Table 8, in all cases the p-values were less than 0.05, the observed F-values were greater than the critical F = 3.07, and all 95% confidence intervals did not cover the value "0". Therefore, H3 was accepted. In other words, at least one of the observed means of the students' learning interest differed between the three groups of teaching science using A-5E-STEM (6A3 class), 5E-STEM (6A4 class), and conventional didactic methods (6A11 class). More specifically, it was the probability that the means of the students' learning interest in group 6A3 (with A-5E-STEM) were greater than group 6A4 (with 5E-STEM), and in group 6A4 were greater than group 6A11 (with conventional didactic methods).

When the ANOVA F-statistics were statistically significant, an ANOVA Post-Hoc test was performed to compare pairs of observed means of the students' learning interest (Table 9).

Table 9. ANOVA Post-Hoc test results for students' learning interest.

Observed Variable	(I) Groups	(J) Groups	Mean Difference (I − J)	Std. Error	Sig.	95% CI Lower	95% CI Upper
Cognitive Attention	6A3	6A4	3.175	0.642	0.000	1.904	4.446
	6A3	6A11	5.200	0.642	0.000	3.929	6.471
	6A4	6A11	2.025	0.642	0.002	.754	3.296
Learning Emotion	6A3	6A4	3.575	0.704	0.000	2.180	4.970
	6A3	6A11	5.329	0.704	0.000	3.934	6.723
	6A4	6A11	1.754	0.704	0.014	.359	3.148
Thinking Activity	6A3	6A4	3.425	0.691	0.000	2.057	4.793
	6A3	6A11	5.750	0.691	0.000	4.382	7.118
	6A4	6A11	2.325	0.691	0.001	0.957	3.693

According to the results shown in Table 9, all p-values were less than 0.05 and all 95% confidence intervals did not cover the value '0' in all cases, indicating that H7 was accepted for all the observed variables of the students' learning interest including cognitive attention, learning emotion, and thinking activity. This meant that the observed means of the students' learning interest differed between the three groups of teaching science using A-5E-STEM, 5E-STEM, and conventional didactic methods. More specifically, all observed means of the students' learning interest in group 6A3 (with A-5E-STEM) were greater than group 6A4 (with 5E-STEM), and in group 6A4 were greater than group 6A11 (with conventional didactic methods). The mean differences of a comparison pair of 6A3 and 6A4 were reported as 3.175 for cognitive attention (p = 0.00 [<0.05]; 95% CI = 1.904 ÷ 4.446), 3.575 for learning emotion (p = 0.00 [<0.05]; 95% CI = 2.180÷4.970) and 3.425 for thinking activity (p = 0.00 [<0.05]; 95% CI = 2.057 ÷ 4.793). Meanwhile, the mean differences of a comparison pair of 6A4 and 6A11 were reported as 2.025 for cognitive attention (p = 0.002 [<0.05]; 95% CI = 0.754 ÷ 3.296), 1.754 for learning emotion (p = 0.014 [<0.05]; 95% CI = 0.359 ÷ 3.148) and 2.325 for thinking activity (p = 0.001 [<0.05]; 95% CI = 0.957 ÷ 3.693). Overall, the mean differences in students' learning interest of a comparison pair of 6A3 and 6A4 were significantly larger than those of a comparison pair of 6A4 and 6A11. Thus, teaching science using the A-5E-STEM model was particularly effective for developing all aspects of the students' learning interest including cognitive attention, learning emotion, and thinking activity in the science curriculum.

4.4. RQ4: How Did Students' Higher-Order Thinking Skills Differ between Teaching Science Using A-5E-STEM, 5E-STEM, and Conventional Didactic Methods?

Students' higher-order thinking skills were observed in three sub-groups including collaboration tendency (with four observed items), critical thinking awareness (with four observed items) and problem-solving tendency (with four observed items). The scores of these sub-groups were calculated as the sum of its four observed items. Then, an unrelated one-way ANOVA was conducted to answer RQ4. The results are presented in Table 10.

Table 10. ANOVA results for students' higher-order thinking skills.

Observed Variable		Mean	Std. Error	95% CI for Mean Lower	95% CI for Mean Upper	ANOVA
Collaboration Tendency	6A3	17.400	0.438	16.514	18.286	F = 27.752 p = 0.00
	6A4	14.050	0.172	13.703	14.397	
	6A11	12.425	0.689	11.032	13.818	
Critical Thinking Awareness	6A3	17.275	0.399	16.469	18.081	F = 38.248 p = 0.00
	6A4	14.025	0.127	13.769	14.281	
	6A11	11.850	0.640	10.555	13.145	
Problem-Solving Tendency	6A3	17.625	0.363	16.891	18.359	F = 33.258 p = 0.00
	6A4	14.200	0.172	13.851	14.549	
	6A11	12.400	0.689	11.007	13.793	

Looking at the ANOVA results in Table 10, in all cases the p-values were less than 0.05, the observed F-values were greater than the critical F = 3.07, and all 95% confidence intervals did not cover the value "0". Therefore, H4 was accepted. In other words, at least one of the observed means of the students' higher-order thinking skills differed between the three groups of teaching science using A-5E-STEM (6A3 class), 5E-STEM (6A4 class), and conventional didactic methods (6A11 class). More specifically, it was the probability that the means of the students' higher-order thinking skills in group 6A3 (with A-5E-STEM) were greater than group 6A4 (with 5E-STEM), and in group 6A4 were greater than group 6A11 (with conventional didactic methods).

When the ANOVA F-statistics were statistically significant, an ANOVA Post-Hoc test was performed to compare pairs of observed means of the students' higher-order thinking skills (Table 11).

Table 11. ANOVA Post-Hoc test results for students' higher-order thinking skills.

Observed variable	(I) Groups	(J) Groups	Mean Difference (I − J)	Std. Error	Sig.	95% CI	
						Lower	Upper
Collaboration Tendency	6A3	6A4	3.350	0.681	0.000	2.001	4.699
	6A3	6A11	4.975	0.681	0.000	3.626	6.324
	6A4	6A11	1.625	0.681	0.019	0.276	2.974
Critical Thinking Awareness	6A3	6A4	3.250	0.624	0.000	2.014	4.486
	6A3	6A11	5.425	0.624	0.000	4.189	6.661
	6A4	6A11	2.175	0.624	0.001	0.939	3.411
Problem-Solving Tendency	6A3	6A4	3.425	0.651	0.000	2.136	4.714
	6A3	6A11	5.225	0.651	0.000	3.936	6.514
	6A4	6A11	1.800	0.651	0.007	0.511	3.089

According to the results shown in Table 11, all p-values were less than 0.05 and all 95% confidence intervals did not cover the value '0′ in all cases, indicating that H8 was accepted for all the observed variables of the students' higher-order thinking skills including collaboration tendency, critical thinking awareness, and problem-solving tendency. This meant that the observed means of the students' higher-order thinking skills differed between the three groups of teaching science using A-5E-STEM, 5E-STEM, and conventional didactic methods. More specifically, all observed means of the students' higher-order thinking skills in group 6A3 (with A-5E-STEM) were greater than group 6A4 (with 5E-STEM), and in group 6A4 were greater than group 6A11 (with conventional didactic methods). The mean differences of a comparison pair of 6A3 and 6A4 were reported as 3.350 for collaboration tendency (p = 0.00 [<0.05]; 95% CI = 2.001 ÷ 4.699), 3.250 for critical thinking awareness (p = 0.00 [<0.05]; 95% CI = 2.014 ÷ 4.486) and 3.425 for problem-solving tendency (p = 0.00 [<0.05]; 95% CI = 2.136÷4.714). Meanwhile, the mean differences of a comparison pair of 6A4 and 6A11 were reported as 1.625 for collaboration tendency (p = 0.019 [<0.05]; 95% CI = 0.276 ÷ 2.974), 2.175 for critical thinking awareness (p = 0.001 [<0.05]; 95% CI = 0.939 ÷ 3.411) and 1.800 for problem-solving tendency (p = 0.007 [<0.05]; 95% CI = 0.511 ÷ 3.089). Overall, the mean differences in students' higher-order thinking skills of a comparison pair of 6A3 and 6A4 were significantly larger than those of a comparison pair of 6A4 and 6A11. Thus, teaching science using the A-5E-STEM model was particularly effective for developing all aspects of the students' higher-order thinking skills including collaboration tendency, critical thinking awareness, and problem-solving tendency in the science curriculum.

5. Discussion

This study achieved the proposed purpose of examining the differences in learning achievement, learning motivation, learning interest, and higher-order thinking skills of middle school students between teaching science using A-5E-STEM, 5E-STEM, and conventional didactic methods. The overall findings indicated that teaching science using the A-5E-STEM model was particularly effective for enhancing all learning outcomes of middle school students in the science curriculum. This positive results may be because the A-5E-STEM model combined the advantages of both the 5E-STEM and argumentation-supported STEM models. While teaching science using the 5E-STEM model guides students in a series of hands-on experiences to solve real-world problems [23,24], the argumentation-supported STEM model helps them in integrating content from all STEM subjects to better justify their engineering design ideas and solutions [17]. In addition, when studying the related literature it was found that both 5E-STEM and argumentation-supported STEM models have a positive effect in enhancing learning achievement, motivation, interest, and higher-order thinking skills of K-12 students in the science curriculum [29]. Therefore, we can agree that the combination of the 5E-STEM and the argumentation-supported STEM is a good idea to further improve the learning outcomes of middle school students in the science curriculum [19]. Because this study was the first study in which the A-5E-STEM model was applied to science courses, results from other similar studies were not available for discussion.

The discussion of RQ1: How did students' learning achievements differ between teaching science using A-5E-STEM, 5E-STEM, and conventional didactic methods?

The first finding of this study revealed that the observed means of the students' learning achievements differed between the three groups of teaching science using A-5E-STEM, 5E-STEM, and conventional didactic methods. More specifically, the observed means of the students' learning achievements in the A-5E-STEM experimental group (mean = 7.938, 95% CI = 7.486 ÷ 8.389) were greater than in the 5E-STEM experimental group (mean = 7.125, 95% CI = 6.598 ÷ 7.652), and the means in the 5E-STEM experimental group were greater than in the conventional didactic group (mean = 5.463, 95% CI = 4.858 ÷ 6.067). Therefore, teaching science using the A-5E-STEM model was particularly effective in further improving students' academic achievement in the science curriculum. The positive results of teaching science using the A-5E-STEM model on students' learning achievement were strongly supported by related research in the area of teaching science using the 5E-STEM model [12,23,24,27], and teaching science using the argumentation-supported STEM model [13,19].

The discussion of RQ2: How did students' learning motivation differ between teaching science using A-5E-STEM, 5E-STEM, and conventional didactic methods?

The second finding of this study revealed that the students' learning attention means differed between the three groups of teaching science using A-5E-STEM (6A3 class), 5E-STEM (6A4 class), and conventional didactic methods (6A11 class). More specifically, the students' learning attention means in the A-5E-STEM experimental (mean = 17.180, 95% CI = 16.198 ÷ 18.162) group were greater than in the 5E-STEM experimental group (mean = 14.150, 95% CI = 13.770 ÷ 14.530), and the means in the 5E-STEM experimental group were greater than in the conventional didactic group (mean = 12.025, 95% CI = 10.782 ÷ 13.268). A related study reported similar results that teaching science using the 5E-STEM model can enhance students' learning attention when compared to teaching using conventional didactic methods [23].

The third finding was found in the remaining three observed variables of students' learning motivation. In particular, the observed means on learning relevance, learning confidence, and learning satisfaction of the students in the A-5E-STEM experimental group were significantly greater than those in the 5E-STEM experimental group and in the conventional didactic group. However, the observed means on learning relevance, learning confidence, and learning satisfaction of the students were not different between the 5E-STEM experimental group and in the conventional didactic group. These findings suggest that teaching science using the A-5E-STEM model was particularly effective for developing the relevance, confidence, and satisfaction of students' learning motivation, whereas teaching science using the 5E-STEM model was not. Contrary to this third finding, a related study found that teaching science using the 5E-STEM model can enhance students' learning relevance, and satisfaction when compared to teaching using conventional didactic methods [23]. In addition, the findings of this study supported a conclusion that the combination of the argumentation model and STEM practices can enhance the learning motivation of middle school students in the science curriculum [16].

The discussion of RQ3: How did students' learning interest differ between teaching science using A-5E-STEM, 5E-STEM, and conventional didactic methods?

The fourth finding of this study revealed that the observed means of the students' learning interest differed between the three groups of teaching science using A-5E-STEM, 5E-STEM, and conventional didactic methods. More specifically, the observed means of cognitive attention, learning emotion, and thinking activity of students in the A-5E-STEM experimental group were significantly greater than those in the 5E-STEM experimental group, and the means in the 5E-STEM experimental group were greater than in the conventional didactic group. Therefore, teaching science using the A-5E-STEM model can enhance all aspects of the students' learning interest including cognitive attention, learning emotion, and thinking activity in the science curriculum. The positive results of teaching science using the A-5E-STEM model on students' learning interest were strongly supported by related research in the area of teaching science using the 5E-STEM model [27], and teaching science using the argumentation-supported STEM model [29]. Teaching science using the A-5E-STEM model can engage students in evidence-based problem solving [29], while making finished tangible STEM products gives students a sense of accomplishment [14].

The discussion of RQ4: How did students' higher-order thinking skills differ between teaching science using A-5E-STEM, 5E-STEM, and conventional didactic methods?

Finally, the fifth finding of this study revealed that the observed means of the students' higher-order thinking skills differed between the three groups of teaching science using A-5E-STEM, 5E-STEM, and conventional didactic methods. More specifically, the observed means of collaboration tendency, critical thinking awareness, and problem-solving tendency of students in the A-5E-STEM experimental group were significantly greater than those in the 5E-STEM experimental group, and the means in the 5E-STEM experimental group were greater than in the conventional didactic group. Therefore, teaching science using the A-5E-STEM model can enhance all aspects of the students' higher-order thinking skills including collaboration tendency, critical thinking awareness, and problem-solving tendency in the science curriculum. The positive results of teaching science using the A-5E-STEM model on students' higher-order thinking skills were strongly supported by related research in the area of teaching science using the 5E-STEM model [12,25,26], and teaching science using the argumentation-supported STEM model [13,19,29]. The fifth finding partially contradicted a related study revealing that using the argumentation-supported STEM model in science education had no effect on the development of reflective thinking skills among middle school students [18].

6. Conclusions

This study has fulfilled the stated research purpose. To our knowledge, the idea of teaching science using the A-5E-STEM model is a novel approach that has not been seen in previous studies. The findings showed that using the A-5E-STEM model in the science curriculum led to significantly superior student learning outcomes when compared to that of the 5E-STEM and conventional didactic methods. From the results of the learning achievement test, it was found that the observed means of the students' learning achievements in the A-5E-STEM experimental group were greater than in the 5E-STEM experimental group, and the means in the 5E-STEM experimental group were greater than in the conventional didactic group. Similar results were also found for the observed means of learning interest, and higher-order thinking skills of middle school students in the science curriculum. From the data of learning motivation, it was found that the observed means of the students' learning attention in the A-5E-STEM experimental group were greater than in the 5E-STEM experimental group, and the means in the 5E-STEM experimental group were greater than in the conventional didactic group. Furthermore, teaching science using the A-5E-STEM model was effective for developing the relevance, confidence, and satisfaction of students' learning motivation, whereas teaching science using the 5E-STEM model was not. In general, it can be said that teaching science using the A-5E-STEM model is more effective than using the 5E-STEM model in further increasing students' learning outcomes when compared to the current curriculum in conventional didactic methods. The results are encouraging and suggest that science teachers increase the use of the A-5E-STEM model in their science courses.

6.1. Implications for Practice

The most significant implication for practice identified in this study is that teaching science using the A-5E-STEM model is more effective than using the 5E-STEM model in the science curriculum to further improve the learning outcomes of middle school students. In other words, teachers should teach science using the A-5E-STEM model instead of using the 5E-STEM model in the science curriculum. In this scenario, teachers should pay attention to two factors for classroom implementation, including (1) guiding students through each "E" phase of the 5E learning process that allows them to solve real-world problems through hands-on activities, and (2) establishing evidence-based arguments in each "E" phase that assists students in better integration of content from all STEM subjects to justify their design ideas and solutions. Therefore, teaching science using the A-5E-STEM model should be widely deployed in the science curriculum to further improve the learning outcomes of middle school students.

6.2. Limitations of This Study and Recommendations

This study has some limitations that should be noted. Firstly, this study was limited to 6th grade students at a public middle school, and studies on teaching science using the A-5E-STEM model should be conducted with students studying in other grades and at other middle schools. Secondly, in this study it was determined that teaching science using the A-5E-STEM model has a positive effect on students' learning outcomes in the science curriculum; however, the sample size was limited to 40 students in the A-5E-STEM experimental group, 40 students in the 5E-STEM experimental group, and 40 students in the conventional didactic group. Therefore, the effects of teaching science using the A-5E-STEM model on students' learning outcomes should be further examined by conducting similar studies with a larger sample size or school-wide program. Thirdly, the scope of this study was limited to a 6th grade science unit over 3 h of class time, future experiments should be conducted in the longer term. Finally, although statistically significant differences in students' learning outcomes of the three groups of teaching science using A-5E-STEM, 5E-STEM and conventional didactic methods were found, as this was a semi-experimental study with post-test only non-equivalent groups design, the results could also have been caused by any confounding variables. Therefore, the experiments in this study should be repeated in the future.

Author Contributions: Author V.T.H., author L.H.C. and author N.V.H. are first co-authors who contributed equally to this study. Conceptualization, L.H.C. and N.V.H.; methodology, L.H.C. and N.V.H.; validation, L.H.C., V.T.H. and N.V.H.; formal analysis, L.H.C. and V.T.H.; investigation, L.H.C. and N.V.H.; resources, L.H.C.; data curation, N.V.H.; writing—original draft preparation, L.H.C. and N.V.H.; writing—review and editing, L.H.C., V.T.H., N.V.H. and B.M.H.; supervision, N.V.H.; project administration, N.V.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in this study.

Data Availability Statement: Not applicable.

Acknowledgments: We would like to thank Nguyen Thi Kim Khue—principal of Le Ngoc Han Middle School, Hanoi City, Vietnam for her approval to allow researchers to teach STEM experimental units. Furthermore, we would like to thank Xuyen Chi—a science teacher at Le Ngoc Han Middle School for her support to teach science units in the experimental program.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Learning Achievement Scale

TEST
(Test time: 30 min)

Full name: Gender: □ Male, □ Female

Task 1: Match the two columns to make the correct answer. (3 points)

Filtration	to separate water from dissolved solids by heating.
Evaporation	to separate solids from liquids or gases using a filter tool.
Liquid–liquid extraction	to separate two different immiscible liquids.

Task 2: Selecting an appropriate technique to separate the mixtures below. (3 points)
(Please mark an X in the appropriate box)

Mixture	Filtration	Evaporation	Liquid–liquid extraction
Sugar and water			
Wheat flour and water			
Cooking oil and water			

Task 3: Please write a step-by-step procedure to separate a mixture of white sugar an wheat flour. What attributes of them allow you to do the above? (4 points)

References

1. Brown, R.; Brown, J.; Reardon, K.; Merrill, C. Understanding STEM: Current perceptions. *Technol. Eng. Teach.* **2011**, *70*, 5.
2. Roehrig, G.H.; Dare, E.A.; Ellis, J.A.; Ring-Whalen, E. Beyond the basics: A detailed conceptual framework of integrated STEM. *Discip. Interdiscip. Sci. Educ. Res.* **2021**, *3*, 11. [CrossRef]
3. Han, J.; Kelley, T.R.; Mentzer, N.; Knowles, J.G. Community of Practice in Integrated STEM Education: A Systematic Literature Review. *J. STEM Teach. Educ.* **2021**, *56*, 5. [CrossRef]
4. Batdi, V.; Talan, T.; Semerci, C. Meta-analytic and meta-thematic analysis of STEM education. *Int. J. Educ. Math. Sci. Technol.* **2019**, *7*, 382–399.
5. Kelley, T.R.; Knowles, J.G. A conceptual framework for integrated STEM education. *Int. J. STEM Educ.* **2016**, *3*, 11. [CrossRef]
6. Long, N.T.; Yen, N.T.H.; Van Hanh, N. The Role of Experiential Learning and Engineering Design Process in K-12 STEM Education. *Int. J. Educ. Pract.* **2020**, *8*, 720–732. [CrossRef]
7. Smith, K.; Maynard, N.; Berry, A.; Stephenson, T.; Spiteri, T.; Corrigan, D.; Mansfield, J.; Ellerton, P.; Smith, T. Principles of Problem-Based Learning (PBL) in STEM Education: Using Expert Wisdom and Research to Frame Educational Practice. *Educ. Sci.* **2022**, *12*, 728. [CrossRef]
8. Acar, D.; Tertemiz, N.; Taşdemir, A. The effects of STEM training on the academic achievement of 4th graders in science and mathematics and their views on STEM training teachers. *Int. Electron. J. Elem. Educ.* **2018**, *10*, 505–513. [CrossRef]
9. Morrison, J. Attributes of STEM education: The student, the school, the classroom. *TIES (Teaching Inst. Excell. STEM)* **2006**, *20*, 2–7.
10. Thibaut, L.; Ceuppens, S.; De Loof, H.; De Meester, J.; Goovaerts, L.; Struyf, A.; Boeve-de Pauw, J.; Dehaene, W.; Deprez, J.; De Cock, M. Integrated STEM education: A systematic review of instructional practices in secondary education. *Eur. J. STEM Educ.* **2018**, *3*, 2. [CrossRef]
11. Rennie, L.; Venville, G.; Wallace, J. Making STEM curriculum useful, relevant, and motivating for students. In *STEM Education in the Junior Secondary*; Springer: Berlin/Heidelberg, Germany, 2018; pp. 91–109. [CrossRef]
12. Eroğlu, S.; Bektaş, O. The effect of 5E-based STEM education on academic achievement, scientific creativity, and views on the nature of science. *Learn. Individ. Differ.* **2022**, *98*, 102181. [CrossRef]
13. Gülen, S.; Yaman, S. The Effect of Integration of STEM Disciplines into Toulmin's Argumentation Model on Students' Academic Achievement, Reflective Thinking, and Psychomotor Skills. *J. Turkish Sci. Educ.* **2019**, *16*, 216–230. [CrossRef]
14. Bybee, R.W. Using the BSCS 5E instructional model to introduce STEM disciplines. *Sci. Child.* **2019**, *56*, 8–12. [CrossRef]
15. Gulen, S. Argumentation Integrated STEM Activity. In *Current Studies in Educational Disciplines 2021*; Kiray, S.A., Tomevska-Ilievska, E., Eds.; ISRES Publishing: Konya, Turkey, 2021; pp. 306–323.
16. Dönmez, İ.; Gülen, S.; Ayaz, M. Impact of Argumentation-based STEM activities on ongoing STEM motivation. *J. STEM Educ. Res.* **2022**, *5*, 78–101. [CrossRef]
17. Siverling, E.A.; Suazo-Flores, E.; Mathis, C.A.; Moore, T.J. Students' use of STEM content in design justifications during engineering design-based STEM integration. *Sch. Sci. Math.* **2019**, *119*, 457–474. [CrossRef]

18. Gülen, S. Determination the effect of STEM integrated argumentation based science learning approach in solving daily life problems. *World J. Educ. Technol. Curr. Issues* **2018**, *10*, 266–285. [CrossRef]
19. Hasançebi, F.; Güner, Ö.; Kutru, C.; Hasancebi, M. Impact of Stem Integrated Argumentation-Based Inquiry Applications on Students' Academic Success, Reflective Thinking and Creative Thinking Skills. *Particip. Educ. Res.* **2021**, *8*, 274–296. [CrossRef]
20. Mathis, C.A.; Siverling, E.A.; Glancy, A.W.; Moore, T.J. Teachers' incorporation of argumentation to support engineering learning in STEM integration curricula. *J. Pre-College Eng. Educ. Res.* **2017**, *7*, 76–89. [CrossRef]
21. Bybee, R.W.; Taylor, J.A.; Gardner, A.; Van Scotter, P.; Powell, J.C.; Westbrook, A.; Landes, N. The BSCS 5E instructional model: Origins and effectiveness. *Color. Springs, Co BSCS* **2006**, *5*, 88–98.
22. Koyunlu Ünlü, Z.; Dökme, İ. A systematic review of 5E model in science education: Proposing a skill-based STEM instructional model within the 21-st century skills. *Int. J. Sci. Educ.* **2022**, *44*, 2110–2130. [CrossRef]
23. Tsai, L.-T.; Chang, C.-C.; Cheng, H.-T. Effect of a STEM-Oriented Course on Students' Marine Science Motivation, Interest, and Achievements. *J. Balt. Sci. Educ.* **2021**, *20*, 134–145. [CrossRef]
24. Ültay, N.; Zivali, A.; Yilmaz, H.; Bak, H.K.; Yilmaz, K.; Topatan, M.; Kara, P.G. STEM-Focused Activities to Support Student Learning in Primary School Science. *J. Sci. Learn.* **2020**, *3*, 156–164. [CrossRef]
25. Hasanah, U. The Impacts of STEM Instruction on Strengthening High School Students' Reasoning Skills. *Sci. Educ. Int.* **2020**, *31*, 273–282. [CrossRef]
26. Pahrudin, A.; Alisia, G.; Saregar, A.; Asyhari, A.; Anugrah, A.; Susilowati, N.E. The Effectiveness of Science, Technology, Engineering, and Mathematics Inquiry Learning for 15-16 Years Old Students Based on K-13 Indonesian Curriculum: The Impact on the Critical Thinking Skills. *Eur. J. Educ. Res.* **2021**, *10*, 681–692. [CrossRef]
27. Yu, H.-P.; Jen, E. Integrating Nanotechnology in the Science Curriculum for Elementary High-Ability Students in Taiwan: Evidenced-Based Lessons. *Roeper Rev.* **2020**, *42*, 38–48. [CrossRef]
28. Bulut, B.; Arikan, I. Argumentation-Based Learning in Social Studies Teaching. *J. Educ. Learn.* **2019**, *8*, 89–94. [CrossRef]
29. Yildirim, B.; Turk, C. The effectiveness of argumentation-assisted STEM practices. *Cypriot J. Educ. Sci.* **2018**, *13*, 259–274. [CrossRef]
30. Cortina, J.M. What is coefficient alpha? An examination of theory and applications. *J. Appl. Psychol.* **1993**, *78*, 98. [CrossRef]
31. Pearson, G. National academies piece on integrated STEM. *J. Educ. Res.* **2017**, *110*, 224–226. [CrossRef]
32. Luo, Z.; Jingying, C.; Guangshuai, W.; Mengyi, L. A three-dimensional model of student interest during learning using multimodal fusion with natural sensing technology. *Interact. Learn. Environ.* **2020**, *30*, 1117–1130. [CrossRef]
33. Chang, D.; Hwang, G.-J.; Chang, S.-C.; Wang, S.-Y. Promoting students' cross-disciplinary performance and higher order thinking: A peer assessment-facilitated STEM approach in a mathematics course. *Educ. Technol. Res. Dev.* **2021**, *69*, 3281–3306. [CrossRef]
34. Kim, T.K. Understanding one-way ANOVA using conceptual figures. *Korean J. Anesthesiol.* **2017**, *70*, 22–26. [CrossRef]
35. Williams, L.J.; Abdi, H. Fisher's least significant difference (LSD) test. *Encycl. Res. Des.* **2010**, *218*, 840–853.