Effect Adaptive Inquiry-Based Learning Model and Group Discussion-Based Learning on the Environmental Knowledge and Sustainability Competencies

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***Abstract*—Environmental education plays a crucial role in enhancing students' sustainability competencies, yet challenges remain in identifiying effective learning models. This article aims to reveal the effects of the adaptive inquiry-based learning model and Group discussion-based learning on the environmental knowledge and sustainability competencies of students. This article also reviews the influence of gender differences on environmental knowledge and sustainability competencies. The research was conducted among high school students in Aceh, Indonesia, with a population of 267 high school students. Using slavin sampling technique, 160 students was selected. The research method used quantitative research from an quasi experimental design with a pretest-postest control group design. Data were collected using Geiger's Environmental Knowledge Test and sustainability competency assessment rubric from Doucette *et al.*, which had been validated for reliability and content accuracy. The analysis utilized Multivariate Analysis of Variance (MANOVA). The results show that adaptive inquiry-based learning is influential and has a strong effect than group discussion-based learning on environmental knowledge and sustainability competencies. However, there is no influence between man and woman on environmental knowledge and sustainability competencies. Practical implications of learning using adaptive inquiry-based learning are discussed and elaborated.**

***Keywords*—adaptive learning, inquiry learning, group discussion learning, environmental knowledge, sustainability competencies**

I. Introduction

The advancement of science and technology continues to increase alongside the growing presence of technological devices in everyday life. This rise in societal needs, often unnoticed, disrupts the balance of nature. Several issues arise, including soil, air, and water pollution caused by chemical waste from factories and fossil fuels consumed by society. These problems lead to universal environmental issues affecting humanity, such as ozone layer depletion, global warming, and climate change [1]. Environmental issues have gained international attention [2, 3]. In recent decades, efforts to address environmental problems such as pollution and environmental degradation have focused on scientific approaches [4]. Through scientific methods, environmental problem-solving is structured within a cause-and-effect framework to find solutions. In other words, environmental issues are approached systematically by identifying the causes of the problems (e.g., pollution, deforestation, etc.) and analyzing their effects (e.g., climate change, loss of biodiversity). This organized framework helps researchers and scientists develop logical and evidence-based solutions to tackle these issues.

One of the main causes and major sources of environmental damage is the lack of public awareness regarding the need to preserve environmental quality. Society has a high level of consumption of non-renewable natural resources, resulting in rapid environmental degradation year after year. One approach to increase environmental awareness is through formal education [5–7]. Educational curricula should include the latest environmental issues and positive concepts related to environmental preservation. Environmental education curricula should contain content related to environmental knowledge.

Environmental knowledge is the understanding and awareness of environmental issues. It includes the ability to assess the state of the environment and take the necessary steps for management [8–10]. Previous studies have indicated that environmental knowledge contributes to pro-environmental behavior [11, 12]. This knowledge can come from social and community knowledge, as well as from formal education. Social and community knowledge relates to local wisdom that focuses on different perspectives of environmental management [13, 14]. Meanwhile, formal education refers to education at the elementary, secondary, and higher education levels. Other research shows that formal education is an effective means of enhancing environmental knowledge [6, 8, 11, 12, 15]. Therefore, there is a need for resources that can teach positive attitudes toward the environment through formal education.

Teachers are agents of change, influencing society's mindset about environmental sustainability. Teachers play a crucial role in environmental education by enhancing knowledge capacity and fostering positive attitudes towards environmental protection [16]. They contribute to the success of educational programs, the development of sustainable lifestyles, and the implementation of sustainability principles

in students. However, research literature findings indicate that students' capacity for knowledge, attitudes, and sustainable principles is still significantly lacking [17]. Other findings suggest that beyond pedagogical abilities, there is a need to improve the capacity for pro-environmental understanding and behavior [18]. Environmental knowledge and sustainability capacity can be taught through higher education. Knowledge and sustainability capacity can be imparted through a learning process that includes curriculum components, teaching materials, modules, and evaluations that contain environmental education. Therefore, environmental education is necessary for future teacher training programs.

Some previous researchers have developed problem-based learning models [18–21], inquiry learning [22], and project based learning [23] to increase pro-environmental capacity. Likewise, the development of learning media integrated with environmental learning [24]. Based on previous research, active participation in learning is essential. However, analysis from past research has not yet revealed the integration of inquiry learning aided by technology for environmental education.

The adaptive inquiry-based learning model is an innovative approach that combines scientific activities with Artificial Intelligence (AI)-assisted adaptive technology. These two models are merged to enhance the reliability of learning models in teaching environmental education. Inquiry-based learning requires students to be active in seeking, understanding, implementing, and evaluating findings during the learning process. The five steps in inquiry-based learning—ask, collect, visualize, create, and act—can be modified and adjusted to make the learning process more meaningful [25]. Adaptive learning is an approach that allows students to learn at their own pace [25–27]. Adaptive learning adjusts to students' needs, improving learning performance [28]. Students can develop independence and analytical skills by exploring information and findings. The use of technology in adaptive learning provides students the flexibility to find the necessary knowledge and analyze problems that need solving. This learning step can be integrated with adaptive learning assistance using AI tools like ChatGPT and AI Mind Map to facilitate idea organization and findings during the learning process [29, 30]. Mind mapping tools have been proven to enhance students' critical thinking skills [30, 31]. The use of ChatGPT has been shown to increase learning effectiveness [29, 32]. Therefore, a syntax has been developed to align with the adaptive inquiry-based learning model for environmental knowledge and sustainability capacity.

Based on the explanation, limited research studies have yet examined the influence of adaptive inquiry learning on environmental knowledge and sustainability competencies of pre-service geography teachers, considering gender. Therefore, the objectives of this current research are to examine:

1) The effect of adaptive inquiry-based learning on environmental knowledge among pre-service teachers taught using adaptive inquiry-based learning compared to those taught using conventional learning approaches.
2) The effect of adaptive inquiry-based learning on the sustainability competencies of pre-service geography teachers taught using adaptive inquiry-based learning compared to those taught using conventional learning approaches.
3) The effect of gender on environmental knowledge and sustainability competencies of pre-service geography teachers.

II. Literature Review

A. Adaptive Learning

Adaptive learning has become the focus of learning ecosystems in the era of technological development. Adaptive learning is defined as learning that is tailored to students' personalities, performance speeds, and interests to achieve the goal of improving academic abilities, motivation, and learning performance [29, 33]. Several studies also outline that adaptive learning ecosystems enhance students' satisfaction with learning [33, 34]. The development of adaptive learning stems from the awareness of diverse student needs, requiring teachers to design different and varied teaching methods within one learning package.

Adaptive learning is also related to personalized learning, viewed from differences in learning profiles such as learning styles and learning resources [35, 36]. Differences in learning style profiles can be distinguished by students' habits and conveniences, such as learning through virtual, auditory, reading, and kinesthetic style tests (VARK learning style). Adaptive learning becomes personalized learning with intelligent tutoring systems [37, 38]. Adaptive learning uses technology and learner profile data to understand students' learning profiles. The implementation of adaptive learning can provide materials and content with up-to-date situations, such as animations, videos, and interactive diagrams as needed [39]. Several previous studies explain that adaptive learning influences knowledge, attitudes, and skills [39–41].

The characteristics of adaptive learning differ from other online learning systems. Adaptive learning has personalization characteristics depending on students' learning needs, access to content created in small sections and units that are personalized, immediate and continuous feedback, a learning flow through content, and a focus on students' needs [33, 41]. Adaptive learning can also be applied to autistic learners [42]. Adaptive learning optimizes students' learning processes, identifies difficult-to-understand learning processes, and selects higher levels if enrichment is required.

B. Inquiry Based Learning

Inquiry learning is popular in developed countries, and many studies have examined inquiry learning [43–45]. Inquiry learning involves inductive thinking. The uniqueness of inquiry learning is the investigation process to discover the truth [46]. Students are engaged in asking questions and providing answers through critical thinking processes. The knowledge gained through inquiry learning is constructed from various resources, including expert opinions, teachers, parents, peers, and the community.

Inquiry learning requires student independence, so students must take responsibility for their own learning. According to several previous studies, inquiry can be integrated with the use of educational

technology [43, 45, 47].

C. Environmental Knowledge

Environmental knowledge involves the cognitive aspect, namely knowledge related to visible objects in the environment. Environmental knowledge is broad and general, including environmental education. The concept of environmental knowledge, according to [48] includes issues ranging from urban problems to wildlife conservation. Environmental knowledge is relevant to human life. According to [49], it includes diversity, environmental problems, and conservation efforts. To study someone's environmental knowledge, it can be done through treatment in environmental education [7]. Environmental knowledge is important because it is the basis for pro-environmental action [50]. To assess environmental knowledge ability, an environmental knowledge test is conducted [50–54].

D. Sustainability Studies

In recent years, sustainability studies have become a focus of research worldwide [23, 54]. Some areas of research also seek to develop measurement tools and improve sustainability skills through education [54–59]. There have been many efforts to design academic programs in line with the growing trend of research in sustainability competencies. In general, competencies are defined as skills, abilities and qualifications that refer to knowledge, skills and attitudes for problem solving [60]. This refers to the complex ability to make ecological, economic, and social changes for problem solving [61]. There are five competencies: systems thinking competency, anticipatory competency, normative competency, strategic competency, and interpersonal competency [54, 62]. Therefore, the ultimate goal in sustainability competencies is to provide students with the ability to plan, implement, and engage in sustainability research and problem solving.

III. Materials and Methods

A. Research Design

This research generated quantitative data from an experimental study. The experimental design used is quasi-experimental design with pretest-postest control group. There are two group, namely learning using adaptive inquiry based learning and learning with group discussion based learning.

This research is based on the results of a 1-month lesson on "Environmental Problems and Solutions" conducted on high school students taking geography subjects in Indonesia. The term environmental education topics refer to subjects that focus on the environment, sustainability, and ecological awareness. Learning is aimed at developing students' sensitivity to environmental problems and providing solutions to the environmental issues in particular environmental damage caused by climate change. Therefore, the research employed a quasi-experimental design with an experimental and control group pretest-posttest design to determine the impact of adaptive inquiry-based learning on environmental knowledge and sustainability competencies. The students were divided into two groups: experimental and control, without differentiating based on gender, academic level, or age. Participants were randomly assigned to the experimental and control classes, regardless of their preferences.

B. Research Participant

This study involved 160 students involved in geography subjects from 5 schools in Aceh, Indonesia. The participants were involved in learning that discussed environmental issues and solutions. Students from different schools were grouped into two classes: experimental and control, regardless of their school of origin. This study focuses on students who completed both the pre-test and posttest, as their participation provided the necessary data to assess the effectiveness of the educational program or intervention. For the research to accurately assess the impact of the educational intervention, it requires data from both the pre-test and the posttest. Students who participate in both tests provide crucial data that allow researchers to compare results and measure learning progress or change. Therefore, students who don't take a pre-test or a post-test are not involved. Based on the attendance data for the pretest and posttest on the Environmental Knowledge (EK) and Sustainability Competencies (SC) tests, data analysis was conducted with 160 participants: 82 students in the experimental group and 78 in the control group. The research design is shown in Table 1.

Table 1. Research design

Group	Pre-test	Instructional Strategy	Post-test
Experimental Group	1. Environmental Knowledge Test	Adaptive Inquiry-Based Learning	1. Environmental Knowledge Test
Control Group	2. Sustainability Competencies Test	Conventional Learning	2. Sustainability Competencies Test

C. Research Implementation

The adaptive inquiry-based learning supported by the ChatGPT tool was implemented in 5 regular classes across different campuses in Indonesia, which served as the experimental group. Similarly, the control group received conventional learning. In conventional learning, instruction was delivered through a slideshow created by the lecturer to explain the material "Environmental Issues and Solutions," while inquiry-based learning supported by ChatGPT as an AI tool in adaptive learning consisted of five steps. The comparison between the experimental and control groups' treatments can be seen in the Table 2.

The time allocation for both the experimental and control groups was the same for one topic, consisting of 4 sessions, each held once a week with a duration of 2 hours per session. Student activity sheets were provided in the adaptive inquiry-based learning to help students organize their work. These activity sheets also aimed to guide students in conducting investigations and organizing their findings and facts in the field. The activity sheets were developed by the researchers in collaboration with the course lecturers. The problem presented to both the experimental and control groups was the issue of waste management in Indonesia.

Table 2. Comparison of treatment between experimental group and control group

	Syntax	Tool	Activities
Adaptive Inquiry Based Learning	Ask	ChatGPT	Students conduct problem identification and develop an environmental problem formula from the article.
	Collect	All source	Students gather data and supporting facts to formulate problem solving; students conduct field studies
	Visualize	AI Mind Map	Students compile a mind map through data and facts, then develop problem-solving possibilities.
	Create	ChatGPT dan AI mind map	Students delineate solutions to environmental problems using data and facts assisted by chatGPT and Mind Map
	Act		Students present problem-solving results and ideas related to solutions for sustainable development
Conventional Learning	Introduction	Ms. Powerpoint Presentation	Students listen to the teachers explaining the material
	Group discussions		Students are divided into 5 groups, then discuss environmental issues
	lectures		Students receive materials from teachers related to sustainable development
	Reflection		Students reflect learning by answering oral questions from teachers

D. Data Collection

Environmental Knowledge and Sustainability Competencies tests were investigated separately, both in the pretest and posttest. The Environmental Knowledge test was administered twice, before and after the treatment. The test instrument, which measures environmental knowledge, was adapted from Geiger's Environmental Knowledge Test [63]. The modification involved translating it into Indonesian and contextualizing the content to better suit local environmental issues. The researchers also aligned the instrument with the Environmental Education curriculum in Indonesia. Before finalizing the test items, the researchers collaborated with two environmental geography experts to ensure the language and context were appropriate for the target participants. The final content domains used to assess environmental knowledge were: 1) basic ecology, 2) climate, 3) resources, 4) consumption behavior, 5) society/politics, 6) economy, and 7) environmental contamination. This resulted in 36 multiple-choice questions, with correct answers scored as 10 and incorrect answers scored as 0.

Case study-based assessment rubrics are used to assess sustainability competencies. Using case study-based tests has the advantage of training students' analytical skills. Researchers developed two case studies used pre- and post-test with a modified sustainability competency assessment rubric from [55]. The case studies, written by the researchers in Indonesian, presented current, real-world challenges requiring potential solutions from the students' perspectives as future geography teachers. The pretest case study focused on global warming and sustainable development, with data on global temperatures from climate.gov and Indonesia's CO_2 contributions across various sectors. Solutions offered included transitioning to electric energy and reforming palm oil policies. The posttest case study focused on soil damage from chemical fertilizers, with data from the Indonesian Central Statistics Agency (bps.go.id). Solutions included organic farming and using organic fertilizers.

The assessment items generated from the EK test were then assessed for the validity and reliability of the question items. An analysis of the validity and reliability of the question items was carried out on students who had completed the environmental problem material. A total of 40 participants participated in the validity and reliability tests of the questions. The results showed a Pearson correlation in the range of 0.312–0.458 and a Cronbach alpha value of 0.513.

EK and SC's initial tests were conducted separately. The EK pre-test was conducted at the first meeting of the material, while the SC pre-test was conducted a week before the material on environmental problems and solutions began. All students in both experimental and control groups received the same questions in the EK test. The evaluation type of the EK test is multiple choice, where the correct answer gets a score of 10 and the wrong answer gets a score of 0. There are four answer choices, where one answer is correct and three other answers are exceptions. Furthermore, the SC test was conducted by allowing all experimental and control group students to read the same pre-test case study and answer the same four questions. From the four questions asked, students are asked to identify challenges, prioritize solutions based on the challenges that have been identified, identify and analyze the basic value of the strategies carried out, identify priority conflicts, and make recommendations for the organization. The assessment refers to a rubric with a score of 0–5, namely a score of 0 (students cannot provide answers) to 5 (students can identify environmental, social, and economic aspects in the scenario). The posttest assessment was conducted a week after the treatment using the adaptive inquiry-based learning model.

E. Data Analysis

Quantitative data was generated from the pre-test and posttest scores of EK and SC. Data from experimental and control groups were analyzed using SPSS 25 for Windows to determine normality, homogeneity, and Multivariate Analysis of Variance (MANOVA) values. Before starting the data analysis, normality was tested using Kolmogorov Smirnov. Then analyzed using Leven's test to test the homogeneity of the data.

IV. Result and Discussion

A. Result

1) The difference of environmental knowledge between adaptive inquiry-based learning versus group discussion based learning

As a prerequisite for testing, the results of the pretest and posttest were tested for normality and homogeneity. The results of the pretest score normality test showed that the data was normal with a normality test result of 0.060 significance (sig) > 0.05). Furthermore, the data was tested using the Leven's test to see the pretest homogeneity value. The results of the homogeneity test showed a value of 0.713 (p> 0.05) which means that it was homogeneously distributed. The

results of the environmental knowledge test were then analyzed using Multivariate Analysis (MANOVA) to determine differences in treatment effects between experimental and control groups. As a prerequisite, normality and homogeneity tests were conducted. MANOVA test results for environmental knowledge are presented in Table 3.

Table 3. MANOVA test results on pre-test environmental knowledge scores

Variants	Wilks λ	F	Hypo df	Error df	*p*	η^2
Group	0.919	1.903	7	152	0.073	0.741

λ: Wilks' Lambd; F: Factor effect; df: Degrees of Freedom; *p*: probability; η^2: effect size.

The MANOVA test results on the pre-test showed no difference in EK scores between the experimental and control groups (Wilks λ = 0.919, F = 1.903). This shows that the pre-test scores of the experimental and control groups are the same. This is because there was no treatment at the beginning of learning. The absence of differences in pre-test scores indicates a strong effect close to 1. Then, a paired sample T-test was used to determine the significant difference between pre-test and posttest scores.

The sample T-test results indicated a significant difference between the pre-test and posttest scores. The sample T-test test value in the experimental group shows a significant difference in the total score (0.922, sig 0.05); if it is more detailed in each sub-indicator, then the basic ecology sub-indicator (0.214 > sig 0.05), climate (0.304 > sig 0.05), resources (0.074 > sig 0.05), economy (0.117 > sig 0.05), and environmental contamination (0.296 > sig 0.05) have a significant difference. While the control class has no difference between pre-test and posttest scores, The results of the paired T-test sample test can be seen in Table 4.

Furthermore, MANOVA analysis was used to compare the post-test scores between the experimental and control groups. Data were tested for normality and homogeneity as a prerequisite for the MANOVA test. The results of the normality test showed that the data was normally distributed with a value of 0.090 (sig > 0.05). Furthermore, the results of the homogeneity test showed that the data was homogeneous with a value of 0.158 (p > 0.05). The results MANOVA test are shown in Table 5. The results of the MANOVA test on the protest showed that there was a difference in EK scores between the experimental and control groups (Wilks λ = 0.171, F = 639.732). To find out the difference in the development of environmental knowledge completely between the experimental group and the control group, a more detailed analysis of the scores between the sub-indicators and the effect of treatment on the total score can be seen in Table 5. The results show that learning activities using adaptive inquiry-based learning effectively improve students' environmental knowledge.

Table 4. Results of a paired sample t-test based on treatment group

Group	Dependent Variable	Measurement	n	Mean	df	r	sig
Experiment	Basic Ecology	pre-test post-test	82	25.85 46.46	81	0.139	0.214
	Climate	pre-test post-test	82	26.34 43.66	81	0.115	0.304
	Resource	pre-test post-test	82	18.66 36.46	81	0.119	0.074
	Consumption Behavior	pre-test post-test	82	45.49 80.49	81	0.264	0.016
	Society	pre-test post-test	82	19.15 38.17	81	0.254	0.021
	Economy	pre-test post-test	82	19.02 37.32	81	0.174	0.117
	Environmental contamination	pre-test post-test	82	22.93 47.44	81	−0.117	0.296
	Total Score	pre-test post-test	82	177.44 330	81	0.011	0.922
Control	Basic Ecology	pre-test post-test	78	28.97 30.13	77	0.964	0.000
	Climate	pre-test post-test	78	28.33 29.49	77	0.921	0.000
	Resource	pre-test post-test	78	21.15 22.69	77	0.834	0.000
	Consumption Behavior	pre-test post-test	78	51.79 53.08	77	0.92	0.000
	Society	pre-test post-test	78	20.51 21.15	77	0.98	0.000
	Economy	pre-test post-test	78	19.1 20.26	77	0.936	0.000
	Environmental contamination	pre-test post-test	78	25.64 28.33	77	0.79	0.000
	Total Score	pre-test post-test	78	195.51 205.13	77	0.929	0.000

n: number of sample; df: degrees of freedom; r: effect size; sig: significance (*p*-value).

Furthermore, MANOVA analysis was used to compare the posttest scores between the experimental and control groups. The results are shown in Table 5. The results of the MANOVA test on the protest showed that there was a difference in EK scores between the experimental and control groups (Wilks λ = 0.171, F = 639.732).

Table 5. MANOVA test results on environmental knowledge

Variance	Wilks λ	F	Hyp df	Error df	*p*	η^2
Group	0.171	639.732	7	152	1.000	0.829

λ: Wilks' Lambda; F: Factor effect; df: degrees of freedom; *p*: probability; η^2: effect size.

Table 6. Paired sample T-test results by group

Group	Dependent Variable	Measurement	n	Mean	df	r	sig
Experiment	Holistic Thinking	pre-test	82	5.06	81	−0.037	0.744
		post-test		17.60			
	Conflict Resolution	pre-test	82	3.51	81	−0.110	0.326
		post-test		14.10			
	Total Score	pre-test	82	8.57	81	0.001	0.996
		post-test		31.70			
Control	Holistic Thinking	pre-test	78	3.78	77	−0.093	0.420
		post-test		9.27			
	Conflict Resolution	pre-test	78	2.91	77	0.239	0.035
		post-test		7.56			
	Total Score	pre-test	78	6.69	77	0.168	0.141
		post-test		16.83			

n: number of sample; df: degrees of freedom; r: effect size; sig: significance (*p*-value).

2) The difference of sustainability competence between adaptive inquiry-based learning versus group discussion based learning

Sustainability competencies were tested using an assessment rubric. The assessment aimed to measure holistic thinking and conflict resolution. Two case studies were developed and administered on the pre-test and posttest to the experimental and control groups. Students were given the task of identifying problems, prioritizing problems, thinking critically, and formulating realistic strategies for problem solving for sustainable development. The pre-test and posttest results were tested for normality and homogeneity. Furthermore, the paired sample T-test results are presented in Table 6.

Table 6 shows that the posttest mean score was higher than the pretest for both experimental and control groups. The total score for the experimental group showed a higher mean posttest score compared to the pretest total score (31.70 > 8.57). The total score also showed a significant difference (0.996 > sig 0.05). When broken down into two indicators Holistic Thinking (HT) and Conflict Resolution (CR), the experimental group showed significant differences: HT (0.744 > sig 0.05) and CR (0.326 > sig 0.05). In the control group, there was also a difference in mean posttest and pretest scores, although the gap was not as wide as in the experimental group (16.83 > 6.69). The total posttest and pretest scores for the control group showed a significant difference (0.141 > sig 0.05). However, when exploring the sub-indicators of sustainability capacities, only the posttest and pretest values for holistic thinking in the control group showed a significant difference (0.420 > sig 0.05).

3) The effect of gender on students' environmental knowledge and sustainability competencies

The study also examined the effect of gender differences on students' environmental knowledge and sustainability competencies. A total of 81 women and 79 men participated in the study. The analysis was conducted without differentiating treatment. Based on the data analysis, it was found that gender differences had no effect on environmental knowledge (0.070 > sig 0.05) and sustainability competencies (0.121 > 0.05). This shows that male students and female students have the same ability. Detailed data can be seen in Table 7.

Table 7. MANOVA test results of gender differences in environmental knowledge and sustainability competencies

	Source	df	Mean Square	F	Sig	ηp^2
Environmental Knowledge	Corrected model	1	16037.525	3.329	0.070	0.021
	Intercept	1	11575937.53	2402.656	0.000	0.938
	Gender	1	16037.525	3.329	0.070	0.021
	Error	158	4817.975			
	Total	160				
	Corrected total	159				
Sustainability competencies	Corrected model	1	154.277	2.436	0.121	0.015
	Intercept	1	95537.452	1508.387	0.000	0.905
	Gender	1	154.277	2.436	0.121	0.015
	Error	158	63.337			
	Total	160				
	Corrected total	159				

df: degrees of freedom; F: Factor effect; Sig: significance (*p*-value); ηp^2: effect size.

B. Discussion Result

The research findings reveal a significant difference in post-test scores between the experimental and control groups for both Environmental Knowledge (EK) and Sustainability Competencies (SC) due to differences in learning treatment. The results also show that there is no difference between male and female students in terms of EK and SC. Based on these findings, it is clear that the variation in learning treatment has the greatest effect on EK and SC skills. Along with current trends in technology-assisted learning, this research reinforces that the effectiveness of technology-assisted learning supports learning success. The EK and SC of the experimental group were significantly

higher than those of the control group. This consistent result is emphasized by [64] who affirmed that technology-assisted learning has become inseparable from modern educational life. There is a positive impact of learning using artificial intelligence as a tool to assist inquiry-based learning. As stated by [31] inquiry assisted by mind mapping makes learning more effective and enhances students' critical thinking skills and learning motivation. Premthaisong and Srisawasdi [44] elaborated that inquiry assisted by technology will improve understanding of science learning conceptions. Similarly, learning using macromedia flash based on guided inquiry has been proven to effectively improve students' critical thinking skills and learning independence.

Inquiry-based learning has the advantage of formulating problem hypotheses and directly engaging with activities that synthesize knowledge based on case comprehension. This is evident from the higher post-test scores in the experimental group compared to the control group. Using inquiry-based learning can improve students' problem analysis skills [65]. The post-test EK scores in the experimental group were higher in almost all sub-indicators (basic ecology, climate, resources, economy, and environmental contamination), indicating that students' inquiry activities developed analytical thinking skills based on knowledge from various sources. Students were given the opportunity to obtain learning resources from a variety of sources, utilizing learning technologies. Relevant studies have found that when students independently find learning resources, they are more likely to understand the material content presented [66]. In terms of knowledge related to consumption behavior and society, no significant effect was found, as this relates to daily habits and behaviors [67]. Improving attitudes and behavior requires habituation [68]. Thus, although other sub-indicators had a significant effect, consumption behavior and society showed less significant differences when taught using the adaptive inquiry-based learning model.

Sustainability competencies refer to the ability to solve sustainable problems in a contextual manner. Both groups showed higher post-test scores for sustainability competencies compared to the pre-test. However, a closer look reveals that learning using the adaptive inquiry-based learning model assisted by technological tools in pedagogical activities was more effective than conventional learning. This is evident from the lack of significant differences in the control group, particularly in conflict resolution skills. The use of adaptive tools allows students to learn according to their needs and learning pace [29], helping them better understand problems. Using adaptive tools such as AI and mind maps can deepen students' understanding of problem contexts, making it easier to determine the best solutions for sustainable development. As noted in previous research, the use of internet-based resources can enhance students' understanding [40]. Furthermore, other findings also support the results of this study, using mind maps can improve students' ability to think holistically and organize information [69]. The "collect and act" activities in inquiry-based learning involve students gathering and using knowledge as the foundation for determining the depth of a problem and the actions that need to be taken. Therefore, the findings indicate that the experimental group's conflict resolution sub-indicator skills were better after learning with adaptive inquiry-based learning compared to the control group that learned with conventional methods.

Adaptive inquiry based learning can adjust to the needs and speed of student learning, and can make students free to learn. The application of learning models can provide students with many opportunities to further explore the surrounding environment. Thus, the results of this study indicate an increase in environmental knowledge and sustainability competencies. However, in terms of gender differences, no significant differences in the tested abilities were found. Lecturers provided the same tasks and opportunities to both male and female students. This finding contrasts with studies [70, 71] which noted that women's environmental literacy and awareness were superior to men's. However, research by [72] supports the current study, showing that men and women have equal environmental knowledge, resulting in similar problem-solving abilities. Male and female students engaged in the same learning activities and resources, leading [73] to conclude that both genders would have similar learning outcomes. Overall, men and women share equal involvement and influence in environmental conditions. Therefore, both genders have an obligation to act as agents of change in addressing environmental issues. As explained by [74] in their research, environmental education should encompass all environmental stakeholders, including young people. Consequently, all students play an equal role in environmental education, as they live and carry out activities that collectively affect the environment.

Analyzing changes in environmental knowledge and sustainability competencies across different treatments in the two groups is an important point that contributes to the originality of this research. No previous studies have examined the impact of adaptive inquiry-based learning on environmental knowledge and sustainability competencies. Another interesting finding is the development of measurement techniques tailored to the needs of the students as the subjects of this research.

V. Conclusion

The improvement in environmental knowledge and sustainability capacity was achieved through the five stages of adaptive inquiry-based learning before and after the intervention, showing a strong effect. Adaptive inquiry-based learning significantly influenced environmental knowledge, with a significance value of 0.922. Furthermore, the implementation of the model significantly impacted sustainability capacity, with a value of 0.996, demonstrating a strong effect on the variables studied. The findings also showed that the largest improvement in environmental knowledge was in the sub-indicators of basic ecology, climate, resources, economy, and environmental contamination, due to the ease of organizing information through multiple sources using mind maps and ChatGPT assistance. Meanwhile, no significant effect was found for the consumption behavior and society sub-indicators, as they are related to daily habits.

Through adaptive inquiry-based learning, students can also improve their sustainability capacity. Two sub-indicators, holistic thinking and conflict resolution, were enhanced

through the "collect," "visualize," and "act" stages of learning. The use of adaptive technology enhances students' holistic thinking abilities. Adaptive learning can provide feedback for independent learning, guiding students on what to know, seek, and analyze in the cases presented during the learning activities. Adaptive technology can give directions, guide learning according to plan, and reorganize students' thinking.

Based on the results of the research data analysis, when adaptive inquiry-based learning was applied, it was found that there was no influence of gender differences on environmental knowledge and sustainability competencies. This was attributed to the equal treatment in terms of task assignments and resource access. The findings also revealed that both male and female students had the same opportunities and challenges in utilizing resources and completing tasks. The effectiveness of learning in environmental knowledge and sustainability capacity should be further improved consistently. The implementation of adaptive inquiry-based learning should be extended to at least eight meetings, allowing for more detailed student activities and maximizing the use of learning tools. Particularly in the assessment of sustainability capacity using rubrics, evaluation should be thorough and accurate. The adaptive inquiry-based learning model has a positive impact and can be developed across broader disciplines and academic fields.

In practice, the adaptive inquiry based learning model can be applied to environmental learning to improve students' sustainability competencies. The findings of the study can also be a support for the development of learning policies that promote active and participatory learning methods, thereby improving the quality of learning and climate change awareness actions in accordance with sustainable development goals. Furthermore, the results of this study also support the constructivist theory by proving the success of adaptive inquiry based learning, where students learn actively by exploring conditions in the environment.

This study has several limitations. This study has a relatively short learning duration, so that the measurement of long-term effects on sustainable competencies cannot be evaluated. Furthermore, research in measuring environmental knowledge and sustainability competencies only uses questionnaires and tests, so direct observation and assessment of practical skills in the real world are still needed. Therefore, suggestions for future research are to expand the duration of treatment to see long-term effects and add observation methods and assessment of practical skills to obtain a more comprehensive picture. Another suggestion that can be given is to compare the learning model with other innovative learning models, so that the best strategy can be found in improving students' environmental knowledge and sustainability competencies.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Rima Meilita Sari designed and developed the main idea of the study, developed the research framework, and performed data analysis. Ridhwan Ridhwan contributed to analyzing the literature review, and validating the instrument. Faiz Urfan helped develop the test instruments and compile the tables in this article. Tengku Muhammad Sahudra was responsible for the main methodology, primary data collection. Tuti Mutia collected supporting references and revised the bibliography according to journal standards. Suri Purnama Febri was responsible for critically reviewing the entire article and providing suggestions for improvement. Ravinesh Rohit Prasad provided theoretical and practical input and provided input in the preparation of the method. All authors have approved the final version.

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