Innovating Middle School Geoscience Education: Development of an Interactive Tectonic Plate Robot

Ahmad Ikliil Fauzi[1], Dinar Maftukh Fajar[2], and Mohammad Wildan Habibi[3]

{ahmadikliil@gmail.com[1], dinarmaftukh@uinkhas.ac.id[2], wildan@uinkhas.ac.id[3] }

Universitas Islam Negeri Kiai Haji Achmad Siddiq Jember, Indonesia[123]

Abstract. Understanding plate tectonics is crucial in geoscience education, yet traditional methods often struggle to convey these concepts effectively. This study develops and evaluates an interactive tectonic plate robot to enhance middle school students' comprehension of tectonic movements. Using a Research and Development (R&D) approach, the study involved needs analysis, prototype design, fabrication, and validation. The robot, constructed with Styrofoam, plasticine, and a hydraulic system, visually simulates convergent, divergent, and transform plate boundaries. Evaluations included expert validation, teacher assessments, and student trials. Data collection utilized questionnaires, interviews, observations, and pretest-posttest analyses. Results showed high validation ratings (92% content validity, 94% media feasibility), strong teacher approval (90% practicality), and positive student engagement (95% interest). Learning effectiveness was confirmed with an N-Gain of 0.8, indicating high improvement. The findings highlight the potential of interactive robotics in geoscience education, enhancing understanding and motivation. Future research should explore augmented and virtual reality integration for deeper engagement.

Keywords: tectonic plate robot, geoscience education, interactive learning, middle school science, STEM teaching aids

1 Introduction

The study of Earth's layers and tectonic plates is a fundamental topic in middle school science curricula, as it provides a foundational understanding of the structure and dynamics of our planet. By studying these concepts, students can gain insight into natural phenomena like earthquakes, volcanoes, and mountain formations, which all significantly impact daily life [1]. Understanding this material aligns with the objectives of science education to foster scientific literacy, enabling students to comprehend and apply scientific concepts in real life and make informed decisions based on this knowledge[2]. In addition to theoretical knowledge, this subject encourages students to think critically and analytically as they observe and interpret natural phenomena[3]. Such understanding is crucial to fostering environmentally conscious individuals who are disaster-aware and capable of contributing to solving geoscience-related issues in the future[4].

Despite its significance, teaching Earth's layers and tectonic plates presents unique challenges[5]. Geological concepts such as plate movement, mountain formation, and

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earthquakes are abstract and dynamic, often leading students to develop misconceptions different from expert understanding[6]. Limited learning resources also pose obstacles, as existing materials frequently fail to visualize these complex phenomena [6], [7]. Teaching aids in schools lack interactivity and do not depict tectonic plate dynamics. As a result, students may struggle to grasp the causal relationships underlying geological phenomena, necessitating innovative approaches to bridge this learning gap[8].

Teaching aids are instrumental in addressing these challenges by transforming abstract scientific concepts into tangible and comprehensible forms [9], [10]. Through visual and interactive representation, these aids assist students in visualizing complex scientific processes. Research highlights the efficacy of visual and interactive media in improving students' conceptual understanding and engagement [9], [11], [12]. Multimedia teaching aids can improve understanding by integrating text, images, and animations to facilitate effective information processing[13], [14]. Additionally, there is evidence that direct object manipulation learning can boost knowledge retention and transfer[15].

Innovations in educational media are essential to address the diverse learning needs of students. Today's technology offers ways to increase interactivity and student engagement. Current trends in education include the use of technology such as Virtual Reality (VR), Augmented Reality (AR), and robotics, providing a more immersive learning experience[16]. These technologies enable students to interact with digital simulations replicating actual scientific processes. Robotics, for instance, can be used to simulate dynamic scientific experiments, allowing students to learn through hands-on experiences [17], [18].

Various researchers have widely studied robotic teaching aids in science education. For instance, Kucuk and Sisman explored student interest in robotics and STEM from a gender perspective [19]. Mwangi mapped the positive impact of robotic teaching aids on attitudes toward STEM and problem-solving abilities[20]. Bravo investigated using robots in storytelling and drama activities for science teaching, demonstrating that this approach supports science concept development, enhances student skills, and fosters a positive, motivating classroom environment[21]. Moreover, the use of LEGO robots has also been explored by numerous researchers and has shown various positive effects on the learning process [22], [23]. However, according to the authors' review, research on robotic teaching aids for tectonic plate topics still requires further exploration to understand its potential better.

While the use of robotic teaching aids has been explored across various STEM topics, its application to tectonic plate dynamics remains under-researched. This research seeks to address this gap by developing a tectonic plate robot to enhance middle school student's understanding of plate tectonics through interactive and immersive learning.

This study aims to develop a tectonic plate robot as a teaching aid to facilitate students' understanding of geological concepts more tangibly and engagingly. Expected benefits of this research include improved student comprehension, increased learning motivation, sparking interest in STEM and robotics integration, and enriching instructional materials for teachers, thereby creating a more dynamic and practical learning experience.

In response to this challenge, the problem formulation was detailed to explore several important aspects of the developed plate tectonics robot trainer. First, the research aims to describe the trainer, including its features and functions. Next, the tool's validity will be evaluated based on the opinions of experts, who will provide a professional perspective on the material and the tool's relevance as a learning medium. In addition, this study will also assess the practicality of the teaching aids according to teachers or users to understand how easy the tools are to use in a learning context. The attractiveness of the teaching aids for students is also an objective to determine how these tools attract students' attention and interest in the learning process. Finally, learning effectiveness will be measured by comparing pretest and post-test results to assess the impact of the teaching aids on students' understanding of the concept of plate tectonics.

2 Method

This study adopts a Design and Development Research approach to develop and evaluate a tectonic plate robot as a teaching aid for Earth’s layers material in the middle school science curriculum. The research process follows an iterative cycle consisting of several stages: preliminary research, prototyping, summative evaluation, and systematic reflection and documentation, as outlined by Akker[24]. Details of these stages are shown in Fig. 1.

The research process begins with the preliminary research stage, where researchers identify challenges in learning earth layer material through literature review and field observations. In the prototyping stage, a prototype design was conducted to design the initial model of the plate tectonic robot. The parties involved in this process include geoscience material experts and science learning media experts, who contribute to the validity evaluation, and teachers and students as the primary users who assess the attractiveness of the teaching aids. At the summative evaluation stage, the initial version of the teaching aids was finalized and tested for functionality in a classroom environment by assessing effectiveness and practicality by teachers and students. The systematic reflection and documentation stage provides a comprehensive evaluation of the entire process undertaken.

The research participants contributing to data collection include two science education media experts, two geoscience content experts, three science teachers, and 38 eighth-grade students from a madrasah in Banyuwangi, East Java, Indonesia.

The research instruments include questionnaires, interviews, and observations to collect data from various subjects. The questionnaire is designed to measure the validity of the teaching aid according to experts and to assess its practicality and appeal based on teacher and student evaluations. Semi-structured interviews were conducted directly to gain in-depth insight into the challenges teachers and students face in learning science, especially regarding the material of the Earth's layers. Additionally, the interviews aim to gather opinions and experiences from experts, teachers, and students on using the developed teaching aid. Classroom observations are conducted to directly observe student interaction with the teaching aid and evaluate how it influences the learning process. The effectiveness of teaching aids is also assessed based on the analysis of pretest and post-test results through the N-gain test with Hake's formula. $(g)=(\%(S_f)-\%(S_i)/(100-\%(S_i))$ where (S_f) and (S_i) are the final (post) and initial (pre) class averages." High-g’’ courses as those with $(g)\geq 0.7$; ‘‘Medium-g’’ courses as those with $0.7>(g)\geq 0.3$; ‘‘Low-g’’ courses as those with $(g)<0.3$[25]. Details of the research instruments are provided in Table 2.

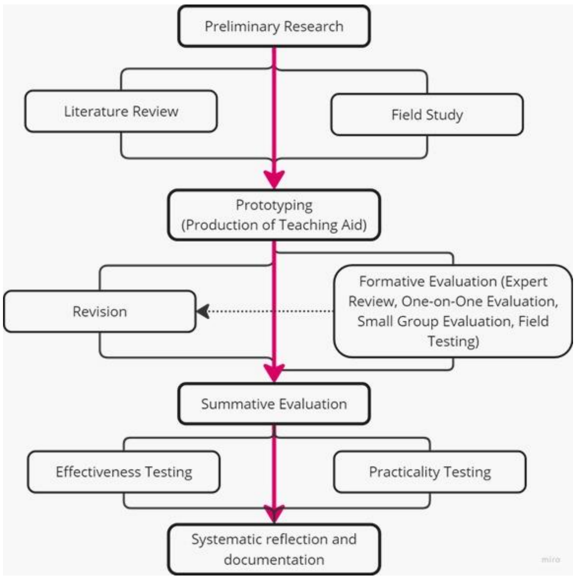


Fig 1. Flowchart of the Hydraulic Tectonic Plate Robot Development Procedure

Table 1 Assessment Instruments

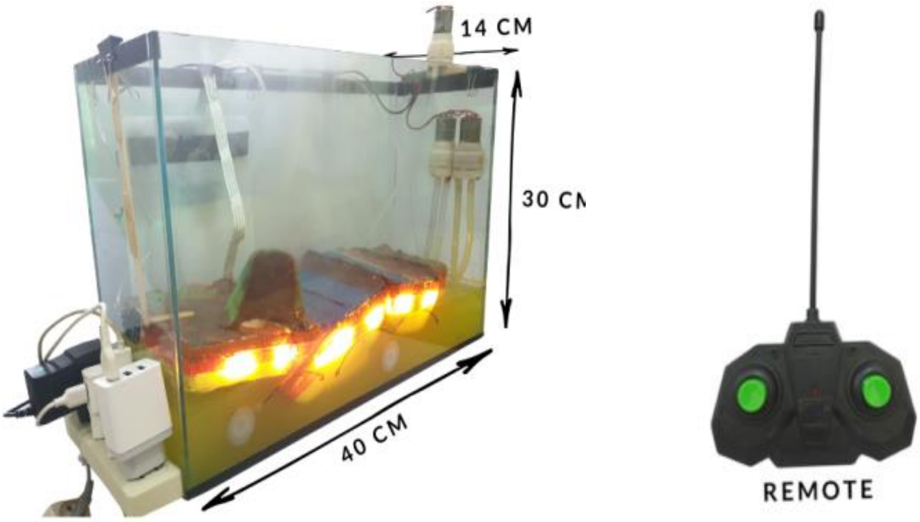
No.	Subject	Aspect	Number of Indicators	Number of Items	References
1.	Media Expert	Durability, accuracy, aesthetics, safety, dimensional efficiency, design, language quality	16	20	Adopted from Cahyaningtyas [26] and Ani [27]
2.	Subject Matter Expert	Relevance to learning materials, usability, content feasibility, presentation, language quality	9	13	
3.	Teacher	Practicality, effectiveness	9	9	
4.	Students				Adopted from Octafandi [28] and Ani [27]
	• One-on-one	Content, technical quality, learning design, implementation	11	11	
	• Small Group	Content, learning design, implementation	9	9	
	• Field Test	Feasibility, sustainability, environmental compatibility, acceptance and appeal	12	12	

The data analysis techniques include both quantitative and qualitative analysis. Quantitative data from the questionnaires are analyzed using descriptive statistics to assess the teaching aid's validity, practicality, and appeal. This questionnaire was adapted considering Akker's theory, which discusses the requirements of learning resources by comparing the results of products that have been used, sustainability and resilience, stakeholder needs, and today's opportunities. Ani said there are several things to consider in learning media: economic value, practicality, ease of obtaining, flexibility, and component suitability. One-on-one and small group is a formative evaluation to test the reliability and validity of questionnaires and pretest and post-test questions and to find shortcomings in the prototype for revision. Quantitative data from the pretest and post-test results are analyzed using the normalized N-gain test proposed by Hake [25]. Meanwhile, qualitative data from interviews and observations are analyzed through thematic analysis to identify patterns, themes, and insights regarding the use and effectiveness of the teaching aid. The results of this analysis are used to evaluate and refine the teaching aid design and to provide recommendations for optimal implementation in the middle school science curriculum.

3 Results and Discussion

3.1 Description of the Tectonic Plate Robot Teaching Aid

After going through a series of iterative processes that include design, development, and evaluation of teaching aids based on input from experts, the resulting teaching aids can be seen in Fig. 2 a and b in the form of plate robots and remotes to control them and Fig. 3 in the form of electronic design/engineering of plate tectonics robots.



(a) (b)

Fig. 2. (a) Tectonic Plate Teaching Aid, (b) Remote Control

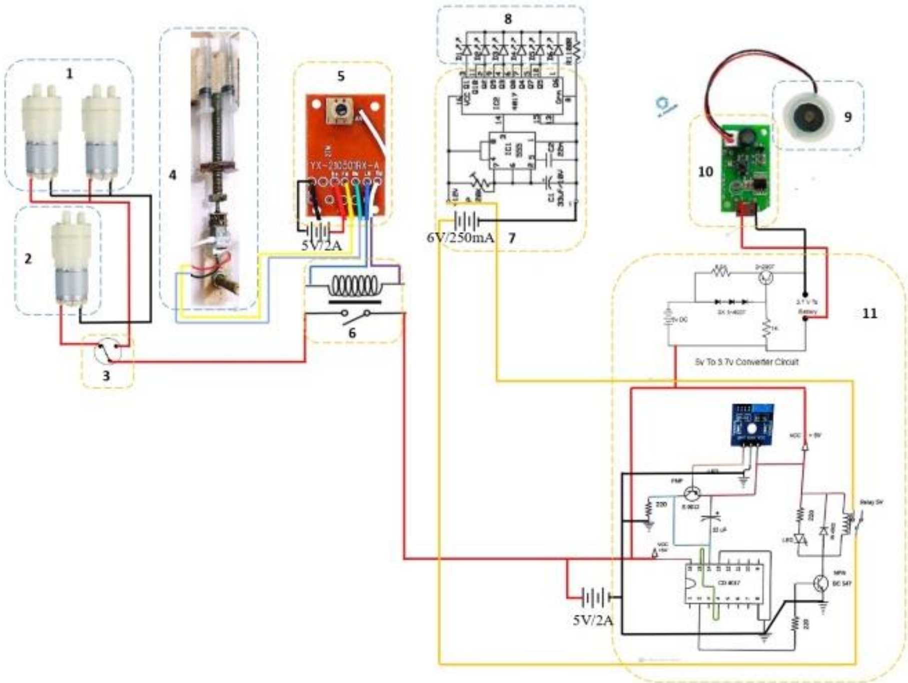


Fig. 3. Plate Robot Electronics Wiring Guide Tectonics

This tectonic plate robot trainer works with a hydraulic system[4]. The electrically powered plate robot that can illustrate smoke through modules and electric water spray[9], [10] uses electricity reduced to DC 3.7V 11 from a 5V power source infrared (IR) switch circuit [11]. This IR switch disconnects and connects electrical power to the running light module[7], and the lamp serves as a pointer for the direction of plate movement[8]. The movement of the converging, diverging, and transforming plates is generated through the movement of the hydraulic piston/lever in moving the 3D media[4] with an electric motor/dynamo motion source controlled through the RC receiver module[5], which produces back and forth movement. There are two RC receiver channels; channel one is a hydraulic system control[4], and channel two controls the relay [6] to power the diaphragm pump. Two diaphragm pumps[1] function as illustrative producers and water convection currents, while one pump removes water in props[2]. The exchange switch[3] changes the electrical power receiver between the two diaphragm pumps.

A detailed breakdown of the teaching aid components is presented in Table 2.

Table 2. The components of the teaching aid.

Photo	Description
Front view	1. Diaphragm water pump for draining water 2. Diaphragm water pump for generating forced convection 3. Illustration of Transform movement with fault phenomenon 4. Illustration of Divergent and Convergent

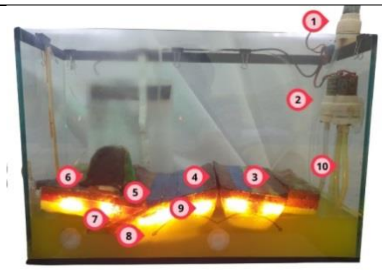
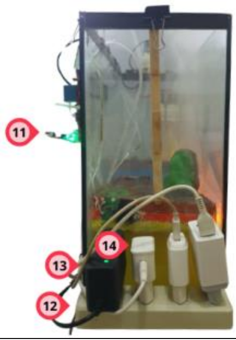
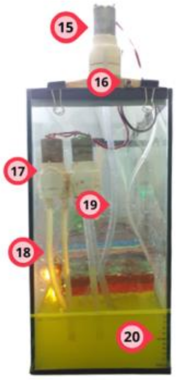
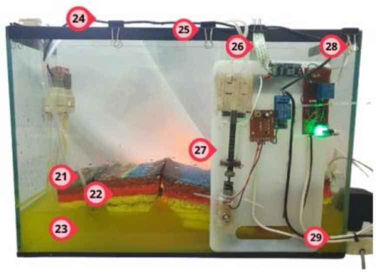
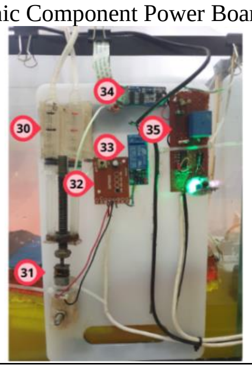
Photo	Description
	movement of oceanic crust 5. Illustration of trench phenomenon due to Convergent movement 6. Illustration of volcanoes and mountains formed due to Convergent movement 7. Illustration of the meeting of continental and oceanic crust plates creating a subduction zone 8. Arrow indicating the direction of forced convection currents 9. Running light showing the direction of plate movement 10. Water pump hose
Right Side View 	11. IR Sensor 12. 220 VAC Socket 13. 12V 1A Power Supply 14. 3 units of 5V 1A Power Supply
Left Side View 	15. Diaphragm water pump for draining water 16. Switch for changing the current on the water pump 17. Diaphragm water pump for generating forced convection 18. Suction and discharge hoses for forced convection 19. Suction hose for draining water 20. Water level measurement limit
Rear View 	21. Hydraulic hose illustrating Transform movement 22. Earth layer illustration 23. Illustration of the Earth's liquid core (magma) 24. The electrical conductor cable for the water pump 25. Paperclip for clipping cables and hoses 26. Flexible electrical cable for the walking light 27. Hydraulic robot power board 28. Flexible cable for electric misting or humidifier 29. Power supply cable to the robot's power components

Photo	Description
Electronic Component Power Board View 	30. Hydraulic cylinder 31. Electric motor (dynamo) with bolts and nuts as the driver for the hydraulic lever using the inclined plane principle. 32. Remote Control Receiver PCB 33. Relay (breaker and connector for the water pump voltage) 34. Walking light module 35. IR sensor PCB and 3V step-down module
Bottom View 	36. Hydraulic cylinder illustrating Transform movement 37. Forced convection hose 38. Support 39. Hydraulic lever illustrating Divergent and Convergent movement 40. Misting membrane or humidifier

This tectonic plate robot teaching aid integrates several concepts from the Tectonic Plates topic in the Grade VIII Science subject of the Merdeka Curriculum, including convection currents and plate movements (convergent, divergent, and transform) and their impacts, such as volcanic formation.

The robot illustrates the three types of plate movement using a hydraulic system. The hydraulic arms[9], [29] move the 3D media, clearly displaying the tectonic plate shift simulation. The arm movements are supported by a DC motor [23] that utilizes the principle of a simple inclined plane (bolt). The tool is equipped with moving lights that indicate the direction of plate movement to enhance the visualization.

According to scientific theory, convection currents are depicted using water pumps that push water to simulate convection flow. These two pumps create water flows in opposite directions, illustrating the cause of convergent movement.

In addition to demonstrating plate movement, the robot depicts natural phenomena resulting from plate shifts, such as the formation of mountains, trenches, and faults. Miniatures of these phenomena are made from plasticine. To add visual appeal, a volcanic smoke illustration [17] is included using electric misting technology or a humidifier.

The selection and use of tools and materials in the plate tectonics robot has considered the value of efficiency and sustainability. The tools and materials used are not affected by age, such as Styrofoam packaging, diaphragm pumps from gallon pumps and flexible cables used for electronic devices. That shows the effort to recycle waste into learning media and use affordable components. The cost required to make this plate tectonics robot is estimated to be relatively affordable. In addition, the electricity consumption required to operate this robot is relatively efficient, only about 30 watts, based on the calculation of three 10-watt adapters. Learning environmentally friendly media that does not produce waste is one of the researchers' goals in creating effective and efficient teaching aids. Thus, this research focuses on the educational aspect and the environmental impact of the tools used.

The teaching aid is equipped with an object sensor-based switch to control the moving lights. Additionally, the robot can be operated wirelessly via a remote control, making it easier for users to run the tectonic plate movement simulation. The following video links demonstrate the teaching aid and its learning process.

3.2 Teaching Aid Validity According to Experts

Two media experts and two subject matter experts assessed the teaching aid and guidebook for validity. The quantitative evaluation results from each expert are presented in Table 3.

The key comments collected from the subject matter experts are as follows. The tectonic plate robot teaching aid was deemed suitable for use as a learning media, although several suggestions and revisions were noted. First, a stronger correlation between the teaching aid concepts and the material is necessary. In addition, the lamp indicating the direction of plate movement in Table 3. front view number 9, should be made brighter to improve visibility. The subject matter experts also recommended socializing this study to students and teachers to ensure the tool functions as a more effective and tested learning media.

Table 3. (a) Subject Matter Experts, (b) Media experts

(a) Geoscience Subject Matter Experts

No.	Aspect	Average Percentage	Category
1.	Relevance to Learning Materials	93%	Very Good
2.	Usability	100%	Very Good
3.	Content Feasibility	90%	Very Good
4.	Presentation	87%	Very Good
5.	Language Quality	90%	Very Good
	Total	92%	Very Good

(b) Media experts

No.	Aspect	Average Percentage	Category
1.	Durability	93%	Very Good
2.	Accuracy	85%	Good
3.	Aesthetics	95%	Very Good
4.	Safety	95%	Very Good
5.	Dimensional Efficiency	93%	Very Good
6.	Design	97%	Very Good
7.	Language Quality	100%	Very Good
	Total	94%	Very Good

On the other hand, the media experts stated that the teaching aid is now valid for use in teaching after being revised based on the suggestions and comments. The revisions included adding images and access to explanatory videos as supplementary materials, considering that the teaching aid cannot directly display the scientific processes of Earth's activities. In addition, there are improvements to the water filling limit mark so that it does not overfill and make the 3D media float too high. The media experts also recommended that this engaging teaching aid be used to support the learning process and continue through the dissemination stage.

3.3 Practicality of the Teaching Aid According to Teachers

Three science teachers also assessed the teaching aids and guidebooks for their practicality. The quantitative assessment results from all three teachers are shown in Fig. 4.

Based on Fig. 4, all aspects of using the teaching aid received relatively high scores (averaging above 90%), except for the maintenance aspect, which only scored 75%. It is likely due to components that are somewhat complex for beginners, making maintenance difficult in case of damage. Nonetheless, in their comments, the teachers evaluated the teaching aid positively, stating that it effectively increased student motivation. The teachers also suggested that the teaching aid be equipped with a guide to facilitate access and use and recommended testing it in various classrooms to assess its effectiveness further.

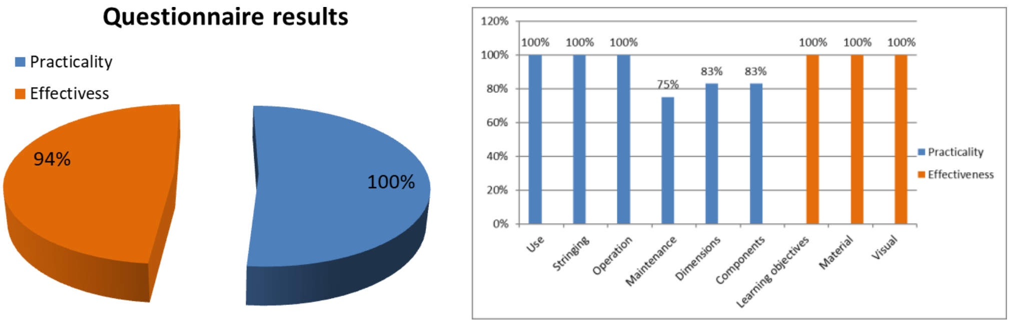
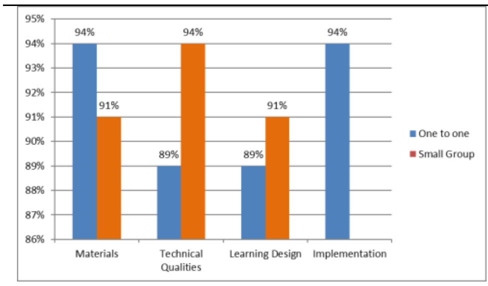


Fig. 4. Quantitative Assessment from Teachers/Users

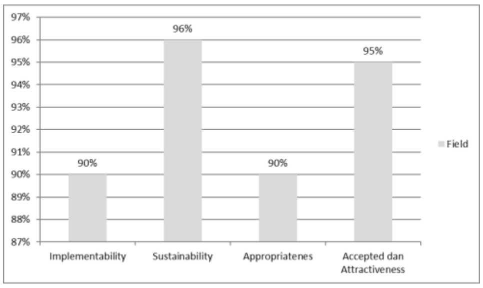
3.4 Appeal of the Teaching Aid According to Students

The teaching aid was implemented in three groups: one-on-one with three students, small group with eight students, and field testing with 27 students. This testing aimed to assess student responses regarding their suitability and appeal and gather their comments. Overall, the teaching aid was deemed suitable as a learning medium. The student responses are presented in Table 4, while the comments are displayed in Figure 4.

Table 4. Quantitative Assessment from Students



No.	Aspect	One-on-One	Small Group
1.	Material	94%	91%
2.	Technical Quality	89%	94%
3.	Learning Design	89%	91%
4.	Implementation	94%	



No.	Aspect	Field Test
1.	Feasibility	90%
2.	Continuity	96%
3.	Suitability with the Environment	90%
4.	Acceptance and Appeal	95%

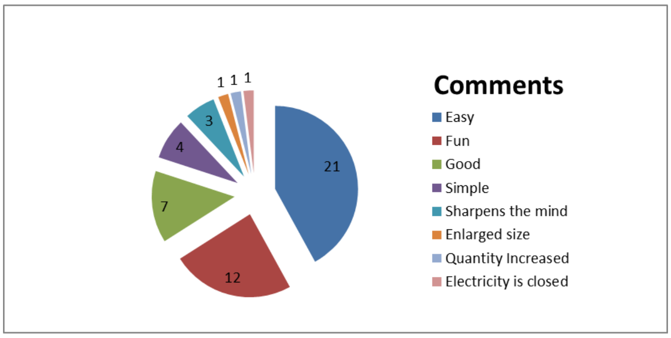


Fig. 5. Qualitative Assessment from Students

Based on Figure 5, the majority of student comments regarding this teaching aid are that it is easy to use, fun, and of good quality. The results of observations when using the plate tectonics robot showed that students seemed to have high enthusiasm in preparing their group to operate the robot, which was characterized by reading and understanding the guidebook. Interviews were also conducted after the lesson, with most students commenting that the plate robot helped them understand and remember the various movements of plate tectonics.

3.5 Effectiveness of Learning Based on Pretest and Post-test Results

Learning effectiveness with the tectonic plate robot teaching aid was measured using a pretest and post-test, with normalized N-Gain based on Hake's criteria[25], as presented in Table 5.

Table 5. Normalized Gain Test

Description	One-on-One		Small Group		Field Test	
	Pretest	*Post-test*	*Pretest*	*Post-test*	*Pretest*	*Post-test*
n	3	3	8	8	27	27
Maximum	60	90	60	100	70	100
Minimum	40	70	30	70	10	70
Average	50	83.3	45	8.5	41.8	88.8
Standard Deviation	10	11.5	9.2	10	16.4	10.5
N-Gain	0.6		0.7		0.8	
N-Gain Criteria	Medium		High		High	

Based on Table 3.5.1, the effectiveness test results for the tectonic plate robot teaching aid show an improvement in students' understanding across all test groups. The one-on-one group achieved an average N-Gain of 0.6 (moderate category), while the small and field test groups achieved 0.7 and 0.8, respectively (high category). The increase in post-test scores across all groups indicates that this teaching aid effectively facilitates more meaningful learning and enhances students' conceptual understanding. This teaching aid is deemed suitable as a learning medium for tectonic plates.

3.6 Discussion

The findings of this study highlight several key points. Based on assessments from experts and teachers, this tectonic plate robot can clearly visualize and demonstrate tectonic activities, greatly assisting students in understanding abstract concepts. It is supported by feedback from students, who expressed that the tool was invaluable in clarifying the concepts being taught. Students' understanding of the material closely relates to using appropriate media and teaching methods. This robot provides a solution to the limitations of student comprehension that often arise when the topic of plate movement is taught through conventional methods or PowerPoint media[30]. Using a plate tectonics robot designed with learning differentiation in mind can provide a varied learning style solution for students; the existence of learning that emphasizes the visuality of abstract material with a combination of student-centered learning can provide a deep understanding evenly for students. Learning on plate tectonics material using animation media can also improve student learning outcomes, but the lack of visuality makes learning dependent on teachers in student learning activities[31]. This teaching aid also significantly enhances students' cognitive aspects by visualizing cause-and-effect phenomena[9].

As the tool description suggests, the plate tectonics robot integrates a range of STEM concepts, allowing learners to see how STEM components work together to create an interactive geoscience teaching aid in contrast to traditional learning that reflects the reproductive aspect rather than the creative potential of the individual[32]. The use of physics and mathematics principles, such as Pascal's law, simple machines, and electronics, in this robot serves as a source of inspiration and an educational tool for students. It is evident from the feedback collected and the demonstration videos that students show high enthusiasm when operating the robot. Science learning through a STEM-based robotic approach offers educational value beyond academic knowledge, supporting the development of practical skills and mental capabilities necessary for success in the modern era[33]. This STEM-based learning also plays a role in building soft skills, such as problem-solving abilities in a collaborative context, which are essential in real-life situations[29]. Furthermore, STEM-based robotic learning has improved students' cognitive understanding, reflected in their positive emotional responses during the learning process[17].

In addition to confirming the improvement in students' understanding of tectonic plate concepts, as shown by the increase in post-test scores compared to pretests, students were engaged in learning activities aligned with the application of the discovery learning method. In this activity (see video 2), when students observed the movement and phenomena displayed, critical questions arose regarding the mechanisms of plate movement and the tool's operation. This process significantly developed students' critical thinking skills, encouraging them to investigate and discover concepts independently. The teaching aids must be aligned with the appropriate method to provide a practical approach according to the curriculum[34]. The demonstrations produced by this teaching aid can enhance students' critical thinking skills through analytical activities[35].

Additionally, the cost-effective and sustainable design of the tectonic plate robot underscores its potential for broad adoption across varied educational contexts. By repurposing readily available materials such as Styrofoam and diaphragm pumps, the tool minimizes expenditure while promoting environmental stewardship, aligning with recent calls for green pedagogical innovations [16], [24]. Moreover, the modular nature of the prototype facilitates iterative enhancements—such as the integration of augmented reality overlays or AI-driven interactive feedback—which could further enrich learners' spatial reasoning and deepen their engagement with geoscientific processes [36], [37]. To maximize impact, future implementations should include structured teacher training workshops, enabling educators to seamlessly integrate the robot into inquiry-based curricula and adapt its use to diverse classroom constraints. Such professional development will be pivotal for ensuring fidelity of implementation and for advancing the scalability of this hands-on STEM approach in middle school science education.

4 Conclusion

This study successfully developed an interactive tectonic plate robot as an innovative teaching aid to enhance middle school student's understanding of plate tectonics. By integrating hydraulic systems, DC motors, and water pumps, the tool effectively visualizes complex geological phenomena such as convergent, divergent, and transform plate movements and their impacts, including the formation of volcanoes, trenches, and faults. The research findings demonstrate that this teaching aid significantly improves students' comprehension of geoscience concepts through hands-on, immersive learning experiences.

The validation process involving subject matter experts and media experts yielded excellent ratings, with an overall content validity score of 92% and a media evaluation score of 94%. Furthermore, the tool's teacher practicality assessment yielded a 90% rating, confirming its ease of use and effectiveness in classroom settings. Student engagement and interest in the learning process were also notably high, with an average appeal rating of 95%. The effectiveness of this teaching aid was further substantiated by the learning outcomes, as indicated by a normalized gain (N-Gain) of 0.8, which falls within the high improvement category.

From a pedagogical perspective, this study contributes to geoscience education by introducing an interactive, technology-enhanced approach that bridges the gap between theoretical knowledge and practical understanding. Using robotics in science education fosters student engagement, promotes critical thinking, and supports STEM integration, which is crucial for developing 21st-century skills. Additionally, this research aligns with sustainable education principles by utilizing recyclable materials, ensuring cost-effectiveness, and minimizing environmental impact.

Despite these promising results, certain limitations remain. The study was conducted within a limited school setting, which may affect the generalizability of findings across diverse educational contexts. Additionally, while the tool effectively demonstrates tectonic plate movement, incorporating augmented reality (AR) or virtual reality (VR) could further enhance the immersive learning experience [36], [37]. Future research should explore large-scale implementations across different schools, assess long-term retention effects, and investigate the integration of advanced technologies such as AR and AI-driven interactive features to optimize the teaching aid's effectiveness further.

This research underscores the potential of robotics-based learning tools in transforming geoscience education. By fostering deeper conceptual understanding and increasing student motivation, the tectonic plate robot presents a viable and scalable solution for enhancing science education in middle schools. Continued development and refinement of innovative teaching aids will contribute to more effective, engaging, and sustainable STEM education.

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