Development of Tuber-Based Microbial Fuel Cell (MFC) STEM KIT as an Environmentally Friendly Alternative Energy Learning Medium

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ABSTRACT

This study aims to develop a STEM-based learning KIT that utilizes the working principle of Microbial Fuel Cell (MFC) using tubers as an environmentally friendly alternative energy source. This KIT is designed as an innovative learning media that integrates science, technology, engineering, and mathematics (STEM), while introducing the concept of renewable energy to students. The method used is research and development (R&D) with reference to the Borg and Gall model which has been simplified into five steps, namely: (1) identification of potential and problems through analysis of potential problems, literature studies, and field observations and interviews; (2) planning through Compiling development objectives and Designing product specifications; (3) initial product development through Making an initial prototype; (4) product testing and validation through Laboratory test results, Validation by material and media experts, and Teacher and student responses; and (5) product revision and refinement based on the evaluation results of the validation test, KIT electrical function testing, and responses from teachers and students. The validation results show that the KIT has a very good level of feasibility, with scores of 92%, 94%, and 94%. The maximum current values generated from cassava, gadung, and taro were 0.25; 0.14; and 0.41 mA, respectively. Positive responses were also given by teachers at 93% and 100%, and by students at 87%. These findings indicate that the tuber-based MFC STEM KIT is suitable for use as an alternative learning media that is environmentally friendly and applicable in the context of science education.

Keywords: STEM, KIT, microbial fuel cell, tubers.

INTRODUCTION

Energy sources derived from fossils (non-renewable energy) still support most of the electrical energy in Indonesia, including oil, coal and gas. The potential for petroleum in Indonesia continues to decline every year. Indonesia is a very fertile country because it is located in the ring of fire area. Various types of plants that can grow in Indonesia such as fruits, tubers, vegetables, nutmeg, and so on. This potential has not been utilized properly as a source of electrical energy in Indonesia. The process of rotting fruits and vegetables containing acid called fermentation, will be more reactive with electrodes, so it will produce high electrical voltage (Amin & Dey, 2005). This process can be called biobattery. Some articles found related to the materials in biobattery and linked as follows: 1) based on categories including: pineapple skin (Jumiati, 2021), banana peel (Kamilah et al., 2020), cassava peel (Sumanzaya et al., 2019), orange peel (Suciyati et al., 2019), tofu waste (Sayuti et al., 2016), cow feces (Rachmad Ananto et al., 2023); and 2) based on non-waste including: kedondong fruit flesh (Kamilah et al., 2020), sweet potato (Zheng et al., 2015), potatoes (Pamungkas, 2017), cassava (Sumanzaya et al., 2019). From several articles that have been found, the use of tubers as the main ingredient of biobatteries is still very little. On the other hand, the decay process can occur due to microbial metabolism of a medium as a catalyst that will convert organic matter into electrical energy by transferring electrons from the anode through a cable then producing an electric current to the cathode and this process is called Microbial fuel cell (MFC). In addition, waste or residual substances from biobatteries/MFCs are environmentally friendly (Shahzad, 2015).

Decay or decomposition is one of the physical chemical changes that causes objects, usually dead living things, to experience damage to the structure carried out by decomposers (including ants, maggots, bacteria and fungi). Decay generally occurs in food. The cause of decay is due to the presence of very small living things, such as bacteria and fungi. Fungi are the main cause of decay. Fungi will easily grow in humid environments. If the environmental conditions are humid and there is a lot of water, fungi will grow well. In addition, fungi grow rapidly in places that have warm temperatures, not too cold. With such conditions, it will accelerate decay. Too much water content in food causes decay to occur more easily. Fungi and bacteria that cause decay will grow rapidly if there is a lot of air. In addition, microorganisms can also affect the pH in the material. The pH of Sargassum Crassifolium increased due to the length of fermentation from pH 5 to 7 for 72 hours (Taslim et al., 2017).

In Indonesia, tubers are not only used as food ingredients, but also as industrial products, such as tapioca, modified starch, and liquid sugar. The limitations of tuber use are its low productivity, limited added value, poor market access, and its perishable nature. In fact, tubers are easy to cultivate, because they have low production costs (Teti Estiasih et al., 2017).

Potato and sweet potato tubers can become bioelectricity (Pamungkas, 2017; Zheng et al., 2015). This is because the material has a content that will be reactive when it meets the electrode so that it can produce an electric voltage. Cassava, gadung, and taro are tubers that are easily found in Central Java. The use of these tubers is still limited to additional food. In fact, when compared to potatoes and sweet potatoes, these tubers have almost the same content. In addition, these ingredients also contain glucose. On the other hand, there is a linear relationship between glucose content and electric current in Ketapang (Terminalia catappa L.)(Hotang et al., 2018). Fresh ketapang paste is known to have a glucose concentration of 23.9 mg/ml and can produce a current of 1 mA, when the biobattery is installed with a resistance of 100 Ω. This means that cassava, gadung, and taro can produce electric current because they contain glucose.

MFCs that are often used are divided into three types, namely Single Chamber, Dual Chamber, and Stack MFC (Anggraini et al., 2018). Of the three types, the one with the smallest internal resistance is the single chamber. This is because the simplest form is only one compartment/container, without a membrane/salt bridge. Thus, the small electric current is not lost when passing through the cable connecting the electrodes. The type of electrode used in MFC also affects the size of the electric current produced (Fauzia et al., 2019). Based on the Volta series theory, if the sum of the cell potentials of two electrodes is large, then the resulting electrical potential is also large (Setiyana, 2020). One of the pairs that has a large electrical potential is copper (Cu) - zinc (Zn). This is because the electrodes are easy to find and relatively cheap. In addition, the total cell reaction produces a fairly high value of 1.1 volts. In addition, in an electrical circuit, the circuit used will affect the size of the electric current. Several studies related to MFC create series circuits to optimize the resulting electric voltage (Ibrahim et al., 2014; Mikrajudin, 1997; Rachmad Ananto et al., 2023). Therefore, how much change in the physical properties of cassava, gadung, and taro needs to be observed and how much electricity is produced needs to be measured when using a single chamber MFC.

The development of science and technology demands a paradigm shift in the world of education, especially in science learning. Science learning is no longer sufficient to be delivered conventionally through lectures and memorization of concepts alone, but needs to be directed at an approach that encourages students to think critically, creatively, and be able to solve real problems in everyday life. One relevant approach in this context is STEM (Science, Technology, Engineering, and Mathematics)-based learning, which emphasizes integration between disciplines to produce real solutions through the design and engineering process (Noor & Malichatin, 2025; Prasetyo et al., 2025).

However, the implementation of STEM learning in schools still faces various challenges, especially in terms of providing innovative and contextual learning media. Many teachers still rely on learning media that are abstract, less applicable, and do not arouse students' curiosity. This has an impact on low student involvement in learning and a lack of understanding of scientific concepts that should be connected to everyday life and global issues, such as the energy and environmental crises.

One innovative approach that can be developed in STEM learning is through alternative energy-based projects, such as Microbial Fuel Cell (MFC). MFC is a technology that utilizes the metabolism of microorganisms to produce electrical energy from organic materials. In the local context of Indonesia which is rich in natural resources, tubers such as cassava, taro, and gadung have the potential to be used as substrates in MFC. The use of tubers as an energy source in MFC is not only scientifically and technologically relevant, but also carries local content and high educational value.

The development of tuber-based MFC STEM KITs as learning media offers a new alternative that is contextual and environmentally friendly. This KIT is designed to support project-based learning, encourage students to explore science concepts directly through experiments, and raise awareness of the importance of renewable energy. Thus, this kind of learning media innovation is expected to improve the quality of STEM learning in schools and prepare a young generation who cares about the environment and has 21st century competencies.

METHOD

This study uses a Research and Development (R&D) approach that aims to develop and produce a product in the form of a STEM Microbial Fuel Cell (MFC) learning kit based on tubers (cassava, gadung, and taro). The R&D model used adapts the stages of Borg and Gall with adjustments into five main stages, namely: (1) identification of potential and problems, (2) planning, (3) initial product development, (4) trials and validation, and (5) product revision and refinement.

Table 1: The R&D model used adapts the stages of Borg and Gall

Stage	Stage Name	Main Activities
1	Identification of Potential and Problems	- Analysis of potential problems - Literature study - Field observations and interviews
2	Planning	- Develop development objectives - Design product specifications
3	Early Product Development	- Create an initial prototype
4	Trial and Validation	- Laboratory test results - Validation by material and media experts - Teacher and student responses

5	Product Revisions and Improvements	- Revision based on feedback - Refinement of the final product

1. Identification of Potential and Problems

This stage is carried out by studying literature on the working principles of MFC, the potential of tubers as a source of substrate, the concept of STEM learning, and observing the need for renewable energy learning media in schools. Data were collected through interviews with teachers and observations of current learning conditions.

2. Planning

Based on the identification results, a kit design was designed which includes the main components of the MFC (container, electrodes, substrate media from tubers, cables, voltage and current measuring instruments, and LED lights as loads), as well as the preparation of supporting devices in the form of STEM-based student worksheets (LKS). The product design takes into account aspects of functionality, safety, and ease of use in the context of learning.

3. Early Product Development

At this stage, the MFC kit prototype is made according to the design. The tubers are processed into a substrate media with a certain weight (eg 150 grams), then assembled in five single series MFC cells. The electrical components are installed and tested to ensure that the device can produce enough voltage and current to light the LED. Experimental guides and LKS are prepared to guide the learning process.

4. Uji Coba dan Validasi

The prototype kit was tested in three main aspects:

- Laboratory Trial: Measuring the voltage, current, and duration of the LED lights during the use of the kit by students. Data was recorded for 6 consecutive days to determine the energy performance produced by each type of bulb.
- Validation by material and media experts: Conducted through questionnaires and interviews with STEM material experts, teachers, and learning media experts to assess aspects of practicality, readability, aesthetics, and the suitability of the contents of the LKS and experimental guides with STEM learning standards.
- This response was obtained after a trial in the classroom using the KIT through a questionnaire of teacher and student responses.

5. Revisions and Improvements

Based on the results of the trial and input from the validation, revisions were made to the kit design and experimental procedures to improve product quality. In addition, it was also strengthened by responses from teachers and students. The final product is expected to meet the technical and pedagogical feasibility criteria as an effective learning medium.

Data Collection Instruments and Techniques

- Voltage and current measurement using a digital multimeter.
- Observation of LED light duration as an indicator of successful energy conversion.
- Validation questionnaire and interviews to obtain expert and user feedback.
- Documentation of the development process and use of the kit

Data analysis

Quantitative data from electrical measurements were analyzed descriptively to describe the performance of the MFC kit. Qualitative data from validation were analyzed using content analysis techniques and score tabulation to determine the suitability of media and materials.

FINDINGS AND DISCUSSION

1. Identification of Potential and Problems

The working principle of MFC Microbial Fuel Cell (MFC) is a bioelectrochemical system that utilizes the metabolic activity of microorganisms to produce electrical energy from organic materials. MFC works by converting chemical energy from substrates (for example organic materials such as tubers) into electrical energy through a biological oxidation process by microorganisms. Microbial Fuel Cell utilizes bacteria as "biological power plants" that convert chemical energy from organic materials into electrical energy directly, without a combustion process. This system is environmentally friendly, efficient, and can be an educational alternative to introduce the concept of renewable energy and biotechnology in STEM learning.

Potential of tubers as a substrate source. Tubers are one of the abundant biological resources in Indonesia and have high organic content, especially carbohydrates such as starch and sugar. This content makes tubers a potential substrate in the Microbial Fuel Cell (MFC) system, because they can be broken down by microorganisms into electrons and protons to produce electrical energy. Characteristics of Tubers that Support MFC Substrates:

1. High Carbohydrate Content
    - Tubers such as cassava, taro, gadung, and others contain high starch.
    - Starch will break down into simple glucose that can be metabolized by microorganisms.
    - Metabolic reactions produce electrons (e^-) and protons (H^+) as raw materials for generating electricity in MFC
2. Easy to obtain and low cost
    - Tubers are local ingredients that are available all year round.

- Utilization of tuber waste or unconsumed parts (such as skins or leftover juice) can reduce costs and support the principles of a circular economy.

3. Supports the Growth of Microorganisms
   - Tubers are rich in nutrients (carbon, nitrogen, minerals) which support the activity of fermentative microorganisms, especially anaerobic bacteria such as Geobacter and Shewanella.
4. Environmentally friendly
   - Does not produce hazardous waste, is easily biodegradable, and is safe to use in learning media.
   - Supports the concept of biomass-based renewable energy.

Observation and interviews at school

The interview activity was conducted on June 3, 2024 at a school in the Kudus area. The interview photo is shown in Figure 1.

Figure 1: Photo of the research team interviewing science teachers

Based on the results of observations and interviews at school, several findings were found as follows.

- Science learning in schools is mostly theoretical and uses conventional media (textbooks and slides).
- Students rarely conduct experiments based on the use of the local environment.
- Several teachers expressed difficulty in linking alternative energy material to the local context, especially in providing relevant and inexpensive teaching aids.
- In the school environment and its surroundings, there is the availability of local tubers such as cassava, gadung, and taro from residents' gardens or students' yards. Images of tubers are shown in Figure 2 a-c.

Figure 2: Picture of tubers found in the Kudus area

(a) Cassava (b) Gadung (c) taro

2. Planning

- Tujuan Pengembangan
  a) Developing innovative STEM-based learning media
  Produce tuber-based MFC KITs that can be used as contextual, interactive science learning media and support the Science, Technology, Engineering, and Mathematics (STEM) approach.
  b) Supporting teachers in implementing contextual learning and independent curriculum
  Providing alternative learning media that are relevant to the learning outcomes of science phase D (junior high school).
- Product Specifications
  The design of the kit includes the main components of the MFC (container, electrodes, substrate media from tubers, cables, voltage and current measuring instruments, and LED lights as loads). The components and specifications of the MFC product are shown in Table 2.

Table 2: MFC KIT Components and Specifications

Component	Specification
1. Substrate Material	o Local tubers such as cassava, taro and gadung
2. Reaction Vessel (Reactor)	o Made of clear plastic or acrylic tube (volume ± 300–500 ml). o Equipped with a perforated cover for electrodes and air vents.
3. Anode Electrode	o Material: graphite rod o Placed in a tuber substrate (anaerobic)
4. Cathode Electrode	o Material: copper wire or activated carbon, placed in an open space (aerobic).
5. Cables and Connectors	o Cable connecting the electrode to an electrical measuring instrument (multimeter, LED, voltmeter).

	○ Alligator clips are provided for flexible connections.
6. Output Measuring Instrument	○ Small LED (as a light indicator) ○ Digital/analog multimeter to measure voltage (Volt) and current (mA).

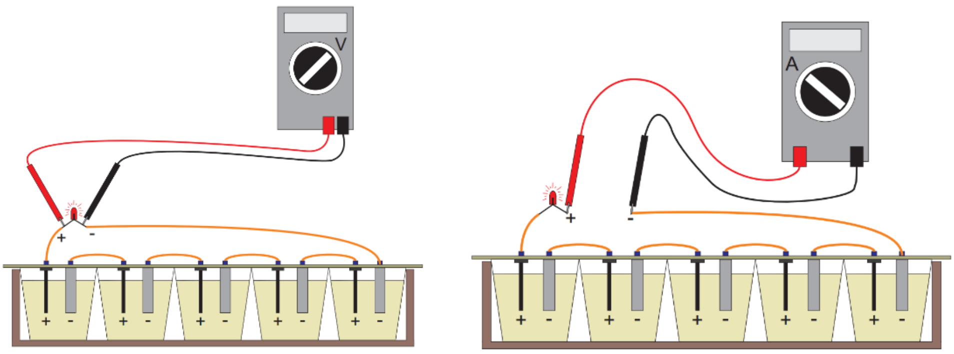
3. Early Product Development

The trial was conducted with a laboratory experiment to test the relationship between variables. The variables used in this study were 1) physical properties (color, odor, texture, and organisms that appear) and 2) electricity (pH, voltage, and electric current). The work steps carried out were as follows: 1) the cassava tubers were cleaned from the soil and peeled, 2) after that washed thoroughly, then the gadung tubers were grated to make a paste, 3) then the pH was measured, 4) the cassava was put into 5 plastic cups, each weighing 150 grams shown in Figure 3a, then closed (the cover has been modified, copper and zinc electrodes are attached shown in Figure 3b), 5) between electrodes connected with cables, 6) then the voltage and electric current were measured, and 7) repeated for gadung and taro tubers. The single chamber MFC series circuit model along with electrical measurements are shown in Figure 4.

Figure 3**:** (a) placement of materials, (b) modified cover

(a) **(b)**

Figure 4: (a) measuring the voltage on the MFC circuit, (b) measuring the electric current



(a) **(b)**

4. Trial and Validation

The prototype kit was tested in three main aspects:

- **Laboratory Testing**

  Properties of Electricity

  The pH measurements on day 1 and 6 are shown in Figures 5 and 6 and the results of the pH analysis are displayed in the form of a graph (Figure 7). Of the three materials, the pH decreased after 24 hours (day 2). This means that the material is increasingly acidic. However, on day 3 (48 hours), the material showed an increasing pH. On day 4 (72 hours) to 6, the three materials showed a fluctuating pH pattern. Meanwhile, the comparison of the electrical voltage on the three materials is shown in Figure 7. The pH acidity of the material at 24 hours decreased. This means that the material experienced an increase in acid content (HCN). After 24 hours, the pH trend increased. This is because the HCN content began to decrease and tended to be alkaline. This finding is the same as the research of Lumbantobing et al (Lumbantobing et al., 2020). The electrical comparison of these materials is shown in Figures 8 and 9. The measurements of electric current and voltage are shown in Figures 10 and 11.

Figure 5: Form and pH of the material on day 1

Figure 6: Form and pH of the material on the 6th day

Figure 7: Tingkat keasaman (pH) berdasarkan waktu pengukuran

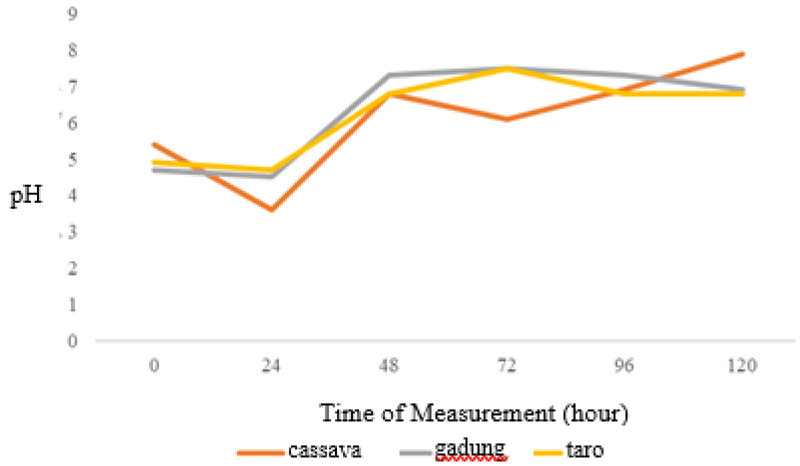


Figure 8: Electrical voltage versus measurement time

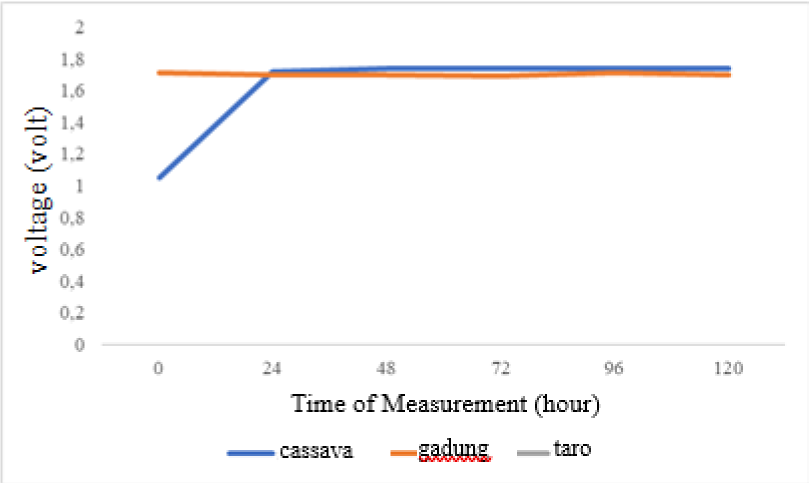


Figure 9: Electric current strength based on measurement time

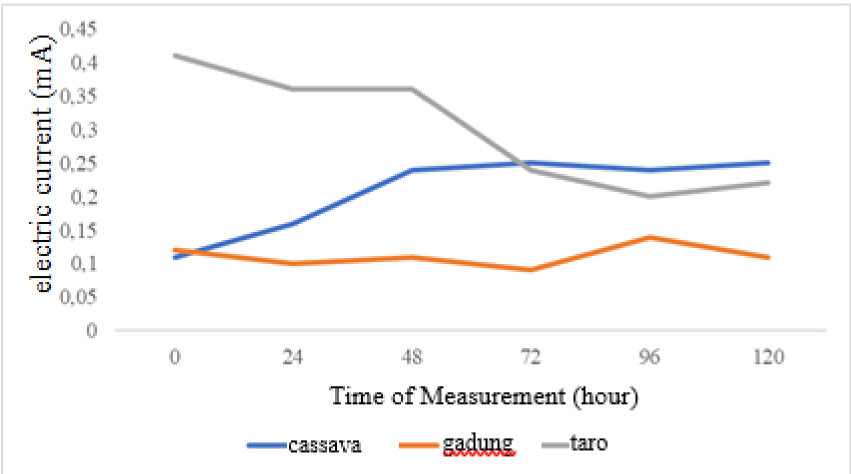


Figure 10: Electric current measurement

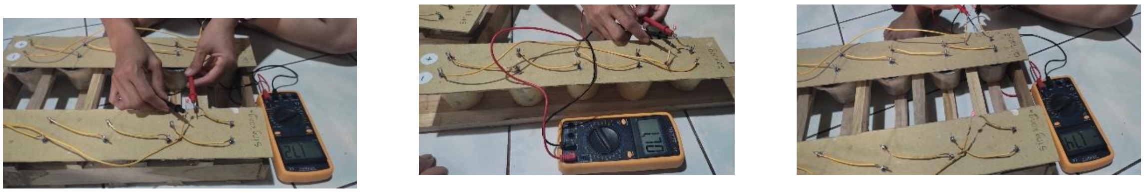
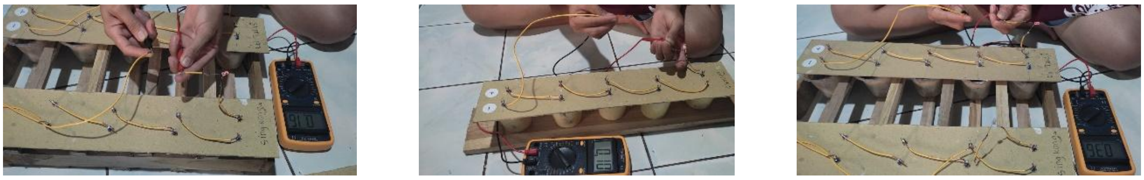


Figure 11: Electrical voltage measurement



After 1 day (24 hours) the three materials showed a relatively stable electrical voltage, namely a range of 1.6-1.8 volts. The electric current strength based on the measurement time on the three materials showed that from 0 - 120 hours an electric current was detected. The maximum electric current achieved by cassava, gadung, and taro were respectively 0.25; 0.14; 0.41 mA. For gadung and taro, it tended to fluctuate, while cassava tended to increase. In addition, LED lights were also used to detect the presence of electric current in the three materials. The results showed that the LED lights could light up for 6 days. The LED lights are shown in Figure 11.

Figure 12: LED lights on all three materials on the 6th day

Based on the test results that have been carried out, it can be analyzed that 1) the length of storage of the material will cause the physical properties of the material to change. However, the electrical voltage of the material tends to be constant. This means that physical properties do not affect the electrical voltage produced. In taro and gadung, the electrical current tends to decrease and cassava tends to increase. This means that changes in physical properties in taro and gadung cause the electrical current to decrease and in cassava to increase. 2) pH which tends to decrease in 24 hours does not affect the voltage produced by the material. This is because the voltage produced is constant. However, the electrical current that occurs is not stable in each material. The graph of electrical current and pH in cassava shows a relationship that tends to be linear. The higher the pH, the higher the electrical current produced. In taro, it tends to be inversely proportional, the higher the pH, the lower the electrical current. While in gadung, the electrical current produced tends to be stable. This is different from what was found by Atina, the lower the pH of the fruit, the higher the voltage and strength of the electrical current and vice versa (Atina, 2015; Fauzia et al., 2019). This difference occurs because the electrical measurements in this study were conducted for 6 days. Meanwhile, previous studies were conducted within 1 day with measurements every few minutes. However, if observed more closely, in this study the pH decreased from 0 to 24 hours but increased afterwards.

- **Validasi oleh ahli materi dan media**
  The validation results of V1, V2, and V3 were respectively: 92%, 94%, and 94%. The validation results are shown in Table 3. This shows that the learning media is suitable for use.

Table 3: Results of Validation by Material and Media Experts

Indicator	No	Statement	V 1	V 2	V 3
Eligibility of Content and Components	1	The materials used in the Learning Tools are in accordance with learning outcomes	4	4	4
	2	The materials used in the Learning Tools are in accordance with the learning objectives	4	4	4
	3	The material presented in the complete Learning Toolkit	4	4	4
	4	The material outlined in the Learning Tools is clear	3	4	4
	5	The material is presented sequentially	4	4	4
	6	Examples of problems in Learning Tools are presented clearly	4	4	4
	7	The practice questions and simple experimental procedures in the	3	3	3

		Learning Tools are presented clearly			
	8	Learning Tools can be used independently	4	4	4
Linguistics	9	Writing Learning Tools in accordance with the general guidelines for correct Indonesian spelling (PUEBI)	3	3	3
	10	The language used is easy to understand	4	4	4
	11	The language used in the Learning Tools is simple and communicative	4	4	4
	12	Use of appropriate Latin names and chemical symbols	3	3	3
Sum			44	45	45
percentage			92%	94%	94%

Some input from the validator is: 1) Make sure the KIT uses materials that are safe for students to use, if there are any that are not safe, provide instructions for use and 2) Provide a label or description on the container to make it more attractive.

- **Teacher and student responses**
  The results of the questionnaire filled out by 2 science teachers are shown in Table 4 and the responses of 30 students in Figure 13.

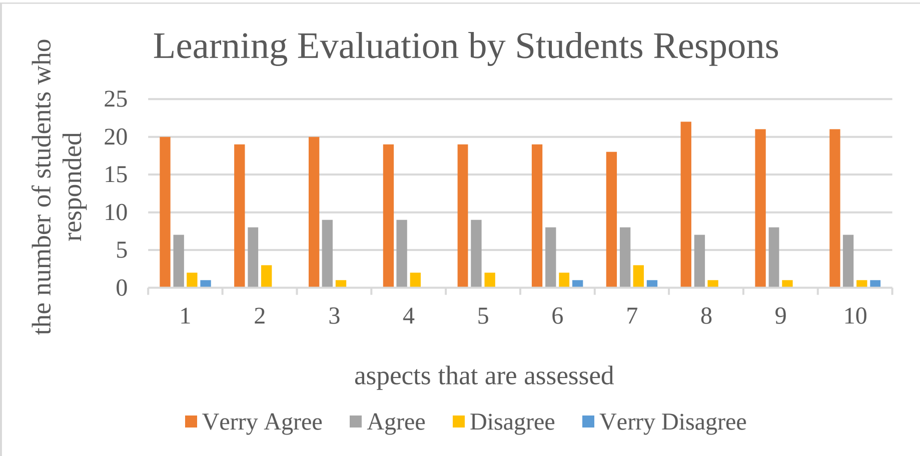
Table 4: Science Teachers' Questionnaire Results

No	Statement	Teacher 1	Teacher 2
1	The use of STEM-based learning devices with the KIT in learning is something new and interesting for me	3	4
2	This learning device helps students to think creatively in studying the material on the characteristics of living things and measurements.	3	4
3	The presentation of material in LKPD and KIT is interesting and easy to understand	3	4

4	The delivery of material in this learning tool is related to everyday life	4	4
5	Presentation of material in learning devices according to learning outcomes	4	4
6	The material presented is in accordance with the order of presentation of the concept	4	4
7	The activity steps contained in the LKPD are easy for teachers and students to understand	4	4
8	The teaching modules that are prepared can be understood and implemented in class	4	4
9	The size and type of font used on learning devices are easy to read	4	4
10	The language used is easy to understand	4	4
Sum		37	40
percentage		93%	100%

The table above 2 teachers gave a score of 93% and 100%. This shows that the KIT that has been developed is feasible to be used in learning. In addition, positive comments were also given by science teachers who stated that this KIT is very helpful in explaining the concept of alternative energy that is often difficult for students to understand abstractly. Through direct practice with tubers that are easily found around them, students become more enthusiastic and understand that energy can be produced from simple materials in the environment.

Figure 13: Student Response



In addition to Table 3 and Figure 13, a positive comment was also given by one of the students as follows. “At first I thought I would only learn the theory of alternative energy. But it turned out I could directly try making electricity from sweet potatoes, and it really turned on! So much fun!”. Based on this, the final product of the MFC STEM KIT is considered feasible and effective to be used as an alternative learning media that is innovative, applicable, and supports the strengthening of scientific literacy and environmental awareness among students.

5. Revisions and Improvements

Based on the results of the trial and input from the validation, revisions were made to the kit design and experimental procedures to improve product quality. Through this revision process, the developed KIT product is expected to not only be technically feasible, but also be able to fulfill the pedagogical aspects as an effective learning medium. This KIT is designed to be able to foster students' curiosity, creativity, and environmental awareness, while introducing the concept of alternative energy that is contextual and relevant to future needs. Thus, the final product can be an inspiring and useful learning tool, and is ready to be widely applied in the school environment.

CONCLUSION

This study successfully developed a tuber-based Microbial Fuel Cell (MFC) STEM KIT as an environmentally friendly alternative energy learning medium. The development results showed that the designed KIT was able to produce electrical energy from the bioelectrochemical process using tuber substrates such as cassava, gadung, and taro. The maximum current values generated from the tubers were 0.25; 0.14; 0.41 mA, respectively. The developed KIT also met the criteria for the feasibility of learning media. This is supported by the results of validation tests from experts with percentages of 92%, 94%, and 94%, respectively. In addition, positive responses to the developed KIT were given by teachers with percentages of 93% and 100%, and by students at 87%. Thus, this tuber-based MFC STEM KIT is worthy of being used as a learning innovation to foster awareness of the importance of renewable and environmentally friendly energy from an early age.

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