

Enhancing critical thinking in physics education: developing an Arduino-based GMC as an innovative learning tool

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ABSTRACT

This research explores the development and innovative implementation of an Arduino Uno-based Geiger-Muller counter (GMC) as a physics learning tool designed to enhance students' critical thinking skills. The aim was to address the gap in effective educational media in teaching radioactivity materials. This research used the analysis, design, development, implementation, and evaluation (ADDIE) model, which includes the analysis, design, implementation development, and evaluation stages. The sample of this study involved 165 students at University of PGRI Pontianak, using a pre-experimental design with one pretest-posttest group. Validation by experts and feedback from students confirmed the high validity and effectiveness of the media, with significant improvements seen in critical thinking indicators such as evaluation, analysis, interpretation, and inference. The use of real-world materials, including red Borneo agate testing, provided a practical context that enriched the learning experience. Although there was no control group, the findings suggest that integrating hands-on technology-based tools into physics education can significantly improve students' critical thinking skills. This study contributes to the growing literature on educational innovation, offering practical solutions to improve critical thinking in science education through interactive and contextually relevant learning media.

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1. INTRODUCTION

Some universities still rely on teaching methods that are limited to theory when learning about radioactive materials. This highlights the need for innovative learning media, especially radioactive materials [1]. Appropriate and innovative media makes the subject matter more enjoyable and easily understood by students [2]. Learning media, such as visual, audio, or interactive technology, can help bring abstract and complex material to life so that students are more interested and motivated to learn [3]. In addition, various learning media can accommodate a variety of student learning styles, allowing each student to understand the material according to the most effective way of learning [4]. Therefore, the selection and use of appropriate learning media are very important to achieve educational goals and improve the quality of learning in the classroom.

In addition to the use of media, another problem is also related to the low ability of students to develop critical thinking skills. Critical thinking skills are essential for students' intellectual development, evaluating information, formulating solid arguments, and making accurate decisions [5]. However, research shows that assessment of learning outcomes is often more focused on mastery of material or facts rather than students' critical thinking skills [6]. Another study reveals that grading is based on the students' success in remembering or understanding information without providing opportunities for students to practice and hone their critical thinking skills [7]. As a result, the students need more initiative to develop skills in depth and feel that more than just conceptual or academic understanding is required [8]. Study programs need to add critical thinking skills to the curriculum to prepare students for success in an increasingly complex and changing world [9]. This can be achieved through projects, group discussions, or assignments that challenge students to apply critical thinking in a real-world context [10]. With this in mind, the students will have a deeper understanding of the material and have sufficient provision related to critical thinking skills.

This study used VOSviewer to analyze the number of studies and citations related to five keywords, namely Arduino Uno, critical thinking, Geiger-Muller counter (GMC), instructional media, and radioactivity from 2019-2024. The data showed that there were 375 journals related to these keywords. A visualization of the network in publications related to the five keywords can be seen in Figure 1. Based on Figure 1, there are 63 terms in six groups (red, green, blue, yellow, orange, and purple) with 929 links and a total link strength of 1492. The larger the node size of the item, the greater the frequency of the appearance of keywords. Based on the node analysis, the keywords critical thinking skills, GMC, and radioactivity have not appeared. This shows that no research specifically develops Arduino Uno-based GMC learning media on radioactivity material to improve students' critical thinking skills. This analysis reveals a gap in the academic literature regarding the use of simple yet effective technologies such as Arduino Uno in the context of science learning. Although the Arduino Uno-based GMC has great potential to provide a practical and immersive experience in understanding the concept of radioactivity, no research has explored how this learning medium can be used to stimulate students' critical thinking skills. These findings emphasize the importance of further research to develop and evaluate the effectiveness of this innovative learning tool in improving the quality of science education at the tertiary level.

Based on these problems, solutions can be provided by developing learning media to improve the students' critical thinking skills. The media is GMC based on Arduino Uno as a tool to detect radioactivity. Students can learn how radiation detectors work practically and interactively by integrating GMC and Arduino Uno [11]. Arduino Uno serves to process and display data obtained from GMC [12]. Thus, the students can see the results of radiation detection in the form of digital numbers that are easy to understand. The use of these tools not only makes the concept of radioactivity more real and exciting, but also teaches students technical skills, such as basic programming and data processing [13]. The project makes physics learning more applicable, allowing students to apply the theory learned in experiments and enhancing students' understanding of critical thinking [14].

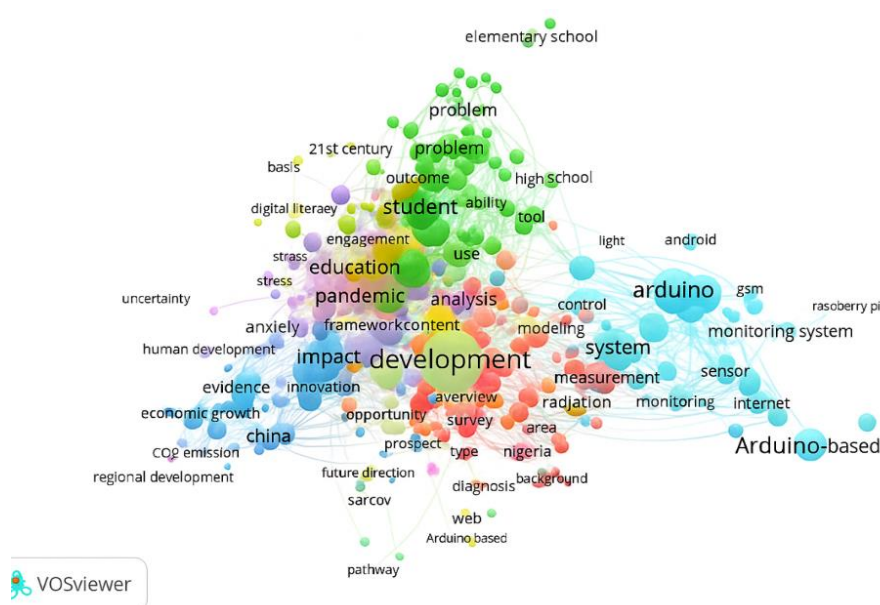


Figure 1. The network visualization in the publication

The novelty of this research lies in the development of media on radioactive materials through testing typical rocks of West Kalimantan, namely agate type red Berneo. This test is needed to improve students' critical thinking skills, especially the radioactive properties of red Berneo rocks used by the community. The radioactive content must be studied to ensure the safety of red Berneo stones that are often used by the community as ring stones. The threshold value of radioactive content in counter per minute (CPM) for health mainly depends on the type of radiation involved and the duration of exposure, i.e., in the range of [15]: normal background radiation levels vary depending on the geographic location but are usually in the range of 5-100 CPM, which is the radiation level considered safe and routine in daily life; 100-200 CPM radiation activity requires further evaluation, 200-500 CPM radiation activation level begins to be a concern, radiation activation levels above 500 CPM are relatively high radiation levels long-term exposure at these levels can be harmful to health, and radiation of 1,000 CPM and above very high radiation levels can damage health in a short time.

2. METHOD

This research was conducted using a research and development method that focuses on developing Arduino uno-based GMC physics learning media for radioactive materials. The research design uses the development model analysis, design, development, implementation, and evaluation (ADDIE) [16]. The research design used a pre-experimental model and a one-group pretest-posttest. This research was conducted at University of PGRI Pontianak. The sample was obtained using a random sampling technique with 165 students. Data collection techniques included questionnaires, tests, and observations. Researchers conducted the first stage to determine the product to be developed, its specifications, and research indicators on critical thinking skills. The research stages can be seen in Figure 2.

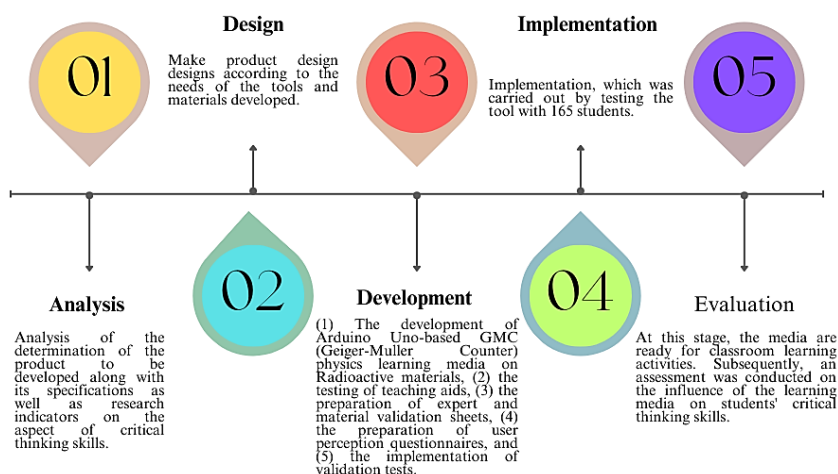


Figure 2. Stages of the research

The second stage was design. At the design stage, the steps taken were to design a product according to the needs of the tools and materials developed, namely the Arduino Uno-based radioactivity measuring device. The third stage was development. At this stage, there were five activities: i) the development of Arduino Uno-based GMC physics learning media for radioactive materials; ii) the testing of props; iii) the preparation of expert and material validation sheets; iv) the preparation of user perception questionnaires; and v) conducting validation tests. Media experts can determine validation criteria using (1) and (2) [17], [18].

$$V = \frac{\sum s}{|n(c-1)|} \quad (1)$$

$$S = r - l_0 \quad (2)$$

Where, V is the Aiken validation score, r is the number given by the validator, l_0 is the lowest validity rating score, c is the highest validity rating score, and n is the number of panelists. The validity of the media is shown in Table 1.

Table 1. The validity of the media developed

Interval (%)	Category
81-100	Very valid
61-80	Valid
41-60	Keep
21-40	Bad
0-20	Too bad

The fourth stage is implementation, which is done by testing the tool with 165 students. After use, students filled out a media usage questionnaire. Students responded to the development of learning media using (3) [19]:

$$\text{Questionnaire Score} = \sum(X_i \times N) \quad (3)$$

X_i indicates the Likert scale score, and N indicates the number of validators. The percentage of the questionnaire score is calculated using (4):

$$P = \frac{\text{score obtained}}{\text{maximum score}} \times 100\% \quad (4)$$

After knowing the percentage results of student responses, they then provided criteria for interpreting the questionnaire scores on the developed media, namely 76-100% with the ability to strongly agree, 51-75% with the ability to agree, 26-50% with the statement disagree, and 0-25% with the ability to strongly disagree [19].

The fifth stage is evaluation. At this stage, the media is ready for learning activities in the classroom. Furthermore, an assessment of the effect of learning media on students' critical thinking skills was conducted. The statistical test used a paired sample t-test to determine the mean difference between two paired samples: pre-test and post-test scores. Furthermore, to assess its effectiveness, we used the N-gain test. The interpretation of the N-Gain value is $g > 0.7$ for the high category, $0.3 \leq g \leq 0.7$ for medium category, and $g < 0.3$ for the low category. The N-gain percentage value obtained was then interpreted with the following characteristics: $g > 76\%$ with effective category, $56\% \leq g \leq 75\%$ with moderately effective category, $40\% \leq g \leq 55\%$ with less effective category, and $g < 40\%$ with ineffective category [20].

3. RESULTS

3.1. Analysis

At the analysis stage, observations were made to find out the use of radioactive learning media at several universities in Pontianak. All universities have not used innovative media to teach radioactive materials. The media used by lecturers were still limited to learning books, PowerPoint presentations, learning videos, projectors, and simple props. When viewed from the learning process, lecturers apply a lecture model which results in less interesting and boring material. These results are corroborated by research conducted in 2021 that lecturers have difficulty with radioactive material and have not utilized practicum media such as sensor-based Arduino [21]. The results are presented in Table 2.

Table 2. Observation of the use of radioactive learning media in Pontianak City, West Kalimantan

College	Use of radioactive learning media
Faculty of Mathematics and Science, Tanjungpura University	Not
Faculty of Teacher Training and Education, Tanjungpura University	Not
Pontianak State Polytechnic	Not
University of Muhammadiyah Pontianak	Not
University of PGRI Pontianak	Not

Furthermore, a questionnaire was used to determine students' critical thinking skills. The results showed that most students had good critical thinking skills, but some still needed more attention. Data analysis showed that students who actively participated in class discussions tended to show higher essential thinking skills than passive students [22]. In addition, the use of learning methods using GMC Arduino physics learning media on radioactive material has proven effective in improving students' critical thinking skills. Therefore, lecturers must continue to develop teaching strategies to encourage students to think critically and actively during learning.

3.2. Design

The initial stage before creating a GMC Arduino Uno-based physics learning media system on radioactive materials as a control circuit system begins with creating a system circuit, as shown in Figure 3. Creating a network aims to determine the location of the system to be created [23]. In addition to being used to determine the layout of components, system design also has the advantage of reducing excessive cost budgets. After designing and creating the system, researchers prepared materials for making learning media. The tool used is a printed circuit board (PCB). The materials used are Arduino Uno, 20×4 LCD, Gc1602Nano Nuclear Radiation Detector Diy Geiger Counter Parts Kit sensor, HX711 module as an amplifier, Green LCD 1602 + I2C IIC Backpack LCD Module for Arduino, resistors, LEDs, boxes, jumper cables, and other components.

Arduino Uno-based GMC physics learning media software for radioactive materials is designed in this research by programming on the Arduino system. This programming is done to set the main function of the learning media as a countermeasure for the radioactivity value of the object [24]. This software is used to enable the working function of the sensor of the diy Geiger counter parts kit Gc1602Nano nuclear radiation detector to measure the radioactivity of objects in the Arduino system [25]. The Arduino software processes the radioactivity measurement results and feeds them into the LCD. The programming language uses C++ [13]. The programming language is illustrated in Figure 4.

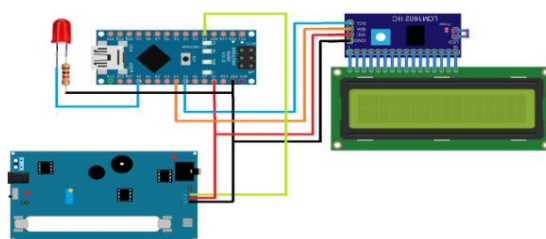


Figure 3. Tool development design

```

#include <Wire.h>
#include <LiquidCrystal_I2C.h>

#define IntegratingTime 15000
#define oneMinute 60000

LiquidCrystal_I2C lcd(0x27, 16, 2);

unsigned long counts = 0;
unsigned long events = 0;
unsigned long cpm = 0;
unsigned int multiplier;
unsigned long previousMillis;
double avgCounts = 0;
double avgCPM = 0;
double avgUSV = 0;
double sumCPM = 0;
double sumUSV = 0;
double uSv = 0;
double dose = 0;

int ledPin = A0, ledDelay=3000;
bool ledState = false;
unsigned long ledStart=0;

void tube_impulse(){
  counts++;
  events++;
}

void setup() {
  lcd.begin();
  lcd.backlight();
  counts = 0;
  cpm = 0;
  multiplier = oneMinute / IntegratingTime;
  Serial.begin(9600);
  attachInterrupt(digitalPinToInterrupt(2), tube_impulse, FALLING);
  pinMode(ledPin, OUTPUT);
  lcd.setCursor(0, 0);
  lcd.print("Radiasi: ");
  lcd.setCursor(0, 1);
  lcd.print("0 uSv/hr ");
}

void loop() {
  unsigned long currentMillis = millis();
  if (currentMillis - previousMillis > IntegratingTime) {
    avgCounts++;
    previousMillis = currentMillis;
    cpm = counts * multiplier; //cpm * 60/15 = cpm * 4
    uSv = (cpm / 151.0);
    sumCPM = (double)cpm + sumCPM;
    sumUSV = uSv + sumUSV;
    avgCPM = sumCPM / avgCounts;
    avgUSV = sumUSV / avgCounts;
    //print cpm on serial
    Serial.print((currentMillis) / 1000);
    Serial.print("\t");
    Serial.print(cpm);
    Serial.print("\t");
    Serial.print(avgCPM);
    Serial.print("\n");
    //print on LCD
    lcd.setCursor(0, 0);
    lcd.print("Radiasi: ");
    lcd.setCursor(0, 1);
    lcd.print(String() + uSv + " uSv/hr ");
    ledDelay=3000 - (2000/3)*uSv;
    if(millis() - ledStart > ledDelay){
      ledState = !ledState;
      ledStart = millis();
    }
    counts = 0;
    //-----
  }
  digitalWrite(ledPin, ledState);
}

```

Figure 4. Learning media programming languages

3.3. Development

Based on Figure 5, the GMC radioactivity learning media using an Arduino Uno-based microcontroller has been completed and is ready to be implemented. The way the device works, namely, the Geiger-Muller or GM tube, detects radioactive particles passing through it. The GM tube is filled with a gas whose ionization is produced by radiation particles, creating an electrical pulse each time ionization occurs. The electrical pulses generated by GM tubes tend to be weak; therefore, they need to be amplified. The amplifier boosts the signal so that the microcontroller can read it. The amplified signal is then sent to the

Arduino Uno microcontroller. The Arduino serves as the central data processing unit. The Arduino counts the number of pulses received from the GM tube in a given unit of time (for example, pulses per minute or CPM). This number is directly proportional to the radiation level. The processed data is then displayed on an LCD or LED screen connected to the Arduino, giving the user immediate information about the radiation level in the form of numbers and graphs. The results of the validator assessment consisting of three lecturers of Physics Education University of PGRI Pontianak also justified that the media was ready to be implemented. The results of the validation assessment are presented in Table 3.

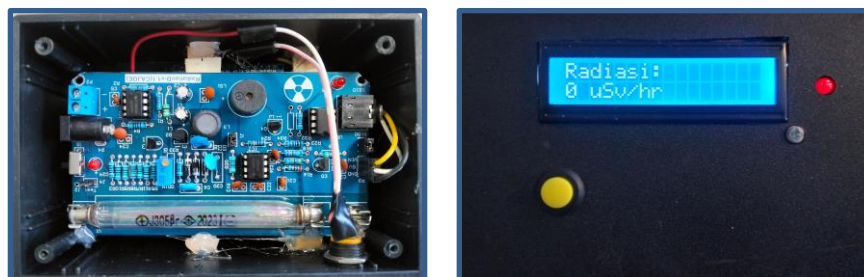


Figure 5. GMC physics learning media GMC based on Arduino Uno development results

Table 3. Table of analysis of the validation results of GMC physics learning media by experts

Material expert			
Component	Validation (%)	Category	
Linkage with teaching materials	82	Very valid	
Educational value	80	Valid	
Tool efficiency	82	Very valid	
Average	81	Very valid	
Media expert			
Tool durability	80	Valid	
Tool accuracy	79	Valid	
The speed of the tool system in the reading of measurement results	83	Valid	
Tool efficiency	82	Very valid	
Aesthetic	83	Very valid	
Security	81	Very valid	
Average	81.3	Very valid	
Total average	81.15	Very valid	

3.4. Implementation

At the implementation stage, student response tests were carried out on the use of Arduino Uno-based GMC physics learning media. This test aims to determine the extent to which the learning media can be accepted by students in the learning process of radioactive material. The results showed that 86.33% of students strongly agreed that this media was effective and feasible to use in learning. The students' responses were measured based on several indicators, such as Learning motivation and understanding the concept of density as a learning medium, operation and performance of learning media, and quality of learning media. Further details of student responses are presented in Table 4.

This tool was also tested as a comparison against typical West Kalimantan rock materials, namely red Berneo agate, ordinary agate, and uranium, to determine the difference in radioactivity levels between these types of rocks. The test was conducted using an Arduino Uno-based GMC. The measurement results show that the average activity value of uranium rock reaches 0.45 $\mu\text{Sv}/\text{hour}$ (184.2 CPM), which is higher than that of red Borneo agate and ordinary agate. The average activity of red Kalimantan agate was recorded at 0.08 $\mu\text{Sv}/\text{hour}$ (16.2 CPM), while ordinary agate had an average activity of 0.08 $\mu\text{Sv}/\text{hour}$ (15 CPM). This difference in activity levels indicates a significant variation in the radioactive content of each rock. The full measurement results are presented in Table 5.

Figures 6 (see in Appendix) shows the process of collecting data on uranium activity, red Berneo agate activity, and agate activity were usually carried out by students. The students prepare the tools and materials to be observed. The Arduino Uno-based GMC counter was turned on in the active position and connected to the laptop. Place the observed rock type next to the device with data capture per minute for five minutes. Every minute, the students recorded how many activity values of each rock observed, after up to 5 minutes a photo graph was displayed on the laptop screen. In Figure 6(a), the radiation detector records a value of 0.45 $\mu\text{Sv}/\text{hr}$

when measuring uranium rocks. This reading is significantly higher than those of the other two samples. The device display shows a relatively high figure, and the graph on the right indicates notable fluctuations in radiation levels over five minutes, with frequent detection peaks. This confirms uranium's radioactive nature, emitting much higher levels of radiation. Figure 6(b) shows measurements for red Borneo agate, with a recorded value of $0.08 \mu\text{Sv/hr}$. This value is much lower than that of uranium rocks and nearly matches background radiation levels. The graph displays some small peaks, but on the whole, it is considerably flatter, signifying that this agate exhibits no significant radioactive activity. In Figure 6(c), the device measures an ordinary agate and yields a result of $0.05 \mu\text{Sv/hr}$. This reading is even lower than that of the red Borneo agate, with the graph being almost flat indicating extremely low and consistent radiation activity near environmental background. Thus, this stone does not contain detectable naturally occurring radioactive sources.

Table 4. Student response using GMC physics learning media based on Arduino Uno on radioactive materials

No	Aspects	Percentage (%)	Category
1	Learning motivation and understanding the concept of density as a learning medium	88	Strongly agree
2	Operation and performance of learning media	86	Strongly agree
3	Quality of learning media	85	Strongly agree
	Percentage average	86.33	Strongly agree

Table 5. Testing tools on typical West Kalimantan rock materials, uranium, red Borneo agate, and ordinary agate

No	Rock name	Time (minutes)	Activity	
			usv/h	CPM
1	Uranium	1	0.49	179
		2	0.44	168
		3	0.44	189
		4	0.41	177
		5	0.47	208
		Average	0.45	184.2
2	Red Borneo agate	1	0.09	19
		2	0.07	14
		3	0.08	16
		4	0.10	23
		5	0.06	19
		Average	0.08	16.2
3	Ordinary agate	1	0.08	17
		2	0.08	16
		3	0.07	11
		4	0.06	21
		5	0.11	10
		Average	0.08	15

3.5. Evaluation

Based on the paired sample T-test results presented, it was found known that the t value=-7.034 and the probability or significance value=0.000. Therefore, the p value<0.05 results in H_0 being rejected and H_1 being accepted. This means there was a significant difference between the pre-test and post-test scores for using learning media on critical thinking skills. The N-gain test was conducted to determine the effectiveness of the media. Evaluation activities were carried out by giving pre-test and post-test questions, with a total of ten multiple-choice questions. The N-gain test results are listed in Table 6. Based on the N-Gain test shown in Table 6, the scores obtained for each indicator of critical thinking ability were evaluation 0.80 (high), analysis 0.76 (high), interpretation 0.76 (high), exheat 0.80 (high), and inference 0.78 (high). Based on these results, it can be seen that the average N-gain score was included in the High category, with an N-gain percentage of 78% and practical accuracy.

Table 6. Results of the N-Gain test on critical thinking skills

Indicators	N-Gain	Category
Evaluation	0.80	High
Analysis	0.76	High
Interpretation	0.76	High
Explanation	0.80	High
Inference	0.78	High

4. DISCUSSION

The novelty of this research was the creation of an Arduino Uno-based GMC tool as a learning medium for radioactivity. The developed press machine was used to improve critical thinking skills by testing typical West Kalimantan rocks, namely red Borneo agate. The results of the media expert test showed that the media was ready to use, with an average validation score of 81.15% (very valid category). Furthermore, the results of statistical tests of critical thinking skills based on paired sample t-tests showed significant differences between pre-test and post-test scores with effectiveness based on the N-Gain test in the high category.

Media is said to improve critical thinking skills if the content of the media can encourage students to think both in analyzing and evaluating data or information [26], [27]. This characteristic is based on the developed media being able to analyze rock characteristics more accurately so that students have direct experience that is not obtained in textbooks. The media presents tools that can be observed directly with materials around the student's environment. Agate is a local wisdom in West Kalimantan that influences students and motivates them to think critically. Through contextual problems, students learn to use their thinking skills to solve existing problems based on previous experience [28].

One of the interesting findings of this research is the improvement of students' critical thinking skills after conducting experiments. This can be seen when students can interpret materials to analyze the radioactive properties of rocks using the developed media. The value of radioactive activity in agate is very minimal compared to uranium rocks. Kalimantan red agate is safe for ring stones, but people are advised not to use it continuously because it can harm the human body for a long time. One of the consequences of radioactivity is that it triggers cancer [29], [30].

Critical thinking skills can be developed when inhibiting factors are adequately addressed. One of them is the learning media used in learning activities. Innovative and interactive learning can help students grow and improve their critical thinking skills [31]. The appearance of the latest learning media and new digital features will attract students' interest in learning. Thus, in this case, students' motivation to learn is linear in their critical thinking skills [22]. The higher the students' motivation to learn, the better their critical thinking skills [32]. In addition, the presentation of material and the addition of practice questions containing critical thinking skills are also effective in improving critical thinking skills [32]. The media presents the material in depth by connecting theory and practice [8]. In addition, questions containing indicators of critical thinking skills are presented in quizzes or competency tests. The purpose of delivering questions in the form of quizzes is so that students can optimize their critical thinking skills within a certain period [33]. Therefore, students can use this developed media to improve their critical thinking skills.

The limitations of this study can be identified from various aspects. One of the main limitations is in terms of the validity and reliability of the measuring instrument. Since this Arduino-based device was developed for educational purposes, the results obtained are less accurate than those of professional radiation measuring devices, especially in measuring low-intensity radiation [34]. In addition, the limited mastery of technology by teachers and students is a challenge. Not all teachers or students have experience in using Arduino or understand the basic concepts of electronics, so it takes time and additional resources to provide training before this tool can be effectively implemented in learning [35]. One way to overcome the limitations related to the validity and reliability of the Arduino-based Geiger-Muller device is to perform periodic calibrations using more accurate commercial radiation measuring devices [36]. Testing and comparing the results of the Arduino device with standard tools will help improve the accuracy of the data obtained [37]. The provision of training and workshops for teachers is essential. This training can be focused on basic Arduino programming [38], hardware usage, as well as the integration of this tool into physics learning methods. In addition, a more structured learning module could be provided to guide classroom implementation, making it easier for teachers and students who are unfamiliar with this technology. Creating a complete and user-friendly user manual can help students and teachers who are just starting out with Arduino. This guide should include installation tutorials, programming steps, as well as solutions to common problems [39]. Video tutorials or online platforms can also be an additional source of learning.

5. CONCLUSION

This study shows that the application of Arduino Uno-based GMC physics learning media on radioactive materials can be declared very valid for use by students. The validity of the media can be proven by the level of student response as a user of 86.33% with a very valid category. This finding shows that media development associated with real problems in the form of testing the quality of rocks in West Kalimantan such as red Borneo makes students eager to learn and more critical in analyzing each problem. The data shows a significant difference between Arduino Uno-based GMC physics learning media on radioactive materials increasing students' critical thinking skills by 78%. This research is useful for lecturers to improve critical thinking skills through the use of innovative media. The research hopes that in the

future various innovative media can be developed which are not only limited to practicum tools in class but can be used to explore every problem in the real world. Universities are expected to be able to create real media that can raise regional potential.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : Conceptualization

M : Methodology

So : Software

Va : Validation

Fo : Formal analysis

I : Investigation

R : Resources

D : Data Curation

O : Writing - Original Draft

E : Writing - Review & Editing

Vi : Visualization

Su : Supervision

P : Project administration

Fu : Funding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest regarding the publication of this paper. All authors have read and approved the final version of the manuscript and have agreed to its submission to this journal. No financial, personal, or professional affiliations or relationships were disclosed that could be perceived as potential conflicts of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

ETHICAL APPROVAL

The research related to human use has been complied with all the relevant national regulations and institutional policies in accordance with the tenets of the Helsinki Declaration and has been approved by the authors' institutional review board or equivalent committee.

DATA AVAILABILITY

The research data supporting this study's findings can be obtained from the corresponding author, [M], through reasonable request. The dataset is not publicly accessible due to privacy and ethical considerations, as it contains information that could potentially compromise participant confidentiality.

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APPENDIX

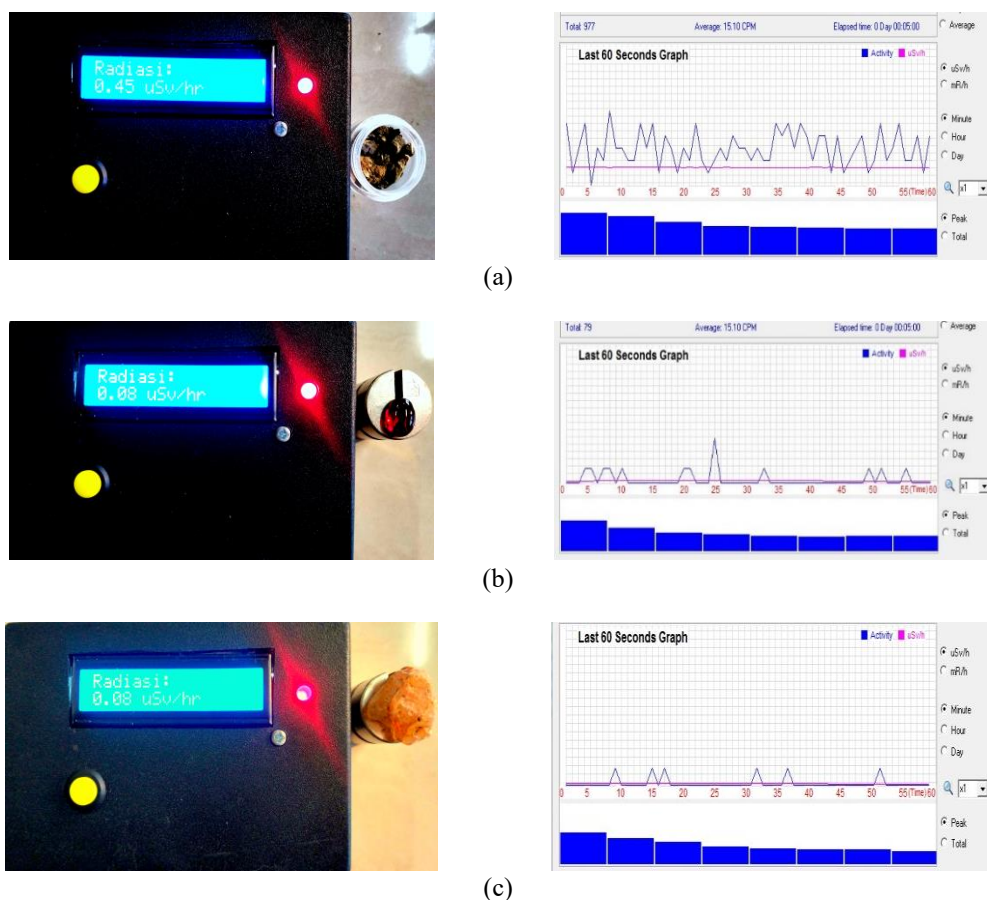


Figure 6. Data collection and display of (a) uranium rocks, (b) red Berneo agate, and (c) ordinary agate

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