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Portable and Inexpensive Blue LED based UV-Vis Spectrophotometer with Smartphone Detector as a Chemistry Learning Innovation

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ABSTRACT

Effective study of chemistry requires access to complete and affordable laboratory equipment. Practical activities provide hands-on learning experiences and help students understand chemical concepts more easily. The spectrophotometer is a key instrument in chemistry labs, but its high cost and complex maintenance often make it unavailable in schools. This study aims to design and develop an inexpensive, simple, and portable UV-Vis spectrophotometer that offers quick analysis, making it accessible for high schools as a contextual chemistry learning tool. Experimental methods were employed in laboratories and chemistry classrooms, focusing on measuring solution content. The UV-Vis spectrophotometer was developed using LED light sources and smartphones as detectors and data processors. Integrating smartphones with the spectrophotometer for data reading represents a significant innovation. Testing revealed that the prototype demonstrated high accuracy and precision, with recovery values between 90-110% and precision test results below 2%, indicating good repeatability. The Limit of Detection (LOD) was found to be 0.43 ppm, and the Limit of Quantification (LOQ) was 20.99 ppm. Classroom implementation involved 23 students from a private school in Surakarta, using questionnaires and learning outcome tests. Results showed that the prototype effectively enhanced students' understanding of stoichiometry, with an 89.217% improvement. Additionally, 89.681% of students responded positively to using the prototype as a learning tool. This research demonstrates that a simple, portable, and affordable spectrophotometer can be developed as an interactive learning medium in high schools, significantly improving students' comprehension and engagement in chemistry. The prototype aligns with the principles of laboratory UV-Vis spectrophotometry and Lambert-Beer's law, where higher solution concentrations correspond to greater absorbance values.

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1. INTRODUCTION

Studying chemistry effectively requires well-equipped laboratories to support practical activities. Practicum activities are essential as they offer students opportunities to develop scientific skills and provide hands-on learning experiences, making chemical concepts easier to grasp (Su & Cheng, 2019; Zammiluni et al., 2018). Among the various instruments used in labs, the spectrophotometer is widely utilized in teaching analytical, organic, pharmaceutical, and biological chemistry (Taha et al., 2017). This instrument measures sample absorbance as a function of wavelength and plays a crucial role in numerous fields (Sölvason & Foley, 2015).

Spectrophotometers serve as valuable learning tools in education, supporting practicum activities and offering students direct and meaningful experiences with instrumentation techniques (Cokley et al., 2024). They help students visualize abstract and complex chemical concepts concretely (Sari & Hidayat, 2017). However, their presence in educational institutions, particularly high schools, is limited. Typically, UV-Vis spectrophotometers are found only in university labs. The high cost of commercial spectrophotometers, ranging from $3,000 to over $20,000, poses a significant barrier, especially in developing countries (Nandiyanto et al., 2016). Alongside the high price, the complexity of maintaining these instruments further limits their accessibility (Shidiq et al., 2020b). Given these challenges, research into developing a portable, simple, and low-cost UV-Vis spectrophotometer is necessary. Such an instrument would make spectrophotometry more accessible to high schools, enhancing chemistry education by providing practical and engaging learning experiences.

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High schools need to introduce spectrophotometers to enhance students' understanding of chemistry. Students face three levels of representation: macroscopic, submicroscopic, and symbolic. Contextual learning media like spectrophotometers help bridge the gap between theory and daily life (Vanderveen et al., 2013b). Students must think critically to solve numeracy problems and understand theoretical concepts. Practicum activities aid in comprehending abstract chemical ideas practically and applying knowledge to everyday life (Sasongko, 2020). These activities allow students to conduct experiments, linking theory with real-world practice. Instruments like spectrophotometers can be incorporated into chemistry labs using STEM approaches, fostering essential thinking skills (Shidiq et al., 2020b, 2021). This hands-on approach makes learning more engaging and effective.

UV-Vis spectrophotometers relate to various chemical substances in high school, such as determining substance levels in stoichiometry materials. Their limited availability in high schools presents an opportunity to develop simple, portable, and affordable versions. Researchers have explored using LEDs as light sources (Jawad et al., 2021), Arduino Uno as detectors (Yohan, 2018), and other methods to create basic UV-Vis spectrophotometers (Marsan et al., 2018; Nandiyanto et al., 2018; Nurrahmawati et al., 2022; Shidiq et al., 2021). Yet, the integration of smartphone detectors, which are widely available among students, still requires further improvement. Research reviewed by Shidiq et al. (2020c) indicates that out of 46 publications on spectrophotometer development, 15 focused on UV-Vis spectrophotometers and 10 utilized smartphone cameras as detectors. This study aims to enhance previous research by developing a simple, portable, and inexpensive UV-Vis spectrophotometer with a smartphone detector. This innovative learning tool leverages the widespread use of smartphone technology, making advanced chemistry education more accessible and engaging for high school students.

Several simple UV-Vis spectrophotometer developments have successfully integrated smartphones, such as the shoebox UV-Vis spectrophotometer (Hosker, 2018) and the 3D printable smartphone spectrophotometer (Grasse et al., 2016). Previous designs aimed to create inexpensive and powerful spectrophotometers, including the LEGO spectrophotometer (Knagge & Raftery, 2002), the low-cost LED spectrophotometer (Yeh & Tseng, 2006), and the mobile phone spectrophotometer (Scheeline, 2010). Despite their innovations, these designs had drawbacks, particularly with manual and time-consuming data display systems. Addressing this issue, the current study proposes using smartphones as comprehensive data detectors and viewers, offering a more efficient and user-friendly experience. This approach allows all students to operate the device directly, enhancing their chemistry learning experience.

A UV-Vis spectrophotometer was developed in this study, designed to be simple, fast, portable, and inexpensive. The design includes a battery pack, a white LED light emitter, a slit, a cuvette and holder, and a smartphone as a detector. This prototype captures absorbed and transmitted light, measuring the concentration and absorbance of samples using smartphone technology. The "portable and inexpensive UV-Vis spectrophotometer" offers a low-cost alternative accessible to high schools, serving as a technology-based contextual learning medium that aids chemical representation for students. This instrument aims to increase flexibility for educational institutions in conducting experiments, providing a contextual and easy-to-understand learning experience for students

2. MATERIAL AND METHOD

Material

The development of the instrument focused on simplicity, ease of construction and use, and cost minimization without compromising performance. All equipment was made using Polylactic Acid (PLA/PLA+) material, assembled through 3D printing to create blocks measuring 15 cm x 10 cm x 20 cm. The light source consisted of a blue LED with a diameter of 5 mm, powered by a 600mAh lithium polymer battery connected to the charging module using a jumper cable. Light from the blue LED passed through a sample placed in a glass cuvette measuring 1.25 cm x 1.25 cm x 4.5 cm. A smartphone camera sensor captured the transmitted light, which was then read using a spectrophotometer detector application. The assembly and repairs were conducted offline at the Solo Technopark with the assistance of experts. Quantitative testing was performed using two instruments, a simple spectrophotometer and a UV-Vis spectrophotometer, at the Central Laboratory of Sebelas Maret University (UNS). The effectiveness of the prototype as a learning medium was tested at a private senior high school in Surakarta, Indonesia.

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Methods

The experimental method was used in the laboratory and at school. Experiments in the laboratory were used to determine the performance of the instrument and ensure that the developed instrument functions according to specifications and provides consistent results. While experiments at school were used to test students' responses in using the instrument which allowed researchers to evaluate students' interactions during the learning process. In addition, as a support for the manufacture of instruments, the literature review is used in the research to critically assess the innovations that will be used to develop a simple UV-Vis spectrophotometer. The formulation of the problem in this study is: How to create a portable and inexpensive UV-Vis Spectrophotometer instrument? How is the effectiveness of the portable and inexpensive UV-Vis Spectrophotometer instrument as a medium for learning chemistry? The implementation stage that will be carried out in this activity consists of several stages, as shown in **Figure 1**.

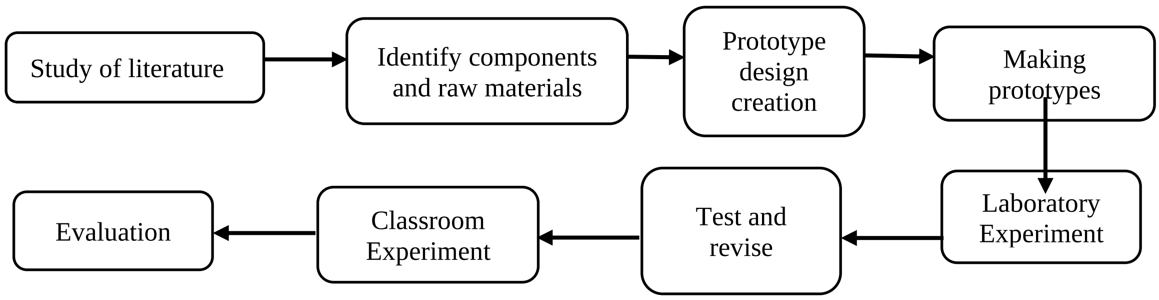

Figure 1. Research flow scheme

The implementation stage involved several steps. Initially, a comprehensive literature study was conducted, reviewing journals, books, articles, websites, and other references related to the prototype. This step helped identify affordable and simple replacement components. The prototype design was developed using SketchUp, Fashion 360, and Blender software. The design was then assembled using Polylactic Acid (PLA/PLA+) material through a 3D printing process, chosen for its stability, flexibility, ease of printing, and affordability. The manufacturing process involved installing electronic components, including a lithium battery, charging module, switch, jumper cable, and blue LED light. A spectrophotometer detector application found on smartphones was utilized. The smartphone camera sensor captured the light from the LED, which then passed through the cuvette and slit before being translated into measurements for the calibration curve. Quantitative testing involved comparing the absorbance values, conducting accuracy and precision tests, and determining the Limit of Detection (LOD) and Limit of Quantification (LOQ). The measurement results from the prototype were compared with those from a UV-Vis spectrophotometer in the FKIP chemistry laboratory. Upon achieving satisfactory results, the final stage involved administering questionnaires and learning outcome tests to students to evaluate the prototype's effectiveness as a chemistry learning medium. This structured approach aimed to ensure the developed instrument was both functional and educationally beneficial.

Data Analysis

The data analysis process for this study involved several key steps to ensure the accuracy and reliability of the Portable and Inexpensive UV-Vis Spectrophotometer prototype. The main components of the analysis included calibration, linearity, accuracy, precision, and the determination of the Limit of Detection (LOD) and Limit of Quantification (LOQ). Initially, a calibration curve was created using standard solutions with known concentrations. The absorbance values of these standards were measured using both the developed prototype and a commercial UV-Vis spectrophotometer at the Central Laboratory of Sebelas Maret University (UNS). Linear regression analysis was then applied to the data to obtain the calibration curve's equation and correlation coefficient (R^2). The linearity of the prototype was compared to the commercial spectrophotometer to ensure that the instrument's response was proportional to the concentration of the analyte.

Accuracy tests were performed by measuring the recovery values of standard solutions with known concentrations. The percentage recovery was calculated to determine how close the measured values were to

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the actual values. Recovery values within the range of 90-110% were considered acceptable, indicating that the prototype provided accurate measurements. Precision was assessed by calculating the Relative Standard Deviation (RSD) for repeated measurements of standard solutions. A low RSD (<2%) indicated high precision and repeatability of the instrument.

The LOD and LOQ were determined to establish the prototype's sensitivity. The LOD represents the lowest concentration of an analyte that can be reliably detected, while the LOQ is the lowest concentration that can be quantified with acceptable accuracy and precision. The LOD and LOQ values for the prototype were compared to those of the commercial spectrophotometer to evaluate its performance. The data from the prototype was compared against the commercial UV-Vis spectrophotometer to validate its performance. Differences in absorbance values, accuracy, precision, LOD, and LOQ were analyzed to determine the effectiveness of the portable and inexpensive UV-Vis spectrophotometer in providing reliable and accurate measurements suitable for educational purposes. These analyses ensured that the developed spectrophotometer met the required standards for use as a teaching tool in high school chemistry laboratories, providing a cost-effective and accessible alternative to traditional spectrophotometers.

3. FINDING AND DISCUSSION

Development of Portable and Inexpensive UV-Vis Spectrophotometer Instruments

Components used

The development of a portable and inexpensive UV-Vis spectrophotometer prototype involves essential components such as light sources, monochromators, detectors, and reading systems. **Table 1** presents alternative simple components used in developing the instrument and the rationale behind their selection.

Table 1. The basis for the selection of technologies used in the development prototype

Alternative Components	Function	Reasons for Selection
Light source (Blue LED) (Nandiyanto et al., 2018; Soranut et al., 2016)	It serves to produce light energy with the intensity required in the visible light spectrum.	A yellow solution will absorb blue light well (Kuntzleman, T., Jacobson, 2016)
cuvette (glass cuvette) (Diawati et al., 2017)	Serves as a sample holder	Reusable and inexpensive (Arifah, 2018)
Detector (Sensor Kamera) (Nurrahmawati et al., 2022)	Captures light sensors and is directly connected to the detector	The sensor with high sensitivity can capture light in low lighting conditions. Easy and practical to carry everywhere
Reading System (Spectrophomoter detector application)	Functions for systems that display measurement result data	It can display measurement data up to calibration curves. Available on Play Store
A power source (Lithium Battery)	Electrical energy source	It can charge faster, last longer, and has a higher power density for longer battery life in a lighter package.

Table 1 outlines the various technologies employed in the prototype development. The construction of other instruments has also utilized diverse methods, including alternative LED light sources (Jawad et al., 2021; Kvittingen et al., 2016; Yohan et al., 2018), laser pointers (Hoang et al., 2021), and alternative LDR detectors (O'Donoghue, 2019). Smartphones have been used as detectors (Grasse et al., 2016; Yohan et al., 2018), and alternative LCD reading systems (Jefriyanto et al., 2017) and laptops (Nandiyanto et al., 2019) have also been explored. LEDs are frequently chosen as an alternative light source due to their affordability and availability.

Prototype Frame Design

Figure 2 illustrates the final design of the portable and inexpensive UV-Vis spectrophotometer prototype frame. The design process included several stages: initial design, testing, redesign, and retesting, culminating in the final prototype. The frame was designed using SketchUp, Fusion 360, and Blender software. The frame includes designated spaces for the charging module, battery, and cables. The prototype features two

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covers: a main cover for placing samples and smartphones during measurements and a side cover for battery charging. Inside the instrument, a slit focuses a small part of the light. Smartphone holders and cuvette holders ensure that the cuvette and smartphone remain stationary during measurements, preventing interference with the process.

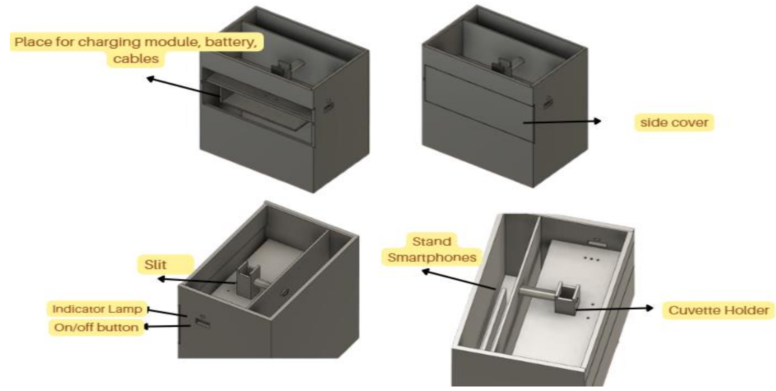

Figure 2. Prototype frame design

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Table 2. Prototype design

Prototype design	Description
Prototype size	15 cm x 10 cm x 20 cm
cuvette holder size	1,5 cm x 1,5 cm x 4,75 cm
Diameter slit	2 cm
Operating voltage	3,7 volt
Voltage current	1 Ampere

Prototype Manufacturing Process

The manufacturing process begins with assembling the prototype body using Polylactic Acid (PLA/PLA+). PLA was chosen for its ease of printing and processing (Setyawan & Ngadiyono, 2022). After selecting the primary materials, the frame design is printed using 3D printing technology. The steps in the prototype manufacturing process are illustrated in **Figure 3.**

Figure 3 outlines the entire manufacturing process, starting with the 3D printing of the instrument design, as shown in **Figure 3a.** The initial print has a rough surface, which requires caulking, sanding, and painting to smoothen the exterior, as depicted **in Figure 3b**. The smoothed prototype sheet in **Figure 3c** is assembled into the desired shape. Following the assembly, the electrical components are installed. This includes the charging modules, 600mAh lithium polymer batteries, switches, and 2mm diameter cables. The switch controls the voltage to the blue LED light source, a 5mm blue LED lamp with a power of 0.5 watts. The operational voltage is 3.7 volts, powered by the battery, with a current of 1A. The electrical installation design process is shown in Figure 3d. The completed prototype, shown in **Figure 3e**, displays the front and side views of the Portable and Inexpensive UV-Vis Spectrophotometer.

The instrument operates by passing monochromatic light from a blue LED light source, with a wavelength range of 402-632 nm, through samples containing substances at specific concentrations (Yohan et al., 2018). The sample absorbs some of this light, while the rest is transmitted. The transmitted light is captured by the smartphone camera sensor, which acts as the detector. The detector measures the received light to determine the absorbed light, which is then processed by the reading system. This operation aligns with the principles of a laboratory UV-Vis spectrophotometer and Lambert-Beer's law. The spectrophotometer application functions as a reading system, displaying measurement results and calibration curves. The measurement results are presented in **Figure 4.**

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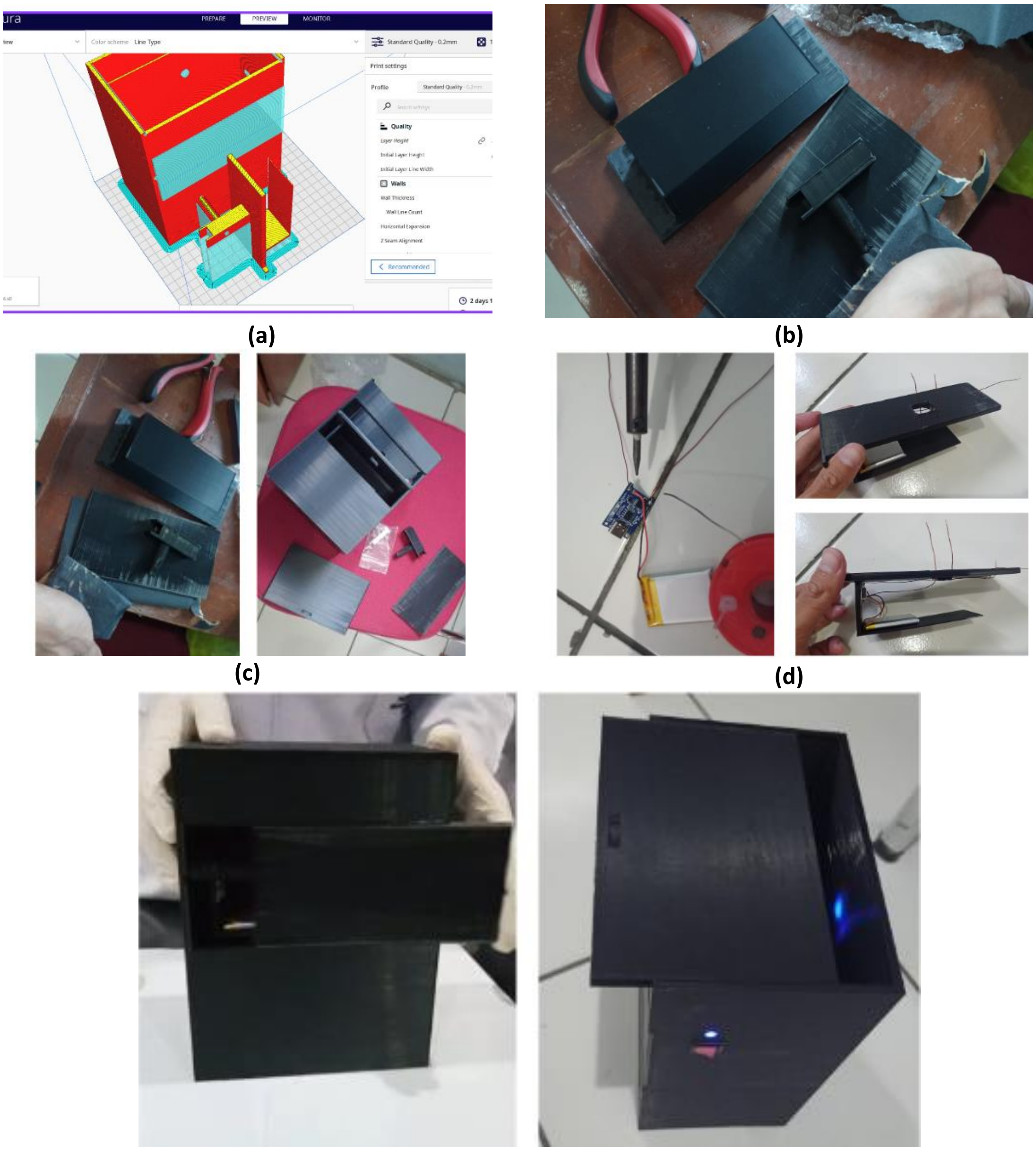

(e)

Figure 3. Prototype Manufacturing Process **(a)** 3D printing; **(b)** Prototype surface caulking and sanding; **(c)** Assembly of 3D printing prototype sheets; **(d)** Design of simple electrical circuits and components; **(e)** Portable and Inexpensive UV-Vis Spectrophotometer Front and Side View

Figure 4 shows the application interface on the spectrophotometer detector. The measurement process begins by entering the sample name and the standard solution in the settings menu. Calibration is performed using an aquifer, followed by measuring the standard and sample solutions in triplicate to obtain absorbance values. At the end of the measurement, a calibration curve with the linear regression equation y = bx + a is generated, from which the sample concentration is determined

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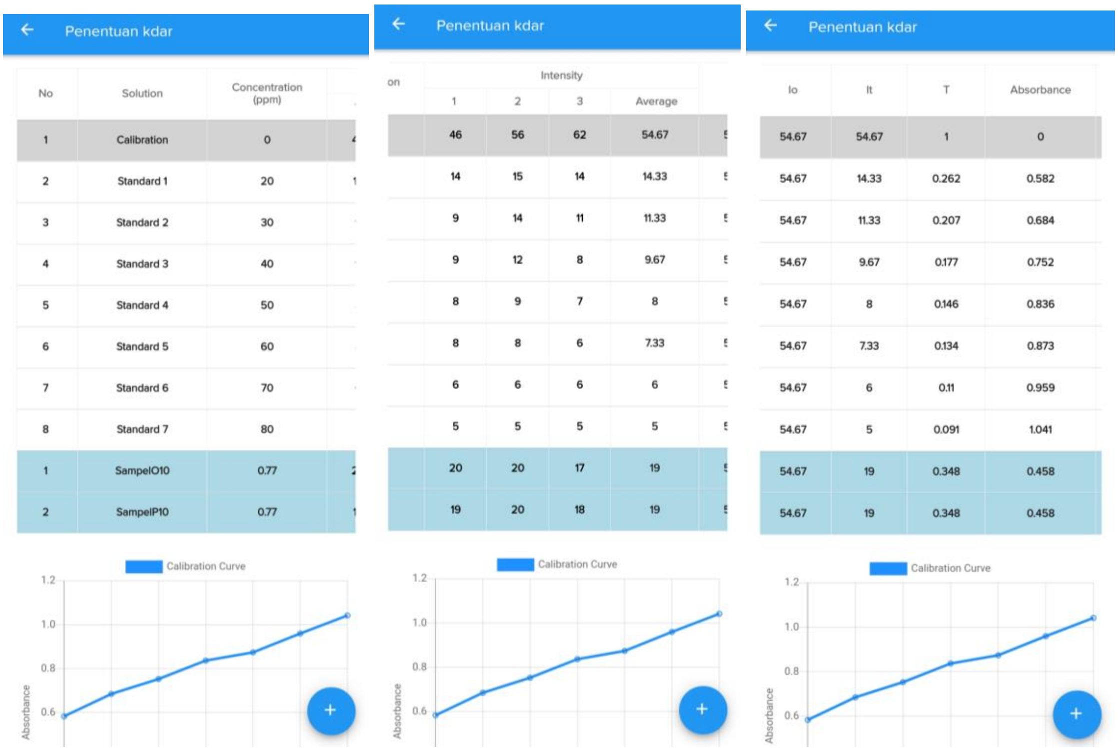

Figure 4. Display of Measurement Results on Spectrophotometer Detector Applications

UV-Vis Spectrophotometer Instruments as a Chemistry Learning Media
Prototype quantitative testing

Table 3. Absorption Value Results

Concentration (ppm)	Absorbance Value	
	Prototype Portable and Inexpensive UV-Vis Spectrophomoter	Central Laboratory UV-Vis Spectrophotometer
20	0,582	0,793
30	0,684	1,193
40	0,752	1,607
50	0,836	1,985
60	0,873	2,355
70	0,959	2,666
80	1,041	3,079

Table 3 compares absorbance values at concentrations of 20 ppm to 80 ppm measured using the Prototype Portable and Inexpensive UV-Vis Spectrophotometer and the UNS Central Laboratory UV-Vis Spectrophotometer. The results of measuring the absorbance value in the standard solution using the developed prototype obtained the linear regression equation y=0.0073x+0.4524 with R^2=0.9922. Meanwhile, the laboratory UV-Vis spectrophotometer obtained a linear equation of y=0.0377x+0.0697 with R^2=0.9987. The correlation coefficient close to 1 indicates strong linearity between variables. Measurements using laboratory UV-Vis spectrophotometers obtained higher results than the developed prototypes because UV-Vis spectrophotometers are more sensitive and accurate, resulting in a higher correlation coefficient. Despite this, the correlation coefficient of both instruments shows good linearity with $R^2 \geq 0.99$ (Ngibad, 2019).

Table 4 compares % recovery values at concentrations of 20 ppm to 80 ppm measured using the Prototype Portable and Inexpensive UV-Vis Spectrophotometer and the UNS Central Laboratory UV-Vis Spectrophotometer at a wavelength of 425 nm. Accuracy is a measure showing the proximity between the measured results and the actual values (Syahriana et al., 2019). A method is considered valid if the % recovery

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value of a sample falls between 90-110% (Mariana et al., 2018). Based on the results, both instruments achieved % recovery values within the acceptance range, indicating good accuracy for the developed prototype. A previous study by Yohan et al. (2018) reported an accuracy value of 87.75%, meaning the new prototype demonstrates better accuracy than previous developments.

Table 4. Accuracy Test Results

Concentration (ppm)	**% recovery value (%)**	
	Prototype Portable and Inexpensive UV-Vis Spectrophomoter	**UNS Central Laboratory UV-Vis Spectrophotometer**
20	88,76	99,93
30	105,75	99,32
40	102,6	101,2
50	105,1	101,6
60	96,03	101,03
70	99,14	98,38
80	100,79	99,78

Table 5. Precision Test Results

Concentration (ppm)	**RSD % Value**	
	Prototype Portable and Inexpensive UV-Vis Spectrophomoter	**UNS Central Laboratory UV-Vis Spectrophotometer**
20	1,22	2,09
30	1,11	1,84
40	1,03	1,59

Table 5 shows the comparison of % RSD values at concentrations of 20, 30, and 40 ppm measured using the Prototype Portable and Inexpensive UV-Vis Spectrophotometer and the UNS Central Laboratory UV-Vis Spectrophotometer at a wavelength of 425 nm. A lower % RSD indicates higher accuracy. Precision is considered good if % RSD is below 2% (Mariana, 2018). Based on the measurements, % RSD values were all below 2%, indicating good repeatability and meeting acceptance criteria.

Table 6. LOD and LOQ Test Results

	Prototype Portable and Inexpensive UV-Vis Spectrophomoter	**UNS Central Laboratory UV-Vis Spectrophotometer**
LOD	0,43 ppm	2,56 ppm
LOQ	20,997 ppm	8,54 ppm

Table 6 compares the LOD and LOQ values measured using the Prototype Portable and Inexpensive UV-Vis Spectrophotometer and the UNS Central Laboratory UV-Vis Spectrophotometer. The prototype demonstrated a sample detection limit (LOD) of 0.43 ppm and a quantization limit (LOQ) of 20.99 ppm. This indicates that the smallest amount of analyte detectable with a significant response compared to blanks on the prototype spectrophotometer is 0.43 ppm (Romadhani, 2017). Conversely, the smallest quantity of analytes in the sample that can be reliably quantified using the prototype is 20.99 ppm. Measurements with concentrations below 0.43 ppm tend to be unstable.

Table 6 highlights that the LOD and LOQ values of the Portable and Inexpensive UV-Vis Spectrophotometer prototype differ from those of the UV-Vis spectrophotometer in the UNS laboratory. The laboratory spectrophotometer exhibits higher sensitivity in sample detection. The prototype tends to become unstable when absorbing samples with very high concentrations, resulting in higher LOD and LOQ values. In contrast, the LOD and LOQ values using the laboratory UV-Vis spectrophotometer are below 10 ppm, reflecting its superior sensitivity and stability in detecting low-concentration samples.

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Table 7. Results of Sample Rate Determination

	Sample A	Sample B
Prototype Portable and Inexpensive UV-Vis Spectrophomoter	0,77 ppm	0,77 ppm
UNS Central Laboratory UV-Vis Spectrophotometer	0,56 ppm	0,27 ppm

Table 7 shows a significant difference in test results between the Portable and Inexpensive UV-Vis Spectrophotometer and the commercial UV-Vis Spectrophotometer. Developing this spectrophotometer instrument also integrates the STEM approach, emphasizing the engineering field through a project. By designing the portable and inexpensive UV-Vis Spectrophotometer, students can evaluate its parts, understand its operation, and use it as a medium for learning chemistry in the classroom (Shidiq et al., 2020a).

Testing The Effectiveness of Prototypes as a Learning Media

After obtaining promising results in the initial trials, the portable and inexpensive UV-Vis Spectrophotometer was tested as a medium for learning chemistry in the classroom. The effectiveness test involved a questionnaire with 30 statements, each having five response options: strongly agree, agree, moderately agree, disagree, and strongly disagree. The test aimed to measure the instrument's effectiveness in enhancing student understanding and its usability as a learning media.

The study involved 23 high school students from the same grade level. Results showed that using the portable and inexpensive UV-Vis Spectrophotometer significantly increased students' understanding of stoichiometry by 89.217%. Additionally, students responded positively to the prototype, with an effectiveness rating of 89.681%. The application of this spectrophotometer effectively improved students' comprehension of chemical concepts. The use of such instruments helps students grasp relevant scientific and mathematical ideas within a technical or technological framework, allowing them to connect and refine these concepts in a practical and scientific manner (Shidiq et al., 2021). Previous research by Albert et al. (2012) designed a visible light absorption spectrophotometer using LEGO to teach high school chemistry and physics. However, the LEGO-based spectrophotometer had limitations, including fragility and manual measurement processes. The portable and inexpensive UV-Vis Spectrophotometer offers a solution with several advantages.

The innovative instrument provides affordability, portability, and easy integration with smartphone technology, making it highly accessible for high school chemistry education. Its affordability means more schools, especially those with limited budgets, can acquire and use this tool, democratizing access to advanced scientific equipment. Portability allows the spectrophotometer to be easily transported and used in various settings, whether in the classroom, laboratory, or on field trips, enriching the learning experience by offering hands-on opportunities in diverse environments. Integration with smartphones leverages a device most students already have, reducing the need for additional costly equipment and simplifying data collection and analysis.

The research has limitations. One significant limitation is the need for repeated testing with various samples to ensure the spectrophotometer's reliability and accuracy across different experimental conditions and chemical substances. Another limitation is the relatively small sample size used in the study. Implementing the tool among a larger and more diverse student population would provide more comprehensive data on its effectiveness and usability. Teachers are encouraged to consider this tool as an alternative learning medium due to its potential to make complex chemical concepts more tangible and understandable. Further extensive testing is necessary to validate the instrument's accuracy and reliability. Broader implementation in various schools would provide more detailed data on its effectiveness and usability, refining the tool and potentially leading to widespread adoption, thus significantly enhancing chemistry education.

4. CONCLUSION

Developing and implementing a portable and inexpensive UV-Vis spectrophotometer effectively addresses the limitations of traditional, high-cost instruments. This innovation utilizes blue LEDs as light sources, lithium batteries, glass cuvettes, and a spectrophotometer detector application, combining unique and accessible components. Integrating smartphones as detectors and data readers makes the instrument user-friendly and comprehensible for students. Balancing accuracy, simplicity, and cost reduction is crucial in educational contexts. The UV-Vis spectrophotometer developed in this study provides quantitatively acceptable

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results while adhering to basic scientific principles. It meets the working principles of laboratory UV-Vis spectrophotometers and follows Lambert-Beer's law. Effectiveness tests in classroom settings demonstrated that this spectrophotometer significantly improves students' understanding of stoichiometry. This confirms that a simple, portable, and inexpensive spectrophotometer can be effectively used and developed as a learning medium at the high school level, offering a practical and accessible solution to enhance chemistry education.

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