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# Promoting Quantitative Analysis in School Chemistry with Technology-Supported Hands-On Laboratory Learning: A Case of Arduino-Based Portable Spectrophotometer

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**Abstract:** This study addresses the need for practical and affordable tools in high school chemistry education, specifically focusing on the development of a simple, portable spectrophotometer. Current educational resources often fall short in providing students with hands-on experience that effectively connects theoretical concepts with real-world applications. The aim of this research is to design and evaluate a cost-effective spectrophotometer for analyzing dye concentrations in beverages, which also serves as a practical tool for teaching chemistry. The methodology includes designing the spectrophotometer with a 5 mm blue LED and an Arduino microcontroller, followed by testing the measurement results of the developed instrument. The instrument's accuracy and precision are assessed by comparing its results with those from standard UV-Vis spectrophotometers. Findings demonstrate that the spectrophotometer achieves an accuracy range of 94-107% and meets precision criteria with %RSD values below 2%. The expected contribution includes offering an accessible tool that enhances student engagement and understanding through a proposed activity involving hypothesis testing and data analysis, thereby integrating scientific argumentation, hands-on activity, and quantification into the learning process.

**Keywords:** Arduino Uno, Blue LED, Learning Media, Tartrazine, UV-Vis Spectrophotometer.

## 1. Introduction

Spectrophotometers have become essential tools in various laboratory experimental setups at universities, schools, and industries. They are particularly utilized in physics and chemistry for analyzing substances by measuring their light transmission or absorption in relation to concentration (Shidiq et al., 2022). UV-Vis spectrophotometers are versatile, allowing for qualitative analysis by determining a sample's maximum absorption wavelength and quantitative analysis by measuring its absorbance. However, with prices ranging from $3,000 to over $20,000, spectrophotometers present a significant financial challenge for schools and universities. Consequently, research focused on developing simple, portable, and affordable chemical analysis tools has become increasingly critical (Nandiyanto et al., 2019; Shidiq et al., 2020a).

Modifications to spectrophotometer instruments have been explored in previous studies, showcasing innovative approaches such as using LEDs as light sources and detectors. For example, photometers with USB data acquisition modules have utilized LEDs for these purposes (Algar et al., 2016; Wang et al., 2016). Similarly, the development of LEGO-based spectrophotometers has employed UV-emitting LEDs for absorbance measurements in the UV range (Kvittingen et al., 2016). The use of Arduino Uno as a detector is another promising development, valued for its straightforward programming system (Grinias et al., 2016; Nhivekar et al., 2022; Sukmafitri et al., 2019). However, while these advancements are significant, there is a notable gap in demonstrating how simple Arduino-based spectrophotometers can be effectively integrated into students' daily lives and hands-on laboratory activities (Shidiq et al., 2020b, 2021). This gap highlights the need not only for affordable and straightforward spectrophotometers but also for practical laboratory contexts that resonate with students' everyday experiences. This study aims to develop an Arduino-based portable spectrophotometer designed to support technology-supported hands-on laboratory learning in school chemistry. By addressing this gap, the study seeks to create a tool that is both cost-effective and closely connected to students' daily activities, enhancing their engagement and practical understanding of chemistry.

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## 2. Method

### *2.1 Method of pilot study*

This study aims to develop and evaluate an Arduino-based portable spectrophotometer to support technology-supported hands-on laboratory learning in school chemistry. Initially, the effectiveness of the tool for accurate measurement will be assessed. Following this, the spectrophotometer will be used in educational settings to enhance hands-on laboratory experiences. The focus is on creating a cost-effective and user-friendly tool that can be integrated into students' everyday activities to address the existing gap in practical applications. For the piloting study, tetrazine dye is selected as the context for a food chemical commonly consumed by students. This choice reflects the widespread availability of tetrazine-containing beverages in schools, aiming to help students understand the relevance and significance of chemistry in their daily lives. It is expected that the findings will provide valuable insights into how this simple spectrophotometer can improve student engagement with laboratory activities and enhance practical understanding of chemistry.

### *2.2 Design*

The instrument design, shown in Figures 1 and 2, features dimensions of 18 cm x 11 cm x 6 cm and employs a single-beam system to measure the absorbance of solutions. It operates at 5 volts with a current of 1 ampere, utilizing a 5 mm blue Light Emitting Diode (LED) with a power of 0.5 watts as the light source. The system includes two low-cost blue LEDs: one serves as an indicator light connected to the analog output channel, and the other as the light source. Light is detected by a 5 mm Light Dependent Resistor (LDR) mounted on the cuvette holder.

The connecting cables are 28 AWG jumper cables with a diameter of 2 mm. The detector is an Arduino Uno R3 microcontroller, based on the ATMega328 datasheet, which operates at 5 volts with a current of 1 ampere. The device features a switch for power control during data acquisition, eliminating the need for a laptop for display. A 600 mAh lithium polymer battery, rechargeable via a built-in charging module, powers the instrument. Additionally, data can be displayed on a 0.91-inch OLED screen as an alternative to Microsoft Excel on a laptop. The laptop display is presented in Figure 3.

The design adheres to the principles of laboratory UV-Vis spectrophotometers and the Lambert-Beer law. Monochromatic light from the blue LED, with a wavelength range of 402-632 nm, passes through a sample at a specific concentration. Some light is absorbed, while the remainder transmits through the sample. The transmitted light is captured by the LDR and processed by the Arduino Uno R3 to determine the substance's concentration. The total development cost of the spectrophotometer is \$60, reflecting its aim to be an affordable, easy-to-use, and practical tool

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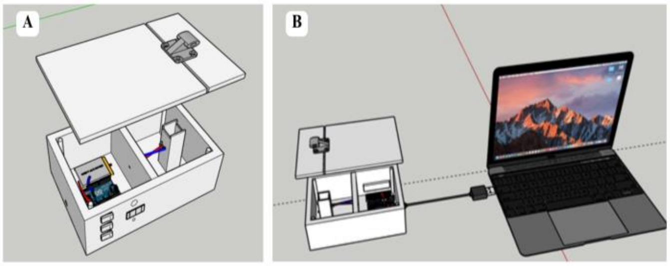


*Figure 1*. (A) Close-up view of the instrument frame design (B) Distant view of the instrument frame design

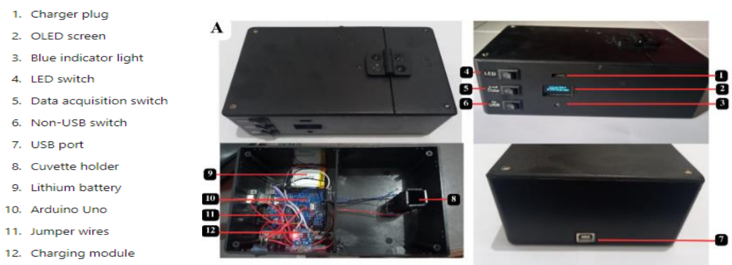


*Figure 2.* (A) Simple Spectrophotometer Instrument Side and Top View

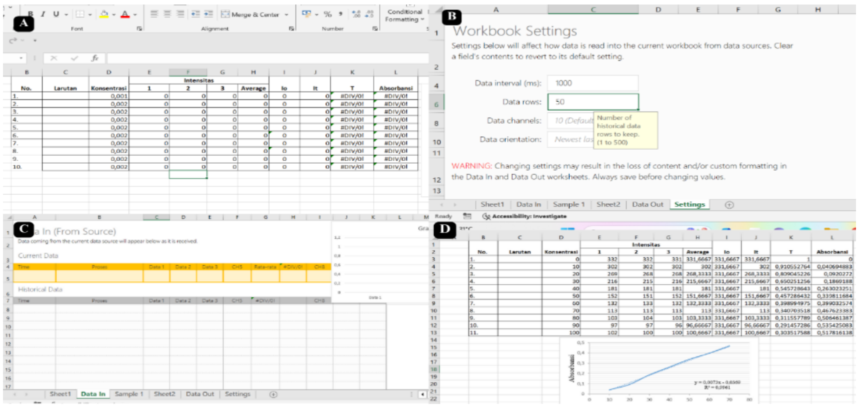


*Figure 3.* (A) Initial Display Before Measurement (B) Settings Screen (C) "Data In" Screen (D) Post-Measurement Display

### *2.3 Data analysis*

The effectiveness of the simple spectrophotometer will be analyzed through laboratory tests. Measurement results of tetrazine samples obtained with the simple spectrophotometer will be compared against standard measurements from UV-Vis spectrophotometers in three different laboratories. The accuracy and precision of the simple spectrophotometer will be calculated based on these comparisons.

## 3. Results and Discussions

### *3.1 The linearity, accuracy, and precision*

The measurement results for concentrations ranging from 10-60 ppm, as shown in Table 1, indicate that the simple spectrophotometer instrument provides good measurement results. The calibration curve graph shows that the increase in concentration is directly proportional to the increase in absorbance. This is consistent with Lambert-Beer's law, which states that absorbance is directly proportional to concentration (Kuntzleman & Jacobson, 2016). The simple spectrophotometer instrument measurement produced the regression equation $y = 0.0074x - 0.0323$, with an $R^2$ value of 0.9944 as shown in Figure 3C. This equation can be used to determine the concentration of each sample. The larger the correlation coefficient, the higher the linearity of the results, indicating that the working conditions align with Lambert-Beer's law (Surbakti et al., 2022). Good linearity is achieved when $R^2 \geq 0.99$. The standard solution used is shown in Figure 4.

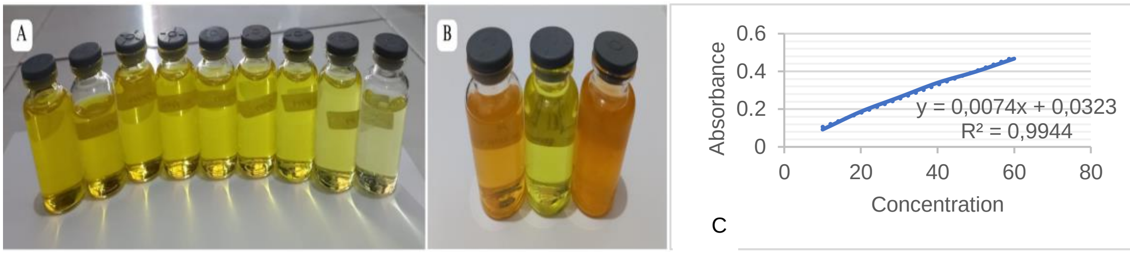


*Figure 4.* (A) Standard tartrazine solution (B) Sample solutions from 3 different brands of beverages (C) Graph of the Relationship between Absorbance and Concentration of Standard Tartrazine Solution

Table 1. *Measurement results*

| No. | Solution | [M] | Intensity | | | | $I_o$ | $I_t$ | T | Abs |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | Average | | | | |
| 1. | Blank | 0 | 332 | 332 | 331 | 331,67 | 331,67 | 331,67 | 1 | 0 |
| 2. | Standard1 | 10 | 269 | 268 | 268 | 268,33 | 331,67 | 268,33 | 0,81 | 0,092 |
| 3. | Standard2 | 20 | 216 | 215 | 216 | 215,67 | 331,67 | 215,67 | 0,65 | 0,187 |
| 4. | Standard3 | 30 | 181 | 181 | 181 | 181 | 331,67 | 181 | 0,54 | 0,263 |
| 5. | Standard4 | 40 | 152 | 151 | 152 | 151,67 | 331,67 | 151,67 | 0,46 | 0,340 |
| 6. | Standard5 | 50 | 132 | 133 | 132 | 132,33 | 331,67 | 132,33 | 0,40 | 0,399 |
| 7. | Standard6 | 60 | 113 | 113 | 113 | 113 | 331,67 | 113 | 0,341 | 0,468 |
| 8. | Sample A | - | 271 | 272 | 271 | 271,33 | 341 | 271,33 | 0,79 | 0,099 |
| 9. | Sample B | - | 220 | 219 | 219 | 219,33 | 340 | 219,33 | 0,64 | 0,190 |
| 10. | Sample C | - | 215 | 215 | 214 | 214,67 | 345,67 | 214,67 | 0,62 | 0,207 |

The percentage recovery of the developed instrument ranges between 94% and 107%, which indicates its accuracy in measuring sample concentrations. Accuracy is determined by how closely the results from the UV-Vis spectrophotometer match the actual content across different laboratories, with a method considered valid if the percentage recovery falls within the 90-110% range (Mariana et al., 2018). For context, a previously developed educational spectrophotometer for analyzing food colorant compounds achieved an accuracy of 87.75%, while another study reported an accuracy of 95.35%. The percentage recovery values obtained with the developed instrument are comparable to those found in prior research on simple spectrophotometer development. Moreover, the developed instrument adheres to the working principles of laboratory UV-Vis spectrophotometers and complies with Lambert-Beer's law. Precision is also crucial, and good precision is indicated when the % relative standard deviation (%RSD) meets the acceptance criteria of %RSD < 2% (Surbakti et al., 2022). The %RSD for the developed instrument meets these requirements, with values of 0.93%, 0.6%, and 0% for each sample. This demonstrates that the developed measurements have good repeatability and meet the precision-acceptance criteria.

### *3.2 The Learning Design Using Simple Spectrophotometer Instrument*

Integrating tools like simple spectrophotometers into school chemistry curricula significantly advances hands-on, inquiry-based learning. This tool can perform quantitative analyses and illustrate fundamental principles such as Lambert-Beer's law, providing an effective bridge between theoretical knowledge and practical application (Shidiq et al., 2022; Carter et al., 2017). Previous studies highlight the value of simple spectrophotometers in education. For instance, Kuntzleman & Jacobson (2016) and Albert et al. (2012) demonstrate how such tools can make complex analytical techniques accessible, even in resource-limited settings. Wang et al. (2021) and Grasse et al. (2015) emphasize the educational benefits of hands-on spectrophotometry, enhancing students' understanding of key concepts through practical experimentation.

The developed instrument stands out by focusing on detecting tartrazine in beverages, allowing students to engage with real-world chemical analysis. This practical application supports stoichiometry and green chemistry lessons, fostering a deeper understanding of chemical processes. In high school settings with limited resources, this instrument offers a cost-effective solution that aligns with educational standards and enhances learning by involving students in meaningful scientific investigations

The proposed learning activity for teaching stoichiometry using the developed simple spectrophotometer integrates real-world applications to enhance students' understanding of chemical concepts. This hands-on laboratory activity is designed to engage students in a multi-step investigative process, focusing on analyzing yellow-colored beverages and their potential dye content. In the initial phase, students are introduced to the issue of beverages containing colorants and the potential health effects of excessive dye consumption. This contextual problem sets the stage for the activity, allowing students to explore the relevance of chemistry in everyday life. Following this introduction, students investigate their surroundings to identify yellow-colored drinks and assess the likelihood of excessive dye usage.

In the subsequent phase, students design and conduct an experiment using the simple spectrophotometer to test their hypotheses about the beverages. This stage emphasizes the development of scientific arguments, where students use the spectrophotometer to measure and quantify dye concentrations in the selected samples. By comparing their measurements across multiple data points, students evaluate the precision of their results.

The final phase involves analyzing the collected data and interpreting the results regarding the claims, evidence, and reasoning (Heng et al., 2015; Walker et al., 2019). Students must argue their findings based on the experimental data, demonstrating their understanding of stoichiometry and quantitative analysis. This approach not only reinforces the concepts of contextualization and scientific argumentation but also fosters data analysis and experimental design skills. Overall, this proposed activity provides a comprehensive framework for teaching stoichiometry, combining theoretical knowledge with practical, hands-on experience to enhance students' learning outcomes.

## 4. Conclusion

The development of the simple spectrophotometer and its proposed integration into high school chemistry curricula presents a significant advancement in educational practice. By utilizing the instrument to analyze dye concentrations in beverages, students engage in a hands-on activity that enhances their understanding of stoichiometry, scientific argumentation, and experimental design. The spectrophotometer's accuracy and precision, validated through rigorous testing, ensure its reliability for educational use. This approach not only bridges the gap between theoretical concepts and practical applications but also fosters argumentation skills and contextual learning. Future research should focus on implementing and evaluating this tool in real classroom settings to assess its impact on student learning outcomes and engagement fully.

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## References

Algar, W. R., De Jong, C. A. G., Maxwell, E. J., & Atkins, C. G. (2016). Demonstration of the Spectrophotometric Complementary Color Wheel Using LEDs and Indicator Dyes. *Journal of Chemical Education*, *93*(1), 162–165. https://doi.org/10.1021/acs.jchemed.5b00665

Grinias, J. P., Whitfield, J. T., Guetschow, E. D., & Kennedy, R. T. (2016). An inexpensive, open-source USB Arduino data acquisition device for chemical instrumentation. *Journal of Chemical Education*, *93*(7), 1316–1319. https://doi.org/10.1021/acs.jchemed.6b00262

Heng, L. L., Surif, J., Seng, C. H., & Ibrahim, N. H. (2015). Mastery of scientific argumentation on the concept of neutralization in chemistry: A Malaysian perspective. *Malaysian Journal of Learning and Instruction*, *12*(1), 85–101. https://doi.org/10.32890/mjli2015.12.5

Kuntzleman, T. S., & Jacobson, E. C. (2016). Teaching Beer's Law and absorption spectrophotometry with a smart phone: A substantially simplified protocol. *Journal of Chemical Education*, *93*(7), 1249–1252. https://doi.org/10.1021/acs.jchemed.5b00844

Kvittingen, E. V., Kvittingen, L., Sjursnes, B. J., & Verley, R. (2016). Simple and Inexpensive UV-Photometer Using LEDs as Both Light Source and Detector. *Journal of Chemical Education*, *93*(10), 1814–1817. https://doi.org/10.1021/acs.jchemed.6b00156

Mariana, E., Cahyono, E., Rahayu, E. F., & Nurcahyo, B. (2018). Validasi Metode Penetapan Kuantitatif Metanol dalam Urin Menggunakan Gas Chromatography-Flame Ionization Detector. *Indonesian Journal of Chemical Science*, *7*(3), 277–284.

Nandiyanto, A. B. D., Ragadhita, R., Abdullah, A. G., Triawan, F., Sunnardianto, G. K., & Aziz, M. (2019). Techno-Economic Feasibility Study of Low-Cost and Portable Home-Made Spectrophotometer for Analyzing Solution Concentration. *Journal of Engineering Science and Technology*, *14*(2), 599–609.

Nhivekar, G. S., Jagdale, S. R., Kamble, S. B., Jadhav, B. T., Kamat, R. K., & Dongale, T. D. (2022). Versatile Three-in-One Single Beam Visible Colorimeter for Undergraduate Chemistry Laboratories. *Journal of Chemical Education*, *99*(11), 3765–3772. https://doi.org/10.1021/acs.jchemed.2c00372

Shidiq, A. S., Permanasari, A., & Hernani, H. (2020a). Pre-Service and In-Service Chemistry Teachers' Views on Teaching Spectrometry in Senior High School. *Journal of Engineering Science and Technology Special Issue on AASEC2019*, *AASEC(2019)*, 80.

Shidiq, A. S., Permanasari, A., & Hernani, H. (2020b). Simple, Portable, and Inexpensive Spectrophotometers for High Schools Lab Activity. *Advances in Social Science, Education and Humanities Research (ASSEHR)*, *438*(Aes 2019), 150–154. https://doi.org/https://doi.org/10.2991/assehr.k.200513.034

Shidiq, A. S., Permanasari, A., Hernani, H., & Hendayana, S. (2021). The use of simple spectrophotometer in STEM education: A bibliometric analysis. *Moroccan Journal of Chemistry*, *9*(2), 290–300. https://doi.org/10.48317/IMIST.PRSM/morjchem-v9i2.27581

Shidiq, A. S., Permanasari, A., Hernani, H., & Hendayana, S. (2022). Contemporary Hybrid Laboratory Pedagogy : Construction of a Simple Spectrophotometer with STEM Project-Based Learning to Introduce Systems Thinking Skills. *Asia Pacific Journal of Educators and Education*, *37*(2), 107–146.

Sukmafitri, A., Bayu, A., Nandiyanto, D., Oktiani, R., Ragadhita, R., & Abdullah, A. G. (2019). Temperature on the Effectiveness of Arduino-Based Portable Spectrophotometer With White Light-Emitting Diode (LED) As a Light Source for Analyzing Solution Concentration. *Journal of Engineering Science and Technology*, *14*(3), 1653–1661.

Surbakti, M. S., Farhan, M., Zakaria, Z., Isa, M., Sufriadi, E., Alva, S., Yusibani, E., Heliawati, L., Iqhrammullah, M., & Suhud, K. (2022). Development of Arduino Uno-Based TCS3200 Color Sensor and Its Application on the Determination of Rhodamine B Level in Syrup. *Indonesian Journal of Chemistry*, *22*(3), 630–640. https://doi.org/10.22146/ijc.69214

Walker, J. P., Van Duzor, A. G., & Lower, M. A. (2019). Facilitating Argumentation in the Laboratory: The Challenges of Claim Change and Justification by Theory. *Journal of Chemical Education*, *96*(3), 435–444. https://doi.org/10.1021/acs.jchemed.8b00745

Wang, J. J., Rodríguez Núñez, J. R., Maxwell, E. J., & Algar, W. R. (2016). Build Your Own Photometer: A Guided-Inquiry Experiment to Introduce Analytical Instrumentation. *Journal of Chemical Education*, *93*(1), 166–171. https://doi.org/10.1021/acs.jchemed.5b00426