UFSM

CIÊNCIA e NATURA

ISSN 2179-460X
OPEN ACCESS

Ci. e Nat., Santa Maria, v. 48, e93058, 2026 • https://doi.org/10.5902/2179460X93058
Submitted: 07/30/2025 • Approved: 07/16/2026 • Published: 11/12/2026

Chemistry

Development of a spectrophotometer employing Arduino microcontroller for educational purposes

Desenvolvimento de um espectrofotômetro usando microcontrolador Arduino para fins educacionais

Alexandre Kevin Rodrigues Diniz[I], **Quedyane Silva da Cruz**[II], **Leonardo Tadeu Boaes Mendonça**[I]

[I] Universidade Federal do Maranhão, São Luís, MA, Brazil
[II] Universidade Federal de Pernambuco, Recife, PE, Brazil

ABSTRACT

In the academic context, didactic tools aim to promote active learning by enhancing interaction between students and educators. Therefore, the primary objective of this work was to develop a low-cost spectrophotometer based on an Arduino microcontroller for educational purposes, aiming to overcome limitations associated with commercial equipment, namely high cost and complexity. The prototype employed a green LED (525 nm), a BPW34 photodiode, and a transimpedance amplifier (TIA) to measure the absorbance of potassium permanganate solutions. Methodologically, standard dilutions were analyzed, and results were compared with those obtained from a commercial spectrophotometer (Spectronic 200). The data demonstrated a correlation coefficient ($R^2 = 0.9629$) for the prototype, validating it for instructional use, despite the influence of noise and low light intensity on measurement accuracy. It was concluded that the device is suitable for illustrating concepts such as Lambert-Beer's Law in hands-on laboratory settings, fostering active learning through accessible technologies in science education. Similar studies corroborate its potential, highlighting applications in chemical analysis and education.

Keywords: Spectrophotometer; Arduino; TIA; Education

RESUMO

No meio acadêmico, ferramentas didáticas têm o objetivo de estimular aprendizagem ativa, melhorando a interação entre alunos e professores. Desta forma, o principal objetivo deste trabalho consistiu em desenvolver um espectrofotômetro de baixo custo a partir de microcontrolador Arduino para fins educacionais, visando superar limitações de equipamentos comerciais (alto custo e complexidade). O protótipo utilizou um LED verde (525 nm), fotodiodo BPW34 e amplificador transimpedância (TIA) para medir a absorbância de soluções

Published by Ciência e Natura under a CC BY-NC-SA 4.0 license.

de permanganato de potássio. Metodologicamente, diluições padrão foram analisadas comparando os resultados com um espectrofotômetro comercial (Spectronic 200). Os dados mostraram correlação (R^2 = 0,9629) para o protótipo, validando o mesmo para ensino, apesar de ruídos e baixa intensidade luminosa afetarem a precisão. Concluiu-se que o dispositivo é viável para ilustrar conceitos como a Lei de Lambert-Beer em aulas práticas, promovendo aprendizado ativo com tecnologias acessíveis. Trabalhos similares corroboraram seu potencial, destacando aplicações em análises químicas e educação.

Palavras-chave: Espectrofotômetro; Arduino; TIA; Educação

1 INTRODUCTION

Spectrophotometry is one of the instrumental analytical techniques capable of measuring the concentrations of chemical species based on the attenuation of light absorbed by them. This interaction follows Lambert-Beer's law, which depends on the optical path length, molar absorptivity coefficient, and the concentration of molecules absorbing at a specific wavelength (Skoog et al., 2017). This technique enables analyses such as quality control of pharmaceutical products, monitoring compounds such as tartrazine, formaldehyde, and borax in food, to prevent public health risks, among other applications (Özgül Artuç, 2020; Sahraei et al., 2013; Syafriani et al., 2024).

Despite the advantages over other instrumental methods such as broad applicability, simplicity, and low operational cost, these equipment are expensive, which hampers their acquisition in university laboratories and directly impacts practical teaching activities due to equipment shortages (Kolesnichenko et al., 2023; Mitsioni et al., 2023). According to Schnider and Hömöstrei (2023), methodologies based on experimental practice and the use of digital technologies, such as microcontrollers for prototyping, significantly enhance learning outcomes, as students construct knowledge through hands-on experiences mediated by real or simulated situations.

In educational and university settings, experimental classes hold great potential to stimulate student learning by transforming them into active agents in the learning process. Consequently, this approach effectively contributes to understanding the content covered in class. It is important to highlight that any environment, including

classrooms, can be suitable for experimental activities, not solely formal environments like laboratories (Ustra & Boaventura, 2018). In addition to infrastructure, investing in educator training is essential, ensuring they do not merely follow a fixed experimental protocol but instead encourage students to question, choose pathways, and fully explore the potential that experimentation offers (Soares et al., 2017).

Given the challenges mentioned, especially the scarcity of well-equipped laboratories and the limited appeal of traditional methodologies, the use of accessible technologies such as Arduino has emerged as a promising solution. Arduino is a low-cost, open-source, and versatile platform for electronic prototyping that allows the construction of scientific instruments, including measurement systems and automated devices. Its application in educational environments stimulates creativity, promotes active learning, and fosters the development of investigative skills, making the teaching process more dynamic and meaningful (Moreira et al., 2018; Schnider & Hömöstrei, 2023; Zadorozhnii, 2024).

Furthermore, the increasing academic production related to the use of Arduino in teaching Physics, Chemistry, and other natural sciences confirms its pedagogical potential. Studies show that activities mediated by this technology significantly increase student engagement and motivation, providing practical experiences that integrate theory and practice (Chitolina & Santos, 2024; Araújo, 2024). Consequently, microcontrollers like Arduino have been foundational in developing low-cost spectrophotometer prototypes for various applications, contributing to the creation of alternative methodologies with portable equipment capable of rapid field monitoring, an advantage over traditional laboratory techniques that often involve expensive, bulky, and difficult-to-use equipment in the field (Debarshi & Khan, 2019; Halim et al., 2023). Kittipanyangam et al. (2016) highlights that many features of commercial spectrophotometers can be omitted when developing prototypes for educational purposes, reducing costs and unnecessary complexity.

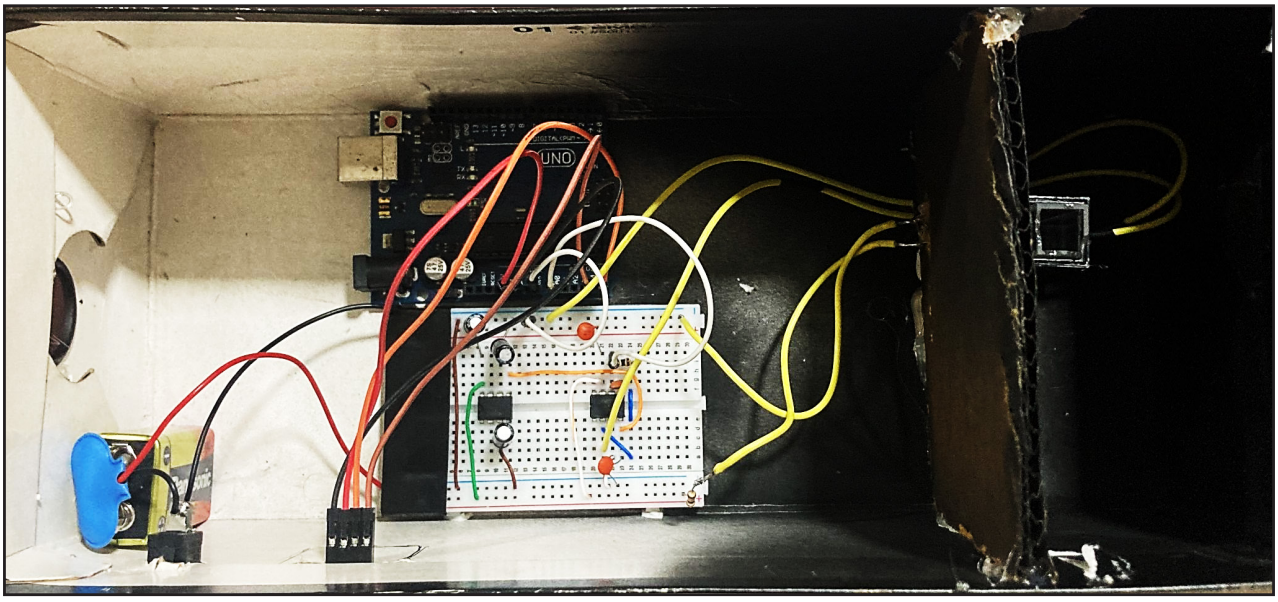
Therefore, developing a spectrophotometer as an educational tool adds more value through its classroom application, enhancing understanding of practical concepts related to quality analysis, process control, and substance monitoring across different matrices,

bringing students closer to real laboratory and industrial contexts. The objectives of this work were: i) to design a closed, internally black-colored structure encasing the electronic components along with the analysis mechanisms: sample holder, LED, and optical sensor; ii) to record transmittance through diluted potassium permanganate solutions; and iii) to compare absorbance values obtained from each diluted solution using the prototype with those from a commercial spectrophotometer, and to construct a calibration curve.

2 METHODOLOGY

The spectrophotometer prototype was constructed within an enclosure approximately 11 × 28 × 9 cm in size, divided into two sections as illustrated in Figure 1. Approximately 30% of the volume was dedicated to the analysis compartment, with the remaining space allocated for electronic components. The analysis compartment was painted with black color to minimize interference caused by light reflection (Agilent, 2021, p. 11; Nandiyanto et al., 2018). A square cuvette holder was made by a 3D-printer using Polylactic Acid (PLA) as a 3D printing material, designed to position a standard cuvette between the light source and detector, ensuring proper alignment along the light path. It was also coated with black color and its internal dimension was 13.7 x 13.7 x 30 mm.

Figure 1 – Internal design schematic of the Arduino based spectrophotometer



Source: Authors (2025)

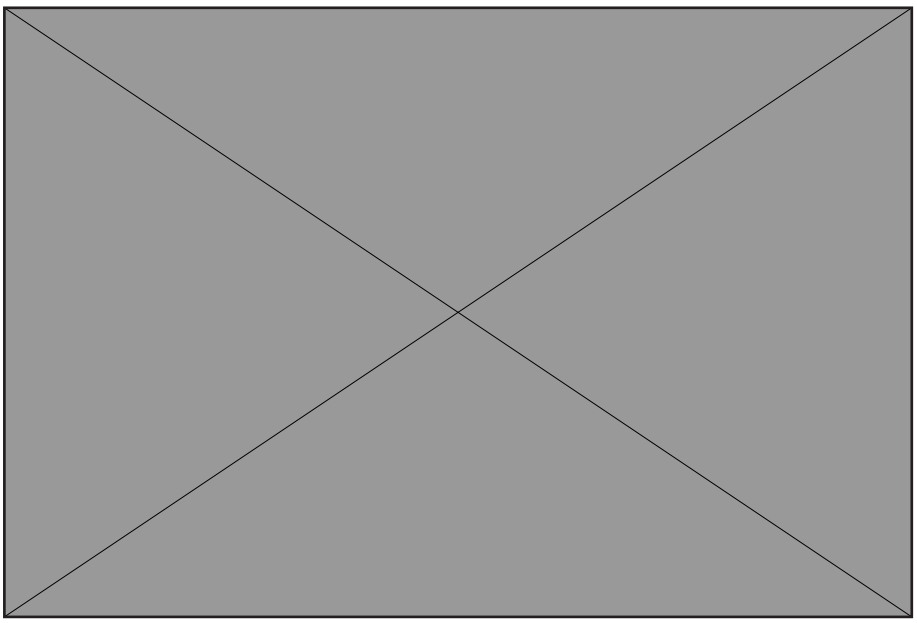
2.1 Electronic

As the light source, a 5mm green LED was used to emit a wavelength closer to 525 nm (Agilent, 2021). Based on these characteristics, specifically wavelength, high sensitivity, and rapid response, the PBW34 photodiode was employed as the photodetector (Vishay, 2011). An OLED display, 128x64 pixels with a 0.96" I2C interface, was integrated with the Arduino for the visualization of transmittance data.

2.1.1 Power Supply and Transimpedance Amplifier (TIA)

The prototype's external power supply consisted of a 9-volt battery to operate the integrated circuits (LF356 and ICL7660) and the LED (light source). The signal from the photodiode (BPW34) was amplified using a TIA modeled after the first stage of the Debarshi and Khan (2019), like the diagram in Figure 2. The TIA circuit employed the LF356 operational amplifier to convert low currents into a usual voltage compatible with the Arduino's analog input. The external power supply of the op-amp was provided by the 9V battery, and the negative voltage required at one pin was provided by the ICL7660 voltage inverter powered by the same battery.

Figure 2 – Amplification circuit of Si-PIN photodiode



Source: Authors (2025)

2.2 Experimental Application Procedure

Using a standard solution of potassium permanganate at mol.L^{-1}, ten dilutions were prepared by adding between 0.1 and 10 mL of the stock solution into 50 mL volumetric flasks, which were then filled with distilled water.

2.2.1 Absorbance Calculation

According to Kittipanyangam (2016), the initial step in analyzing similar prototypes involves obtaining the blank transmittance, followed by the transmittance of each sample expressed in Volts, according to Equation 1:

$$T = \frac{I}{Io} \quad (1)$$

Where:
T = transmittance
I = transmittance of the sample
Io = transmittance of the blank

Following Lambert-Beer's law, absorbance can be derived from transmittance as shown in Equation 2:

$$A = -\log(T) \quad (2)$$

Where:
A = absorbance

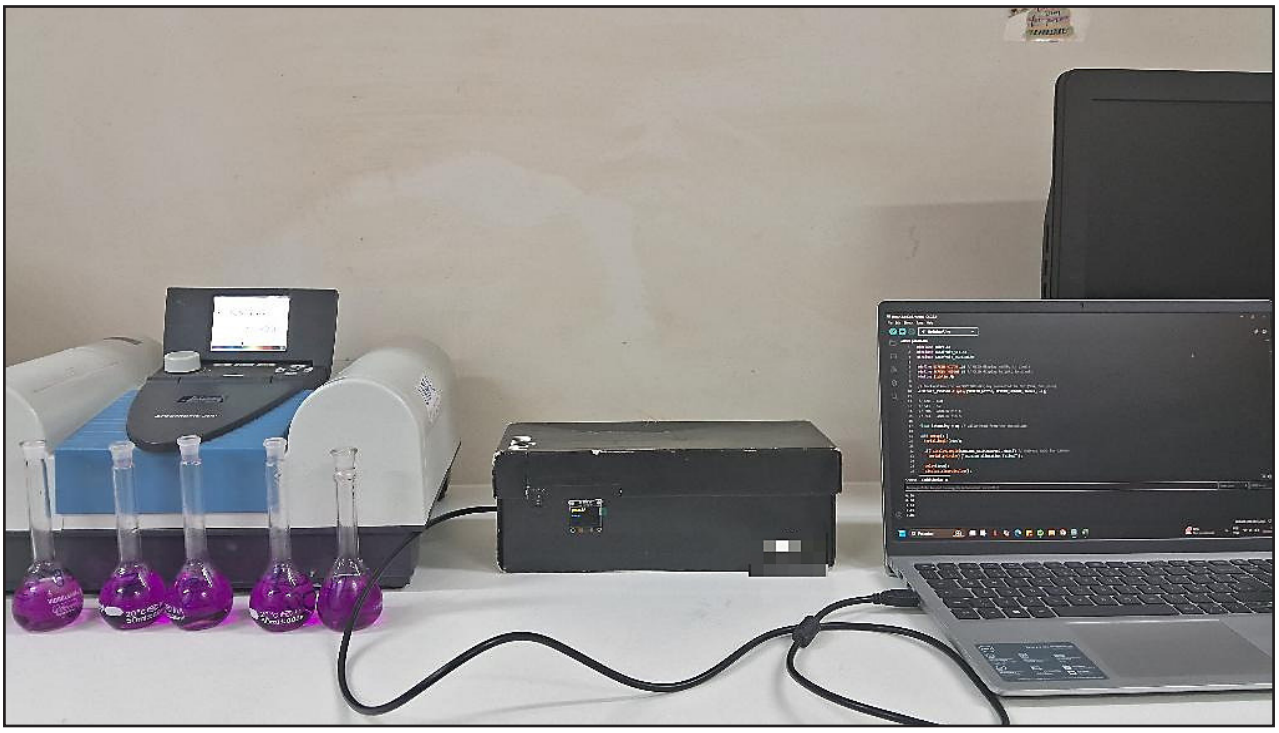
Each measurement was compared to the spectrophotometer readings (Spectronic 200 - Thermo Scientific) at a wavelength of 525 nm to optimize absorbance (Rouessac & Rouessac, 2013, p. 188).

3 RESULTS AND DISCUSSION

Initially, signal oscillations occurred but were quickly resolved by disconnecting the OLED display from the Arduino. From that point onward, data acquisition was carried out

using a computer, as shown in Figure 3, with transmittance readings collected through the serial port of the Arduino, which can be accessed via its integrated development environment (IDE). According to Horowitz and Hill (2015), increased noise can accompany signal amplification, particularly when the signal-to-noise ratio (SNR) is low, making the system more susceptible to interference. The low intensity of the LED (light source), combined with high amplification directly reduced the SNR, leading to poor measurement quality.

Figure 3 – Experimental setup of the prototype and standard spectrophotometer



Source: Authors (2025)

The solution analyses and their respective absorbances began with measuring the transmittance of the blank (deionized distilled water) in a standard 12.5 x 12.5 x 45 mm glass cuvette. The measured value was 1.62 V, which is lower than expected, given the relatively high resistance of 10 MΩ of the feedback resistor. This result is likely due to the use of a 5 mm diffuse LED, without any optical focusing mechanisms, positioned just directly in front of the sample.

Subsequently, the transmittance of each sample was calculated using Equation 1, and absorbance was derived via Equation 2. The sample analyzed was then measured

using the commercial spectrophotometer to obtain a reference absorbance value for comparison. Table 1 presents the concentration in mol·L^{-1} and the corresponding absorbance values obtained from both instruments.

Table 1 – Comparison of absorbance between the prototype and the standard UV-Vis spectrophotometer (Spectronic 200 - Thermo Scientific)

Potassium permanganate (mol.L-1)	Prototype Absorbance	Standard Uv-Vis spectrophotometer Absorbance
4×10^{-5}	0.048	0.08
8×10^{-5}	0.156	0.176
1.2×10^{-4}	0.265	0.249
1.6×10^{-4}	0.295	0.334
2×10^{-4}	0.346	0.412
2.4×10^{-4}	0.396	0.496
2.8×10^{-4}	0.431	0.597
3.2×10^{-4}	0.477	0.674
3.6×10^{-4}	0.537	0.769
4×10^{-4}	0.556	0.806

Source: Authors (2025)

The correlation coefficients between the prototype and the commercial spectrophotometer were 0.9629 and 0.9974, respectively. The primary factor affecting the correlation was the light source's characteristics. Mancini (2002) emphasizes how noise can limit information transfer within a system, and poor light intensities exacerbate the difficulty in distinguishing signal from noise, as described by Equation 3:

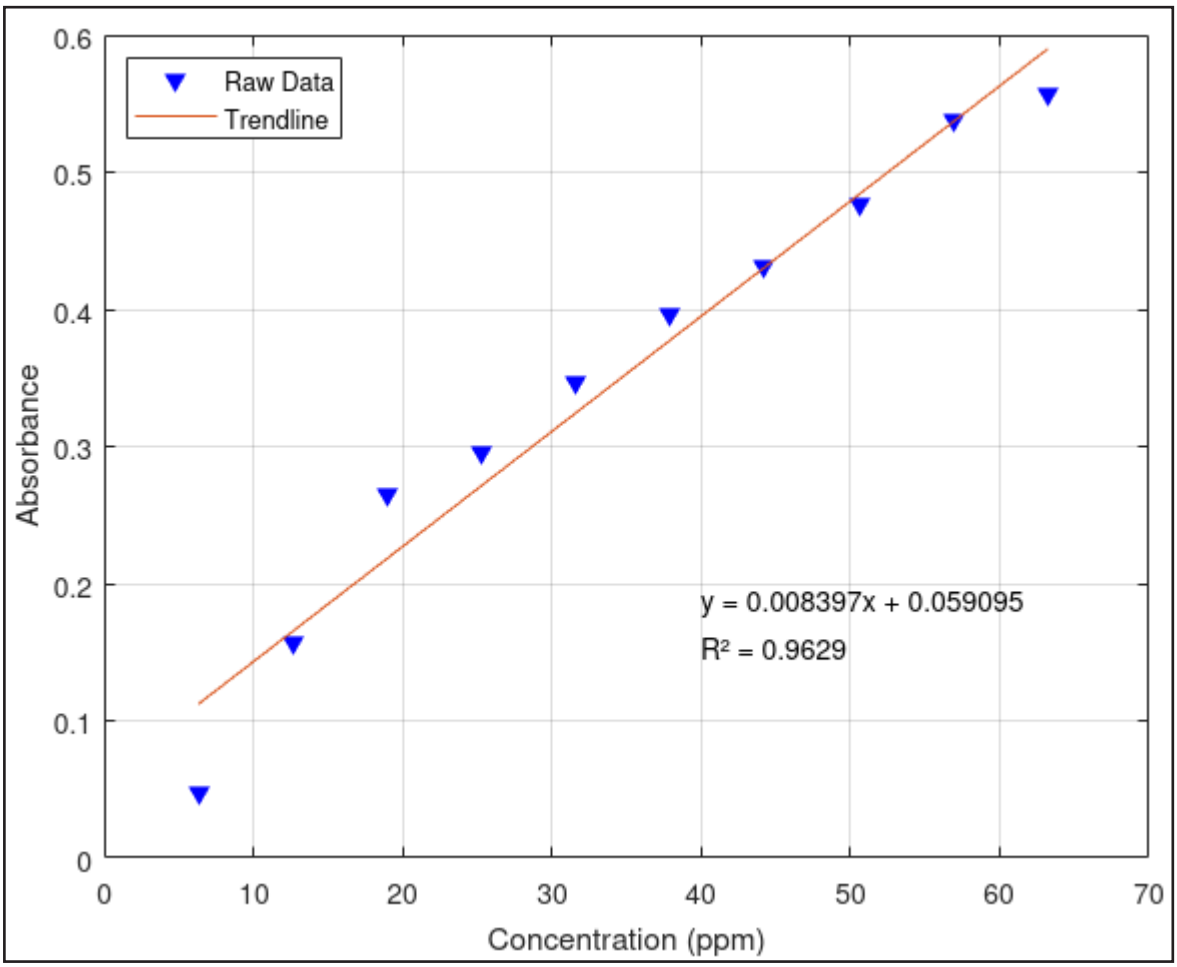
$$SNR = 20log_{10}(\frac{Vsignal}{Vnoise}) \quad (3)$$

Where:
SNR = signal to noise ratio

Based on the analyses and the issues discussed, Figure 4 demonstrates

that Lambert-Beer's law still holds, showing increased absorbance with higher concentrations. For educational purposes, this validates the prototype's potential to illustrate key concepts in classroom settings.

Figure 4 – Absorbance x Concentration ($KMnO_4$)



Source: Authors (2025)

Other Arduino-based spectrophotometer prototypes employing different mechanisms have achieved promising results with high correlation coefficients. Rosa et al. (2019) developed a prototype for copper sulfate analysis using a diffraction-based light mechanism with a CD and LDR as a light sensor, obtaining an R^2 of 0.9575. Similarly, Yuniati and Rifai (2019) reported an R^2 of 0.9702 adding operational amplifiers. Some prototypes have even outperformed the commercial spectrophotometer in accuracy. Halim et al. (2023), analyzing BPA (bisphenol A)

and triclosan, achieved correlations above 0.997 and lower limit of detection (LOD) and limit of quantification (LDQ). Comparing similar prototypes, Debarshi and Khan (2019) also reported favorable results, proposing models for field use in nitrite detection in urine.

4 CONCLUSIONS

The development of an Arduino-based spectrophotometer has proven to be a viable and cost-effective alternative for educational purposes, surpassing the limitations of commercial equipment. Despite measurement challenges caused by noise and low light intensity affecting measurement accuracy, the prototype showed a satisfactory correlation ($R^2 = 0.9629$) with a conventional spectrophotometer, thereby validating its application in teaching concepts such as Lambert-Beer's Law. The use of accessible technologies, including microcontrollers and simple electronic components, proved effective in promoting active learning, encouraging experimentation and fostering interdisciplinary learning. Future work could focus on enhancing the system's sensitivity by exploring more efficient light sources and implementing noise reduction techniques. Overall, this study underscores the potential of innovative educational tools to democratize access to analytical instrumentation in learning environments.

REFERENCES

Agilent. (2021). *The basics of UV-Vis spectrophotometry: A primer*. https://www.agilent.com/cs/library/primers/public/primer-uv-vis-basics-5980-1397en-agilent.pdf

Araújo, S. G. B. de. (2024). Utilização do Arduino como ferramenta pedagógica para o ensino de química. *Revista Sociedade Científica*, *7*(1), 1600-1612. https://doi.org/10.61411/rsc202431117

Chitolina, D., & Santos, P. J. S. dos. (2024). Impacto do uso do Arduino sobre a motivação estudantil: Resultados de uma intervenção didático-pedagógica no ensino da Física. *RENOTE*, *22*(1), 186–195. https://doi.org/10.22456/1679-1916.141545

Debarshi, S., & Khan, M. M. (2019). Portable and low-cost LED based Spectrophotometer for the Detection of Nitrite in simulated-Urine. *2019 International Conference on Electrical, Electronics*

and Computer Engineering (UPCON), 1–4. doi: 10.1109/UPCON47278.2019.8980097.

Halim, A. N. S., Qian, T. Y., Keyon, A. S. A., & Nor, N. S. M. (2023). Development of a home-built UV-visible spectrophotometer employing arduino microcontroller system for chemical analysis. *Malaysian Journal of Analytical Sciences*. 27(5), 935-945. https://mjas.analis.com.my/mjas/v27_n5/pdf/Abdul%20Halim_27_5_2.pdf

Horowitz, P., & Hill, W. (2015). *The art of electronics* (3rd ed.). Cambridge University Press. https://kolegite.com/EE_library/books_and_lectures/Електроника/_The%20Art%20of%20Electronics%203rd%20ed%20%5B2015%5D.pdf

Kittipanyangam, S., Abe, K., & Eguchi, K. (2016). Design of a measurement device explaining the relationship between the concentration of solution and the light absorbance for chemical education. *2016 13th International Conference on Electrical Engineering/ Electronics, Computer, Telecommunications and Information Technology (ECTI-CON)*, 1–6. doi: 10.1109/ECTICon.2016.7561271.

Kolesnichenko, P. V., Eriksson, A., Lindh, L., Zigmantas, D., & Uhlig, J. (2023). Viking spectrophotometer: A home-built, simple, and cost-efficient absorption and fluorescence spectrophotometer for education in chemistry. *Journal of Chemical Education*, *100*(3), 1128–1137. https://doi.org/10.1021/acs.jchemed.2c00679

Mancini, R. (2002). *Op Amps For Everyone*. https://web.mit.edu/6.101/www/reference/op_amps_everyone.pdf

Mitsioni, M. F., Stouras, M., & Makedonas, C. (2023). Taking School Instrumentation One Step Forward: A Do-It-Yourself Type Spectrophotometer and a Jupyter Notebook That Enable Real Time Spectroscopy during School Lessons. *Journal of Chemical Education*, *100*(7), 2704–2712. https://doi.org/10.1021/acs.jchemed.3c00248

Moreira, M. P. C., Romeu, M. C., Alves, F. R. V., & da Silva, F. R. O. (2018). Contribuições do Arduíno no Ensino de Física: uma revisão sistemática de publicações na área do ensino. *Caderno Brasileiro De Ensino De Física*, *35*(3), 721–745. https://doi.org/10.5007/2175-7941.2018v35n3p721

Nandiyanto, A. B. D., Zaen, R., Oktiani, R., Abdullah, A. G., & Riza, L. S. (2018). A simple, rapid analysis, portable, low-cost, and Arduino-based spectrophotometer with white LED as a light source for analyzing solution concentration. *TELKOMNIKA (Telecommunication Computing Electronics and Control)*, *16*(2), 580. https://doi.org/10.12928/telkomnika.v16i2.7159

Özgül Artuç G. (2020). Farmasötik Yumuşak Kapsülde α-Tokoferolün Spektrofotometri ile Kantitatif Tayini. *Experimed*. https://doi.org/10.26650/experimed.2020.0009

Rosa, C. L., Martins, F.P. De O. S., Arantes, R. Dos S., Silva, V. M. Da S., Oliveira, T. M., & Saliba, W. A. (2019). Construção de espectrofotômetro visível para fins didáticos. *Journal of Exact Sciences -JES*, *21*(1), 20–25. https://www.mastereditora.com.br/periodico/20190407_145828.pdf

Rouessac, F., & Annick Rouessac. (2013). *Chemical Analysis*. John Wiley & Sons.

Sahraei, R., Farmany, A., & Mortazavi, S. S. (2013). A nanosilver-based spectrophotometry method for sensitive determination of tartrazine in food samples. *Food chemistry*, *138*(2-3), 1239–1242. https://doi.org/10.1016/j.foodchem.2012.11.029

Schnider, D., & Hömöstrei, M. (2023). The influence of arduino-based student experimentation on the development of students' skills and competences. In *Challenges in Physics Education,* 185–198. https://doi.org/10.1007/978-3-031-44312-1_14

Soares, B. C., Campos, M. E. C. de, Thomaz, J. R., Pereira, G. D. C., & Roehrs, R. (2017). The importance of experimentation in the teaching of sciences to elementary school. *Revista Monografias Ambientais*, *15*(2), 1. https://doi.org/10.5902/2236130827003

Syafriani, Y. F., Anis, M., Kartika, I. R., & Kurniadewi, F. (2024). Analisis Kandungan Formalin dan Boraks dalam Mi Kuning, Kerupuk Merah, dan Ayam Menggunakan Metode Rapid Test Kit dan Spektrofotometri UV-Vis. *Jurnal Kimia Unand*, *13*(1), 1–6. https://doi.org/10.25077/jku.13.1.1-6.2024

Ustra, S. V., & Boaventura, A. C. (2018). EXPERIMENTOS DIDÁTICO-CIENTÍFICOS NO CONTEXTO ESCOLAR: CONTRIBUIÇÕES PARA O APRENDIZADO DE CIÊNCIAS SOB A PERSPECTIVA DISCENTE. *Educere Et Educare*, *13*(30), DOI: 10.17648/educare.v13i30.19230. https://doi.org/10.17648/educare.v13i30.19230

Vishay. (2011). Silicon Pin Photodiode. (2.1) [Data Sheet]. https://www.vishay.com/docs/81521/bpw34.pdf

Yuniati, A., & Rifai, R. (2019). Study of simple spectrophotometer design using LDR sensors based on arduino uno microcontroller. *Journal of Physics: Conference Series*, *1153*. https://doi.org/10.1088/1742-6596/1153/1/012099

Zadorozhnii, V. M. (2024). Using Arduino to develop research competencies of students in school physics education. *CTE Workshop Proceedings*, *11*, 427-441. https://doi.org/10.55056/cte.663

Authorship contributions

1 – Alexandre Kevin Rodrigues Diniz

Bachelor's degree in Industrial Chemistry (Universidade Federal do Maranhão).
https://orcid.org/0009-0002-8924-8610 • kke_kevin@hotmail.com
Contribution: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Resources, Software, Visualization, Writing – original draft, Writing – review & editing.

2 – Quedyane Silva da Cruz

PhD candidate in Oceanography (Universidade Federal de Pernambuco).

https://orcid.org/0000-0001-9386-0146 • quedyane.cruz@ufpe.br
Contribution: Data curation, Formal Analysis, Methodology, Resources, Supervision, Visualization, Writing - original draft, Writing - review & editing.

3 – Leonardo Tadeu Boaes Mendonca

Assistant Professor (Universidade Federal do Maranhão).
https://orcid.org/0000-0002-7792-6333 • leonardo.boaes@ufma.br
Contribution: Project administration, Resources, Supervision, Validation, Visualization, Writing - review & editing.

How to quote this article

Diniz, A. K. R., Cruz, Q. S. & Mendonca, L. T. B. (2026). Development of a spectrophotometer employing Arduino microcontroller for educational purposes. *Ciência e Natura*, 48, e93058. DOI: 10.5902/2179460X93058. Available in: https://doi.org/10.5902/2179460X93058.