# Development of an Arduino-Based Photometer for Reactive Red 120 Dye Detection COVID-19

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**Abstract**
During the COVID-19 pandemic, traditional laboratory access was limited, prompting innovative approaches to education and research. An undergraduate chemistry student undertook the development of an Arduino-based photometer as a remote learning final year project. This project aimed to measure RR-120 dye concentrations in water using affordable and accessible technology, providing practical experience in photometry, electronics, and programming despite the constraints of the pandemic. The removal of Reactive Red 120 from water bodies is a significant environmental concern. The photometer, constructed using an Arduino UNO microcontroller, a green LED (500-570 nm), resistors, a plastic cuvette, and a BH1750FVI digital light intensity sensor module, is designed to be a cost-effective and user-friendly device for classroom and laboratory use. The device's operation is controlled via Arduino IDE 1.8.19 software, providing hands-on experience with programming and electronics. Calibration with seven RR-120 solutions (0.2 to 1.4 mg/L) produced an $R^2$ value of 0.9823, with a detection limit of 0.47 mg/L. The photometer achieved 98.66% accuracy demonstrating its reliability. Performance comparison with a commercial benchtop UV-Visible spectrophotometer ($R^2$ = 0.9956) further demonstrates the photometer's reliability. This Arduino-based photometer not only offers a practical application for teaching principles of photometry and spectroscopy but also illustrates the integration of affordable technology in scientific education, enhancing student engagement and learning in STEM fields during challenging times. Most importantly, this device also provided hands-on experience in photometry, enhancing remote learning during restricted lab access. The device's scalability suggests potential applications in broader environmental monitoring and educational settings, beyond the initial scope of dye detection.

**Keywords**: Arduino, Photometer, COVID-19 remote learning, Home-built, Dye, Reactive Red 120

## Introduction

Dyeing and finishing processes in textile production are estimated to contribute to approximately 20% of worldwide pollution of clean water resources as highlighted by Kant (2012). Synthetic dyes that exhibit resistance to light and biological degradation can pose a toxic and hazardous risk to the environment. This is attributed to the resonance of their aromatic structure, which enhances their persistence in water bodies presented in Ardila-Leal *et al.*, (2021). Since synthetic dyes are very soluble in water, effluents from the textile dyeing industries may easily transport and distribute them to rivers and lakes.

Dyes have been identified as causing toxic effects in their parent molecules or intermediate metabolites. Islam *et al.*, (2023) further emphasizes textile dyes, like numerous other industrial pollutants, are highly toxic and have the potential to be carcinogenic, resulting in significant environmental damage and posing various health issues for both animals and humans. The utilization of textile dyes in the textile industry has been associated with a range of health problems affecting humans, animals, and the environment. Azo dyes make up approximately 70% of the total

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industrial dye consumption, which amounts to 9.9 million tons annually. Gürses *et al.*, (2016) has highlighted the global market value of azo dyes is estimated at USD 30.42 billion. Balapure *et al.*, (2015) has reported reactive Red 120 (RR-120) is a commonly utilized azo dye in the textile industry due to its notable chemical, biological, and photocatalytic stability. As a diazo dye, RR-120 is known for its exceptional durability and resistance to degradation. However, this resistance to breakdown poses challenges in terms of environmental degradation over time, as exposure to sunlight, detergents, water, and microorganisms have limited effectiveness in breaking down RR-120 as discussed by Solís *et al.*, (2012). Hence, it is imperative that water bodies remain nearly free of substances that create visually displeasing colours for aesthetic reasons. Non-natural colours, including dyes, should be imperceptible to the human eye, as these colours are particularly unwanted to individuals who derive pleasure from observing water in its unaltered state. According to Department of Environmental Malaysia (2009), chemical analysis and additional treatment is usually conducted in the textile wastewater plant to remove the color before they are discharged into the water bodies. Moreover, understanding how to measure and analyse pollutants like RR-120 dye in water ties learning to real-world environmental issues, increasing student engagement and awareness of global challenges.

A benchtop analytical instrument known as an ultraviolet-visible (UV-Vis) spectrophotometer is usually utilized to assess the absorbance of light by the analyte at specific wavelengths. Different materials exhibit varied absorption at certain wavelengths, enabling the instrument to analyse and quantify their characteristics. It is applicable as most of the synthetic dyes are made up of organic compounds which have a strong chromophore to be detected in visible region, ranging from 400 nm – 700 nm. Benchtop spectrophotometry provide accurate results but are often expensive, require skilled operators, and demand sophisticated laboratory settings, making them impractical for on-site analysis. Carrying heavy and complex instruments for on-site investigations is also impractical. Alternatively, portable, and cost-effective solutions based on Arduino microcontroller are becoming popular to facilitate rapid monitoring and detection of dye concentrations in wastewater. Arduino, a popular open-source platform in building electronics projects consisted of a hardware part, a physical programmable circuit board, called microcontroller, and a software part, namely Integrated Development Environment (IDE), which are used to control the physical board by giving instructions. A Universal Serial Bus (USB) interface is a common connection between the hardware and software part of the Arduino.

The Arduino microcontroller, equipped with different sensors, can be used for different purposes and assessment. By integrating Arduino microcontrollers with optical sensing components, students can learn to develop and use practical tools for real-world applications. This hands-on approach not only reinforces theoretical knowledge but also enhances problem-solving and technical skills that are invaluable for educational settings. The Arduino-based photometer project offered an alternative that could be assembled and operated at home, providing a valuable educational experience. This practical experience helps students understand complex concepts in photometry, electronics, and programming through direct application. Furthermore, this project bridges multiple disciplines, including chemistry, physics, computer science, and environmental science, allowing students to see the interconnectedness of these fields and how they come together to solve real-world problems. By working with Arduino microcontrollers and sensors, student develop a range of skills from basic electronics and circuit design to programming and data analysis, all of which are highly valuable in many STEM (Science, Technology, Engineering, and Mathematics) careers.

Several successful studies have been conducted on the development of home-built photometers for various compounds. Wang *et al.*, (2016) demonstrated the ease of constructing a single-wavelength photometer using inexpensive light-emitting diodes (LEDs) and household items for acid-base analysis. Steinberg *et al.*, (2014) has developed a novel wireless photometer that was tested and measured the color intensity as a function of dye concentration. These collective studies demonstrate the possibility of building an Arduino-based photometer as a screening tool for dye detection. While these previous studies have demonstrated the practicality of Arduino-based systems for photometric analysis, there are still significant gaps in the literature. These studies primarily focused on simple chemical analyses and did not address the detection of more complex pollutants, such as azo dyes, nor did they explore the integration of these tools in remote learning environments during emergencies like the COVID-19 pandemic. With the onset of the COVID-19 pandemic, educational institutions worldwide faced unprecedented challenges in delivering hands-on laboratory experience to students. Remote learning became the primary mode of education, making it essential to provide students with practical, home-based alternatives to traditional lab equipment. To date, no studies have focused on using Arduino-based photometers as a remote learning tool for environmental and chemical analysis, particularly for complex pollutants. This gap is critical because it highlights the lack of resources available to students during periods of restricted laboratory access, as was the case during the pandemic.

Notably, Balapure *et al.*, (2015) has reported reactive Red 120 (RR-120), an azo dye commonly used in the textile industry poses significant environmental challenges due to its chemical stability and resistance to degradation. The need for affordable, accessible tools for detecting pollutants like RR-120 is especially pressing in regions with limited access to sophisticated laboratory equipment. The use of photometer enables the determination of RR-120 dye concentration in water, which is in rather low concentration and imperceptible to be observed by naked eyes.

In the development of an Arduino-based photometer, an Arduino microcontroller is used as the microprocessor in the system, while LED can be used as the light source. Arduino board is simply connected to a computer or laptop using a USB cable. The whole system is controlled by connected computer, using Arduino languages written in C or C++ language script. The primary aim of this work was to develop an Arduino-based photometer that could be used to determine RR-120 dye concentration in water, specifically for educational purposes during the COVID-19 pandemic, when access to traditional laboratories was restricted. This project not only served as a valuable tool for remote learning but also contributed to enhancing students' practical skills in photometry, electronics, and programming. The objectives were to develop an Arduino-based photometer complete with the programming script, determine the RR-120 dye concentration, and subsequently validate the findings with values obtained using a commercially available benchtop UV-visible spectrophotometer instrument. Traditionally, students rely on benchtop UV-Visible (UV-Vis) spectrophotometers to understand the principles of light absorption and photometry.

However, access to these expensive instruments is often limited, particularly in under-resourced institutions or during times of restricted access like the COVID-19 pandemic. The Arduino-based photometer developed in this study provides a cost-effective alternative, allowing students to build their own devices and gain practical experience with scientific instruments at home. Students learn about the principles of spectroscopy, including the interaction of light with matter, absorption spectra, and the Beer-Lambert law, which relates absorbance to concentration. By constructing and calibrating the photometer, students gain practical insights into these theoretical concepts. They learn how different wavelengths of light can be used to detect specific compounds, understanding the role of chromophores in dyes like RR-120, which absorb visible light and cause coloration. This hands-on approach to learning enhances their comprehension of key chemical principles and their applications in environmental monitoring. By leveraging the computational capabilities of Arduino and incorporating optical sensing techniques, an undergraduate student has successfully created an affordable, customizable, and user-friendly photometer. This device not only serves as a practical tool for environmental monitoring but also provides an engaging educational platform for the student to explore the intersection of technology and chemistry. Through this project, the student gains hands-on experience and develops a deeper understanding of both scientific principles and the impact of technology on environmental science. Additionally, the project fosters an independent learning experience, promoting self-reliance, critical thinking, and the ability to undertake complex scientific tasks individually.

## Materials and Methods

This study was divided into two parts, where the Arduino-based photometer was developed at the first stage, and it was then used in the analysis of RR-120 dye at the second stage. The materials used in this project were chosen for their accessibility, affordability, and educational value, providing a rich learning experience for an undergraduate student. All the materials and components used for development of Arduino-based photometer were brought via Cytron (2022) Official Website and Shopee online platform.

The primary component was an Arduino UNO microcontroller, an open-source platform renowned for its simplicity and versatility, making it an ideal tool for educational purposes. The features of Arduino UNO were as follows: microprocessor controller Atmel Atmega328P; USB chip Atmel Mega16u2 (CP2012 driver); digital input/output from 0 to 13; analog input/output from 0 to 5; PWM pin of 3, 5, 6, 9, 10, 11; input voltage was using USB Cable / 7-12 V DC plug; output voltage was 5 V and 3.3 V DC. A green LED, with a wavelength range of 500 to 570 nm, served as the light source, allowing the student to gain hands-on understanding of the properties of light and its interactions with various materials. The LED had an intensity from 3000- 4000 millicandela (mcd). A digital ambient light sensor (BH1750FVI) with an unsoldered pin, acted as a luminance to digital converter was used in this study. I2C communication protocol was used by this sensor to make an easier to be controlled by a microcontroller. The photometric analysis was controlled by using a laptop through an USB interface. The software Arduino IDE 1.8.19 was used and the programmes was written in C++ programming language. The Arduino IDE 1.8.19 software provided a user-friendly interface for writing and uploading code to the Arduino board, thus fostering programming skills within a real-world context. The standard RR-120 dye calibration solutions were prepared in the concentration of 0.2 – 1.4 mg/L and analysed first by using the home-built Arduino-based photometer, followed by result validation using benchtop Shimadzu-1800 UV-Vis spectrophotometer.

In the analysis using home-built Arduino-based photometer, the incident light intensity, I0, was observed via scanning of blank, i.e., ultrapure water. Then, 2.5 mL of standard calibration solution was filled into the plastic cuvette and the data was recorded as transmitted light intensity, I. The plastic cuvette holds the dye solutions, which introduced the student to sample handling and preparation in chemical analysis. The absorbance, A was calculated using Equation (1). The R2 value obtained from the calibration curved plotted, whereas the limit of detection (LOD) was calculated using Equation (2) and (3). The results were compared with that of analysed using benchtop Shimadzu-1800 UV-Vis spectrophotometry.

$$A = \log_{10}\frac{I_o}{I} \quad (1)$$

$$\text{Intercept of SD} = \text{Intercept of SE} \times \sqrt{N} \quad (2)$$

$$\text{LOD} = 3.3 \times \frac{\text{Intercept of SD}}{\text{slope}} \quad (3)$$

## Results and Discussion

*The set-up of the home-built Arduino-based photometer*

The successful setting up of the home-built Arduino-based photometer was a significant educational milestone for the undergraduate student, integrating theoretical knowledge with practical application. A photometer consists of four basic components, which are the light source, filter, detector, and a control system. The basic principle of this technology involves measurement of quantity of light absorbing analyte, either organic or inorganic, in a solution at a certain wavelength. The home-built Arduino-based photometer was set up as in Figure 1. It shows the arrangement of components and Arduino UNO board. The cuvette was placed in between the light source (green LED) and the sensor module to maximize the light intensity reached the sensor. The green LED was fixed on the breadboard while the sensor module was fixed on a vertical cardboard. There was a cardboard with a small hole in between the light source and the cuvette, acted as the entrance and exit slit to minimize the light dispersion and focus the light on the power diagnostic area of the sensor. This hands-on experience reinforced several key educational concepts. Firstly, the student applied principles of photometry, understanding how light absorption and transmission through a sample can be used to determine the concentration of a substance. The use of an LED as a light source and a digital sensor to measure light intensity provided practical insights into the interaction between light and matter, an essential concept in both chemistry and physics.

The Arduino board was firstly connected with the breadboard as in Figure 2a, using male to male jumper wires. The breadboard was used to connect LED and resistor in series with Arduino board without any soldering. These basic electronic components help the student learn the fundamentals of circuit design and assembly. The green LED was selected due to its wavelength in the range of 495 – 570 nm, which was suitable for the detection of RR-120 dye. It was connected to digital pin 9 with a 100 ohm (Ω) current limiting resistor in series. The behaviour of the green LED was controlled by connected computer through Arduino IDE 1.8.19, using Arduino languages written in C++. Programming the Arduino was the next crucial step. Using the Arduino IDE, the student wrote a program to control the LED and read data from the light intensity sensor. Figure 2b shows the coding script to light up the green LED using Arduino UNO microcontroller.

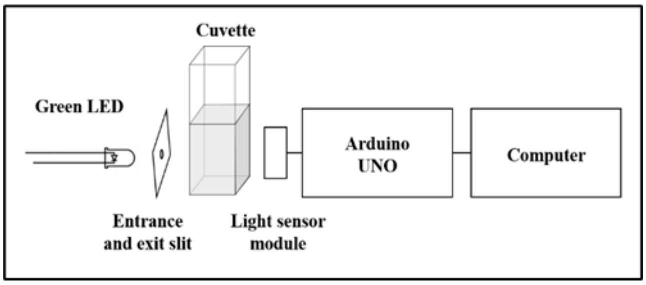


**Figure 1. The diagram of the home-built Arduino based photometer showing the arrangement of components and Arduino UNO board.**

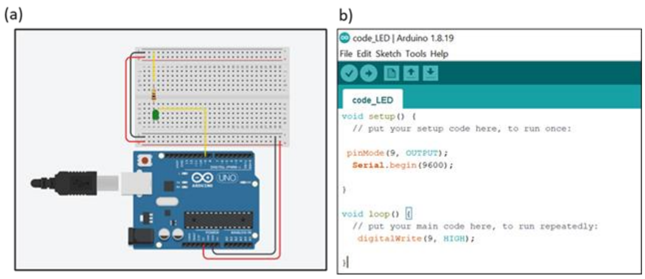


**Figure 2. The a) schematic diagram of the connection between green LED and Arduino UNO board and b) the code to light up the green LED.**

As for the connection of digital light sensor module with Arduino board, the library of the BH1750FVI digital light sensor module was first downloaded into the computer from the website GitHub (2022). (https://github.com/claws/BH1750), and the header pin for this sensor module was soldered properly and carefully before the connection started. Then, the sensor module was connected to the Arduino board, using male to female jumper wires as in the schematic diagram in Figure 3a. The behaviour of the sensor was controlled and monitored through Arduino IDE 1.8.19 on the computer, using Arduino languages written in C++. The necessity to debug and refine the code fostered problem-solving abilities and a deeper understanding of how software can be used to control hardware for specific scientific measurements. The code to control and monitor the sensor was shown in Figure 3b.

Both green LED and the sensor were connected simultaneously with the Arduino board as in schematic diagram in Figure 4a. The coding parts of green LED and BH1750 digital light intensity sensor were combined in an Arduino file as in Figure 4b. The photograph in Figure 4c showed the connection between (1) Arduino UNO board and (2) breadboard (3) green LED (4) light sensor module.

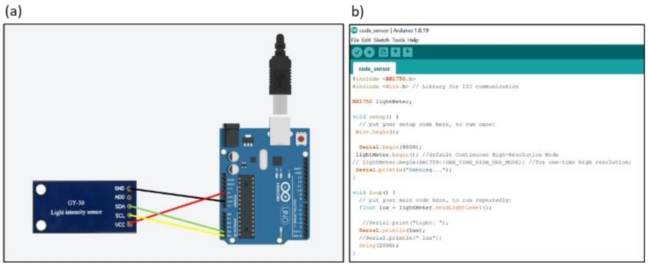


**Figure 3. The a) schematic diagram of the connection between BH1750FVI digital light intensity sensor and Arduino UNO board and b) Schematic diagram of the connection between BH1750FVI digital light intensity sensor and Arduino UNO board.**

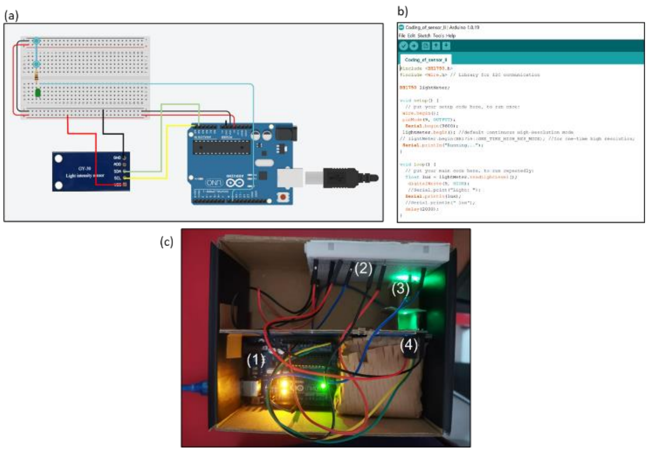


**Figure 4. The a) schematic diagram of the connection between all components and Arduino UNO board, b) The code to control both green LED and BH1750FVI digital light intensity sensor simultaneously, and c) the photograph showing all the connection.**

*Analysis of RR-120 dye standard solutions using the home-built Arduino-based photometer*

The functionality of the home-built Arduino-based photometer was tested to assess its reliability and accuracy in measuring light transmittance and absorbance. The data analysis phase of the project provided the student with practical experience in interpreting scientific data. Standard solutions with known concentrations of RR-120 dye were prepared and used to evaluate the photometer's performance. This step provided hands-on experience in solution preparation and dilution techniques, which are fundamental skills in any chemical analysis. The output signal from the sensor was measured as lux and then recorded as light transmittance. The absorbance was calculated using Equation 1.1. To establish the relationship between RR-120 dye and absorbance, a calibration curve was constructed as shown in Figure 5.

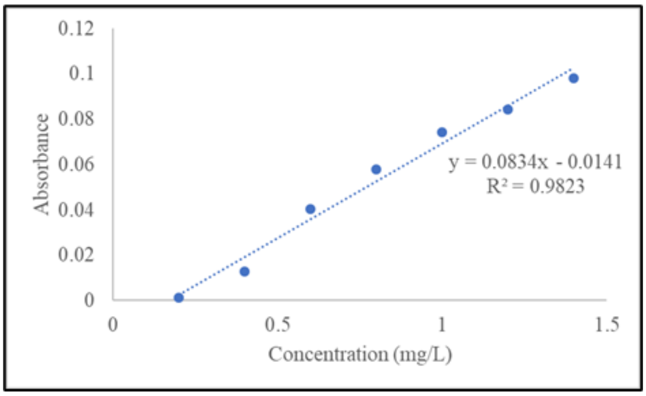


**Figure 5. The calibration curve of RR-120 dye measured using home-built Arduino-based photometer device.**

The acceptable $R^2$ value of 0.9823 showed quite a linear relationship between the RR-120 dye concentration and the absorbance measured using the developed device. The $R^2$ value indicates how well the calibration curve fits the data points, and a value close to 1 signifies a strong correlation. The intercept of standard error (SE) was calculated using the "Regression Statistic" in "Data Analysis" of Microsoft Excel, at 95% confident level. The data obtained was used in the calculation of the intercept of standard deviation (SD) using Equation (1), and LOD was then calculated using the Equation (1), where n is the number of RR-120 dye concentration, n=7. The LOD obtained from the analysis of RR-120 dye using home-built Arduino-based photometer was 0.4686 mg/L, which indicated the lowest concentration of RR-120 dye in the solution that can be consistently detected at 95% confidence level. The relatively low LOD indicates the photometer sensitivity and capability to detect trace amount of the dye in the tested solutions. These results were then compared with that of analyzed using a commercially available benchtop UV-Vis spectrophotometer. The commercially available benchtop Shimadzu-1800 UV-Vis spectrophotometer was used to verify the result obtained using the home-built Arduino-based photometer. The maximum absorption peak of RR-120 dye was observed at 514 nm in visible regions. Figure 6 illustrates the calibration curve for dye absorbance at 514 nm using the benchtop spectrophotometer, with R2 value of 0.9953. The calibration curve showed a strong linear relationship between dye concentration and absorbance value. The LOD obtained from the analysis of RR-120 dye using benchtop UV-Vis spectrophotometer was 0.2394 mg/L, which indicated the lowest concentration of RR-120 dye in the solution that could be consistently detected at 95% confidence level. The LOD value was close to the LOD that the home-built Arduino-based photometer measured. The difference in LOD and correlation values between the two instruments was marginal, highlighting the Arduino-based photometer's reliability as a cost-effective alternative for educational and field use. This exercise taught the student about the importance of calibration, validation, and the reliability of scientific instruments.

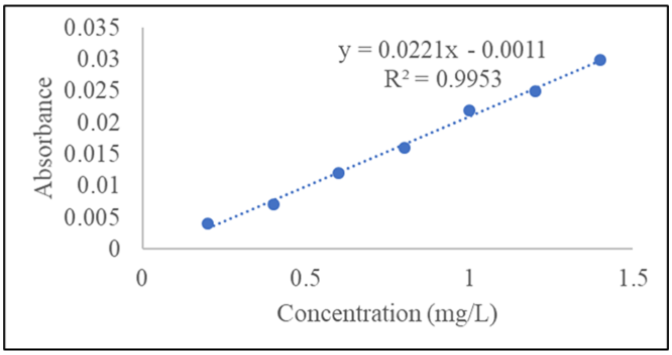


**Figure 6. Calibration curve of RR-120 dye measured at 514 nm using benchtop UV-Vis spectrophotometer.**

The error rate of the analysis of RR-120 dye using home-built Arduino-based photometer was calculated using Equation 4. The $R^2$ value obtained from analysis using benchtop UV-Vis spectrophotometer was used as the true value, while the $R^2$ value obtained from analysis using home-built Arduino-based photometer was used as the observed value. Then, the accuracy of RR-120 dye analysis using home-built photometer was calculated using Equation 5.

$$\text{Error rate} = \frac{|\text{True Value} - \text{Observed Value}|}{\text{True Value}} \times 100\% \quad (4)$$

$$\text{Accuracy} = 100\% - \text{Error rate} \quad (5)$$

The analysis of RR-120 dye using the home-built Arduino-based photometer has demonstrated its reliability and high accuracy, with an impressive precision of 98.66%. This level of accuracy indicates that the photometer could consistently and dependably measure RR-120 dye concentrations with a high degree of confidence. The strong linear relationship observed in the calibration curve ($R^2$ value of 0.9823) further supports the accuracy of the photometer's measurements. While the Arduino-based photometer demonstrated high accuracy and strong linearity, several potential sources of error and limitations should be noted. The open setup of the Arduino-based photometer makes it more susceptible to ambient light interference, which could affect the accuracy of the absorbance measurements. To mitigate this, measurements were conducted in a controlled environment, but in field applications, additional shielding around the setup would be necessary to prevent external light from affecting the results. The combination of the photometer's accuracy, cost-effectiveness, and portability makes it a valuable tool in environmental monitoring, water quality assessment, and various industrial applications. The photometer's ability to reliably measure dye concentrations above 0.4 mg/L ensures it could be employed in scenarios where higher dye levels are expected or need to be monitored. This realization underscored the educational value of the project, showing how innovative, cost-effective solutions can be developed using readily available technology.

### Educational Impact and Curriculum Integration

In addition to the technical results, this project has significant educational implications. The Arduino-based photometer provides a practical, hands-on experience for students learning about photometry, spectroscopy, and environmental monitoring. By constructing and programming the device, students gain valuable skills in electronics, data analysis, and programming, all of which are crucial in STEM fields. Furthermore, the affordability and accessibility of the Arduino platform make it an ideal tool for educational institutions with limited resources. This project can be easily incorporated into undergraduate chemistry and environmental science curricula, providing a low-cost alternative to traditional spectrophotometry labs. Students can build the photometer themselves, learning not only the principles of photometry but also how to program and calibrate scientific instruments. This do-it-yourself (DIY) approach enhances problem-solving skills and fosters a deeper understanding of how scientific instruments work. Instructors could use this project to teach topics such as (a) the Beer-Lambert Law and its application in determining absorbance and concentration, (b) the role of light wavelengths in detecting specific compounds, (c) calibration and validation techniques using scientific instruments and (d) the environmental impact of textile dyes and methods of monitoring pollution. Given the increasing need for flexible and remote learning tools, especially during the COVID-19 pandemic, the Arduino-based photometer offers a way for students to conduct meaningful scientific experiments at home. It allows for the continuity of hands-on learning despite restricted access to laboratories, making it an invaluable educational tool during times of crisis. This project could also be adapted for fieldwork, where students can use the portable device to monitor environmental pollutants in real time.

### Conclusion

The development of an Arduino-based photometer by an undergraduate chemistry student during the COVID-19 pandemic demonstrated both scientific innovation and educational resilience. Despite the challenges of remote learning and limited laboratory access, the student successfully constructed and validated a portable device for measuring Reactive Red 120 (RR-120) dye concentration in water. The photometer's performance, with high accuracy and reliability, underscored the potential of affordable technology in scientific research. The hands-on process of designing, assembling, and programming the photometer enhanced the student's skills in electronics and programming. The photometer's LOD of 0.47 mg/L indicates its sensitivity in reliably detecting low concentrations of RR-120 dye. Moreover, the accuracy of 98.66% comparable to the results obtained from a benchtop Shimadzu-1800 UV-Vis spectrophotometer demonstrates the photometer's reliability in quantifying dye concentrations. This project demonstrated that a cost-effective and portable photometer can be constructed using accessible components and open-source technology. Validated against a commercial UV-Vis spectrophotometer, the device showed high accuracy and reliability. This developed photometer could be used as a screening tool to identify the presence of RR-120 dye in a suspected dye-contaminated sample. Saying that, it is important to assess its suitability for specific industrial processes and environmental monitoring scenarios, which would be the future scope of this study. The interdisciplinary nature of the project highlighted the interconnectedness of STEM fields, providing a holistic educational experience that emphasizes the real-world applications of theoretical knowledge during challenging times. While the device has certain limitations, its high accuracy and reliability make it a valuable tool for teaching, research, and fieldwork. Future research could focus on improving the sensitivity of the light sensor, refining the design to reduce ambient light interference, and expanding the photometer's application to detect other pollutants or compounds. By incorporating this project into the STEM curriculum, educational institutions can provide students with hands-on experience that bridges theoretical knowledge and practical application, fostering a deeper understanding of both the science and technology behind environmental monitoring.

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## Conflict of Interest

The authors declare no conflict of interest.

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