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Determination of Glucose Solution Concentration Using Arduino-Based System

Herbert Innah[1]*, & Maniur Arianto Siahaan[2]
[1]*Universitas Cenderawasih, Indonesia, [2]Universitas Sari Mutiara Indonesia, Indonesia
*Co e-mail: herbert.innah@gmail.com[1]

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ABSTRACT

Glucose is one of the most important biomolecules, playing a critical role in biological systems, food products, and clinical diagnostics. Conventional methods for glucose concentration measurement, such as spectrophotometry and enzymatic assays, although accurate, are often costly, time-consuming, and require skilled personnel. This study presents the development of a low-cost Arduino-based optical detection system for measuring glucose concentration using RGB LEDs as light sources and a photodiode sensor as the detector. The Arduino microcontroller processes voltage signals corresponding to light intensity and calculates absorbance values based on Beer-Lambert's law. Calibration was performed using glucose solutions of varying concentrations, and the results indicated that the red LED source provided the most accurate and stable absorbance readings, with an average relative error below 5%. The proposed system offers an affordable, portable, and reliable alternative to conventional spectrophotometers, making it suitable for educational laboratories, small-scale food industries, and preliminary biomedical testing. Its implementation demonstrates the potential of microcontroller-based systems in enhancing accessibility to analytical tools in resource-limited environments.

Keywords: *Glucose Concentration, Arduino, Optical Sensor, Photodiode, Absorbance Measurement*

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INTRODUCTION

Solution concentration is an essential parameter in product design, industrial testing, biomedical research, and educational practices. Concentration represents the amount or level of a substance dissolved in a liquid medium, which directly determines the physicochemical properties of the solution. In the context of analytical chemistry, concentration measurements are particularly important in processes such as fermentation, food quality control, pharmaceutical formulations, and clinical diagnostics. Among the different analytical approaches, optical methods using visible light sources are widely utilized due to their non-destructive nature, rapid measurement capability, and adaptability to various types of samples. The development of spectrometers based on visible light sources has therefore been the subject of many studies, ranging from commercial devices with high precision to research prototypes designed for specific low-cost applications.

Despite the availability of commercial spectrometers, their procurement for educational laboratories, small-scale research, or developing regions remains challenging due to the high cost of acquisition and maintenance. Commercial spectrometers often include advanced features such as automated wavelength scanning, high-resolution detectors, and complex software interfaces, which may not always be necessary in basic experimental setups or preliminary studies. As a result, researchers have explored various alternatives to build spectrometers using more affordable and accessible components. Examples include Arduino and LabVIEW-based spectrometers, prism spectrometers utilizing WebCams, and WebCam-based spectrometers employing DVD discs as diffraction gratings. Each of these approaches offers unique advantages and limitations. For instance, the WebCam-based spectrometer allows direct visualization of spectra, making it suitable for qualitative demonstrations in educational settings; however, it is less reliable for quantitative analysis due to sensitivity to external light, misalignment, and the need for manual comparison with reference spectra. Furthermore, the accuracy of such systems is strongly influenced by experimental parameters such as slit width, grating groove density, stability of the optical system, and the intensity of the light source. Data analysis also requires careful consideration, since recorded images must be processed to extract pixel intensity values for each color channel, which introduces additional sources of error.

Arduino is an open source microcontroller platform widely used for electronic prototyping and sensor integration. It allows users to process analog and digital signals with minimal hardware complexity. In this study, Arduino Uno was selected because of its ease of programming, compatibility with optical sensors, and low cost, making it suitable for developing a compact and portable optical detection system. The flexibility of Arduino also enables data acquisition, processing, and visualization in real time, which supports efficient calibration and measurement procedures.

To address these limitations, this study proposes the development of a glucose concentration measurement system using an Arduino-based optical sensor setup. In this configuration, glucose concentration is determined by measuring the transmitted light intensity through the sample, based on the principle of absorbance. The experimental setup employs a photodiode sensor positioned at the end of a cuvette containing glucose solution at different concentrations prepared with distilled water. An LED light source is used to emit light into the cuvette, and optical fibers guide the light both into and out of the sample chamber. After passing through the glucose solution, the transmitted light is detected by the photodiode via another optical fiber, and the signal is subsequently processed by the Arduino microcontroller to obtain voltage readings proportional to light intensity.

The underlying principle of this system relies on Beer-Lambert's law, which states that absorbance is directly proportional to the concentration of an absorbing species in solution. By calibrating the system with standard glucose solutions of known concentrations, a relationship between transmitted light intensity (or absorbance) and glucose concentration can be established. This calibration curve allows the system to be used for predicting unknown glucose concentrations with reasonable accuracy. Compared to image-based spectrometers, the use of a photodiode sensor offers higher stability, faster response time, and reduced susceptibility to observational errors. Furthermore, since Arduino is open-source and widely supported by the scientific community, the system can be easily replicated, modified, and integrated with additional modules such as wireless communication, data logging, or IoT platforms for remote monitoring.

The proposed method not only provides a low-cost and portable alternative to conventional spectrometers but also enhances the feasibility of implementing hands-on laboratory experiments in educational institutions with limited resources. By reducing dependency on expensive equipment, students and researchers can gain practical experience in optical measurement techniques, microcontroller programming, and sensor integration. This system also has potential applications beyond the classroom, such as in small-scale food industries, fermentation monitoring, and preliminary biomedical testing, where rapid and affordable glucose concentration measurement is required.

METHODS

This study employed glucose powder (analytical grade), distilled water, and cuvettes with a 1 cm optical path length to prepare and contain glucose solutions. The measurement system consisted of an LED light source (430–650 nm), optical fibers, a BPW34 photodiode sensor, and an Arduino Uno microcontroller connected to a PC with Arduino IDE for data acquisition. The system operated on the absorbance principle of Beer-Lambert's law, where light transmitted through glucose solutions was detected by the photodiode and converted into voltage signals for processing by the Arduino.

Glucose solutions with concentrations of 0–100 mg/dL were prepared, transferred into cuvettes, and placed between the LED and photodiode with careful fiber alignment. For each sample, the Arduino recorded voltage outputs for 30 seconds at 1 Hz, and measurements were repeated three times. Calibration was performed using distilled water as the blank reference, and absorbance values were calculated using $A = log(I0/I)$ calibration curve was plotted to evaluate the linearity, sensitivity, and correlation coefficient (R^2). Data analysis using Excel and MATLAB included regression analysis, standard error, limit of detection (LOD), and limit of quantification (LOQ), with results validated against standard spectrophotometric measurements.

RESULTS

Sensor calibration was carried out to determine the relationship between sensor output voltage and light intensity. The objective was to establish equations that could be used to convert the photodiode output voltage into light intensity values, which were further processed to obtain absorbance and transmittance of glucose solutions. Calibration was performed by comparing the sensor output voltage with light intensity readings using a standard Light Meter (LX-101A).

The results showed a linear correlation between output voltage and light intensity. The relationship was expressed by the following calibration equations:

$$I = 9.9168V - 0.1192(red\ LED) \quad (1)$$
$$I = 66.543V + 0.2434(green\ LED) \quad (2)$$
$$I = 3.569V - 0.0095(blue\ LED) \quad (3)$$

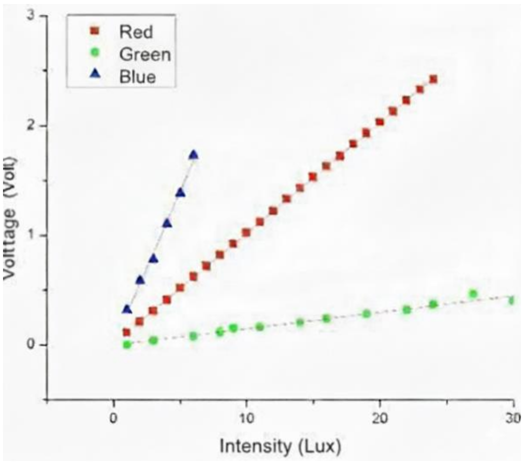

Figure 1. Shows the Correlation Between Sensor Output Voltage and Light Intensity

The experimental setup for light intensity measurement, using both the Light Meter and the photodiode sensor, is illustrated in Figure 1. shows the correlation between sensor output voltage and light intensity. The data reveal a clear linear trend, indicating that as the light intensity increases, the photodiode produces a proportionally higher output voltage. This relationship confirms that the sensor responds consistently to variations in light intensity for all LED colors. The linearity of this correlation forms the basis for deriving calibration equations, which are essential for converting voltage readings into accurate light intensity values during subsequent measurements.

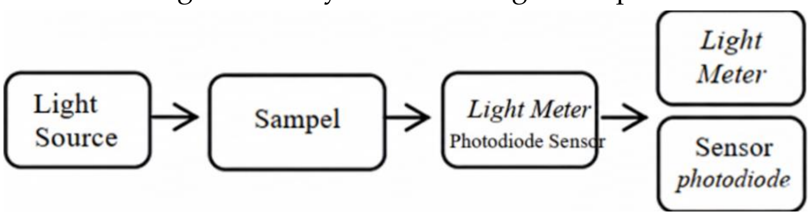

Figure 2. Setup for Light Intensity Measurement Using Light Meter and Photodiode Sensor

Sample preparation was carried out by dissolving 1 g of glucose in 1 L of distilled water, producing a stock solution of 1000 ppm. Subsequent dilutions were made according to Equation (4):

$$V_1C_2 = V_2C_2 \quad (4)$$

The concentrations of the diluted glucose solutions used as samples were: 1000 ppm, 950 ppm, 902.5 ppm, 857.38 ppm, 814.51 ppm, 773.78 ppm, 735.09 ppm, and 698.34 ppm. Each solution was mixed with 10 drops of Benedict reagent and heated at 100 °C before measurement.

Measurement data were obtained for three different light sources: red LED (Table 1), green LED (Table 2), and blue LED (Table 3).

Table 1. Glucose Solution Data Using Red LED

No.	C_H (ppm)	T	A	C_U (ppm)	% Relative Error
1	1000	0.13	0.88	1034.79	3.48 %
2	950	0.26	0.58	898.42	5.43 %
4	857.38	0.30	0.53	868.46	1.29 %
5	814.51	0.36	0.44	806.93	0.93 %
6	773.78	0.42	0.37	758.29	2.00 %
7	698.34	0.45	0.34	733.00	4.96 %

Table 1 presents the measurement results of glucose solutions using a red LED as the light source. The data show that as glucose concentration decreases from 1000 ppm to 698.34 ppm, transmittance (T) increases from 0.13 to 0.45, while absorbance (A) decreases from 0.88 to 0.34. This pattern aligns with the Beer–Lambert law, indicating that solutions with higher glucose concentrations absorb more light. The calculated concentration values (CU) are close to the actual concentrations (CH), with relative errors ranging between 0.93% and 5.43%. The lowest error occurs at 814.51 ppm, suggesting that the red LED provides accurate readings within the mid-range concentration levels. However, slightly higher errors are observed at extreme concentrations, indicating limited sensitivity at very low or very high glucose levels.

Table 2. Glucose Solution Data Using Green LED

No.	C_H (ppm)	T	A	C_U (ppm)	% Relative Error
1	1000	0.13	0.9	973.42	2.66 %
2	950	0.16	0.8	931.6	1.94 %
4	857.38	0.19	0.72	891.57	3.99 %
5	814.51	0.22	0.66	853.26	4.76 %
6	773.78	0.32	0.49	737.06	4.75 %
7	698.34	0.34	0.47	715.79	2.50 %

Table 2 shows the results obtained using a green LED. Similar to the red LED results, a decrease in glucose concentration leads to an increase in transmittance and a decrease in absorbance. The calculated concentrations (CU) exhibit strong agreement with the actual concentrations (CH), with relative errors ranging from 1.94% to 4.76%. The data trend demonstrates that the green LED provides stable and consistent sensor responses across the tested concentration range. Compared to the red LED, the green LED produces smaller fluctuations in relative error, indicating better linearity and stability in the measurement. These findings suggest that the green LED wavelength interacts more evenly with the colored glucose Benedict complex.

Table 3. Glucose Solution Data Using Blue LED

No.	C_H (ppm)	T	A	C_U (ppm)	% Relative Error
1	1000	0.27	0.57	1025.17	2.52 %
2	950	0.36	0.44	929.40	2.17 %
4	857.38	0.45	0.34	842.58	1.73 %
5	814.51	0.48	0.32	815.48	0.12 %
6	773.78	0.56	0.25	751.48	2.88 %
7	698.34	0.59	0.23	727.31	4.15 %

Table 3 presents the results obtained using a blue LED as the light source. The data show a clear trend where transmittance increases and absorbance decreases with decreasing glucose concentration, consistent with optical absorption behavior. The relative errors for the blue LED are the lowest among the three, ranging from 0.12% to 4.15%, with the smallest deviation observed at 814.51 ppm. This indicates that the blue LED provides the most accurate and consistent readings, particularly in the mid-concentration range. The high sensitivity of the blue wavelength to color variations in the Benedict reagent reaction makes it highly effective for detecting glucose concentration differences. Thus, the blue LED demonstrates the best performance in terms of accuracy and reliability.

The evaluation of measurement results was further analyzed by examining the relationship between glucose concentration and optical response. To provide a clearer understanding, the experimental data were plotted to show how transmitted intensity varies with glucose concentration, alongside the corresponding relative error percentage. These visual representations are presented in Figures 3 and 4, which serve to highlight the performance and accuracy of the measurement method.

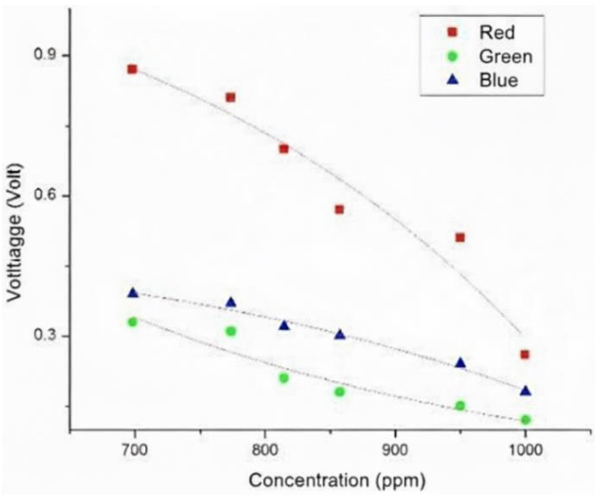

Figure 3. Plot of Glucose Concentration Versus Transmitted Intensity

Figure 3. presents the relationship between glucose concentration and transmitted light intensity for the three LED light sources. The plot shows a negative correlation, where transmitted intensity decreases as glucose concentration increases. This occurs because higher glucose concentrations result in greater light absorption by the colored complex formed in the Benedict reaction. Among the three LEDs, the blue LED demonstrates the most pronounced decrease in transmitted intensity, indicating its higher sensitivity to concentration changes. The green LED provides a relatively smoother trend, while the red LED shows a moderate response. These findings confirm that the optical detection system accurately follows the Beer Lambert principle, in which absorbance increases proportionally with concentration.

Figure 4. Glucose Solutions After Reaction with Benedict Reagent and Heating Process

Figure 4. displays the visual appearance of glucose solutions after reacting with the Benedict reagent and heating. The observed color transition from light yellow to deep orange indicates increasing glucose concentration. The formation of orange cuprous oxide (Cu_2O) precipitate intensifies with higher glucose levels, confirming the presence of reducing sugar. The gradation of color intensity visually corresponds with the quantitative data obtained from the optical sensor, reinforcing that color variation serves as a qualitative indicator of glucose concentration.

The color change to various shades of orange indicates the presence of reducing sugar, with the intensity of the color reflecting differences in glucose concentration.

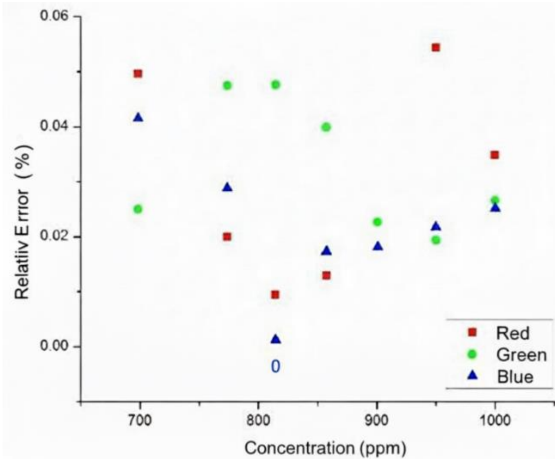

Figure 5. Relationship Between Glucose Concentration and Relative Error Percentage

Figure 5. shows the variation of relative error percentage with glucose concentration for each LED light source. The relative error values remain consistently low, generally below 5%, indicating high reliability of the sensor system. The green LED yields the most stable error values across all concentrations, while the red LED exhibits slightly higher deviations at low and high concentration levels. The blue LED produces the smallest error around 800 ppm, demonstrating superior accuracy within that range. Overall, the results validate that the Arduino-based optical detection system performs accurately and reproducibly, with the blue LED offering the best precision among the tested light sources.

DISCUSSION

Sensor calibration was an essential step in this experiment to establish the relationship between the sensor output voltage and the incident light intensity. This procedure ensured that the photodiode sensor could provide reliable data when exposed to different light sources. The calibration was carried out by comparing the output voltage of the sensor with a standard light meter (LX-101A). The obtained calibration curves showed a clear linear relationship, which was expressed in the following equations:

1. For the red LED source: $I = 9.9168V - 0.1192$
2. For the green LED source: $I = 66.543V + 0.2434$
3. For the blue LED source: $I = 3.569V - 0.0095$

These linear correlations confirm that the photodiode sensor responds proportionally to the incident light intensity, validating its use as a low-cost optical detection system.

In the measurement process, glucose solutions of varying concentrations (1000 ppm to 698.34 ppm) were prepared using the dilution formula ($V_1C_2 = V_2C_2$), followed by the addition of Benedict's reagent and heating at 100 °C. The transmitted light was then measured using red, green, and blue LEDs as light sources. Results showed that the red LED provided the highest absorbance values, ranging from 0.47 to 0.90, indicating a stronger light–sample interaction at longer wavelengths. In contrast, the green and blue LEDs exhibited lower absorbance responses, consistent with the weaker interaction of shorter wavelengths with the glucose-Benedict solution.

The error analysis further revealed that measurements using the green LED produced the highest relative error (1.94%–4.76%). However, the overall relative error across all measurements remained within an acceptable range of 0.12%–5.43%. This finding highlights that while the Arduino-based optical system cannot yet match the precision of laboratory-grade spectrophotometers, it provides sufficiently accurate results for educational, experimental, and preliminary analysis purposes.

Overall, the discussion demonstrates that the Arduino–photodiode system successfully detects glucose concentrations by correlating output voltage with light intensity and solution absorbance. The use of red LED as the light source was shown to be most effective, while the green LED produced the least accurate results. These findings are consistent with Beer–Lambert's law, where absorbance is wavelength-dependent, and confirm the potential of this system as a portable and affordable alternative for glucose concentration monitoring.

CONCLUSIONS

The measurement results showed that yellow light produced a higher output voltage than violet light because glucose solution absorbs violet light more effectively. The absorbance values of glucose solution ranged from 0.34–0.88 for the red LED, 0.47–0.90 for the green LED, and 0.23–0.57 for the blue LED, with an average relative error below 5.43%. The green LED provided the highest absorptivity, while overall concentration measurement errors ranged from 0.12% to 5.43%, indicating that the system performed with good accuracy. The developed Arduino-based optical system offers advantages in control automation, which improves measurement efficiency, and cost-effectiveness, as it uses low-cost electronic components without reducing reliability.

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