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Real-Time Glyphosate Detection Using a Colorimetric Optical Sensor

Khairul Azman Ahmad[1], Noramalina Abdullah[2]*

[1] *Electrical Engineering Studies,*
Universiti Teknologi MARA Cawangan Pulau Pinang, 13500 Permatang Pauh, Pulau Pinang, MALAYSIA
[2] *School of Electrical and Electronic Engineering,*
Universiti Sains Malaysia, Engineering Campus, 14300 Nibong Tebal, Pulau Pinang, MALAYSIA

*Corresponding Author: eenora@usm.my
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Abstract

The availability of clean water is a growing global concern, exacerbated by pollutants such as glyphosate, a common herbicide. Conventional detection methods are often time-consuming and require laboratory analysis, which risks sample degradation. This study introduces the development of an in-situ colorimetric optical sensor for glyphosate detection, providing an integrated, real-time solution. The sensor utilizes a reaction between glyphosate and 2,4-dinitrofluorobenzene (DNFB), producing a yellow-colored compound as an indicator. Food coloring was used to simulate the glyphosate-DNFB reaction product due to laboratory constraints and to demonstrate the proof-of-concept. Although the actual reaction with glyphosate was not carried out, the optical properties of the yellow coloring provide a comparable behavior in terms of absorbance characteristics for sensor calibration purposes. A regression model was developed to estimate glyphosate concentration, and the sensor's performance was compared with a spectrometer, yielding coefficients of determination of 0.9079 and 0.9715, respectively. While the spectrometer showed highlighter accuracy, the colorimetric sensor offers a cost-effective, portable, and reliable method for on-site monitoring, aligning with integrated engineering approaches for environmental management.

1. Introduction

The world is currently facing a crisis in clean water availability (Li et al., 2024). Most water sources, including rivers, lakes, and drainage channels, require prolonged treatment due to contamination from waste, toxic residues, excessive fertilizers, herbicides, and insecticides (Zlati et al., 2024). The escalating use of these chemicals poses a significant challenge, as water treatment processes become time-consuming and may not effectively address high concentrations of pollutants (Zlati et al., 2024; David et al., 2023; Narayanan et al., 2024). Furthermore, it was difficult to sustain the water in the lake and the river.

According to (Wibawa et al., 2010) the rate of usage of herbicides has been studied to control weeds unfortunately, the usage of herbicides has increased year by year. To address this issue, the development of in situ methods for detecting herbicides and insecticides directly in water is essential. In this study, glyphosate has been focused on because it is a commonly used herbicide. In addition to this, glyphosate is carcinogenic to humans and it can enter to food chain, air, and water. In this study, a colorimetric optical sensor simulating glyphosate detection was used. The method involves a chemical that mimics glyphosate's colour response, allowing for intensity measurement through colour change, without using actual glyphosate(Rawat et al., 2023). The process involves mixing glyphosate with a reactive agent, resulting in a yellowish colour. By assessing this colour, the glyphosate

concentration has been quantified in the water. Inspired by prior glyphosate detection techniques using colorimetric methods, a new colorimetric optical sensor was developed to simulate detection via observable colour intensity. Colorimetric optical sensors were highly sensitive and precise in detecting specific chemicals by using principles like fluorescence, absorbance, or colorimetry (Valle et al., 2023; Aydin et al, 2023). These sensors present the possibility of quick on-site readings in the context of herbicides, enabling quicker reactions to contamination incidents (Bombardi et al, 2021). This work aimed to develop a sensing system that can be used for in situ measurement of water quality parameters based on colorimetric approach and light absorbance principles (Aydin et al., 2022). Absorbance is defined as the amount of light a solution can absorb that also known as colorimetric optical density. Absorbance also related with the Beer-Lambert law or known as Beer's law where the characteristics of the medium through which light is moving will affect how much the light is attenuated (Yorozu et al., 1987; Mayerhöfer et al., 2019).

Furthermore, the regression equations and coefficients of determination for two different colorimetric devices, the colorimetric optical sensor and a spectrometer were compared. While both methods yield valuable insights, the colorimetric optical sensor demonstrates promising accuracy. The implications of our findings have been discussed and concluded with recommendations for further research.

2. Methodology

The flowchart for designing a colorimetric optical sensor for measuring the colour that simulates the concentration of glyphosate is shown in Figure 1. In the flowchart, the first objective is to design the sensing device, then for next objective is to prepare the sample preparation and calibration, and lastly, do the testing, data collecting, and data analysis. The yellow food coloring matches the visual response of glyphosate's reaction with DNFB, which similarly results in a yellow solution. This approach allows the system to be tested under safe and accessible laboratory circumstances while keeping applicability to real glyphosate detection. Although this offers a suitable first testbed, it ignores any matrix effects and interferences present in actual environmental samples. Future studies will include actual glyphosate testing to further evaluate the sensor's real-world applicability.

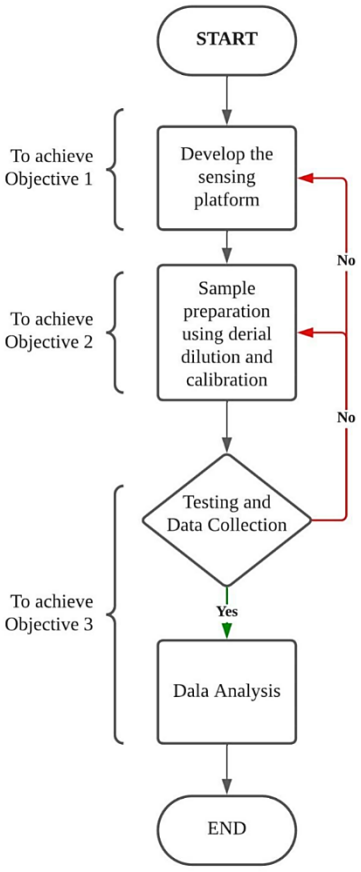

Fig. 1 *Overall design flow*

Int. Journal of Integrated Engineering Vol. 17 No. 5 (2025) p. 350-362

2.1 Developed Sensing Device

A colorimetric optical sensor was developed to sense the colour of liquid and transduced it into voltage or current which differentiate the detected colour. The detected colour measured using the technique translating colour variations in the characteristics of light manner, like absorption or reflection, into electrical impulses that are quantifiable and interpretable. A colorimetric optical sensor was depended on the light source, which offers the illumination required for the sample contact (Duy et al., 2011). Its function is to permit light to travel through the coloured solution whose absorbance need to be measured. The colour wheel for selecting the LED's colour as the light source is displayed in Figure 2 below.

Fig. 2 *Colour wheel*

The performance and specificity of the colorimetric optical sensor or colorimeter are strongly influenced by the properties of the light source (Raja and Sankaranarayanan, 2007). Pairs of colours known as complementary colours combine to create white light. This phenomenon has its origins in the subtractive colour model, which calculates colours by deducting certain light wavelengths (Nhivekar et al., 2022). The wavelengths of light of colour sample were not meant the sample colour have been absorbed when it passes through. Addition of that, the colour was seen as a product of either reflected or transmitted light. Thus, the maximal absorption of light intensity can be attained by selecting the appropriate light source. The blue colour LED was used as a light source for the liquid colours for yellow. When light passes through a medium (such as a liquid), it can be absorbed, transmitted, or scattered. The colour of the liquid affects how it interacts with light. In the absorption case, the yellow liquids absorb certain wavelengths of light (such as blue and violet) while allowing others to pass through, then in transmission case, the transmitted light will consist of the wavelengths that were not absorbed by the liquid. The behaviour of transmitted light through a liquid can be quantified using the Beer-Lambert law. This law describes the relationship between the intensity of transmitted light, the concentration of the absorbing substance (the yellow liquid), and the path length through the liquid. Mathematically, it is expressed as in Equation 1:

$$I = I_0 \cdot e^{-\alpha cd} \tag{1}$$

where:

(I) is the intensity of transmitted light.
(I_0) is the initial intensity of incident light.
(α) is the absorption coefficient (specific to the liquid and wavelength).
(c) is the concentration of the absorbing substance.
(d) is the path length through the liquid.

Light dependant resistor (LDR) was chosen for light sensor because of their simplicity, cost-effectiveness, and adaptability across various applications. An LDR, also known as a photo resistor or photocell, operates based on the principle of photoconductivity. The principle is when the light falls on the LDR's surface, its resistance is changes accordingly to the light intensity. Specifically, in bright light, the resistance decreases and opposite of that in darkness, the resistance increases (Place et al., 2019). This behaviour allows LDRs to sense changes in ambient light levels. In contrast, the LDR in a light-activated design is positioned to receive the maximum amount of light, which lowers the resistance (Asheim et al., 2014; Place et al., 2019). The circuit was constructed and simulated as shown in Figure 3. The simulation used the context of a colorimeter to forecast the behaviour of the colorimetric optical sensor circuit, which is made up of parts such as light-emitting diodes (LEDs) and light-dependent resistors (LDRs), in response to variations in colour and light intensity. An open-source simulation software called Tinker

CAD was used to model the colorimetric circuit to test and confirm the suggested system's operation as shown in Figure 4. The figure showed the circuit schematic has four primary components: a multimeter, an LED, an LDR, and a 5V power supply.

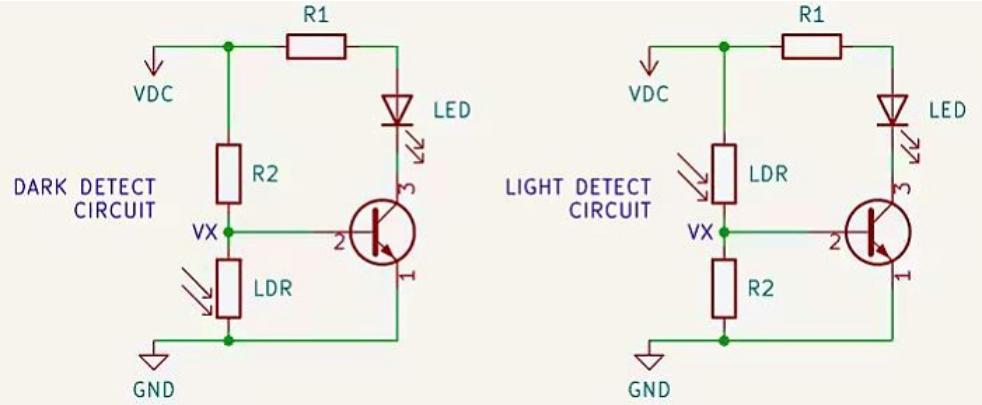

Fig. 3 *LDR configuration, dark-activated mode, and light-activated mode*

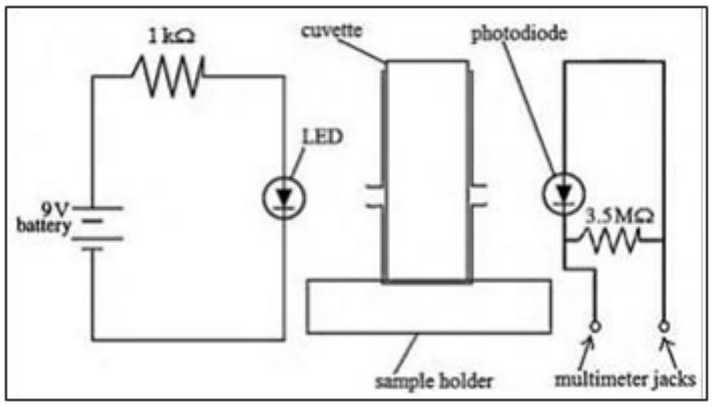

Fig. 4 *Basic circuit of colorimeter*

In simulation, a dark activated configuration detecting scheme was employed as shown in Figure 4 (Place et al., 2019). The higher or lower the output voltage, the lighter that was absorbed between the light source and LDR. The output voltage that results from this was then proportional to the liquid's or material's absorbance between the light source and absorbance. To divide the detected voltage, a resistor is employed as a voltage divider. These different light intensities were used to determine the relevant absorbance values using Equation 2, which controls the voltage generated within the simulated circuit (Mayerhöfer et al., 2019).

$$A = -Log_{10}\left[\left(V - V_{offset}\right) / \left(V_0 - V_{offset}\right)\right] \quad (2)$$

where,
A = Absorbance
V = Voltage obtained for any given solution
V_0 = Voltage obtained with 100% transmittance
V_{offset} = Voltage obtained with no solution

This process is crucial for understanding how the LDR responds to different levels of incident light. The sensitivity and accuracy of the LDR can be enhanced by designers by carefully examining the absorbance values in various simulated light settings (Gordon and Harman, 2002). This will guarantee that the LDR can accurately identify and measure compounds of interest in a variety of environmental settings. The multimeter was used to measure the voltage that the LDR sensed at various brightness levels throughout the simulation procedure. Comprehending the response of the LDR to fluctuations in the intensity of the incident light was contingent upon this stage (Delgado, 2022). The corresponding absorbance values were then manually calculated using Equation

Int. Journal of Integrated Engineering Vol. 17 No. 5 (2025) p. 350-362

2 and the obtained voltage values (Mayerhöfer et al., 2019). An ideal assumption was made regarding V_0, which is the voltage with 100% transmittance and serves as the baseline or reference value, in order to validate the conversion process. By comparing the simulated absorbance values with an expected reference, this assumption makes it possible to verify that the conversion appropriately captures variations in incident light intensity. This validation process is essential for confirming how consistently the colorimeter responds to various lighting situations.

The hardware of colorimetric optical sensor was shown in Figure 5.

Fig. 5 *Optical circuit system (a) External view; (b) Internal view*

The colorimetric optical circuit components, including the LED and LDR, were placed and connected according to the specifications derived from the Tinker CAD model. The black box enclosure was chosen to minimize external interference and ambient light, creating a controlled environment for precise colorimetric optical measurements. The correct arrangement ensured that the incident light, emitted by the LED, interacted effectively with the sample, and was accurately detected by the LDR. Therefore, the strategic alignment of the LED and LDR positions inside this arrangement was important. When the LED emits light, it travels directly towards the sample, and the LDR was positioned to receive the maximum amount of light that interacts with the sample.

2.2 Sample Preparation and Calibration

The sample preparation of solutions contained the target ingredient in known quantities. The solutions have functioned as calibration standards, and the colour they display indicates the substance's concentration. To imitate the glyphosate-DNFB reaction product as referred in Figure 6, we used food coloring in Figure 7 due to lab limits. This substitution was acknowledged in the manuscript for transparency. The yellow food coloring's optical qualities match absorption, allowing us to prove the hypothesis. The food colouring solution was used to simulate the sample solution for glyphosate.

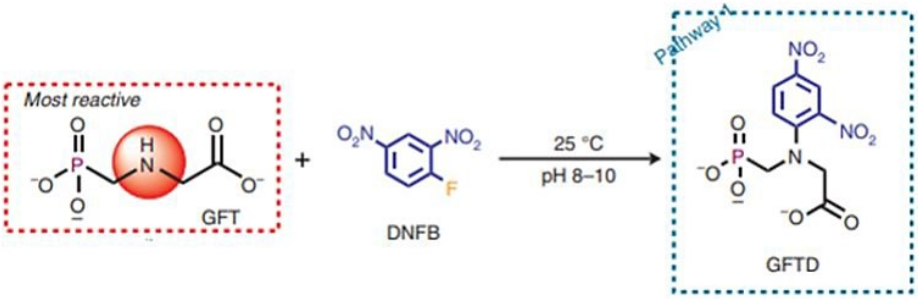

Fig. 6 *Chemical reaction between glyphosate, GFT and 1-Fluoro-2,4-dinitrobenzene, DNFB*

Fig. 7 *Lemon yellow powder*

A concentrated and standardized solution used as a supply of a certain material, usually a solute or reagent, is called a stock solution. The main objective of this solution, which has been made to have a known concentration, is to be diluted in order to obtain solutions with lower concentrations for different purposes. Accurately measuring a known amount of a material, such as a solute or chemical compound, and dissolving it in a predetermined volume of a solvent are the steps involved in creating a stock solution. To guarantee even dispersion of the material, the resultant solution is well blended. In Figure 8, the stock solution utilized is 20 mg/ml. Concentration equation as in Equation 3, which is used to determine a solution's concentration, was used to prepare this solution. Therefore, the mass of sample coloured powder used is 2 g with the volume of 100 ml.

$$C\ (mg/ml) = m(g)\ /\ V(ml) \tag{3}$$

where,
C = Concentration, M
m = mass of the coloured powder
V = volume of solvent

A laboratory technique called serial dilution was used to gradually lower the concentration of a substance in a solution. A series of solutions with lowering concentrations, a known volume of a stock solution was diluted with a solvent. A single stock solution can be serially diluted to produce a range of solutions with concentrations spanning multiple orders of magnitude. This stock solution has been diluted to produce solutions at different concentrations. Equation of serial dilution as shown in Equation 4 were used to determine the volume of stock solution needed for each dilution level once the stock solution was prepared. Furthermore, the proper solution for each concentration level was diluted using concentration of 20M of the stock solution with the volume of each solution equal to 20 millilitres. The concentrations used in this experiment range from 0.5 mol to 5.0 mol with a 0.5 mol increment for each solution, as shown in Table 1.

Table 1 *Volume needed before dilution*

C_2 (M)	V_1 (ml)
0.5	0.625
1.0	1.250
1.5	1.875
2.0	2.500
2.5	3.125
3.0	3.750
3.5	4.375
4.0	5.000
4.5	5.625
5.0	6.250

Int. Journal of Integrated Engineering Vol. 17 No. 5 (2025) p. 350-362

Fig. 8 *The stock solution*

2.3 Data Collection

Data collection was involved with obtaining information from the devices in accurately. The colorimetric optical sensor used information gathered from samples and calibration standards for colorimetric analysis. Data collection throughout the calibration procedure involved measuring the absorbance of solutions with known concentrations which called a reference dataset, and it was demonstrates the relationship between colour intensity and substance content. The quantitative analysis of unknown materials was based on these calibration data. When using the colorimetric optical sensor, data collection was collected the absorbance values that were produced when the device measured the test samples. The samples were prepared using a pipette, which represented the sample under investigation in each experimental trial, and carefully dispensed into a glass cuvette, as shown in Figure 9. A cuvette with a 10 mm path length was used in this instance. The distance light travels through the sample are known as the path length, and it was an important parameter to consider when measuring absorbance. Although a longer path length would require a bigger sample volume, then it also increases measurement sensitivity. On the other hand, a shorter path length can result in less sensitivity but also need less sample volume. A colorimetric optical sensor was optimized to make it more effectiveness which was placed the sample, cuvette, blue LED, and LDR sensor in the black box as shown in Figure 10. This setup was reduced the amount of light interference from outside sources so that the light passing through the sample was a primary light to the LDR sensor.

Fig. 9 *Cuvette with sample solution*

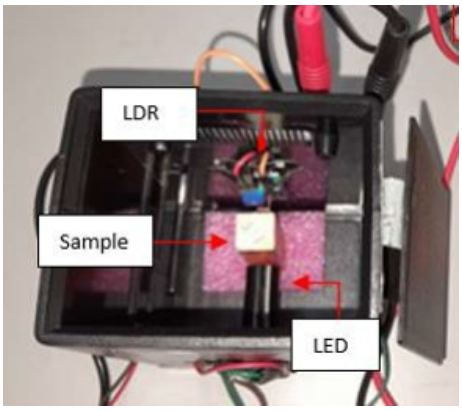

Fig. 10 *The configuration between LED, cuvette and LDR in the test black box*

3. Result & Discussion

The data was arranged and analysed using a methodical and exacting technique. The main goal was to regressive and correlate the data between the voltage, absorbance, and concentration factors. The sets of voltage readings that were derived from the experimental setup were carefully tabulated so that their patterns and variances can thoroughly examined. The collected data was transformed into graphical representations like plots and charts as part of the analytical process. The correlation between voltage, absorbance, and concentration were explored in an understandable and perceptive manner by means of these graphical representations.

The output values of the coloured solution which the absorbance readings were collected three times, then the recorded readings were calculated to became average voltage ($V_{average}$) as shown in Table 2. This data was clarified the dynamic interaction between voltage and absorbance at different concentration. The results highlight a clear trend: absorbance and the recorded voltage of the sample solution both rise in tandem with the concentration as it increases from 0.5 M to 5.0 M. Although actual glyphosate was not used, the yellow food coloring exhibited similar optical absorbance characteristics to those expected from glyphosate-DNFB reactions. This enabled effective sensor development and calibration under controlled, safe laboratory conditions. The concentrations have changed according to absorbance and voltage was showed that the responsive of colorimetric optical sensor towards colour changing. According to the direct relationship, larger concentrations cause greater absorbance, which was reflected in higher voltage measurements.

Table 2 *Data obtained from the handmade colorimeter measurements*

Concentration (M)	Potential (V)				Voffset	Potential with 100% transmittance, Vo	Absorbance (A)
	V1	V2	V3	Vaverage			
0.5	4.09	4.08	4.09	4.09	5.26	1.97	0.45
1.0	4.12	4.12	4.11	4.12	5.26	1.97	0.46
1.5	4.12	4.11	4.12	4.12	5.26	1.97	0.46
2.0	4.23	4.23	4.22	4.23	5.26	1.97	0.50
2.5	4.21	4.19	4.20	4.20	5.26	1.97	0.49
3.0	4.24	4.23	4.22	4.23	5.26	1.97	0.50
3.5	4.22	4.21	4.22	4.22	5.26	1.97	0.50
4.0	4.26	4.25	4.24	4.25	5.26	1.97	0.51
4.5	4.27	4.28	4.27	4.27	5.26	1.97	0.52
5.0	4.32	4.31	4.31	4.31	5.26	1.97	0.54

3.1 Voltage vs Concentration

A graph of relationship between voltage and concentration is shown in Figure 11. The graph demonstrates a clear positive correlation between voltage (V) and glyphosate concentration (M)**.** As the concentration increases from 0.5 M to 5.0 M, the voltage also rises. At a concentration of 0.5 M, the voltage is approximately 4.08 V, increasing to 4.12 V at 1.0 M, and reaching 4.31 V at 5.0 M. This consistent increase highlights the sensor's ability to detect varying glyphosate concentrations accurately. Although slight deviations in individual data points occur, they reflect an approximate 5% margin of error, which is considered acceptable for in-situ measurements. The overall linearity of the voltage response to concentration is significant because it shows a predictable and proportional relationship, simplifying the calibration process. The sensor uses an LED light source to transmit light through the sample solution, where some light is absorbed and the remaining light is refracted and captured by the LDR (Light Dependent Resistor). The LDR converts this refracted light into voltage readings, which correlate directly with glyphosate concentration. As the concentration increases, more light is absorbed, and the LDR, having a high resistance at low light levels, produces higher voltage readings. The linearity observed is critical because it indicates that the sensor produces a consistent and proportional output with changes in concentration, which is beneficial for calibration and prediction purposes. This consistent sensitivity across the range of concentrations ensures the sensor's reliability for both low and high glyphosate levels without frequent recalibration. In conclusion, the sensor's linear voltage response to glyphosate concentration makes it a robust tool for real-time environmental monitoring. This predictability and precision, supported by the data, make it suitable for applications requiring accurate and timely contamination detection.

Int. Journal of Integrated Engineering Vol. 17 No. 5 (2025) p. 350-362

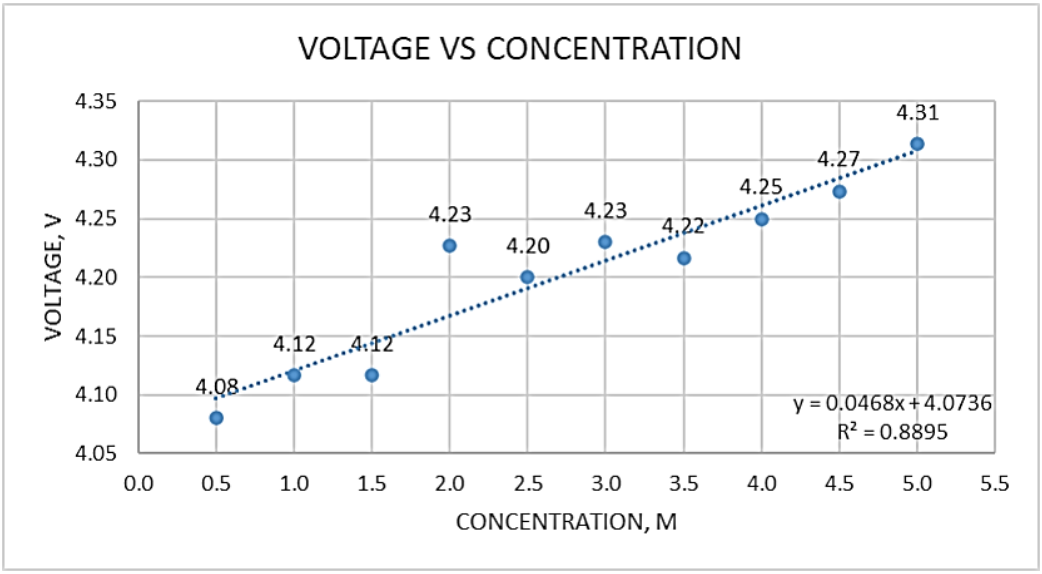

Fig. 11 *Voltage vs concentration wheel*

3.2 Absorbance vs Concentration

Figure 12 illustrates a clear positive correlation between absorbance (A) and glyphosate concentration (M), demonstrating that as the concentration increases from 0.5 M to 5.0 M, the absorbance rises steadily. At 0.5 M, the absorbance is measured at 0.45 A, increasing slightly to 0.46 A at 1.5 M. The absorbance then rises to 0.49 A at 2.0 M, and stabilizes at 0.50 A between 2.5 M and 3.0 M. At 4.0 M, the absorbance increases further to 0.51 A, eventually reaching 0.54 A at 5.0 M. This gradual increase in absorbance with higher concentrations confirms the sensor's reliable and proportional response to different glyphosate levels. The linear trend, with a positive slope, reinforces that as glyphosate concentration increases, absorbance also increases proportionately, validating the sensor's capability to detect changes in the optical properties of the solution effectively. The linear relationship simplifies the quantification of absorbance relative to concentration, enhancing the sensor's predictability and accuracy.

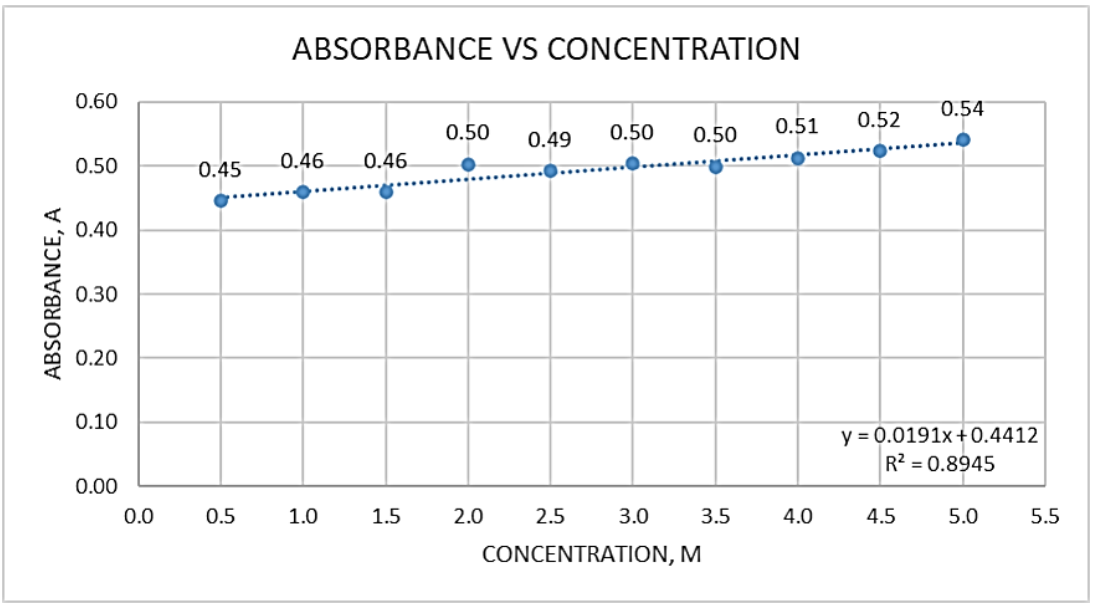

Fig. 12 *Absorbance vs concentration*

This proportionality is crucial for ensuring consistent performance across a wide range of analyte concentrations, a key feature for real-time environmental monitoring. The sensor's sensitivity to even small changes in concentration is underscored by the steady increase in absorbance values, reflecting its capacity to detect minor fluctuations in glyphosate levels. Moreover, the linear trend indicates that this system can be easily

calibrated and interpreted, as changes in concentration are reflected by uniform changes in absorbance. This dependability boosts the sensor's analytical performance, allowing for precise measurements across a broad range of concentration levels. Nonetheless, the graph confirms that the colorimetric optical sensor is effective for accurate and real-time glyphosate detection, making it suitable for environmental applications.

3.3 Spectrometer Data

A spectrometer was used to test colour sample solutions because it allowed for detailed and precise analysis of the spectrum of light absorbed or transmitted by the sample. This experiment yields valuable insights into the chemical composition of the food coloring through the interaction of light with a colored solution. The absorbance and transmittance of the colored sample solution were assessed by the device. The collected data from the spectrometer, as shown in Table 3, showed the intensity, the concentration, and absorbance of the sample solution related to one another. The quantity of light that a sample absorbed was measured by its absorbance. The sample was absorbed more light based when increased of absorbance at higher concentrations.

Table 3 *Data collected using spectrometer for sample concentration*

Concentration, M	Absorbance, A	Transmittance, %T
0.5	2.159	0.7
1.0	2.189	0.6
1.5	2.211	0.6
2.0	2.231	0.6
2.5	2.253	0.6
3.0	2.264	0.5
3.5	2.282	0.5
4.0	2.303	0.5
4.5	2.311	0.5
5.0	2.313	0.5

This phenomenon was followed the Beer-Lambert Law, also known as Beer's Law, which describes the relationship between the absorption of light by a sample and its concentration and path length. Consider to absorption and concentration case, when light passes through a sample (such as a coloured solution), it can be absorbed by the molecules in that sample. The more concentrated the sample is, the lighter it absorbs. The data in the table demonstrates a clear relationship between concentration, absorbance, and transmittance. As the concentration of the solution increases from 0.5 M to 5.0 M, absorbance values consistently rise, starting from 2.159 A at 0.5 M and reaching 2.313 A at 5.0 M, indicating a positive correlation between concentration and absorbance. Meanwhile, transmittance decreases from 0.7% at 0.5 M to 0.5% at concentrations of 3.0 M and above, reflecting the reduction in light transmission as more light is absorbed by higher concentration solutions. The data shows that the sensor is capable of detecting changes in optical properties effectively, with a steady increase in absorbance corresponding to higher concentrations, and a stabilization of absorbance values at higher concentrations, suggesting the sensor's near saturation or detection limit. This consistent pattern highlights the sensor's reliability and sensitivity, especially in lower concentrations, making it suitable for detecting variations in the sample solution.

Figure 13 showed the rising absorbance indicates that the sample was absorbed more light as its concentration increases. This phenomenon is essential to quantitative analysis since it makes it possible to calculate a substance's concentration by measuring its absorbance. A colorimeter and spectrometer are two device that can measure colour using absorption or transmission technique. But the advantages of colorimeter are affordable, portable, and easy to use, meanwhile for spectrometer, it has high sensitivity and dynamic range. A colorimetric is suitable for basic colour measurement applications, but for spectrometer, it preferred for demanding colour measurement applications. An important measure of how well a model, in this example the spectrometer and handcrafted colorimeter, fits the experimental data is the coefficient of determination (R^2). Based on Table 3, an R^2 value of 0.8495 for the handmade colorimeter indicates that the model can account for roughly 84.95% of the variability in absorbance or concentration. This implies a reasonably decent fit, although about 15.05% of the variability is still unaccounted for. By comparison, the spectrometer has a far greater degree of fit, accounting for almost 97.15% of the variability, with a R^2 value of 0.9715. This suggests that there is a strong correlation between the observed concentrations and the expected values. The higher value of R^2 for the

Int. Journal of Integrated Engineering Vol. 17 No. 5 (2025) p. 350-362

spectrometer implies that its measurements are more closely aligned with the true values or expected concentrations, signifying a superior accuracy in comparison to the handmade colorimeter. The value of R^2 can be related to the accuracy and the selectivity of the device. It is used to show how well the performance of both devices

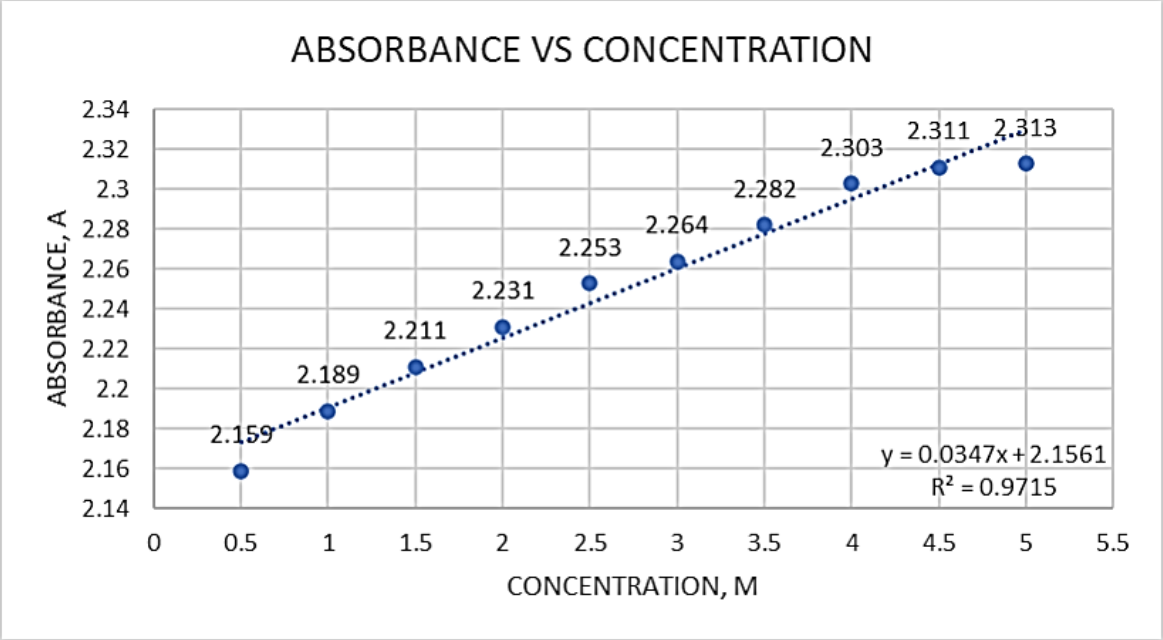

Fig. 13 *Absorbance vs concentration from spectrometer*

Accuracy refers to the closeness of a measured value to the true or expected value. In the context of the measurements, a higher R^2 value suggests a better fit of the data to the model, indicating that the measurements are closely aligned with the true concentrations. Therefore, in terms of accuracy, the spectrometer, with its higher R^2 value (0.9715), is likely providing more accurate measurements compared to the handmade colorimeter (0.8495). A measuring system's selectivity is its capacity to separate the target analyte from other elements in the sample. Although R^2 is usually used to evaluate goodness of fit, selectivity is not directly measured by it. A model that closely matches the data is more likely to capture the precise fluctuations connected to the analyte and be less impacted by other causes, so a higher R^2 value could imply better selectivity. In fact, if the spectrometer is used as a benchmark due to its larger R^2 value, this suggests that the model built from its observations is a more accurate depiction of the concentration-absorbance relationship. As a benchmark for accuracy, the spectrometer's measurements are closely matched with the expected concentrations, as indicated by the greater R^2. Increasing the specificity of the procedure, fine-tuning the calibration model, or changing the experimental setup could all help to improve the homemade colorimeter's accuracy and selectivity. The accuracy and selectivity gap between the spectrometer and the handmade colorimeter can be reduced by examining the variations between the two systems, locating causes of variability, and resolving them.

4. Conclusion

In this study, a cost-effective, real-time colorimetric optical sensor system was successfully developed for the in-situ detection of glyphosate in water samples. The handmade sensor was designed to be lightweight and portable, making it ideal for on-site water quality assessment. The system operates by converting light absorbance into voltage readings, which correlate with glyphosate concentration levels in the sample. The development process involved four key stages: constructing the sensing platform, preparing and calibrating the sample, testing and collecting data, and finally, analyzing the results to establish the system's accuracy. The use of a blue light source, selected for its optimal absorbance of yellow-colored products formed in the glyphosate-DNFB reaction, proved effective in ensuring accurate detection. The relationship between absorbance and voltage was carefully calibrated, and linear regression analyses demonstrated strong correlations between concentration and both voltage (R^2 = 0.8895) and absorbance (R^2 = 0.8495), confirming the sensor's reliability. To ensure consistency, each concentration was tested multiple times, with results showing an error margin of approximately 5% between 0.5M and 5.0M. The calibration curve created from known glyphosate concentrations provides a robust reference for analyzing unknown samples. High absorbance values indicate elevated glyphosate levels, making this sensor an effective tool for monitoring potential contamination. While the sensor showed promising results with a

simulated glyphosate sample, validation using actual glyphosate and real water matrices is necessary to confirm performance in practical scenarios. Future work will include testing with actual glyphosate, optimization of the optical path, and incorporation of wireless data logging for field deployment.

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Conflict of Interest

Authors declare there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm their contribution to the paper as follows: ***study conception and design:*** *Noramalina Abdullah;* ***data collection:*** *Khairul Azman Ahmad and Noramalina Abdullah;* ***analysis results:*** *Khairul Azman Ahmad;* ***draft manuscript preparation:*** *Noramalina Abdullah, Khairul Azman Ahmad. All authors reviewed the results and approved the final version of manuscript.*

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