Indonesian Physical Review
Volume 09 Issue 03, September 2026
P-ISSN: 2615-1278, E-ISSN: 2614-7904

Design of a Portable Colorimetric System Based on the Color Sensor TCS3200 (GY-31) for Detecting the Concentration of Methylene Blue in Solutions

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Article Info

Article info:
Received: 16-01-2026
Revised: 22-06-2026
Accepted: 06-07-2026

Keywords:
Optical colorimetry; RGB sensor; TCS3200 (GY-31); Methylene blue detection; Calibration analysis

How To Cite:
L. T. Permana, M. Siddiq, H. Alatas, E. Rustami, "Design of a Portable Colorimetric System Based on the Color Sensor TCS3200 (GY-31) for Detecting the Concentration of Methylene Blue in Solutions," Indonesian Physical Review, vol. 9, no. 3, p 569-587, 2026.

DOI:
https://doi.org/10.29303/ipr.v9i3.648

Abstract

A low-cost colorimetric system based on an Arduino microcontroller and a TCS3200 (GY-31) RGB sensor was investigated for estimating methylene blue (MB) concentration in aqueous solutions. Measurements were conducted using a transmission-mode optical configuration, in which a white-light source passes through a cuvette with a fixed optical path length, and the transmitted light is detected as a frequency output. The frequency signal was used as a relative indicator of light intensity, and absorbance was calculated as the ratio of the transmitted to the reference frequency. Calibration was performed over a concentration range of 0.1–20 ppm, and the results were compared with those obtained using a UV–Vis spectrophotometer. The system showed an approximately linear response to MB concentration with a coefficient of determination (R^2) of 0.9807. An average relative error of 18% was observed in the validation results, with limits of detection (LOD) and quantification (LOQ) of 3.95 ppm and 13.17 ppm, respectively. The relatively high LOQ is primarily due to the broadband RGB detection characteristics and signal variability of the low-cost sensor system, which limit sensitivity at low concentration levels. Repeated measurements yielded a coefficient of variation below 3%, indicating acceptable short-term repeatability. These results demonstrate the feasibility of the proposed low-cost system for preliminary screening or indicative assessment of MB concentration, particularly at concentration levels close to regulatory limits. Further improvements in optical stabilization, spectral selectivity, and calibration procedures are required to enhance sensitivity and accuracy for broader analytical applications.

Introduction

Methylene blue (MB) is a synthetic thiazine dye widely used in textile processing, aquaculture, and biomedical applications. Its high chemical stability and resistance to natural degradation make MB a persistent pollutant in aquatic environments. Even at low concentrations, MB can pose ecological and health risks due to its intense coloration, potential toxicity, and its ability

to reduce light penetration in water, thereby disrupting photosynthetic activity [1]. Conventional determination of MB concentration is commonly performed using ultraviolet–visible (UV–Vis) spectrophotometry and high-performance liquid chromatography [2]. Although these techniques provide high analytical accuracy, they require expensive instrumentation, trained operators, and laboratory-based procedures, which limit their practicality for rapid or preliminary assessment in resource-limited or field-based settings.

To address these limitations, colorimetric techniques have attracted increasing attention as low-cost and portable alternatives for solution analysis. Colorimetry utilises changes in color intensity as a quantitative indicator of analyte concentration, making it particularly suitable for dyes such as methylene blue that exhibit strong visible absorption [3]. Digital color sensors, such as the TCS3200 (GY-31), enable objective color quantification by converting the intensities of red, green, and blue light components into frequency outputs that can be processed by microcontrollers [4].

Several previous studies have demonstrated the feasibility of TCS3200-based systems for colorimetric applications. Jefriyanto et al. [5] reported the integration of a TCS3200 (GY-31) sensor with an Arduino platform for analytical measurements, while Surbakti et al. [6] showed strong linear agreement between a portable RGB-based system and UV–Vis spectrophotometry for Rhodamine B determination. Similar low-cost RGB sensor approaches have also been applied to detect other colored analytes, including cyanide and food dyes, with promising qualitative and quantitative performance [7].

However, despite these advances, several gaps remain in the application of low-cost RGB-based colorimetric systems for methylene blue analysis. In many previous studies, validation against UV–Vis spectrophotometry is limited or reported only qualitatively, particularly at low parts-per-million (ppm) concentration levels. In addition, important analytical performance parameters, such as the limits of detection (LOD) and quantification (LOQ), are often not explicitly reported. Furthermore, the optical measurement mode (reflection or transmission) and its implications for Beer–Lambert-based absorbance estimation are not always clearly specified, which complicates direct comparison with conventional spectrophotometric methods.

In this work, a low-cost, portable colorimetric system based on an Arduino microcontroller and a TCS3200 (GY-31) sensor operating in a transmission-mode optical configuration is investigated for estimating methylene blue concentration in aqueous solutions. The novelty of this study lies in the quantitative evaluation of a TCS3200-based colorimetric system specifically for methylene blue, with explicit validation against UV–Vis spectrophotometry and systematic reporting of analytical performance metrics. The main contributions include assessing calibration linearity, precision, and accuracy relative to a reference spectrophotometer, and determining LOD and LOQ, providing a clearer picture of the capabilities and limitations of low-cost RGB-based colorimetric sensing for preliminary MB analysis.

Methodology

Design of detection systems

The TCS3200 (GY-31) sensor-based colorimetric system is designed to detect changes in color intensity in liquid solutions. The system consists of four main components: a TCS3200 (GY-

31) sensor, an Arduino UNO module, a white LED high-intensity light source (XHP70.3, Cree LED), and spectral emission spanning 400 nm to 780 nm. The source was powered directly by a stabilized 5V DC supply from an Arduino pin. All liquid samples were contained in a cuvette with an optical path length of 10.0 ±0.1 mm. The measurement is conducted in a transmission configuration, in which light emitted by the source passes through the solution before reaching the sensor. The TCS3200 (GY-31) sensor detects the transmitted light and produces a frequency output proportional to the detected signal intensity [8]. Figure 1(a) and 1(b) show the block diagram and hardware implementation of the developed colorimetric detection system.

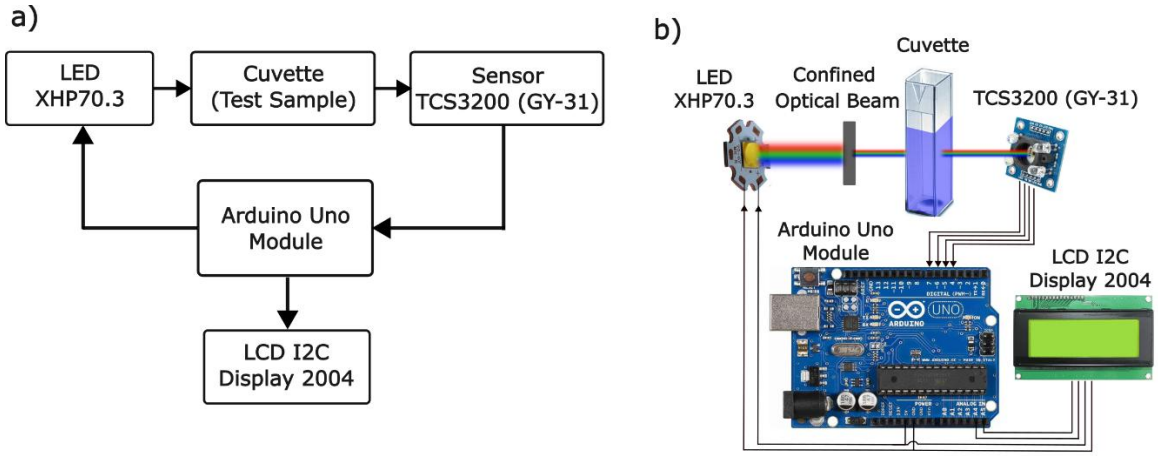

Figure 1. Design of the developed colorimetric detection system: (a) block diagram of the system and (b) hardware implementation.

The optical components were arranged in a fixed geometry to ensure repeatable measurement conditions. The distance between the light source and the cuvette, as well as between the cuvette and the sensor, was kept constant throughout the experiments to minimize variations in illumination intensity and ambient light interference. This fixed configuration enables consistent relative-intensity measurements and supports absorbance-based analysis.

Testing the response of TCS3200 (GY-31) to test solutions

The system output is the frequency (Hz) corresponding to the color intensity of the tested solution. System testing was first conducted using food-dye solutions corresponding to the sensor's primary color channels, followed by methylene blue solutions as the main analyte. For each concentration, frequency data were recorded at ten sampling points with a one-second interval between samples. This measurement procedure was repeated five times for each concentration to improve data reliability. The mean frequency value was used for further analysis. The food dye solutions used in this study were commercially available food-grade dyes (Koepoe Koepoe, Indonesia). The concentration variations of the food dye solutions are presented in Table 1 [9].

The higher concentration range used for food dye solutions was intended for preliminary characterization of RGB channel responses over a broader dynamic range and was not associated with environmental threshold evaluation, unlike the methylene blue analysis. Before each measurement series, a blank distilled water sample was measured to obtain the reference

frequency for zero concentration. Measurements were then carried out using methylene blue solutions prepared by dilution, following the same procedure used for food-dye solutions, ensuring methodological consistency. Commercial methylene blue reagent (ROFA, Indonesia) at a stock concentration of 10,000 ppm (1%) was used to prepare the analyte solutions in this study. The concentration variations of methylene blue used in this study are listed in Table 2. The selected calibration range was designed to cover concentrations around and above the commonly cited 5–10 ppm reference range, as specified in the Decree of the Minister of Environment KEP-51/MENLH/10/1995, while also extending beyond this range to evaluate system performance at lower and higher concentrations.

Table 1: Concentration variation of food dye solutions

Target concentration (ppm)	Source concentration (ppm)	Source volume (ml)	Volume of distilled water (ml)
10.00	1000.00	0.20	19.80
50.00	1000.00	1.00	19.00
100.00	1000.00	2.00	18.00
500.00	1000.00	10.00	10.00
1000.00	1000.00	20.00	0.00

Table 2 Concentration variation of methylene blue solutions

Target concentration (ppm)	Source concentration (ppm)	Source volume (ml)	Volume of distilled water (ml)
0.10	100.00	0.05	49.95
1.00	100.00	0.50	49.50
5.00	100.00	2.50	47.50
10.00	100.00	5.00	45.00
20.00	100.00	10.00	40.00

After testing food dye and methylene blue solutions, the developed system was validated using an SR2 Versatile spectrophotometer (Ocean Insight, USA) with a spectral resolution of approximately 1.5 nm operated in transmission mode under comparable optical conditions, as the reference instrument. The spectrophotometer was operated in transmission mode using a cuvette holder under measurement conditions comparable to those of the colorimetric system. Sensor frequency outputs were converted into absorbance values using the Beer–Lambert approach and compared directly with spectrophotometric absorbance values to evaluate system accuracy and agreement with standard laboratory measurements [9].

Data Analysis

The analytical procedure was designed to quantitatively evaluate the performance of the TCS3200 (GY-31) color sensor and validate its measurements against a reference spectrophotometer. The analysis specifically focused on determining key analytical performance parameters, including sensitivity, linearity, precision, and detection capability, in order to assess the reliability of the proposed colorimetric system for quantitative methylene blue detection. The analysis comprised

frequency data processing, optical parameter conversion, calibration modeling, performance evaluation, and spectrophotometer-based validation. The calculated parameters were subsequently used to evaluate calibration sensitivity, linearity, precision, and analytical performance of the developed system.

The average frequency value was calculated from repeated measurements to obtain a representative response for each concentration level. The standard deviation was used to evaluate signal stability and measurement repeatability during repeated measurements [10][11]. The sensor response was normalized relative to the reference measurement to estimate the transmitted light intensity through the sample solution. Absorbance values were estimated from the ratio between transmitted and reference frequency signals following Beer–Lambert-based proportionality [9][12]. The resulting absorbance estimates were further analyzed to evaluate concentration-dependent response characteristics and calibration performance.

Prior to calibration analysis, the sensor response was verified to operate within its linear dynamic range under the selected transmission optical configuration and illumination conditions. No signal plateau or clipping behavior was observed across the investigated concentration range, indicating that the sensor was not operating in saturation. This confirms the validity of using frequency as a surrogate for light intensity in the present analytical setup. Calibration curves were constructed by linear regression between absorbance and concentration

$$A = mC + b \tag{1}$$

where m represents the sensor sensitivity and b is the intercept, indicating the system's baseline response. The goodness-of-fit was evaluated using the coefficient of determination, a standard approach in analytical calibration [13][14]. Calibration sensitivity was determined from the slope of the linear regression curve obtained for each sensor channel [15]. For methylene blue, the standard error of regression was calculated as [16]

$$\sigma = \sqrt{\frac{\sum \varepsilon^2}{n-2}} \tag{2}$$

and used to determine the analytical detection limits. The limits of detection (LOD) and quantification (LOQ) were estimated using the standard deviation of the blank signal and the slope of the calibration curve following standard analytical chemistry approaches [16].

$$LOD = \frac{3.3\sigma}{m} \tag{3}$$

$$LOQ = \frac{10\sigma}{m} \tag{4}$$

The calculated analytical parameters were subsequently used to assess the suitability of the proposed system for concentration-dependent detection and preliminary screening applications. The selected calibration range of 0.1–20 ppm was chosen to encompass both low-level detection capability and regulatory thresholds for dye contamination in water systems. While regulatory

limits are typically set at 5–10 ppm, this study included lower concentrations to evaluate the proposed system's sensitivity for early detection and screening. Therefore, the developed colorimetric device is primarily intended as a preliminary monitoring tool capable of detecting both low-level contamination and concentrations above regulatory limits.

The obtained calibration characteristics were subsequently compared with spectrophotometric measurements to assess the correlation trend and analytical capability of the proposed system. Validation of the developed colorimetric system was performed by comparing sensor-derived absorbance values with spectrophotometric absorbance obtained using the SR2 Versatile spectrophotometer. The relationship between sensor-derived absorbance and spectrophotometric absorbance was evaluated using linear correlation analysis expressed as [17]

$$A_{spectro} = mA_{sensor} + b \quad (5)$$

where $A_{spectro}$ represents spectrophotometric absorbance, and A_{sensor} represents absorbance estimated from the portable RGB-based system. This comparison was used to evaluate the analytical consistency and correlation trend between the developed colorimetric device and the laboratory reference instrument [18].

Results and Discussion

Final System Configuration and Performance

Figure 2 shows the assembled portable colorimetric system with a fixed optical alignment between the white LED, cuvette, and TCS3200 (GY-31) sensor. This configuration reduced ambient light interference and provided stable signal acquisition, which is essential for quantitative colorimetric measurements. Compared to previously reported open RGB-based systems, the enclosed design improved measurement repeatability while maintaining system simplicity.

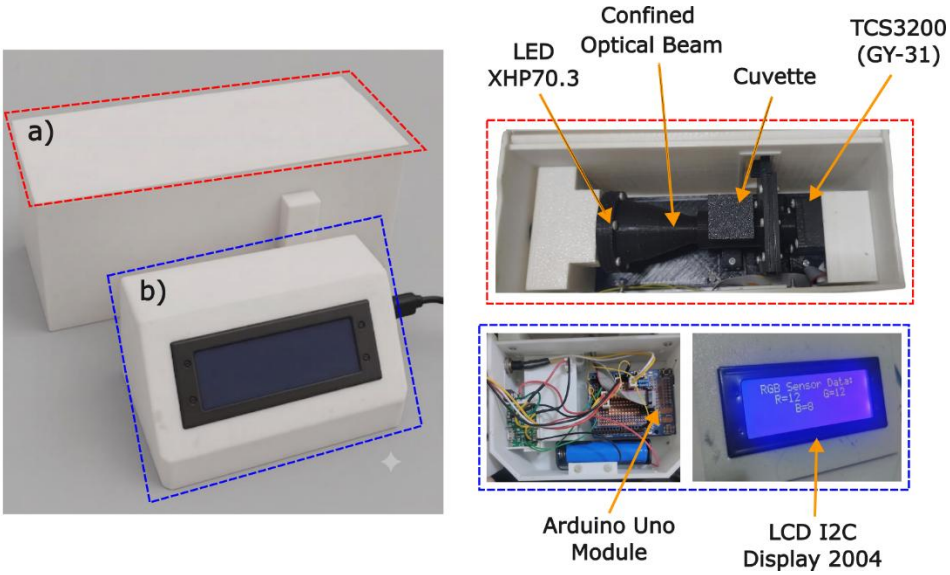

Figure 2 Complete color detection system: a) optical compartment, b) electronics compartment

Figure 2(A) represents the optical compartment of the developed system. The distances between optical components were carefully fixed to maintain optimal sensor performance, with a separation of 5 cm between the light source and the cuvette and 3 cm between the cuvette and the TCS3200 (GY-31) sensor, in accordance with manufacturer recommendations [8]. Excessively short distances may lead to nonuniform illumination or sensor saturation, while larger separations reduce transmitted light intensity and degrade measurement accuracy. Positioning the sensor closer to the cuvette is therefore advantageous for minimizing signal loss and improving measurement reliability, as also reported in previous optical system studies [19].

Figure 2(B) illustrates the electronics compartment, which is responsible for sensor operation, data processing, and real-time result display. The Arduino UNO acts as the main controller for acquiring frequency signals from the TCS3200 (GY-31) sensor, which detects red, green, and blue light intensities using color-filtered photodiodes. The photocurrents generated at characteristic wavelengths of approximately 620 nm, 540 nm, and 450 nm are converted into frequency outputs by an internal current-to-frequency converter circuit [8]. These signals are captured using the 16-bit timer on the ATmega328P microcontroller and converted to calibrated RGB values, which are subsequently displayed on the I2C 2004 LCD module [20].

The combined stability of the optical configuration and the reliability of the signal acquisition process directly influence the precision and linearity of the sensor response. This system architecture serves as the basis for the calibration results discussed in the following section, in which the quantitative relationship between color intensity and solution concentration is evaluated.

Results of Sensor Response Testing

Initial tests were performed using diluted liquid food dyes corresponding to the primary color channels of the TCS3200 (GY-31) sensor, followed by measurements using diluted methylene blue solutions prepared according to Tables 1 and 2. Figure 3 summarises the sensor's frequency responses to both food dye and methylene blue samples, which form the basis for the response analysis discussed below.

The frequency response of the TCS3200 (GY-31) sensor to varying concentrations of four different solutions, as shown in Figures 3(a–d), exhibits a consistent decrease in output frequency across all RGB channels with increasing sample concentration. This behavior reflects the reduction in transmitted light intensity due to increased optical absorption. In Figure 3(a), corresponding to the red solution, the red channel maintains the highest frequency response, as the solution exhibits a dominant response in the red wavelength region while the green and blue components experience stronger attenuation, consistent with the principle of selective absorption in colored substances [9][21]. At low concentrations, the blue channel occasionally showed slightly higher frequency values due to overlapping broadband sensitivities among the RGB channels and minor fluctuations in transmitted light intensity under dilute conditions. However, as the concentration increased, the dominant absorption characteristics of the red solution became more pronounced, resulting in the expected channel-dependent response trend.

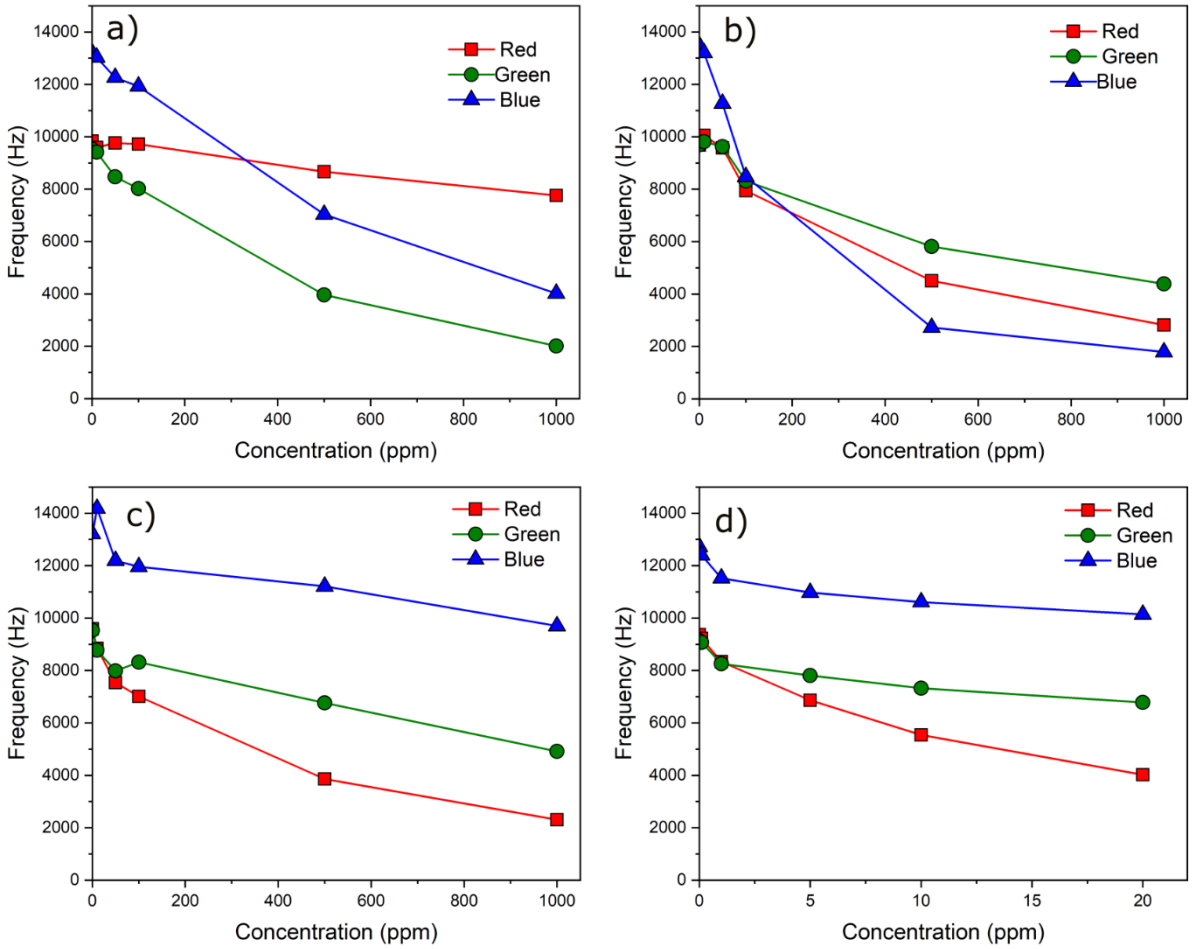

Figure 3 TCS3200 (GY-31) sensor response test results (a) red solution response, (b) green solution response, (c) blue solution response, (d) methylene blue solution response

In Figure 3(b), representing the green solution, the blue channel shows the largest frequency decrease due to stronger absorption in the shorter-wavelength region, whereas the green channel exhibits a more gradual decline because green wavelengths dominate the detected signal [22]. Similarly, Figure 3(c) shows that for the blue solution, the red and green channels experience greater frequency reductions due to increased absorption at longer wavelengths, while the blue channel retains the highest frequency response, indicating its higher sensitivity to blue wavelengths [23].

A distinct response pattern is observed in Figure 3(d) for the methylene blue solution. Unlike the primary color solutions, methylene blue exhibits a strong absorption band in the red region at approximately 660–670 nm, leading to a pronounced decrease in frequency in the red channel [24][25]. Consequently, the red channel demonstrates the highest sensitivity to variations in methylene blue concentration, whereas the green and blue channels retain higher residual frequency responses due to weaker absorption at shorter wavelengths.

Calibration Curves

Calibration curves relating absorbance to concentration were used to evaluate the linearity and sensitivity of the sensor for each solution and RGB channel, as shown in Figures 4(a–d).

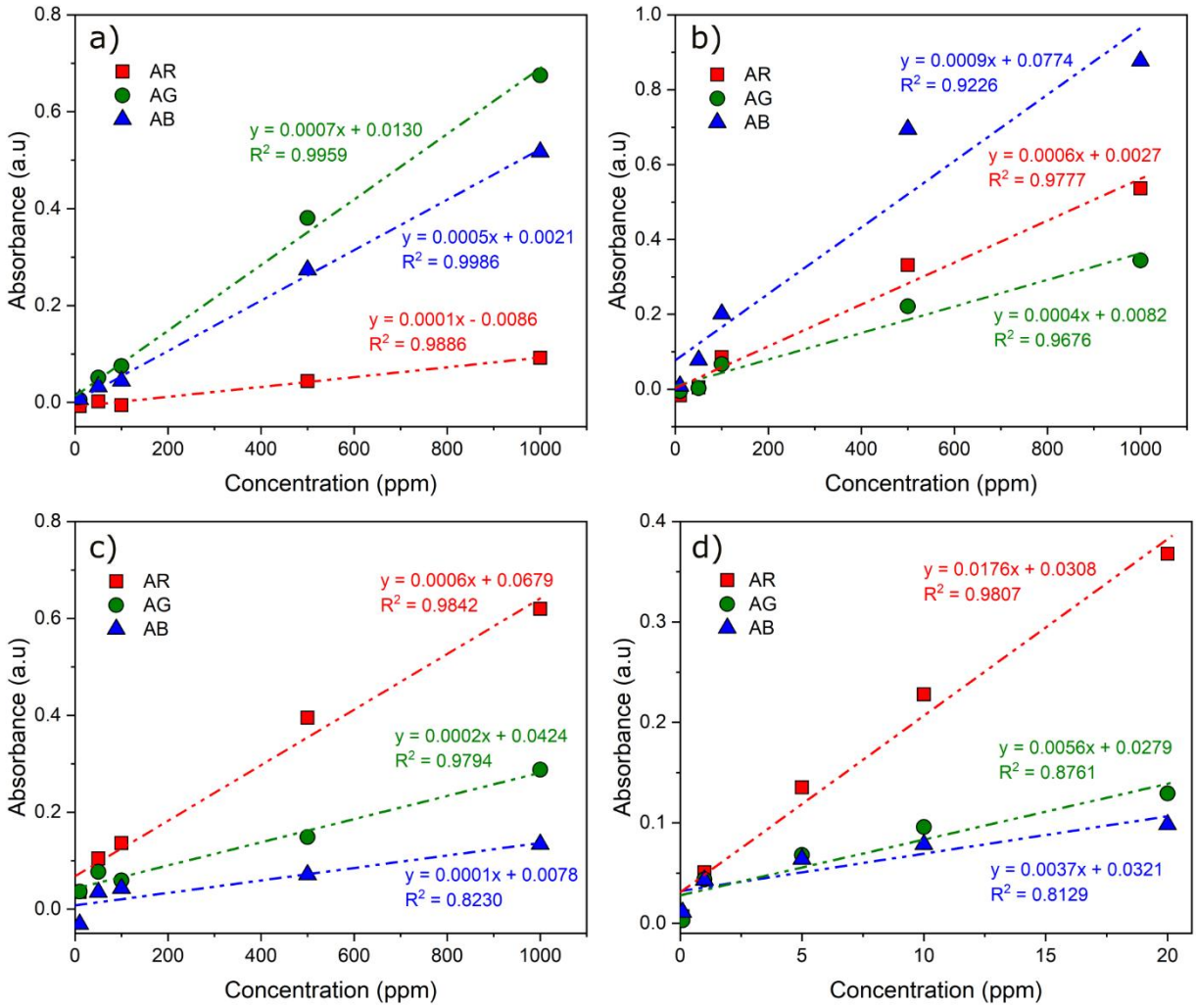

Figure 4 Sensor calibration curves (absorbance versus concentration), where AR, AG, and AB represent absorbance values derived from the red, green, and blue sensor channels, respectively: (a) red solution calibration, (b) green solution calibration, (c) blue solution calibration, and (d) methylene blue solution calibration.

Figure 4(a) presents the calibration behavior of the red food dye solution. The higher sensitivity observed in the green channel is consistent with the absorption of complementary wavelengths by the red food dye solution. Similar channel-dependent responses have been reported in recent RGB colorimetric studies, in which green channels show higher sensitivity for red food-dye quantification due to stronger attenuation of green light [26][27]. Figure 4(b) shows the calibration curves for the green food dye solution, where the blue channel exhibits the largest slope and strong linearity. This behavior agrees with recent reports indicating that a green food-dye solution preferentially absorbs shorter-wavelength components, resulting in enhanced sensitivity in the blue channel when using low-cost RGB sensors [28][29].

In Figure 4(c), corresponding to the blue food-dye solution, the red channel shows the highest sensitivity and linearity. This result is consistent with the strong absorption of longer wavelength light by blue food dye solutions and has been widely observed in portable colorimetric instruments employing RGB sensors for quantitative analysis [26][27]. Figure 4(d)

presents the calibration curves for methylene blue. A significantly higher slope is obtained in the red channel, confirming that this channel is the most sensitive for methylene blue detection. This behavior is consistent with the strong absorption band of methylene blue in the red wavelength region around 660–670 nm, as reported in recent spectroscopic and sensor-based studies [30][31].

Overall, the calibration results demonstrate that the analytical performance of the TCS3200 (GY-31) based colorimetric system is governed by the spectral absorption characteristics of the analytes. These findings are consistent with recent developments in portable RGB-based color sensors and support the applicability of the proposed system for quantitative colorimetric analysis [28][29].

Comparison with Spectrophotometric Measurements

A comparison between the TCS3200 (GY-31) sensor and a reference spectrophotometer was performed to evaluate the accuracy of the developed system. Absorbance values obtained from the sensor after frequency-to-absorbance conversion were directly compared with spectrophotometric measurements, demonstrating the portable system's ability to reproduce the responses of a standard instrument. The comparison was conducted for both food dye solutions and methylene blue, with the results for the red dye presented in Figure 5.

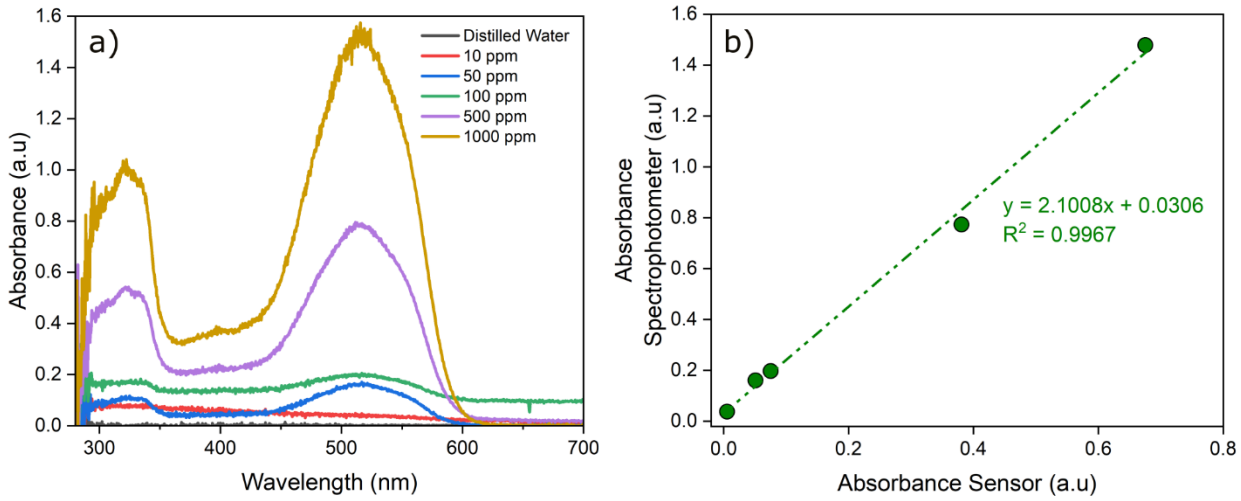

Figure 5 Testing of red dye solution (a) red dye spectrum (b) correlation of sensor absorbance values with spectrophotometer

In Figure 5(a), the spectrophotometric spectra exhibit increasing absorbance with concentration in the visible region, which serves as a reference for evaluating sensor performance [32]. Figure 5(b) shows a strong linear correlation between sensor-derived absorbance and spectrophotometric absorbance, indicating good agreement between the two methods [26]. The absorbance values obtained from the portable RGB-based system represent relative absorbance estimates derived from frequency-based transmittance calculations and therefore may differ in magnitude from spectrophotometric absorbance values. Consequently, the analysis primarily focuses on the correlation trend and concentration-dependent response rather than absolute absorbance equivalence between the two measurement systems. The green channel shows the closest correspondence with the spectrophotometer results, reflecting its higher sensitivity to the red dye than the red and blue channels [33]. This channel-dependent agreement confirms that selecting an appropriate RGB channel is critical for achieving accurate quantitative

measurements and supports the use of the optimal channel for subsequent calibration and analysis [34][35]. Next, the comparison of green solutions is shown in Figure 6.

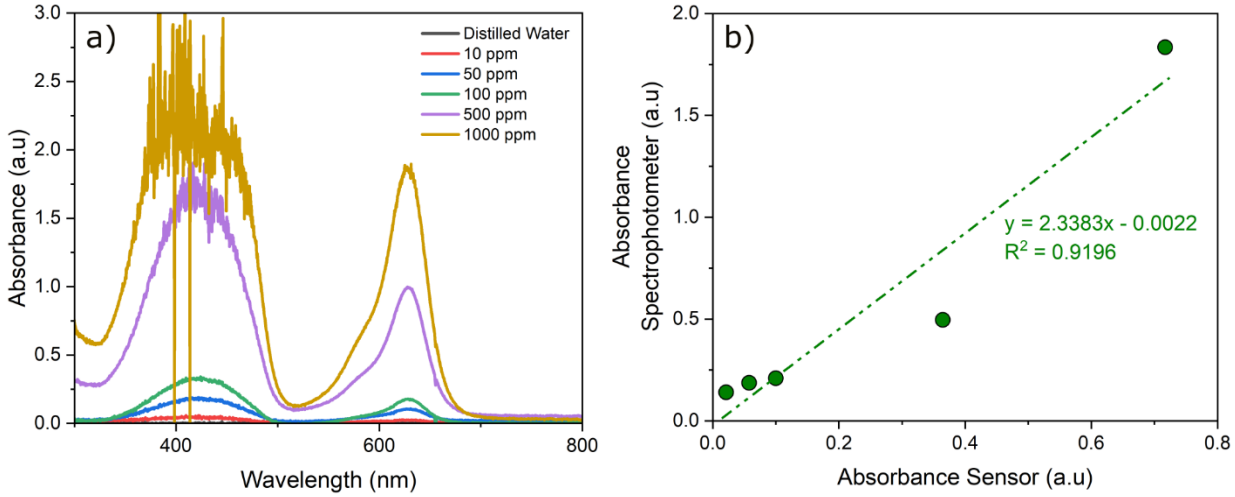

Figure 6 Testing of green dye solution (a) green dye spectrum (b) correlation of sensor absorbance values with spectrophotometer

Figure 6(a) shows the spectrophotometric absorption spectra of the green food dye at various concentrations. There is a trend for absorbance to increase with concentration (especially in the visible region, with alternating strong absorption bands at wavelengths complementary to green). This spectral response will serve as a reference for comparing the TCS3200's (GY-31) RGB channels [24][36].

Figure 6(b) shows the correlation between absorbance values obtained from the sensor and those measured by the spectrophotometer. A generally linear relationship is observed, although the green channel shows slightly lower linearity than the responses obtained with the red and blue food dye solutions. This behavior may be attributed to overlapping spectral responses between the green and blue RGB channels, as well as the broader absorption characteristics of the green food dye solution. Nevertheless, the green channel still demonstrates the closest correspondence with spectrophotometric absorbance among the RGB channels, indicating its relatively higher sensitivity for green food dye detection [37][38]. However, the green channel exhibited a lower R^2 value than the other channels, which may be attributed to broader spectral overlap and reduced channel selectivity during green dye detection. This result suggests that channel selection plays an important role in improving measurement performance and calibration accuracy in RGB-based colorimetric systems [39][40]. For a comparison of blue solutions, see Figure 7.

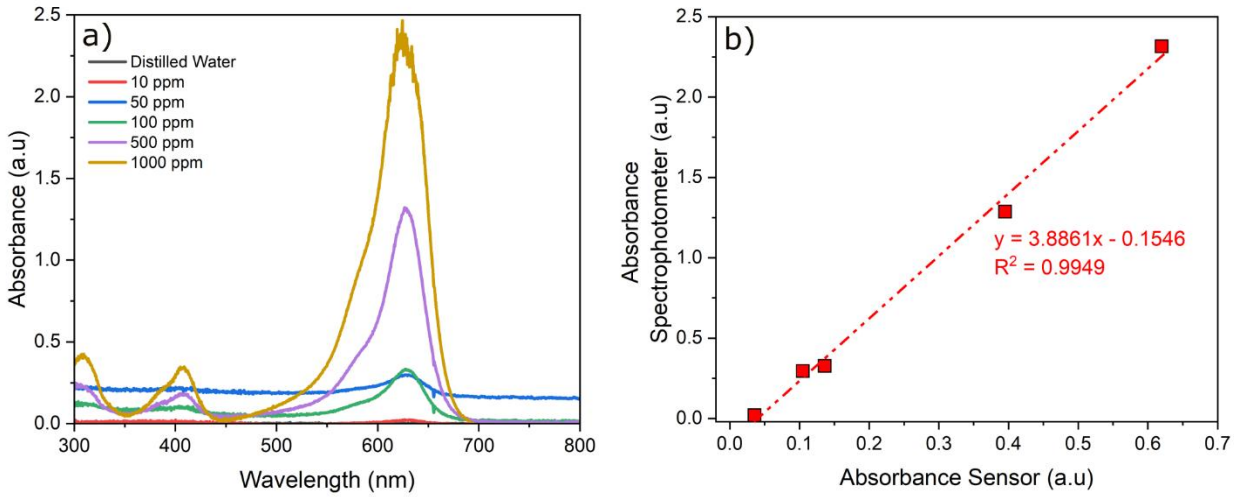

Figure 7 Testing of blue dye solution (a) blue dye spectrum (b) correlation of sensor absorbance values with spectrophotometer

Figure 7(a) shows the absorbance spectra of the blue food dye measured using a spectrophotometer, where the absorbance peak increases clearly with concentration, particularly in the red wavelength region. This confirms that the blue dye strongly absorbs longer wavelength light, providing a suitable basis for channel-specific evaluation [41][42]. Figure 7(b) demonstrates a generally good correlation between sensor-derived absorbance and spectrophotometric absorbance, with the red channel showing the closest correspondence due to its higher sensitivity to the blue food dye [43][44]. Although the portable sensor does not provide full spectral resolution, the optimal channel enables it to reliably reproduce spectrophotometric trends, highlighting its suitability for quantitative screening while acknowledging its limitations compared to laboratory-grade instruments [45][46]. Overall, the absorbance values estimated by the RGB-based system were generally lower than those obtained with the spectrophotometer, due to the system's broadband detection and optical losses in the portable setup. The final comparison for system testing is the main analyte, namely, methylene blue (MB), shown in Figure 8.

Figure 8(a) shows a clear absorption maximum in the red wavelength region around 660–670 nm, with absorbance increasing proportionally with concentration [47]. The constant peak position across concentrations indicates Beer–Lambert behavior, confirming that the optical response is dominated by concentration-dependent absorbance rather than spectral shifting or aggregation effects [48][49].

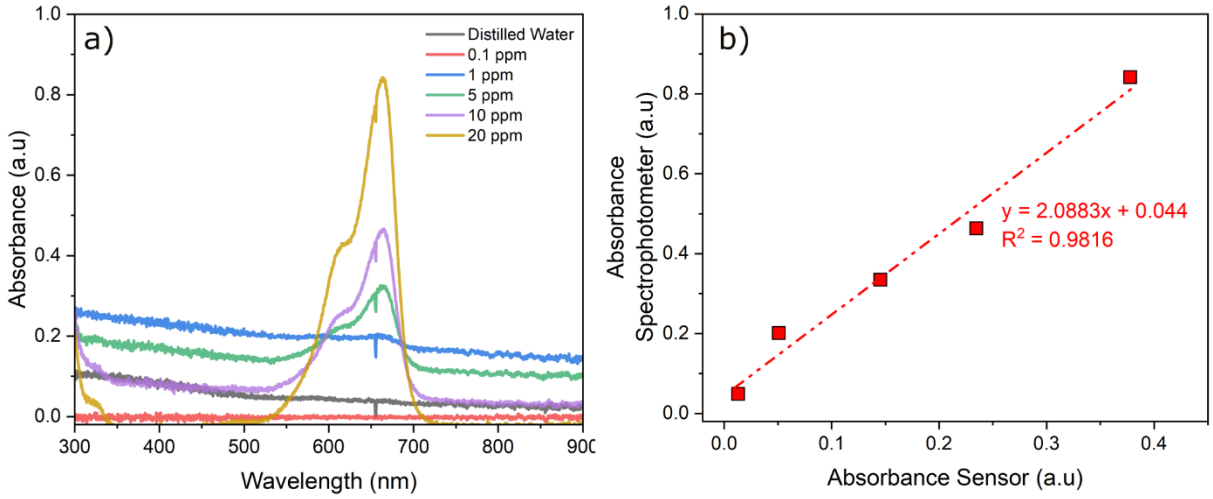

Figure 8 Testing of methylene blue solution (a) methylene blue spectrum (b) correlation of sensor absorbance values with spectrophotometer

As shown in Figure 8(b), the red channel exhibits the highest correlation and sensitivity relative to the green and blue channels [25][50]. This response arises from the strong spectral overlap between the red channel of the TCS3200 (GY-31) sensor and the main absorption band of MB, resulting in pronounced attenuation of transmitted red light as concentration increases. The reduced sensitivity observed in the green and blue channels reflects their limited interaction with the MB absorption band [31].

These results confirm that spectral matching between the analyte and sensor channel is the primary factor governing analytical performance. Although the RGB sensor lacks narrowband spectral resolution, the strong red-channel correlation indicates that it can reliably reproduce spectrophotometric trends for quantitative methylene blue analysis over the investigated concentration range. In general, the absorbance values estimated by the portable RGB-based system were lower than those measured using the reference spectrophotometer. This difference is mainly due to the broadband nature of RGB detection, which integrates light over a wider wavelength range than the monochromatic spectral measurements performed by the spectrophotometer. Additional factors, such as optical losses, stray light, and non-ideal sensor spectral sensitivity, may also contribute to the lower absorbance estimates observed in the portable system.

System Performance Evaluation

To further evaluate the analytical performance of the developed colorimetric system, a quantitative assessment was conducted using key performance parameters derived from the calibration and validation results. These parameters include sensitivity, linearity, precision, accuracy, and detection capability, which collectively describe the reliability and applicability of the system for concentration measurements. The performance evaluation was carried out separately for food dye solutions and methylene blue to account for differences in spectral characteristics and channel responses. The resulting metrics are summarised in Tables 3 and 4 and discussed in detail to highlight the influence of channel selection and analyte properties on overall system performance.

Table 3. Evaluation of system performance against food dye solutions

Solution	Best Channel	Sensitivity ± SD (Slope)	Linearity (R^2)	Precision ($\overline{CV}$%)	Accuracy (Average Error)
Red	G	$0.0007 \pm 1.54 \times 10^{-5} A/ppm$	0.9959	2.20%	8.20%
Green	B	$0.0009 \pm 3.53 \times 10^{-5}$ A/ppm	0.9226	2.06%	39.00%
Blue	R	$0.0006 \pm 1.09 \times 10^{-5} A/ppm$	0.9842	2.62%	44.00%

Table 3 summarises the performance of the TCS3200 (GY-31) sensor for food dye detection based on analytical parameters including sensitivity, linearity, precision, and accuracy. Sensitivity and linearity were obtained from the slope (m) and coefficient of determination of the linear calibration model Eq. (1), consistent with established colorimetric sensor analysis methodologies [26]. Precision was evaluated using the coefficient of variation (CV%), defined as the ratio of the standard deviation to the mean response, while accuracy was assessed through relative error analysis by comparing sensor-derived absorbance with spectrophotometric measurements. The observed variation in optimal detection channels, according to the spectral properties of each analyte, aligns with previous studies showing the importance of spectral matching in RGB-based sensors [26][28]. The consistently low CV values (< 3%) indicate good repeatability and signal stability of the proposed system.

However, relatively large accuracy deviations were observed for certain food dyes (up to 39% and 44%), suggesting limitations of broadband RGB-based detection. These discrepancies are primarily due to spectral channel mismatch between the wide RGB sensitivity bands and the narrow absorption peaks of individual dyes, leading to incomplete capture of peak absorbance. Additional contributing factors include nonlinear sensor response at higher absorbance levels, potential stray light within the optical compartment, and cumulative uncertainties associated with dilution preparation. Therefore, the proposed system is more appropriately positioned as a rapid screening tool rather than a substitute for spectrophotometric-level quantitative accuracy.

Table 4 presents the performance evaluation for methylene blue. The red channel exhibits the highest sensitivity and linearity. The sensitivity (0.0176 *A/ppm*) and coefficient of determination (R^2 = 0.9807) reported were obtained from the calibration curve shown in Figure 4d. Minor variations between tabulated regression parameters and plotted values may arise from rounding during numerical processing and graphical fitting, which are commonly observed in sensor-based calibration analyses and do not affect the overall interpretation of linear behavior. This behavior arises from the pronounced absorption of methylene blue in the red region, where absorbance increases proportionally with concentration, following Beer–Lambert law under dilute conditions [30].

The superior response of the red channel reflects effective spectral matching between the methylene blue absorption maximum at approximately 660–670 nm and the broadband sensitivity of the red photodiodes in RGB sensors. Similar channel-dependent behavior has been reported in recent studies of portable, low-cost colorimetric systems, where optimal channel selection significantly enhances calibration slope and correlation with spectrophotometric measurements [9][11][12]. Although a linear absorbance–concentration relationship was observed, the portable system does not perform spectral measurements; instead, it relies on broadband RGB channel responses. Therefore, the observed behavior should be interpreted as

an approximate Beer–Lambert-type proportionality rather than strict spectroscopic validation, since broadband detection integrates light over a wide wavelength range rather than measuring monochromatic absorbance.

Table 4. Evaluation of system performance against methylene blue

Parameter	Value
Best Channel	R
Sensitivity (Slope±SD)	0.0176 ± 0.0005 *A/ppm*
Linearity (R^2)	0.9807
Precision ($\overline{CV}$%)	3.10%
Accuracy (Average Error)	18.00%
Limit of Detection (LOD)	3.95 *ppm*
Limit of Quantification (LOQ)	13.17 *ppm*

The average error of 18% suggests a moderate correlation trend with spectrophotometric measurements for an RGB-based system and is consistent with previously reported portable colorimetric devices that rely on broadband optical channels rather than monochromatic detection [28]. Although the obtained error values are higher than those typically achieved by laboratory-grade spectrophotometric instruments, the performance remains acceptable for preliminary screening and indicative concentration assessment, particularly in situations requiring rapid, low-cost, and portable measurements rather than high-precision quantitative analysis. Such deviations primarily arise from spectral mismatch effects, non-ideal optical geometry, and the inherent limitations of broadband sensing, which restrict the system from achieving laboratory-grade analytical accuracy. The limits of detection (LOD) and quantification (LOQ) were calculated using the standard deviation of the blank signal and the slope of the calibration curve, as described in Eqs. (3) and (4), yielding values of 3.95 ppm and 13.17 ppm, respectively. This statistical approach for estimating detection capability is widely adopted in analytical chemistry and for validating colorimetric sensors [16].

The obtained detection limits demonstrate that the proposed system can detect methylene blue at concentrations relevant for rapid screening and preliminary environmental monitoring, particularly in situations where laboratory-based spectrophotometric analysis is impractical. The selected calibration range also allows the device to identify concentrations both below and above commonly reported regulatory thresholds, supporting its application as an early-warning screening tool rather than a compliance-grade analytical instrument.

Conclusion

This study demonstrates the feasibility of a low-cost colorimetric detection system based on the TCS3200 (GY-31) RGB sensor for estimating methylene blue concentration. The developed system showed good repeatability (CV < 3%) and a linear response with a coefficient of determination of 0.9807 for the optimal detection channel. The obtained detection and quantification limits were 3.95 ppm and 13.17 ppm, respectively. However, the average error of approximately 18% relative to spectrophotometric measurements indicates that the system is better positioned as a

preliminary screening tool rather than a substitute for UV–Vis analysis. Its main advantage lies in providing rapid, low-cost, and portable indicative monitoring of dye concentration levels. The current system is limited by broadband RGB detection, sensitivity to optical alignment, and relatively high quantification limits. Future improvements may include enhanced optical shielding, fixed measurement geometry, optical filtering, and expanded calibration strategies to improve accuracy and extend detection capability.

Acknowledgment

The authors gratefully acknowledge the Department of Physics, Faculty of Mathematics and Natural Sciences, Institut Pertanian Bogor, and the Research Center for Photonics, National Research and Innovation Agency (BRIN), for providing facilities, instrumentation, and technical support for this research.

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