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Development of Low-Cost Optical Sensor-Based Device for Real-Time Microalgae Concentration Measurement

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Abstract

Conventional methods for measuring microalgae concentration in water require several steps and must be carried out in the laboratory. These measurements are usually performed by counting microalgae filaments under an optical microscope using the Sedgewick Rafter Counting (SRC) method or by spectroscopy, utilizing light absorption by microalgae's chlorophyll. In this study, we propose an innovative and portable spectroscopic device for real-time measurement of microalgae concentration by integrating a light-dependent resistor (LDR) sensor and a microcontroller-based processing unit. The microalgae used in this study were Spirulina, a filamentous microalga from the class Cyanophyceae. The SRC method was used as a reference for measuring Spirulina concentration. UV-Vis spectroscopy data showed that the absorption of chlorophyll a and b was in the range of 400 - 450 nm. The absorption coefficients obtained from the UV-Vis absorbance vs. concentration relationship were in good agreement with those obtained from the logarithmic light intensity vs. concentration relationship across all tested predictive models. We confirmed that the emission spectrum of the LED used was aligned with the dominant absorption of Spirulina chlorophyll, ensuring accurate optical detection of microalgae concentration. The developed device demonstrated rapid estimation of microalgae concentration, with an average accuracy of more than 75%. This study showed that a portable and low-cost microalgae concentration measurement system can be developed using optical sensors and microcontrollers as an alternative to laboratory-based measurements. In addition, the designed device can be integrated with Internet of Things (IoT) platforms, enabling real-time monitoring of environmental conditions for applications such as water quality assessment, aquaculture, and biofuel production.

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Introduction

Monitoring microalgae concentration plays a crucial role in various fields, including aquaculture, water quality assessment, and biofuel production [1], [2]. In aquaculture, uncontrolled microalgae growth can cause ecosystem imbalances, reduce dissolved oxygen levels, and potentially lead to mass mortality of aquatic organisms [2], [3] In environmental monitoring, increased microalgae concentration is often an indicator of eutrophication caused by high levels of nutrients such as nitrogen and phosphorus from anthropogenic activities [3], [4]. Additionally, in biofuel production, monitoring microalgae concentration is necessary to In addition, in the biofuel production process, monitoring of microalgae concentration is required to ensure efficient growth and optimize biomass production [1], [2]. Therefore, an accurate, fast, and field-applicable measurement method is needed to support this application.

Currently, conventional methods for measuring microalgae concentration fall into two main categories: optical microscopy-based methods and UV-Vis spectrophotometry. One commonly used microscopy technique is Sedgewick Rafter Counting (SRC), where microalgae cells are manually counted under a microscope using a counting chamber [5], [6] While this method can provide reasonably accurate results, it is time-consuming, requires skilled personnel, and is prone to subjective errors. Meanwhile, UV-Vis spectrophotometry measures microalgae concentration based on light absorption by chlorophyll at specific wavelengths, offering a more quantitative approach [7], [8] However, this method requires expensive laboratory equipment and is not always accessible for on-site monitoring [9]. With advances in optical sensor technology and microcontroller-based systems, opportunities are emerging to develop more efficient, portable, and real-time monitoring [10], [11], [12][9]. Light-based sensors, such as Light-Dependent Resistors (LDRs) combined with Light-Emitting Diodes (LEDs), offer a promising alternative for measuring microalgae concentration based on light absorption, correlated with standard methods like SRC and spectrophotometry [13].

Although optical sensors have great potential for water quality monitoring, research that explicitly integrates a low-cost LDR sensor with a microcontroller-based processing unit for real-time microalgae concentration measurement remains limited. Most previous studies have focused on spectrophotometry or fluorometry, which still rely on expensive laboratory equipment and are not always portable [9]. Additionally, many studies on optical sensors for microalgae detection have been limited to laboratory conditions, without validation against conventional methods such as SRC or UV-Vis spectrophotometry. To address this research gap, this study proposes developing a portable spectroscopic sensor system based on LEDs and LDRs, calibrated according to the absorption characteristics of Spirulina chlorophyll. Furthermore, this study will validate the measurement results from the developed device against SRC methods to ensure that the device achieves reliable accuracy for field applications [7].

This study aims to develop a portable optical sensor system using an LDR and LED light source to measure Spirulina concentration in real-time and at low cost. Additionally, the study evaluates the system's performance by comparing its measurement results with conventional methods (SRC). This system is designed to measure light absorption by chlorophyll -*a* and -*b* in Spirulina at specific wavelengths [14], for more accurate and efficient detection. Through this validation, the proposed portable sensor system is expected to provide accuracy comparable to laboratory methods while offering advantages in lower cost, ease of use, and field adaptability [9]. The findings of this study are also expected to open opportunities for

implementing Internet of Things (IoT)-based systems for automated and sustainable water quality monitoring across various aquatic environments[15], [16], [17], [18], [19].

Furthermore, integrating this system with IoT platforms can provide a more advanced solution for remote and automated microalgae monitoring. Microcontroller and IoT-based technologies have advanced significantly across various fields, including environmental monitoring [17], [18], [20]. Microcontroller-based devices enable the integration of multiple sensors with efficient computational capabilities, allowing automated measurement, data storage, and real-time information transmission to cloud-based platforms [12], [21]. In the context of microalgae monitoring, a portable optical sensor system based on microcontrollers can offer a low-energy, cost-effective solution compared to conventional laboratory methods [9], [20]. Furthermore, IoT connectivity enables real-time monitoring data to be instantly sent to user devices, allowing for quicker and more precise decision-making based on up-to-the-minute information [15], [16]. Implementing this technology not only improves efficiency in water quality monitoring but also supports a more sustainable and smart technology-based water management strategy [15], [17], [18], [19].

Theory and Calculation

Spirulina and Its Optical Properties

Spirulina is a free-floating filamentous microalga commonly used in a variety of fields such as aquaculture, biotechnology, environmental monitoring, and for supplements and food/cosmetic applications. Spirulina has a high protein content, fast growth, and can growth in a variety of aquatic environments; Spirulina has attracted significant interest in both research and commercial industries [1], [2]. The ability to accurately measure Spirulina concentrations is essential for optimizing growth conditions, ensuring product quality, and monitoring environmental impacts [3], [4].

One of the main optical properties of Spirulina is its selective light absorption, which is mainly controlled by chlorophyll-*a* and *b* [14]. Spirulina absorbs light in a specific spectral range, with absorption peaks in the blue region (400–450 nm) and the red region (650–670 nm) [22], [23], [24] These absorption characteristics make optical methods, such as light attenuation and spectrophotometry, effective for estimating its concentration in solution. By using this characteristic, a real-time monitoring system can be developed to dynamically track the growth of Spirulina.

Beer-Lambert Law and Optical Absorption

The Beer-Lambert law describes the relationship between light absorbance and concentration in solution [24], [25], [26], [27]. This law is the basis for spectrophotometry and optical sensor design. Because this law provides a theoretical basis for measuring microalgae concentration using variations in light intensity. The Beer-Lambert equation is stated as:

$$ln\left(\frac{I}{I_o}\right) = A = \alpha \cdot d \cdot c \quad (1)$$

With I_o and I Intensity of incoming and received photon energy (lux) by the detector (lux), A absorbance, α absorptivity coefficient (liter/cell.cm), d sample thickness (cm), c sample concentration (cell/liter). In the case of Spirulina concentration measurement, the Beer-Lambert law implies that as the microalgae concentration increases, more light is absorbed,

leading to a decrease in transmitted light intensity. This principle forms the foundation for optical-based microalgae detection systems, including those utilizing LDR sensors.

However, real-world applications of the Beer-Lambert law are often influenced by additional factors such as light scattering, turbidity, and path length variations, which can introduce measurement error [8], [25], [28] These factors necessitate careful sensor calibration and validation against established methods such as a microscopic counting techniques.

Light-Dependent Resistor (LDR) Sensor and LED Light Source

A LDR is an optical sensor whose resistance varies with the intensity of incident light. When exposed to higher light intensity, the LDR resistance decreases, whereas when less light reaches the sensor, the resistance increases. This property enables LDRs to be used in microalgae concentration measurement, where variations in transmitted light intensity correlate with changes in microalgae density.

In the developed system, an LED light source with a wavelength range of 375–440 nm is used. This wavelength was selected because it aligns with the primary absorption peaks of chlorophyll-*a* and *b*, ensuring an optimal response for detecting Spirulina concentration optically [14], [22]. The working principle of the system can be described as follows: the LED light passes through the Spirulina solution, where a portion of the light is absorbed and scattered depending on the cell density. The remaining transmitted light is then detected by the LDR sensor, which responds to variations in light intensity. As a result, the LDR resistance changes according to the amount of received light, allowing the system to estimate the Spirulina concentration accurately.

Sedgewick Rafter Counting (SRC) and UV-Vis Spectrophotometry

The SRC method is a widely used technique for quantifying microalgae concentration microscopically [5], [6]. It is particularly useful for analyzing filamentous microalgae such as Spirulina, where direct cell counting is necessary for determining population density [7]. The SRC method involves using a specialized counting chamber designed to hold a known volume of liquid sample. The counting procedure typically involves pipetting a fixed volume of microalgae solution into the SRC counting chamber, which is then placed under an optical microscope for direct visualization. The microalgae filaments are manually counted within a defined grid area, allowing for the estimation of concentration per unit volume.

This method provides high accuracy and detailed morphological analysis, making it a preferred technique for research, water quality assessment, and aquaculture applications. However, since the process requires manual counting and microscopic observation, it is best suited for controlled laboratory conditions rather than real-time monitoring in the field.

Ultraviolet-visible (UV-Vis) spectrophotometry is a widely adopted analytical technique for measuring the concentration of dissolved or suspended substances based on their light absorption properties [29]. This method relies on the fundamental principle that different substances absorb light at specific wavelengths, allowing for quantitative analysis [7]. In the context of microalgae concentration measurement, UV-Vis spectrophotometry is based on the absorbance characteristics of chlorophyll-*a* and *b*, which serve as indicators of biomass concentration [22].

Bland-Altman Analysis

The Bland-Altman analysis is a statistical approach for assessing the agreement between two measurement techniques, particularly when comparing a new method against an established reference standard [30], [31]. This method effectively evaluates whether a newly developed sensor system can produce results comparable to conventional laboratory methods [32], [33]. The Bland-Altman analysis involves plotting the mean on the x-axis and the difference between the two measurements plotted on the y-axis. Then, he means that bias is determined, representing the systematic difference between methods. Finally, the limits of agreement (LoA) are established, calculated as:

$$\text{LoA} = \text{Mean Bias} \pm 1.96 \times \text{Standard Deviation of Differences}$$

If the majority of data points fall within the limits of agreement (LoA), the new method is deemed reliable and comparable to the reference standard [30], [32]. However, significant deviations at very high or low concentration levels may suggest systematic errors that need further refinement [30], [33].

Experimental Method

Device Components and brief principal measurement

The components (**Table 1**) used are easily available in online and offline markets at affordable prices. The total cost of this device is approximately Rp. 400,000, which, when converted to the exchange rate on April 17, 2025, at 10 AM (1 USD = Rp. 16,822.15), is 25.08 USD. Thus, it can be considered affordable and reasonably priced. The selection takes into account factors such as accessibility, cost-effectiveness, and compatibility with the required electronic systems and software. Before assembly, each component is tested to ensure it meets the required specifications.

Table 1. List of components and functions of the Spirulina concentration measuring device

Components	Functions	Cost (IDR)
Arduino Uno module	Central Processing Unit, controlling the flow of data and instructions	80,000
LED	Light source passed through a liquid containing spirulina	300
LDR	Sensor to measure the intensity of light transmitted by spirulina-filled liquid	500
LCD display	Display notifications, status, or measurement results	40,000
Resistor	Current limiter and voltage divider	1,000
Kuvet	A sample holder to hold the liquid containing spirulina	150,000
Sample housing	Box to place the cuvette or a measurement room to avoid outside light	100,000
Power adaptor	A voltage source to turn on the device	30,000
Project box	Device casing with size (7.5 cm x 10 cm x 3.5 cm)	20,000

Spirulina concentration measurements were performed using the device with simple spectrophotometric principles based on the LDR sensor. The measurement begins by turning on the LED light source, whose rays pass through the Spirulina solution's cuvet before reaching the LDR sensor. This sensor then measures the change in light intensity passed through the solution, which is then converted into a voltage change. The voltage detected by

the LDR is measured using an Arduino microcontroller, which is then used to calculate the resistance value of the sensor. Based on the resistance value, the light intensity passing through the solution is calculated using a previously calibrated approximation equation. The concentration of Spirulina is then calculated as a logarithmic function of the light intensity obtained following the basic principles of the Beer-Lambert law. The results of this concentration calculation are then displayed in real-time on the LCD screen for easy monitoring.

Preparation of Microalgae Concentration

Pure Spirulina platensis cells were used to create 10 samples with varying concentrations. The samples were prepared by dissolving the spirulina seeds in water at different ratios, from 1:10 (10 ml seeds and 100 ml distilled water) to 10:10 (100 ml seeds and 100 ml distilled water). The samples' actual concentration (cell/ml) ($|C|_{SRC}$) was determined using the SRC method. The UV-VIS spectroscopy characterization was conducted to determine the absorbance spectrum of the used Spirulina seeds.

Characterization of Sedgewick Rafter Counting

In this study, the SRC method was used as the standard for determining the actual concentration of Spirulina, considering that Spirulina is a living organism. Therefore, its concentration is calculated based on the number of cells per unit volume.

The first step in this method involves measuring the average filament length of Spirulina and the number of cells within each filament using the microscope (Olympus CX23) integrated into the SRC device (Sedgewick Rafter Counting SR-130). A 1 mL Spirulina solution was used, diluted ten times with distilled water, and shaken to ensure homogeneity. The microscope was set to 40x magnification, and measurements were taken from 60 filaments and 150 cells to determine the average filament and cell lengths. Based on these average values, the number of cells per filament (cells/filament) was obtained, serving as a conversion factor to calculate the number of cells from the filaments observed in subsequent test solutions. Further explanations of the SRC method and the equations used can be found in the theory section.

Characterization of UV-Vis Absorbance and LED Emission Spectrum

The absorbance spectrum of Spirulina was measured using UV-Vis spectroscopy (UV-VIS BEL-PHOTONICS UV-M51) within the wavelength range of 350–700 nm. The wavelength of 384 nm was selected to identify absorbance changes related to variations in Spirulina concentration. This wavelength falls within the absorption range of *a*-chlorophyll in Spirulina and the emission range of the device's light source (blue LED). Absorbance data at 384 nm were compared with Spirulina concentration to calculate the absorbance coefficient, which complies with the Beer-Lambert law.

Meanwhile, the light spectrum emitted by the LED was measured using an Ocean Optics spectrophotometer. Measurements were made by directing the LED light directly onto the sensor probe of the spectrophotometer; then, the numerical spectrum data were recorded and stored via computer for further analysis.

Characterization of Light-Dependent Resistor Sensor

This characterization evaluated the response of the LDR sensor to light intensity variations. The first stage involved testing the sensor's response to different light intensities, where the intensity of a blue LED (used as the light source) was varied by adjusting the variable resistor

(R_v) to control the current passing through the LED (**Figure 1**). The LDR sensor or a lux meter (Solar PMA 2200) is placed alternately at a fixed distance of approximately ~2 cm from the LED; for each variation in light intensity, both the measured intensity and the corresponding LDR voltage (V_{LDR}) were recorded, then converted into LDR resistance (R_{LDR}). The collected data then fit with three different models, Model-1, Model-2, and Model-3 to predict the light intensity received by the LDR sensor as a function of its resistance.

After the initial characterization, the second test tests the response of the LDR sensor to variations in transmitted light intensity caused by different concentrations of Spirulina solution. The LDR resistance values in this experiment were then substituted into Model-1, Model-2, and Model-3 to predict the transmitted light intensity through the Spirulina solutions. The logarithmic relationship between the predicted intensity and Spirulina concentration was then fitted to a linear equation following the Beer-Lambert law to determine the absorption coefficient and the initial LED intensity. Finally, the derived linear equation was used to establish a predictive model for estimating the concentration of test Spirulina solutions

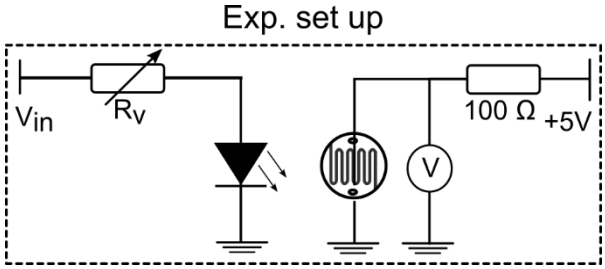

Figure 1. Experimental setup for characterizing the relationship between LDR resistance and variations in the intensity of the blue LED. The LED intensity is adjusted using the variable resistor (R_V)

Electronic Design

Figure 2 shows the complete electronic circuit of the spirulina concentration measuring device, which is based on the Arduino Uno microcontroller. The system is powered by a 9V DC adapter connected to the Arduino Uno board. The onboard voltage regulator on the Arduino steps down the 9 V input to a stable 5 V output, which is then distributed to all components in the system. The Arduino Uno microcontroller operates at 5 V. The LDR and resistor 100 Ω circuit (voltage divider) is powered with 5 V. The analog voltage output from this divider varies based on the intensity of light passing through the spirulina solution, ranges between 0 V and 5 V and is read by the Arduino's analog input pin. The LED as the light source also operates at 5 V and is connected in series with a 270 Ω current-limiting resistor to prevent overcurrent. The 16x2 LCD module, which displays the concentration readings, is powered through the 5 V line and communicates with the Arduino via the I2C interface. Thus, all components in the system—sensor, microcontroller, display, and light source—operate at a regulated 5 V supplied by the Arduino board.

The signal from the LDR sensor is processed using the internal 10-bit ADC (Analog-to-Digital Converter) feature of the Arduino Uno microcontroller, which provides a resolution of 0–1023 over a 0–5 V range. To reduce signal noise and fluctuations, a simple averaging technique is applied: the analog voltage from the sensor is measured five times in succession, and the average value is calculated. This averaged voltage is then used to compute the LDR resistance, corresponding to the amount of light transmitted through the spirulina sample. The resistance value is subsequently used to estimate the spirulina concentration.

To minimize the influence of ambient light, the sample cuvette and the sensor components are enclosed in a closed measurement box integrated into the device casing. This physical shielding effectively blocks external light interference, ensuring that the LDR only detects light emitted from the system's LED source, thereby improving measurement accuracy and consistency.

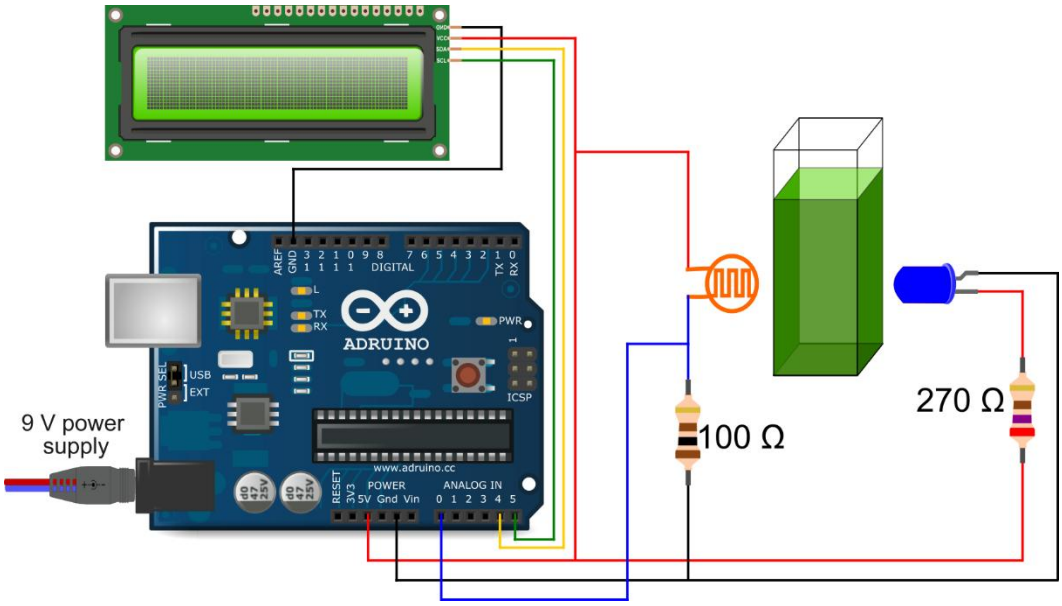

Figure 2. The electronic circuit of the spirulina concentration measuring device. The device uses an Arduino Uno module as the controlling processing unit, an I2C LCD module for data display, and an LDR as a light intensity sensor that detects light passing through the spirulina solution.

Evaluation of Device Performance

The measurement performance of the device was evaluated by comparing its measurement results with those obtained using the SRC method. The measurement results of Spirulina concentration in the test solution by the device and SRC were plotted on a graph; the x-axis is the concentration measured by SRC, and the y-axis is the concentration measured by the device. The true value line in the graph is the concentration measured by the SRC. The more the measurement results are close to the true value line, the more accurately the device can determine the concentration. The measurement results by the device were also analyzed using the Bland-Altman Plot to examine the bias and variability of the difference between the device's and SRC's measurement results. In this graph, the difference between the two measurement methods can be seen on the Y-axis and the average of both on the X-axis. The systematic bias and the Limits of Agreement (LoA) limit can be identified, calculated as the mean difference ± 1.96 SD. The two methods are comparable if most points fall within the LoA. Still, a trend in the difference or many outliers indicates proportional bias or a problem with the measurement method. In general, this method can evaluate alternative measurement methods (by device) without relying solely on their correlation.

Result and Discussion

Characterization of Sedgewick Rafter Counting

The SRC method was chosen as a standard for measuring Spirulina concentration because of its unique filamentous structure [5], [6]. Unlike simple chemical solutions that can be directly quantified using spectrophotometry, Spirulina consists of elongated filaments of multiple cells containing chlorophyll-*a* and -*b* [7]. While these pigments enable optical absorbance-based measurements, filament length and cell density variations can introduce uncertainties in direct optical quantification. To address this, SRC provides a complementary approach by determining the actual number of cells within filaments, serving as a reference for validating concentration measurements obtained through optical methods [28], [34].

As seen in the inset of **Figure 3a**, Spirulina appears as long, thread-like filaments made up of multiple cells. Measurements show that each filament is, on average, about (3 ± 1) mm long, while individual cells measure approximately (2.3 ± 0.8) µm in length, as determined using the SRC method. From these values, it is estimated that each filament consists of around 1,304 cells. This cell count is the essential factor in analyzing optical measurements, as it helps establish a more straightforward relationship between chlorophyll absorbance and the actual Spirulina concentration in the culture medium [14], [35]. Combining SRC data and optical measurements makes it possible to develop a more precise and reliable approach to measuring Spirulina density.

Figures 3(b-c) show the length distribution of both filaments and individual cells. It reveals natural variations in their sizes. The filament length exhibits a distribution centred around 3 mm, with a standard deviation of ±1 mm, suggesting that Spirulina filaments grow to different lengths within the culture. The variation is likely influenced by factors such as nutrient availability, light exposure, aeration, and the age of the culture, as younger filaments tend to be shorter than older ones. However, the primary factor affecting filament length is aeration; if aeration or mixing is too strong or intense, the filaments may remain short. [2], [22]. Similarly, the distribution of the individual cell length follows a pattern with an average of 2.3 µm and a standard deviation of ±0.8 µm. The variation in cell length may be attributed to heterogeneous growth rates among individual cells within a filament and external factors like shear stress, oxygen availability, and competition for resources [36]. Both distributions appear to follow a bell-shaped curve, indicating a normal (Gaussian-like) trend.

The illustration of cell concentration and dilution ratio is shown in **Figure 3d**, where a clear increasing trend in cell count is observed as the dilution ratio decreases. This indicates that the SRC method can accurately capture variations in Spirulina density across different concentrations. The data show as that as the culture becomes less diluted, the cell concentration rises, reflecting the effectiveness of SRC in quantifying Spirulina populations in dilute and dense solutions. This consistency reinforces SRC as a valuable reference method, particularly when combined with optical-based approaches [13].

Visual observation of the samples (**Figure 3e**) showed a color change in the Spirulina culture that supported the observed trend. As the concentration increased, the color of the culture shifted from light green to dark green, which corresponds to a higher chlorophyll content in the denser solution. This shift reflects an increase in the number of Spirulina cells and a corresponding increase in chlorophyll concentration, a key marker of biomass density. The absorbance properties of chlorophyll a and *b* play an important role in the optical

measurement of Spirulina concentration. This principle is utilized by the device developed in this study. Measuring the absorbance of light at specific wavelengths in the chlorophyll absorption region, the device offers a practical and non-invasive method for estimating cell concentration [7], [8].

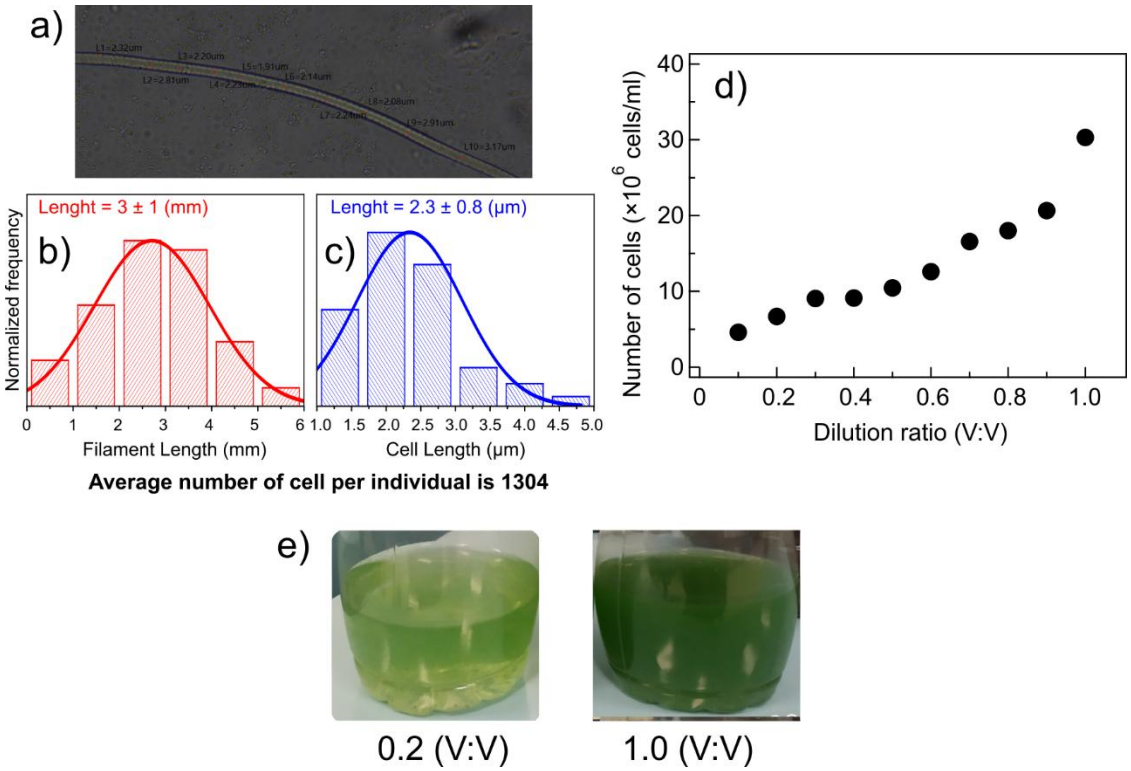

Figure 3. *(a)* Photograph of Spirulina under optical microscope at 40x magnification, *(b)* the distribution of filament length, averaging 3 ± 1 mm, with a red normal distribution curve. *(c)* of cell length distribution, averaging 2.3 ± 0.8 µm, with a blue normal distribution curve. *(d)* The relationship between the dilution ratio (V:V) and the number of cells (cells/mL) shows a clear upward trend as dilution increases. *(e)* photograph of culture samples.

Characterization of UV-Vis Absorbance and LED Emission Spectrum

The absorbance spectrum of Spirulina (**Figure 4a**) reveals its characteristic absorption peaks, primarily influenced by the presence of Chlorophyll-*a* and -*b* [7], [8]. Chlorophyll-*a* and -*b*, the pigments in Spirulina, absorb light most efficiently at wavelengths of approximately 430 nm and 665 nm for chlorophyll-*a*, and 450 nm and 640 nm for chlorophyll-*b*, respectively [22], [23], [24]. This absorption region is important for photosynthetic activity and enhances Spirulina's ability to absorb light. Understanding the nature of this absorption is necessary to design an optical-based detection system to measure its concentration, since the absorption rate is directly correlated with the biomass concentration in the liquid medium.

The emission spectrum of the blue LED (**Figure 4b**) demonstrates a prominent peak around 400 nm, which aligns closely with one of the primary absorption peaks of Chlorophyll in Spirulina [22]. This spectral overlap suggests that the blue LED can be a highly effective

excitation source for optical detection systems targeting Spirulina. Since light absorption is proportional to the concentration of Spirulina in the solution, the blue LED can illuminate the sample, while the photodetector measures the intensity of the transmitted or scattered light. The greater the Spirulina concentration, the higher the absorption and the lower the transmitted light intensity. This relationship forms the basis for developing an optical detection system capable of real-time Spirulina concentration monitoring, which is particularly useful in controlled bioreactors, aquaculture systems, and laboratory-scale biomass assessments [17], [18].

The optical detection system being developed uses an LED light source to transmit light through a Spirulina solution, while a LDR sensor measures the transmitted light. By analyzing the reduction in light intensity caused by Spirulina's absorption, the system can accurately estimate the concentration of Spirulina in a liquid sample. This method offers a non-invasive, real-time, and cost-effective measurement for monitoring biomass concentration that is superior to traditional spectrophotometric techniques that require large equipment. In addition, this LED-based optical detection system can be further refined for applications in environmental monitoring, food production, and biofuel research, where Spirulina concentration is a critical factor in optimizing yield and productivity [9], [16].

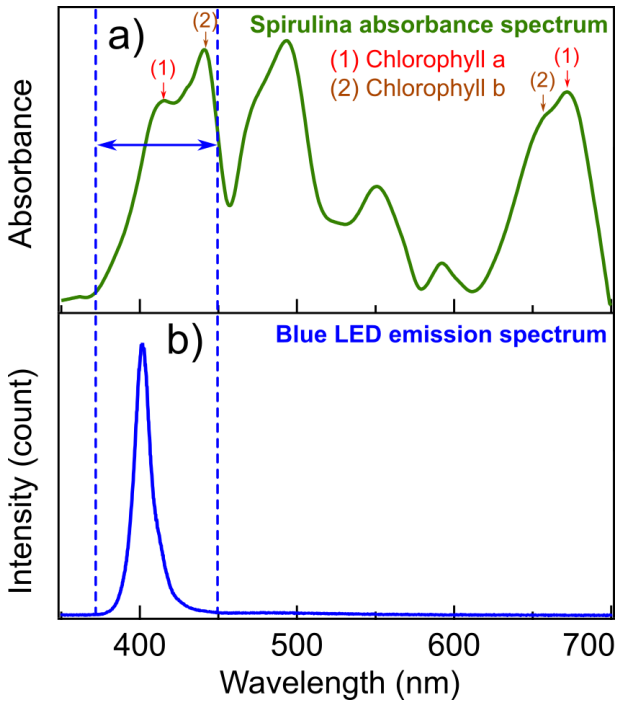

Figure 4. (a) Absorbance spectrum of Spirulina, highlighting characteristic absorption peaks corresponding to Chlorophyll-*a* (marked as (1)) and Chlorophyll-*b* (marked as (2)). (b) Emission spectrum of the blue LED. The absorption peaks at approximately 430 nm and 665 nm indicate strong light absorption by Chlorophyll-*a*, while Chlorophyll-*b* shows absorption at around 450 nm and 640 nm. The peak emission of the LED is around ~400 nm, which overlaps with the absorption region of Chlorophyll-*a*, suggesting its potential as an effective light source for detecting Spirulina concentration.

Characterization of LED intensity V.s Resistance of the Light Dependent Resistor

The LDR used in this study was characterized based on its datasheet specifications [37]. The dark resistance of the LDR is reported to be approximately 1 MΩ, which indicates a high resistance value when the sensor is not exposed to light. The relative spectral response of the sensor is peaked around 540 nm, with a response of approximately 15% at a wavelength of ~400 nm. This suggests that the LDR is well-suited to detect light in the blue region of the spectrum, especially from the 375–440 nm LED used in this work, which falls within the

sensor's operational range. These characteristics confirm the suitability of the LDR for the optical measurement of Spirulina concentration, particularly with blue LED illumination.

Developing a smart device for measuring microalgae concentration based on a low-cost optical sensor and microcontroller requires a deep understanding of the relationship between light intensity, absorbance, and cell concentration. Experimental results show an exponential relationship between light intensity (Lux) and the resistance (R_{LDR}) of the photodetector used (**Figure 5a**). The fitting was performed using three mathematical models (**Table 1**), all showing good agreement with the experimental data. These results indicate that the optical sensor used in this device can detect changes in light intensity passing through a liquid medium, allowing it to be utilized to estimate microalgae concentration based on changes in light transmission due to the cell density of Spirulina in the sample.

Figure 5b illustrates how the LDR resistance (R_{LDR}) increases as Spirulina concentration ($|C|_{SRC}$) rises, indicating that less light reaches the sensor at higher concentrations. This happens because Spirulina cells absorb and scatter light, primarily due to the presence of chlorophyll-*a* and -*b*, which absorb specific wavelengths [22], [23], [24]. The trend of LDR resistance change with concentration is nearly linear, indicating a consistent relationship between cell density and light attenuation, meaning that R_{LDR} can be used as an indirect measure of Spirulina concentration. By applying these data to Model-1, Model-2, and Model-3, the transmitted light intensity can be predicted. These results demonstrate the potential of LDR-based optical sensors as a low-cost, real-time solution for measuring Spirulina concentration. Concentration measurement using LDR sensors offers an alternative to spectrophotometric methods that are in line with the Beer-Lambert law, as further analyzed in **Figure 5c**.

Figure 5c shows the logarithmic transformation of the light intensity predicted using the three models in **Table 2**, which results in a linear relationship with spirulina concentration. A clear linear correlation is observed, where the increase in spirulina concentration corresponds to the decrease in light intensity. Similarly, the relationship between absorbance at the wavelength of 384 nm and spirulina concentration can be approximated by the linear equation, with the y-intercept at zero when x is zero (**Figure 5d**). This linear approach follows the Beer-Lambert law, where the increase in cell density within the medium is directly proportional to the increase in absorbance. From this linear equation, key parameters can be extracted (**Table 3**) to predict spirulina concentration based on changes in light intensity transmitted through the spirulina-containing solution.

Evaluation of Device Performance

Figure 6. presents the comparative analysis of three predictive models (Model-1, Model-2, and Model-3) for estimating the light intensity passed by the spirulina solution, which further determines the Spirulina cell concentration by the developed device. The accuracy and agreement with reference values are evaluated using Bland-Altman analysis. The accuracy of each model is shown in **Figures 6(a-c)**, which shows three models showing an average measurement accuracy of 88.65%, 89.20%, and 86.10%, respectively.

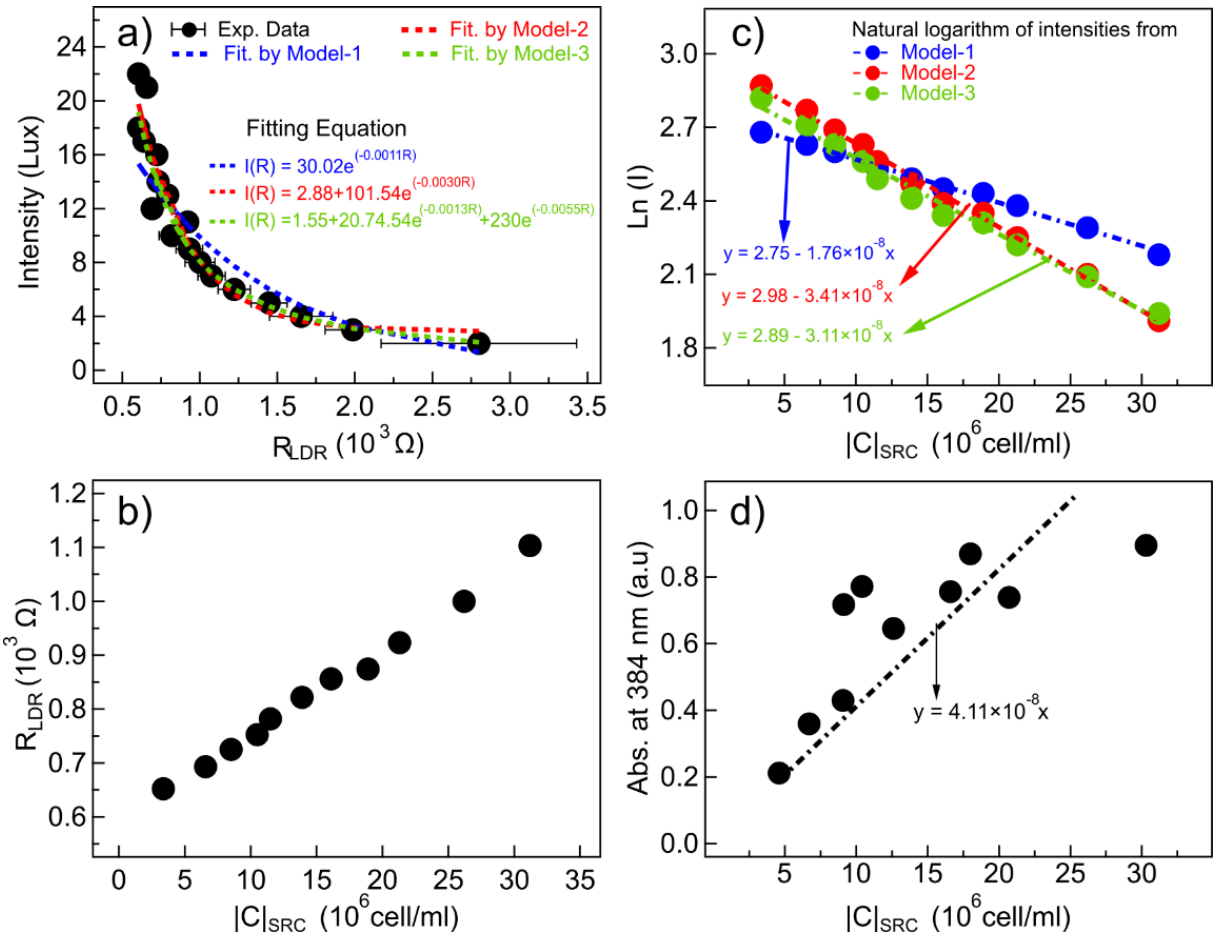

Figure 5. (a) Experimental data (black circles) and fitting curves from three different models: Model-1 (blue dashed line), Model-2 (red dashed line), and Model-3 (green dashed line), illustrating the response of the LDR sensor (R_{LDR}) to variations in LED light intensity. The corresponding fitting equations for each model are also provided. (b) Response of the LDR sensor (R_{LDR}) to variations in transmitted light intensity, which is affected by different Spirulina concentrations in the solution. (c) Logarithmic relationship between predicted light intensity from Model-1, Model-2, and Model-3 and Spirulina concentration ($|C|_{SRC}$), based on resistance values obtained from **5b**. The respective linear fitting equations for each model are shown. (d) Absorbance at 384 nm as a function of Spirulina concentration ($|C|_{SRC}$), with the corresponding linear fitting equation provided.

A closer examination of the extracted parameters (**Table 3**) reveals that the absorption coefficient obtained from the linear prediction equation of the relationship between logarithmic intensity and Spirulina concentration closely approximates that derived from the relationship between absorbance at 384 nm and Spirulina concentration. This consistency in absorption coefficients suggests that the attenuation of blue LED intensity used in the system is primarily due to absorption by chlorophyll-*a*. As shown in **Figure 4**, the emission peak of the blue LED falls within the absorption range of chlorophyll-*a* in spirulina. This result confirms the decrease in transmitted light intensity is influenced not only by scattering but also significantly by the absorption of chlorophyll-*a*, which validates the accuracy and reliability of the optical sensing system in measuring the concentration of Spirulina.

Table 2. Equation for predicting the falling intensity on to the LDR as function of R_{LDR}.

Model name	Equation	R^2 (%)
Model-1	$I(R_{LDR}) = 30.02\ e^{-0.0011R_{LDR}}$	84.65
Model-2	$I(R_{LDR}) = 2.88 + 101.54\ e^{-0.0030R_{LDR}}$	92.49
Model-3	$I(R_{LDR}) = 1.55 + 20.74\ e^{-0.0013R_{LDR}} + 230\ e^{-0.0055R_{LDR}}$	92.87

Table 3. Extract parameters from fitting equations of ln(I) v.s $|C|_{SRC}$ which the intensity was calculated with three models (**Table 2**), representing the logarithmic relationship of the light pass to the sample for varying concentrations, following the Beer-Lambert law. The equation for this fitting is $y = a + bx$ which correspond to equation $ln(I) = ln(I_o) + (\alpha \cdot d) \cdot |c|_{SCR}$

Intensity calculation	Equations ln(I) vs $\|C\|_{SRC}$	a (lux)	b (cell·m/ml·lux)	I_o (lux)	a (cell/ml)
Model-1	$ln(I) = 2.75 - 1.76\ \times 10^{-8}\|C\|_{SRC}$	2.75	-1.76×10^{-8}	15.64	1.41×10^{-8}
Model-2	$ln(I) = 2.98 - 3.41\ \times 10^{-8}\|C\|_{SRC}$	2.98	-3.41×10^{-8}	19.69	2.73×10^{-8}
Model-3	$ln(I) = 2.89 - 3.11\ \times 10^{-8}\|C\|_{SRC}$	2.89	-3.11×10^{-8}	17.99	2.49×10^{-8}
-	$A(\lambda_{384}) = -4.12\ \times 10^{-8}\|C\|_{SRC}$	2.98	4.12×10^{-8}	0	3.30×10^{-8}

Figure 6d compares the predicted cell concentrations from the three models to the actual values ($|C|_{SRC}$), represented by the black reference line. The closer the data points align with this reference line, the more accurate the predictions. The figure shows that all three models effectively capture the reference trend, with data points consistently clustering around the true values, indicaring that the models are good at predicting Spirulina concentrations [30]. Additionally, the distribution of data points indicates that the models maintain strong predictive accuracy across varying concentration levels [31]. While some deviations exist, they remain within the acceptable range. The results confirm that the relationship between LDR resistance and light transmission can be effectively modelled to estimate cell concentrations, supporting the feasibility of using the low-cost optical sensor system for real-time Spirulina monitoring [9], [17], [18].

The Bland-Altman plots in **Figure 6(e-g)** provide a detailed assessment of the agreement between the predicted values and the reference values to measure the reliability of the device for the three models [32]. The solid lines in each plot indicate the average bias, indicating whether the prediction systematically overestimates or underestimates the actual values, the dashed lines deal with the upper and lower limits of agreement (LoA), which serve as a measure of variability between the two methods [31]. The results show all data points fall within the LoA range; it shows the models effectively predict Spirulina concentrations at various levels. This agreement confirms the robustness of the models in estimating Spirulina concentrations based on LDR resistance measurements [33]. However, at both low and high concentration levels, the data points tend to be closer to the LoA boundaries. We assume this phenomenon is likely due to greater variations in the measured R_{LDR} values at these concentration extremes, which could arise from increased light scattering at higher cell densities and sensitivity limitations at lower concentrations.

Despite the variation in the test data, the overall trend shows the model consistent in accurately predicting concentrations across a wide range. The observed biases remain within

acceptable ranges, meaning that even small deviations do not significantly impact the overall prediction accuracy [30], [31]. These results also support the potential application of the developed optical sensor as a low-cost solution for real-time monitoring of Spirulina concentrations, which could potentially be applied in microalgae-based research and wider industrial applications.

Future Prospects: IoT-Enabled Automated Spirulina Cultivation

In the future, integrating these sensors with Internet of Things (IoT)-based systems could enable real-time data collection, remote monitoring, and automated control of microalgae cultivation. With an IoT system, Spirulina concentrations could be continuously monitored, with real-time data sent to a cloud-based platform where users could track trends, receive alerts for critical concentration levels, and adjust growing conditions remotely [3], [15]. This integration would benefit large-scale cultivation setups, such as those in biofuel production, the nutraceutical industry, and wastewater treatment, where maintaining proper microalgae densities is critical to maximizing productivity [1], [19]. In addition to real-time monitoring, IoT-driven automation can also minimize manual intervention and reduce operational costs [19]. By integrating real-time sensor feedback, nutrient settings, and light intensity control, microalgae cultivation could be fully automated. Adding predictive modelling and AI-assisted data analysis could allow researchers and industry professionals to fine-tune growing conditions based on past trends and environmental factors [15], [16], [18]. The combination of affordable optical sensors, predictive modelling, and IoT connectivity could pave the way for intelligent microalgae monitoring systems. This technology has the potential to transform laboratory research and commercial bioproduction, making Spirulina cultivation more efficient, practical, and easier to manage in real-time.

Conclusion

In conclusion, this study successfully developed a portable and cost-effective optical sensor system for real-time Spirulina concentration measurement. The system integrates a LDR sensor and a microcontroller-based processing unit, demonstrating reliable performance with an average accuracy exceeding 75%, using the SRC method as a benchmark. The validation results show that the absorption coefficient measured with UV-Vis spectroscopy closely matches the values obtained through the logarithmic transformation of light intensity. This confirms that light attenuation is a reliable indicator of Spirulina concentration. The system's LED source (375–440 nm) was found to match the key absorption peaks of chlorophyll-*a* and -*b*, ensuring an effective optical measurement approach. Further analysis using Bland-Altman plots showed that the predicted Spirulina concentrations across three models consistently fell within the LoA, supporting the robustness of the optical sensing system. The relationship between R_{LDR} resistance and Spirulina concentration followed a nearly linear trend, with deviations remaining within an acceptable margin. While minor variations were observed at extreme concentration levels, the system maintained a high level of reliability across a wide range of cell densities.These findings confirm the potential of using spectroscopy-based sensors with LDR and LED sources as a practical alternative to conventional laboratory-based methods. In addition, the system offers potential for integration with IoT platforms. Paving the way for real-time monitoring in aquaculture, water quality assessment, and biofuel production applications.

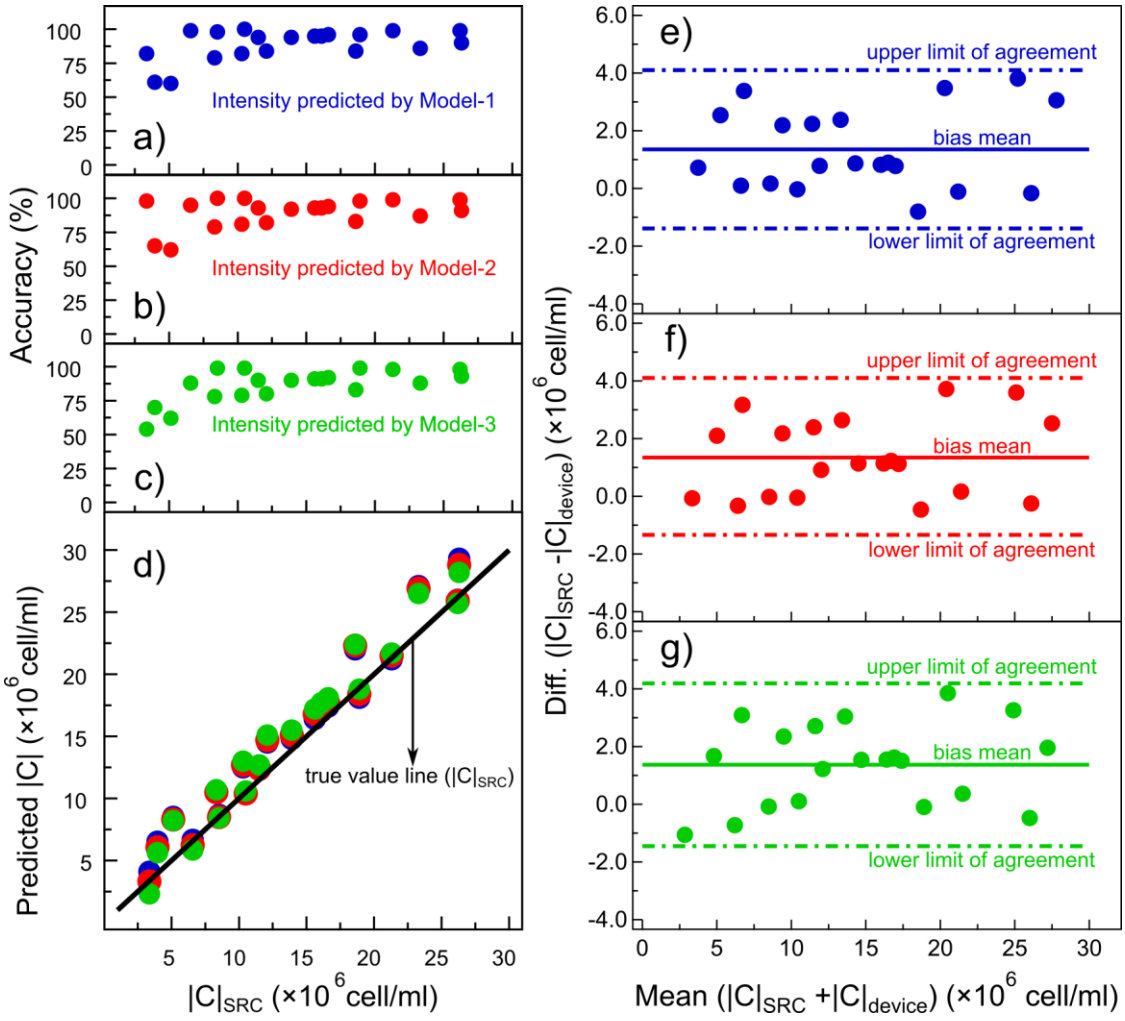

Figure 6. *(a–c)* Accuracy of intensity predictions from Model-1, Model-2, and Model-3, showing their performance in estimating cell concentration. *(d)* Comparison of predicted cell concentrations using the three models against the true concentration values ($|C|_{SRC}$), where the solid black line represents the reference (true value) line. *(e–g)* Bland-Altman plots illustrating the agreement between predicted cell concentrations and reference values for Model-1, Model-2, and Model-3, respectively. The solid lines indicate the bias mean, while the dashed lines represent the upper and lower limits of agreement (LoA). The spread of data points within the LoA provides insight into the consistency and systematic bias of each model.

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