CONTINUOUS MONITORING OF DISSOLVED OXYGEN CONCENTRATION USING LOW-COST MULTISPECTRAL SENSORS

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Abstract

This study proposed an approach for continuously monitoring dissolved oxygen concentration using absorption spectroscopy with a low-cost multispectral sensor. An experimental system was built to investigate the correlation between dissolved oxygen concentration and absorbance of several wavebands in the visible and near-infrared regions. An optimized linear regression model with four wavebands at 460, 485, 585, and 900 nm gave the best prediction results with coefficient of determination and root mean square error of 0.85 and 0.68 mg/L, respectively. The experimental results demonstrated that the proposed absorption spectroscopy with a low-cost multispectral sensor has great potential for continuously monitoring dissolved oxygen concentration in water in a non-contact manner.

Keywords: *Absorption spectroscopy; continuous monitoring; dissolved oxygen; low-cost multispectral sensor; non-contact measurement.*

1. Introduction

Dissolved oxygen concentration in water is an important criterion for evaluating water quality in aquaculture, wastewater treatment, and other environmental parameter measurement applications. Therefore, continuous monitoring of dissolved oxygen concentration in water is essential. Dissolved oxygen measurement methods are often divided into three main groups: iodometric titration, electrochemical, and optical. Among these methods, Winkler titration (iodometric titration) is considered the standard method with the highest accuracy and is measured in the laboratory [1, 2]. Meanwhile, the optical method is more commonly used in practical applications for rapid testing of dissolved oxygen concentration in the field because this method does not consume dissolved oxygen and requires lower maintenance. However, the cost of optical dissolved oxygen sensors is quite high and the accuracy of the sensor is easily affected by ambient light and chlorine concentration in water [3].

To improve the accuracy and other features of the electrochemical and optical methods, some previous studies have tested several approaches. Nguyen *et al.* [4]

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proposed to use of thin film polymers for improving the sensitivity, response time, energy consumption, and cost of electrochemical sensors with an average coefficient of determination of 0.84. Similarly, Vu and Dang [5] also proposed a solution to improve the efficiency of electrochemical sensors by fabricating electrochemical sensors using electrodes made from different materials with an accuracy of 98.7%. For the optical method, Luong *et al.* [6] proposed a solution using low-cost MEMS optical sensor to create a dissolved oxygen device with an accuracy of 94.6%.

In addition, Wei *et al.* [1] have conducted an overview of technical solutions and recent achievements in dissolved oxygen measurement around the world. The overview results of this group indicate that research groups around the world are also focusing on finding new materials to fabricate alternative electrodes in the electrochemical method. For the optical method, most studies have focused on finding highly sensitive materials and more reasonable optical sensor arrangements. In addition, some research groups are also interested in researching smart dissolved oxygen sensors - sensors that can send data wirelessly, process data, and compensate for environmental influences.

Although electrochemical and optical methods are commonly used for field measurement of dissolved oxygen, both of these methods are contact measurement solutions. In these contact measurement solutions, the sensor needs to be immersed directly into the water. This leads to low durability and stability of the sensor due to the influence of temperature, salinity, humidity, and other adverse environmental conditions. Due to high investment costs and being easily affected by environmental factors, these dissolved oxygen measurement solutions have not been widely applied to continuous monitoring of dissolved oxygen in water, especially in aquaculture ponds of households.

To overcome the drawback of immersing the sensor directly into the water when measuring dissolved oxygen, this study proposes a non-contact approach for continuous monitoring of dissolved oxygen concentration using the absorption spectroscopy technique. Absorption spectroscopy is a technique that measures the absorption of electromagnetic radiation when it interacts with a sample. Figure 1 shows the general principle of absorption spectroscopy.

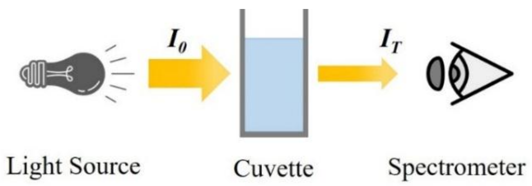


Fig. 1. The general principle of absorption spectroscopy.

The radiant energy emitted from the light source (I_0) can be partly absorbed by the solution placed in the cuvette, resulting in an attenuation in the radiant energy collected at the spectrometer (I_T). This amount of attenuation is often expressed through two quantities: transmittance (T) and absorbance (A). The calculation of transmittance and absorbance is done through (1) and (2) as follows:

$$T = \frac{I_T}{I_0} \tag{1}$$

$$A = -\log_{10}\left(T\right) \tag{2}$$

According to the Beer-Lambert law, the absorbance is related to the optical path length (the width of the cuvette) and the concentration of the solution and is shown in (3):

$$A = \varepsilon l c \tag{3}$$

where l is the optical path length, c is the concentration of the solution in the cuvette, and ε is the absorption coefficient.

Based on the transmittance or absorbance, absorption spectroscopy can be used to provide qualitative and quantitative information about the sample [7]. Miura *et al.* [8] tested the measurement of dissolved oxygen in water using absorption spectroscopy in the ultraviolet region with regression coefficients ranging from 0.8 to 0.99 depending on the type of water. Their results showed that absorption spectroscopy has the potential for non-contact measurement of dissolved oxygen. However, the equipment used in their study was expensive and the use of light sources in the ultraviolet region poses potential health risks. Therefore, the objective of this study was to propose and evaluate a non-contact solution of continuous dissolved oxygen measurement using absorption spectroscopy in the visible and near-infrared regions with a low-cost multispectral sensor. The following sections of this paper will present the experimental methods, data collection, data processing, and evaluation of the proposed solution.

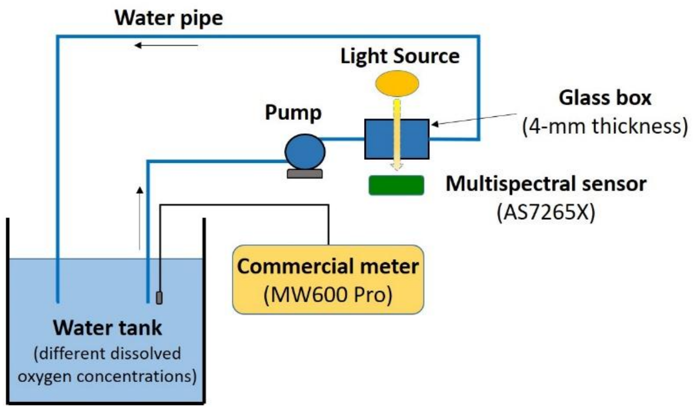
2. Materials and methods

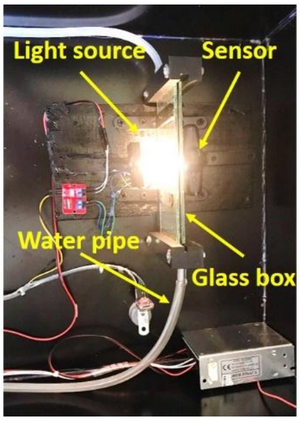
2.1. Experimental system

To evaluate the proposed solution, an experimental system was built with four main components including light source, multispectral sensor, water delivery system, and water tank. Figure 2 shows the layout of the experimental system components.

The light source used in this study was a 5 W halogen lamp from Philips (Model 12961CP). This lamp was powered by a 12 VDC-regulated power supply. A low-cost multispectral sensor AS7265x (https://www.sparkfun.com/products/15050, about

70 USD) from an ams-OSRAM company was used to measure the light intensity after the light source passed through the water sample. This sensor has been effectively used as a low-cost spectrometer in several studies related to absorption spectroscopy [9, 10]. The AS7265x sensor has 18 wavebands covering both the visible and near-infrared regions including 410, 435, 460, 485, 510, 535, 560, 610, 645, 680, 705, 730, 760, 810, 860, 900, and 940 nm [11]. The water delivery system consisted of pipes, a pump, and a transparent glass box. This water delivery system was responsible for continuously pushing water from the water tank to the transparent glass box and then back to the water tank without allowing outside oxygen to enter during the water delivery and measurement process. In this study, the transparent glass box with a 4-mm thickness was placed between the light source and the sensor to help the light intensity remain high enough after passing through the glass box with the water sample. The water tank is a 30-liter plastic container used to hold water samples with different oxygen concentrations.





(a) *(b)*

Fig. 2. Overview of the proposed system (a) and system prototype (b).

2.2. Sample preparation

The water source used in this study was clean water provided by Can Tho Water Supply and Sewerage Joint Stock Company. To actively increase the concentration of dissolved oxygen in the water tank, an aerator with four jets (Resun ACO-001) was used. In addition, placing fish in the water tank with the tank lid tightly closed was applied to reduce the concentration of dissolved oxygen in the tank.

2.3. Data acquisition

• Spectral data

When the light passed through water samples with different dissolved oxygen concentrations, the light intensity was changed and recorded by the AS7265X sensor.

A computer program called *ams_Spectral_Sensor_Dashboard* (provided by the ams-OSRAM company) was used to read and save the light-intensity data to a computer. The light intensity at each water sample was collected 20 times to calculate the average value. The average light intensity was then converted to absorbance using (2). The spectral data (in the form of absorbance) were combined with the dissolved oxygen concentration measured from a commercial meter to build a regression model.

• Reference measurement

To accurately determine the dissolved oxygen concentration in the water sample, a commercial dissolved oxygen meter called the MW600 Pro from Milwaukee company (Milwaukee Electronics Kft., Szeged, Hungary) was used and set up as shown in Fi. 2b. The MW600 Pro meter has a measuring range of 0.0 – 19.9 mg/L and an error of ±1.5% [12]. This meter probe was placed next to the inlet pipe of the water delivery system to ensure that the water sample pumped into the delivery system and the MW600 Pro meter were the same. During the spectral data acquisition, the dissolved oxygen concentration was recorded at three points in time: the beginning of the measurement, the middle of the measurement, and the end of the measurement. The dissolved oxygen concentration of each water sample was the average value of these three measurement points.

2.4. Data analysis and evaluation

In this study, a multiple linear regression (MLR) model was used to predict dissolved oxygen concentration with the independent variables being absorbance at different wavebands of the AS7265X multispectral sensor. These independent variables were calculated by (2). The MLR is a basic model and is widely used in absorption spectroscopy when the number of independent variables (wavebands) is less than the number of data samples [9]. The MLR equation is as follows:

$$\hat{y}_i = b_0 + b_1 x_{i,1} + b_2 x_{i,2} + \ldots + b_k x_{i,k} \tag{4}$$

where $\hat{y}_i$ is the estimated dissolved oxygen concentration (predicted concentration) from the model of the i^{th} water sample, coefficients from b_1 to b_k are estimated coefficients, b_0 is the estimated dissolved oxygen concentration value when the independent variables $x_{i,1}$ to $x_{i,k}$ are equal to 0.

To compare and evaluate the prediction performance of regression models, two evaluation criteria were used including the coefficient of determination (R^2) and root mean squared error (*RMSE*). The values of R^2 and *RMSE* are calculated by (5) and (6) as follows:

$$R^2 = 1 - \frac{\sum_{i=1}^{n} \left(y_i - \hat{y}_i \right)^2}{\sum_{i=1}^{n} \left(y_i - \overline{y} \right)^2} \quad (5)$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left(\hat{y}_i - y_i \right)^2} \quad (6)$$

where y_i and $\hat{y}_i$ are the measured dissolved oxygen concentration from the MW600 Pro device and the predicted dissolved oxygen concentration from the model of the i^{th} water sample, n is the number of water samples, and $\overline{y}$ is the average value of the measured dissolved oxygen concentrations. MATLAB 2024a (trial version) was used in this study to perform calculations and plot graphs.

3. Results and discussion

3.1. Light intensity with increasing dissolved oxygen concentration

In this study, the monitoring of light intensity with changing dissolved oxygen concentration values was performed to find the wavebands that affect dissolved oxygen concentration. Figures 3, 4, and 5 show the light intensity obtained at 18 wavebands of the AS7265X multispectral sensor when the dissolved oxygen concentration gradually increased from 1.8 mg/L to 7.5 mg/L.

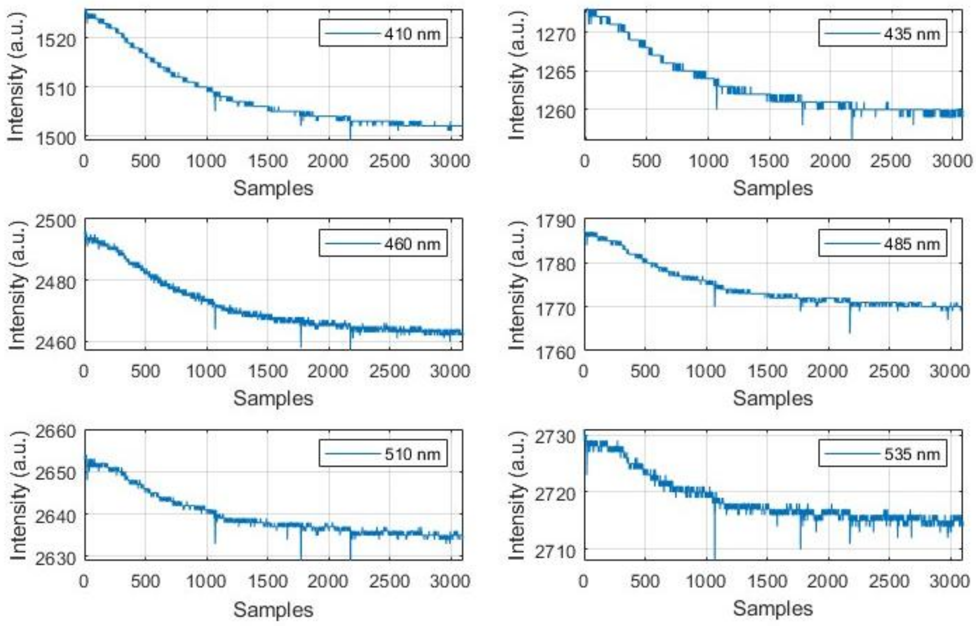


Fig. 3. Light intensity at 410, 435, 460, 485, 510, and 535 nm when increasing dissolved oxygen concentration.

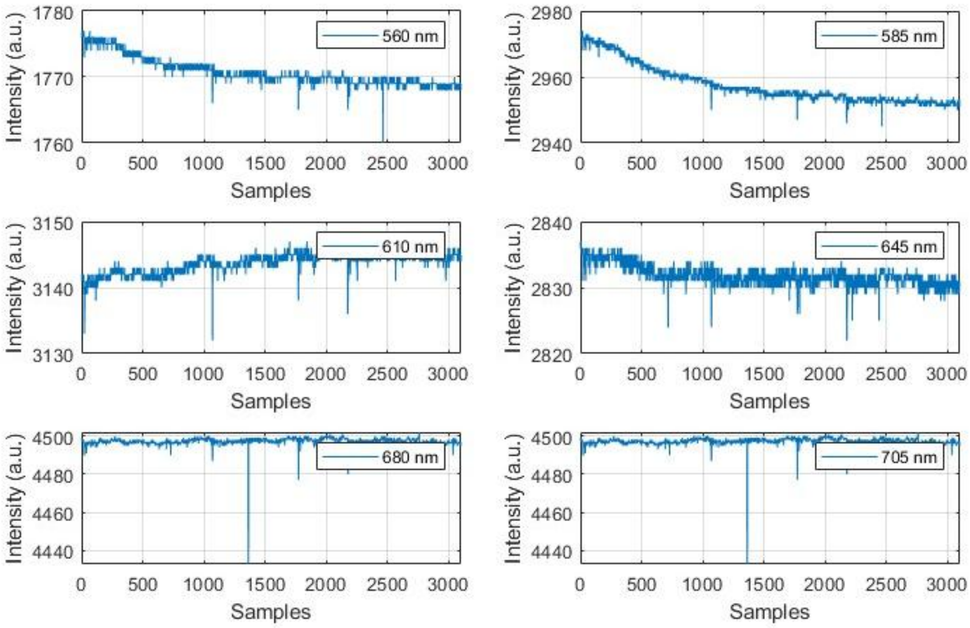


Fig. 4. Light intensity at 560, 585, 610, 645, 680, and 705 nm when increasing dissolved oxygen concentration.

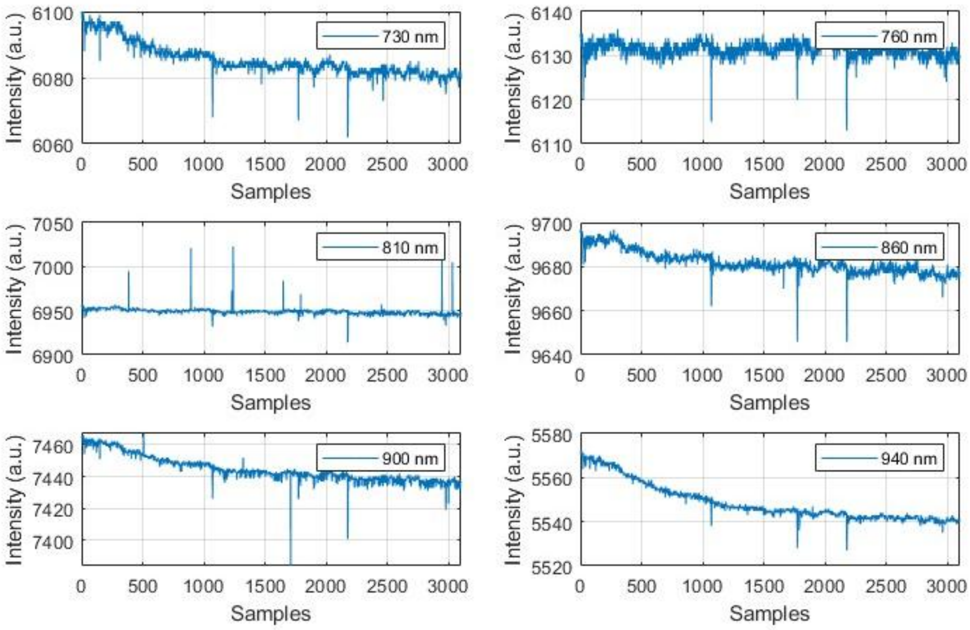


Fig. 5. Light intensity at 730, 760, 810, 860, 900, and 940 nm when increasing dissolved oxygen concentration.

The light intensity at all six wavebands shown in Fig. 3 tended to decrease as the dissolved oxygen concentration increased. The amount of change in light intensity was different at different wavebands. The waveband of 460 nm gave the largest change with 32 AU. The wavebands of 410 and 485 nm had changes of 22 and 18 AU, respectively. The wavebands of 510 and 535 nm obtained the same change at 15 AU. The lowest change was recorded at the waveband of 435 nm with 12 AU. This result showed that the wavebands in Fig. 3 could have a certain influence on the dissolved oxygen concentration.

Figure 4 shows that only the light intensity at 560 and 585 nm had a decrease while the dissolved oxygen concentration increased. The amount of change in light intensity at these wavebands was 6 and 20 AU, respectively. The remaining wavebands persisted at a constant light intensity or changed in an increasing direction as the dissolved oxygen concentration increased. This indicated that the wavebands at 560 and 585 nm could affect the dissolved oxygen concentration

According to the results obtained in Fig. 5, the light intensity at the wavebands of 760 nm and 810 nm was almost unchanged as the dissolved oxygen concentration increased. Meanwhile, the remaining four wavebands of 730, 860, 900, and 940 nm had a gradual decrease in light intensity with changes of 18, 16, 20, and 30 AU, respectively.

From the results shown in Figs. 3, 4, and 5, ten wavebands at 410, 460, 485, 510, 535, 585, 730, 860, 900, and 940 nm illustrated a large decrease in light intensity (greater than 15 AU) when the dissolved oxygen concentration increased from 1.8 to 7.5 mg/L. Therefore, these ten wavebands were selected to build regression models to predict the dissolved oxygen concentration.

3.2. Regression models for predicting dissolved oxygen concentration

To improve the prediction performance and build the optimal prediction model, a sequential forward selection algorithm was used [13]. This algorithm aimed to find a combination of wavebands that could predict the dissolved oxygen concentration with the minimum number of wavebands. The search process started by selecting an optimal one-waveband with the highest correlation coefficient between the spectral data and the dissolved oxygen concentration. Next, the optimal two-waveband combination was determined by calculating the correlation coefficient for all combinations of the optimal one-waveband in the previous step with the remaining wavebands and selecting the two-waveband combination with the highest correlation coefficient. The optimal k-waveband combination was performed similarly until the model's prediction ability reached the best result according to the evaluation criteria R^2 and RMSE.

In this study, 76 data samples were collected at different dissolved oxygen concentrations ranging from 1.7 to 7.6 mg/L to build a dissolved oxygen concentration prediction model. Table 1 shows the statistical information on dissolved oxygen concentrations of the 76 data samples in this study.

Table 1. Some statistical information about the data samples

Item	Value
Number of samples	76
Minimum value (mg/L)	1.7
Maximum value (mg/L)	7.6
Average (mg/L)	4.53
Standard deviation (mg/L)	1.75

Figure 6 shows the correlation coefficient of the spectral data and dissolved oxygen concentration at each waveband. According to Fig. 6, the waveband of 585 nm exhibited the highest correlation coefficient, so this waveband was selected as the optimal one-waveband. The process of finding the optimal waveband combination has been carried out and the prediction performance of the MLR models with different waveband combinations is shown in Table 2.

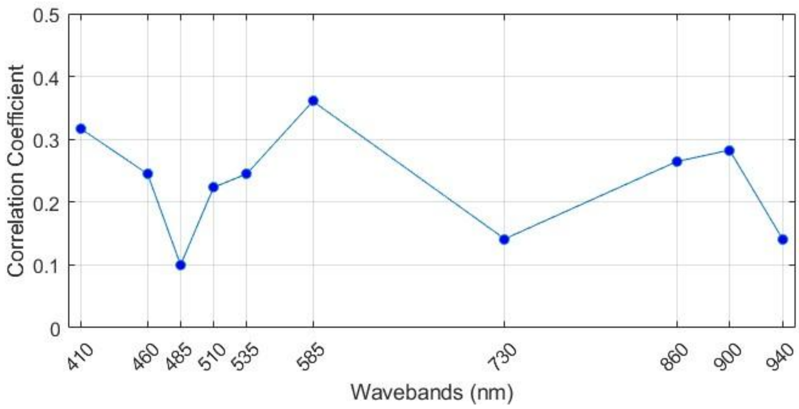
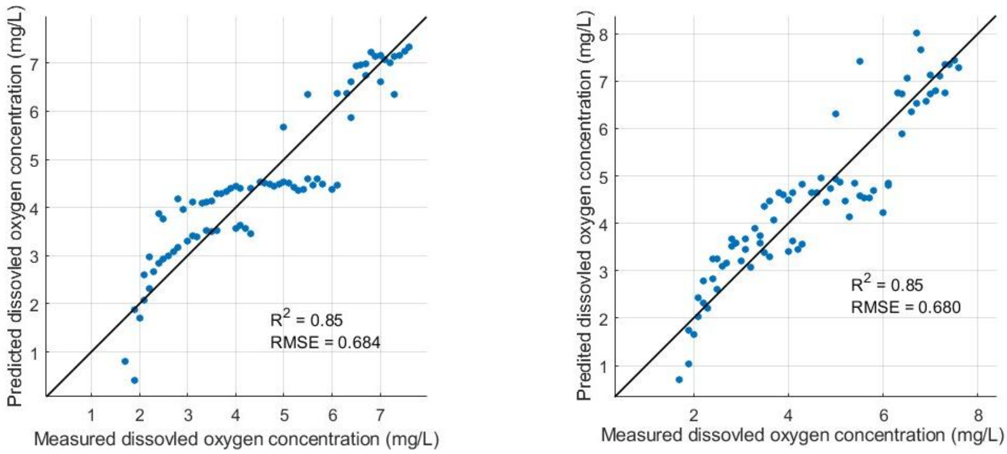


Fig. 6. The correlation coefficient of the spectral data and dissolved oxygen concentration at each waveband.

The prediction results of the MLR models with No. 1, 2, 3, and 4 in Table 2 showed that as the number of wavebands in the combination increased, the value of R^2 increased and the value of $RMSE$ decreased. This table showed that a combination of four wavebands at 585, 460, 900, and 485 nm (No. 4) had a good prediction performance with R^2 = 0.85 and $RMSE$ = 0.680 mg/L. However, if the waveband of 435 nm was added to the model (No. 5), the prediction performance of that model was still not improved (R^2 = 0.85 and $RMSE$ = 0.685). In addition, the prediction results of the model using four wavebands of 585, 460, 900, and 485 nm (No. 4) were still comparable to the results of the model using all 10 wavebands (No. 6). Therefore, the MLR model with four wavebands of 585, 460, 900, and 485 nm was considered the optimal model in this study. Figure 7 shows the relationship between the measured dissolved oxygen concentration and the predicted dissolved oxygen concentration by the MLR model using all 10 wavebands and the optimal four-waveband combination.

Table 2. Prediction performance of the MLR models with different waveband combinations

No.	Wavebands (nm)	R^2	$RMSE$
1	585	0.36	1.616
2	585, 460	0.68	0.983
3	585, 460, 900	0.81	0.767
4	**585, 460, 900, 485**	**0.85**	**0.680**
5	585, 460, 900, 485, 435	0.85	0.685
6	All 10 wavebands	0.85	0.684



(a) *(b)*

Fig. 7. Relationship between measured and predicted dissolved oxygen concentrations for all 10 wavebands (a) and for the optimal four-waveband combination of 460, 485, 585, and 900 nm.

3.3. Discussion

The prediction performance of the model using only four wavebands of 460, 485, 585, and 900 nm was comparable to that of the model using all 10 wavebands, indicating that the waveband selection process had been effective because the complexity of the model reduced but the prediction performance did not change. The selected wavebands in this study are also similar to previous studies investigating the absorption wavelengths of oxygen [14-17].

Although the values of R^2 and RMSE were not as equivalent as the results of studies using electrochemical or optical methods [18], the results of this study show the feasibility of a non-contact approach to predict dissolved oxygen using absorption spectroscopy in the visible and near-infrared regions with low-cost multispectral sensors. In addition, the following issues may need further consideration:

• Further investigation of the effects of temperature, pH, salinity, etc. to develop appropriate compensation solutions.

• Experiment with different machine learning algorithms in building more linear and non-linear models to predict dissolved oxygen concentration to find an optimal model with better performance.

4. Conclusion

In this study, a non-contact solution for measuring dissolved oxygen concentration using absorption spectroscopy with a low-cost multispectral sensor was proposed. This solution was tested by building the optimal MLR model to predict dissolved oxygen concentration with R^2 = 0.85 and *RMSE* = 0.680. The results of this study revealed that the proposed solution has great potential for continuous monitoring of dissolved oxygen concentration. However, further investigation of the influence of environmental factors to build a suitable regression model needs to be further considered and evaluated.

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GIÁM SÁT LIÊN TỤC NỒNG ĐỘ OXY HÒA TAN SỬ DỤNG CẢM BIẾN ĐA PHỔ GIÁ RẺ

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Tóm tắt: Nghiên cứu này đề xuất một giải pháp giám sát liên tục nồng độ oxy hòa tan bằng kỹ thuật quang phổ hấp thụ với cảm biến đa phổ giá rẻ. Một hệ thống thực nghiệm đã được xây dựng để tìm kiếm mối tương quan giữa nồng độ oxy hòa tan và độ hấp thụ của một số bước sóng trong khu vực nhìn thấy và cận hồng ngoại. Một mô hình hồi quy tuyến tính tối ưu với bốn bước sóng tại 460, 485, 585 và 900 nm đã cho kết quả dự đoán tốt nhất với hệ số xác định và căn bậc hai của sai số bình phương trung bình lần lượt là 0,85 và 0,68 mg/L. Kết quả thực nghiệm này cho thấy kỹ thuật quang phổ hấp thụ với cảm biến đa phổ giá rẻ được đề xuất có tiềm năng lớn trong việc giám sát liên tục nồng độ oxy hòa tan trong nước một cách không tiếp xúc.

Từ khóa: *Quang phổ hấp thu; giám sát liên tục; oxy hòa tan; cảm biến đa phổ giá rẻ; đo không tiếp xúc.*

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