Mathematic Modelling of Bok Choy Plant Canopy Area on Different Artificial Light at Plant Factory

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ABSTRACT

In the plant factory, plants carry out the process of photosynthesis using artificial light sources in the form of growth lights instead of sunlight. Each type of lamp will emit light with a different wavelength, so the effect on the photosynthesis process is also different. This study examines the pattern of canopy area expansion on plants in response to the light quality of artificial light in the plant factory. Canopy area of Bok choy (*Brassica rapa subsp. Chinensis*) plant samples for white LED dan red-blue LED treatments were measured non-destructively every two and three days using the Easy Leaf Area application. The growth data is then modeled using linear and polynomial regression. The results showed that the canopy area of the plant in the plant factory increased with the growth period. The plants exposed to red-blue LED lights grew better than plants exposed to white LED, indicating that red-blue lights supported the photosynthesis process better than white light. The regression results also show that the growth of plants in plant factories with a combination of red-blue LED lights is better in terms of MAPE (Mean Absolute Percentage Error) values. The model validation and prediction are also better using red-blue LED than white LED. Based on prediction using the best regression model, the result shows that red-blue LED as artificial light sources better support plant growth in plant factories than white LED lamps.

Keywords: *LED, leaf canopy area, plant factory, plant growth*

1. INTRODUCTION

The phenomenon of urbanization and the limitation of agricultural land due to increasing land use are two factors that have caused the issue of food security, especially in urban areas, which has received serious attention in recent years. Cities are expected to supply their food needs independently, even with dwindling land conditions and clean water resources. Plant factory is one of the technologies developed in urban areas to overcome this problem. With this technology, plants can be grown even in a closed room, in the form of a plant growth chamber, with maintained climatic conditions, and can be adjusted to suit the plant's needs [1].

Besides being applied to narrow land with vertical agriculture, plant factories can even be applied to land that cannot be planted, such as ex-mining land or waste disposal [2]. This plant factory commonly uses a hydroponic or aeroponic technique where the planting media does not use soil but water media. Although considered to be in line with the development of sustainable agriculture and has better water use efficiency (WUE) and land use efficiency (LUE) than conventional agriculture [3], the application of plant factories on a large scale is considered less appropriate in terms of energy requirements. This is mainly due to the high electricity requirement for controlling microclimate conditions in the growth chamber. In addition, the plants developed at the plant factory are currently still limited to horticulture plants such as vegetables.

One of the microclimate parameters that still needs to be studied further in plant factory development is the intensity and distribution of artificial light as a substitute for sunlight. Indonesia is located around the equator, so it has a tropical climate with sunlight distributed evenly

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throughout the year. As reported by the previous researcher, the daily sunlight intensity usually fluctuates; the value is low in the morning, achieves the highest peak in the afternoon, then decreases in the evening [4]. Therefore, artificial light can be combined with exposure to sunlight to reduce the use of electrical energy in the plant factory. Artificial light is only used in conditions of low sunlight intensity due to atmospheric conditions with high water vapor content.

The use of various types of lamps as artificial light sources to replace sunlight in plant factories has been widely studied recently; Light Emitting Diode (LED) is one of them [5,6]. In addition to LED lamps, fluorescent lamps are commonly used in plant factories. Exposure of fluorescent lamps to the plant for an extended period can increase the productivity of roses in autumn and winter in terms of number, length, weight, and stem size [7]. However, LEDs produce the lowest heat compared to other lamps, which are more suitable for plant needs. Therefore, LED is preferable to be applied in an extensive plant factory.

Several researchers have studied plant growth patterns in plant factories [8,9]. However, few still discuss plant growth patterns with different artificial lights in plant factories. This study examines the pattern of plants' canopy area increase in response to LED lamps with a diverse light spectrum. In addition, this study aims to determine the mathematical regression model that best describes the pattern of canopy area increase in plants in a plant factory.

2. METHODOLOGY

2.1. Materials and Method

The plants observed in this study were bok choy (*Brassica rapa subsp. Chinensis),* aged seven days after seeding (DAS). Rockwool was used as a planting medium and placed in a net pot. A flannel cloth was added at the bottom of the net pot to help distribute water when plant roots still cannot reach the nutrient solution. AB mix nutrients were added periodically with concentrations corresponding to the plant growth phase. The water level in the hydroponic container was added every two days at a height of 4.5 cm (Figure 1).

This study planted the plants in a plant growth chamber equipped with a temperature and humidity control system using an exhaust fan and humidifier. Plants are grown in 45 cm x 45 cm x 7.5 cm of hydroponic containers. The tool used to monitor the condition of the nutrient solution in the container was the TDS-meter. Meanwhile, a pH meter was used to monitor the nutrient solution's pH conditions.

(a) (b)

Figure 1 Measurement of TDS and the height of the nutrient solution in the Hydroponic container in the red-blue LED (a) and white LED (b) treatment.

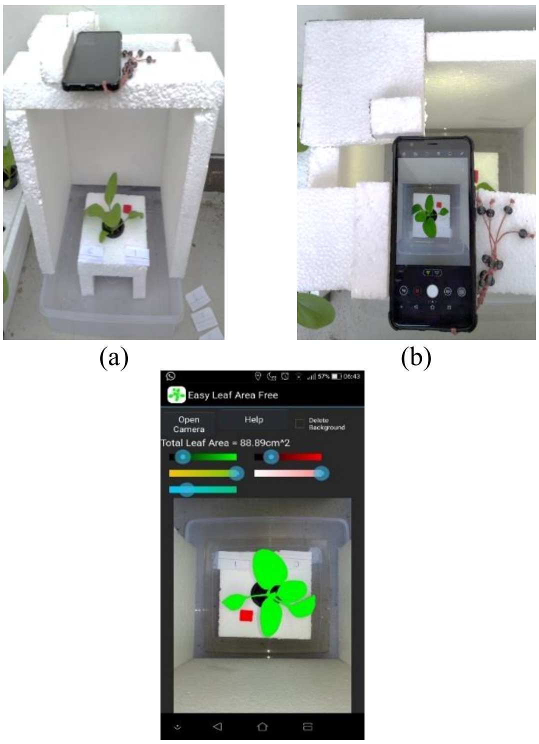
Each plant growth chamber (Figure 2) was equipped with different artificial lights, *i.e.,* a series of blue and red LED lights (1:1) and white LED. An Arduino microcontroller-based monitoring system with a data logger connected to a BH1750 sensor (light intensity) and a DHT22 sensor (temperature and humidity) is used to monitor microclimate parameters in the plant factory. Microclimate monitoring is essential, as anomalies may occur, which can be caused by an uncontrollable microclimate and technical disturbances [10]. Luxmeter and digital thermohygrometer are used for the sensor data calibration process.

(a) (b)

Figure 2 Growth chamber with treatment using red-blue LED (a) and white LED (b).

An Android-based mobile phone with installed Easy Leaf Area software [11] was used to manually measure the leaf canopy area of plants during growth every 2-3 days. The plants were placed in a box with a mobile phone on top to take photos of the canopy area (Figure 3). This measurement used red paper of 2 cm x 2 cm for calibration.

Figure 4 shows the flowchart of this experimental research. After the literature study was completed, the plant factory preparation was conducted. Then, after the components had been set up, the seeds were sowed and planted in the hydroponic container after 3 or 4 leaves appeared. The plant growth data were taken manually during the growth period, whereas the microclimate parameters were recorded automatically. At the end of the observation, the leaf canopy area data was processed using R-Studio Software to be modeled using linear and polynomial regression approaches.



(a) (b) (c)

Figure 3 Measurement of leaf canopy area: front view (a), top view (b), and Easy Leaf Area application display (c).

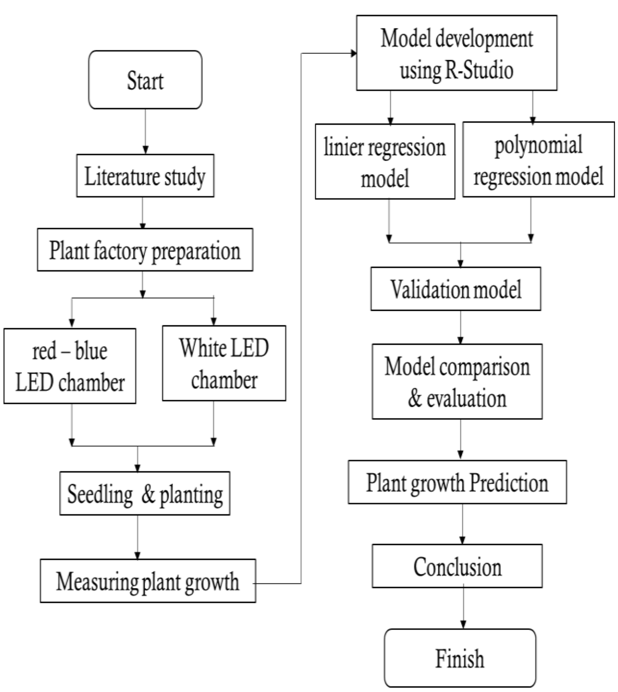


Figure 4 Research Flowchart

2.2. *Linear regression models of plant growth*

Plant growth in the plant factory needs to be modeled with mathematical equations to evaluate whether the designed plant factory is suitable for plant metabolism. The linear regression model is one of the mathematical equations that apply statistical procedures to calculate the predictive value of the dependent variable based on the independent variable [12]. The dependent variable in this study was the day of observation (X); the independent variable was plant growth (Y), represented by the leaf canopy area of the bok choy plant. The relationship between these two variables can be expressed by Equation (1).

$$Y = a + bX \quad (1)$$

The equation's regression coefficient values a and b are obtained from Equation (2). In comparison, the correlation coefficient (R) and the coefficient of determination (R^2) are determined using Equation (3) and Equation (4).

$$a = \frac{\sum y - b.(\sum x)}{n} \quad (2a)$$

$$b = \frac{n(\sum xy) - (\sum x).(\sum y)}{n(\sum x^2) - (\sum x)^2} \quad (2b)$$

$$R = \frac{n\sum XY - \sum X \sum Y}{\sqrt{\{n\sum X^2 - (\sum X)^2\}\{n\sum Y^2 - (\sum Y)^2\}}} \quad (3)$$

$$R^2 = R.R \quad (4)$$

2.3. *Polynomial regression models of plant growth*

Modeling using polynomial regression was conducted to test whether the data had a quadratic tendency. This regression model is usually used if the processed data is not linear [13]. One of the drawbacks of modeling using linear regression is its inability to fit data; therefore, advanced polynomial regression can improve the fit [14]. The N-order polynomial regression model can be written according to Equation (5) [15].

$$y_i = \beta_0 + \sum_{j=1}^{d} \beta_j x_i^j + \varepsilon_i \;,\; i = 1,2, \ldots n \quad (5)$$

2.4. *Model validation*

The two best linear and polynomial models for each treatment were validated using actual data. Then the error value is investigated using the Mean Absolute Percentage of Error (MAPE) and Mean Absolute Deviation (MAD) approaches, as shown by Equation (6) and Equation (7). The prediction data used in this validation is obtained from the model equation (Ft). The actual data (At) is accumulated average leaf canopy area data that was not used to prepare the model.

$$MAPE = \frac{1}{n}\sum\frac{F_t - A_t}{F_t} \times 100\% \quad (6)$$

$$MAD = \frac{1}{n}\sum F_t - A_t \quad (7)$$

2.5. Plant growth prediction

Based on the model validation, the best model was then determined to predict plant growth using leaf canopy area data. Predictions were made to compare the trend of plant growth in the two artificial light treatments in the plant factory. Predictive data were calculated using the regression equation for the observation period after the last day of data collection.

3. RESULTS AND DISCUSSION

3.1 Mathematical modeling of plant growth

The growth of bok choy plants during the planting period for the two artificial light treatments can be seen in Figure 5. Based on the graph, the leaf canopy area of the bok choy plants in the red-blue LED treatment increased faster than in the white LED treatment. On the 10th day of observation, the plants in the red-blue LED treatment had expanded 3.6 times compared to the 3rd day of observation. As for the white LED treatment, the leaf canopy area only increased 1.86 times for the same observation period. In simple terms, the increase in leaf canopy area in the red-blue LED treatment was about two times greater than in the white LED treatment. Further analysis using mathematical equations is needed to clarify which artificial light treatment is better for plant growth in the plant factory.

The linear regression model resulting from the relationship between leaf canopy area and observation days is shown in Figure 5. The linear regression equation for red-blue LED is y = 7.3770 + 5.4984x with R^2 = 0.9822. While the equation for white LED is y = 24.68514 + 2.9182x and the value of R^2 = 0.9915. The regression coefficient value (b) for the red-blue LED treatment (5.4984) was greater than the white LED treatment (2.9182). This result shows that, at the appropriate time, the leaf canopy area in the plant factory with red-blue LED will increase by 5.4984 cm^2, while in the growth chamber with white LED only increases by 2.9182 cm^2. The constant value in the white LED treatment was greater (24.6851) than in the red-blue LED treatment (7.3770). However, the leaf canopy area of the bok choy plant was greater in the red-blue LED treatment because the regression coefficient value was much larger than in the white LED treatment.

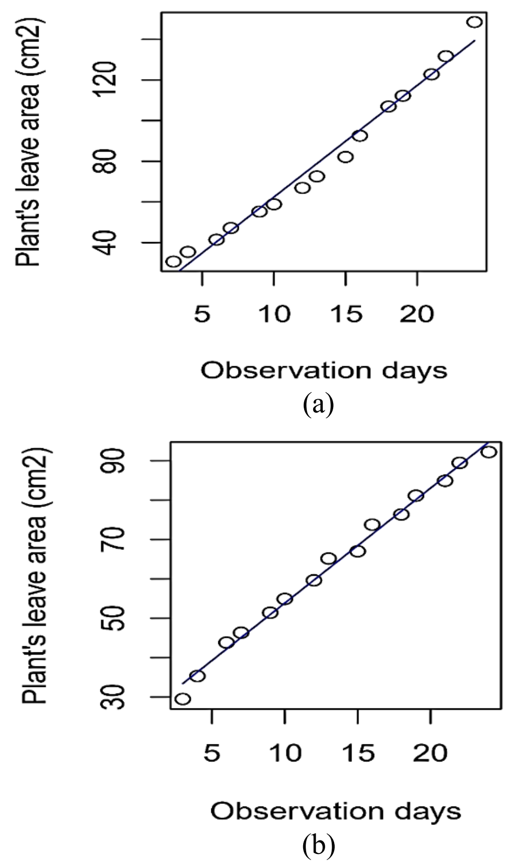
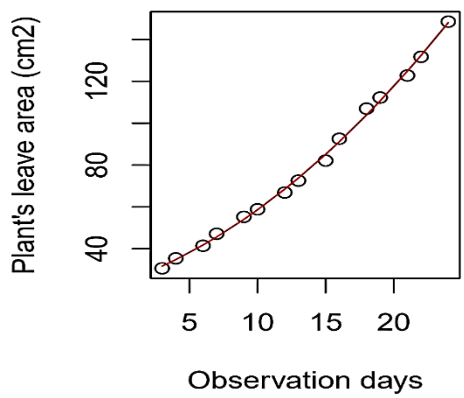


Figure 5 Linear regression equation model of bok choy plants treated with different artificial light sources: (a) red-blue LED, (b) white LED

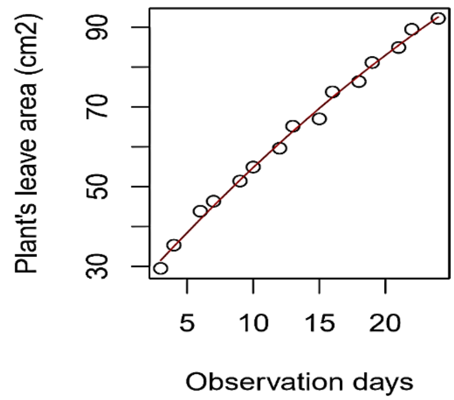
Table 1. R^2 and equations for 2nd, 3rd, and 4th polynomial regression model

Treatments	Red-blue LED	White LED
2nd order Polynomial	$y = 0.12104x^2 + 2.27472x + 23.74958$ $R^2 = 0.9981$	$y = -0.02998x^2 + 3.71665x + 20.62980$ $R^2 = 0.995$
3rd order Polynomial	$y = 2.007e\text{-}04x^3 + 1.130e\text{-}01x^2 + 2.368e{+}00x + 2.347e{+}01$ $R^2 = 0.9981$	$y = 0.001884x^3 - 0.105698x^2 + 4.588863x + 18.008562$ $R^2 = 0.995$
4th order Polynomial	$y = -0.0003894x^4 + 0.0212106x^3 - 0.2704279x^2 + 5.0638883x + 17.6728089$ $R^2 = 0.9982$	$y = -0.0005725x^4 + 0.0327728x^3 - 0.6693752x^2 + 8.5528947x + 9.4850340$ $R^2 = 0.9966$

In general, the larger the order used, the better the resulting data fit. Table 1 shows the polynomial regression model's equations, the coefficient of determination (R^2) value for the leaf canopy area, and the observation time for the red-blue LED and white LED treatments using the 2nd, 3rd, and 4th orders of the polynomial regression model. Figures 6, 7, and 8 show that the polynomial regression model produced is more representative of the observations data as the order increases. Figure 9 shows the relationship between all the regression models used in this study.

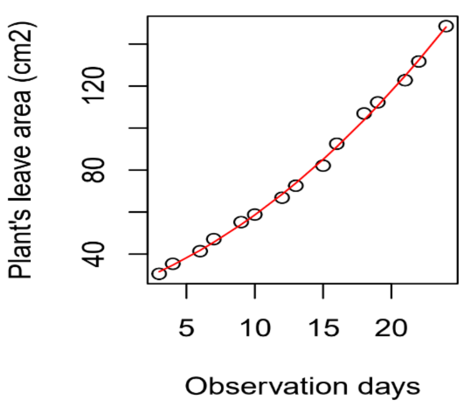


(a)

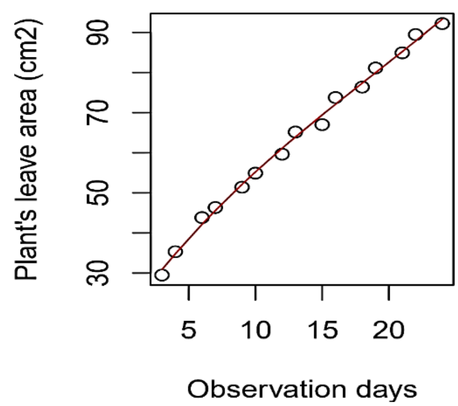


(b)

Figure 6 Model of 2nd order polynomial regression equations of (a) red-blue LED and (b) white LED treatment on bok choy plants leaf (canopy) area

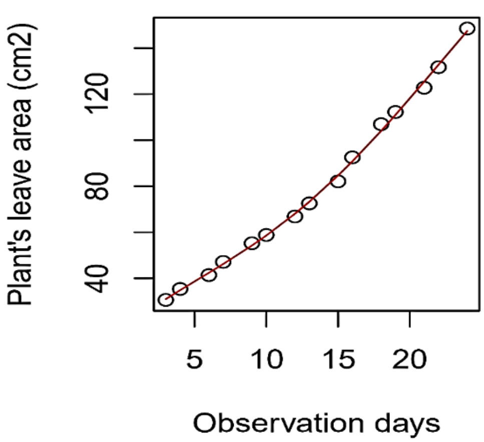


(a)

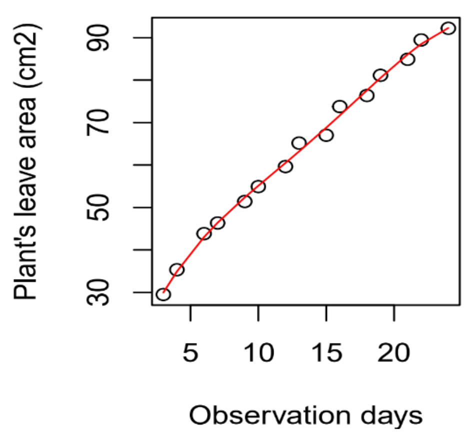


(b)

Figure 7 Model of 3rd order polynomial regression equations of (a) red-blue LED and (b) white LED treatment on bok choy plants leaf (canopy) area



(a)



(b)

Figure 8 Model of 4th order polynomial regression equations of (a) red-blue LED and (b) white LED treatment on bok choy plants leaf (canopy) area

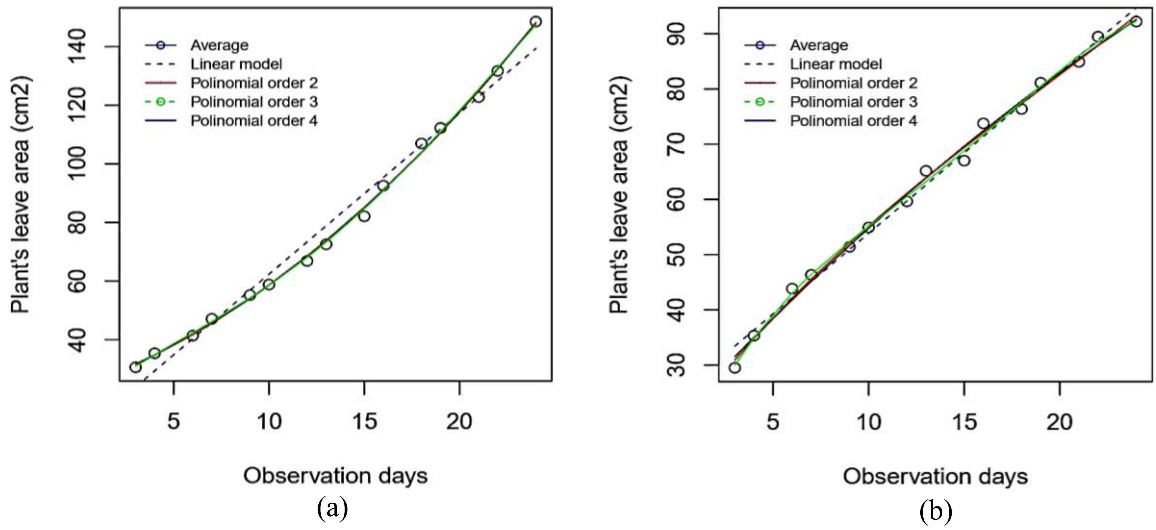


Figure 9 Comparison of the linear and polynomials regression model of (a) red-blue LED and (b) white LED treatment on bok choy plants leaf (canopy) area.

3.2 Model Validation Results

It is necessary to conduct a validation test using actual plant growth data to measure the model's accuracy. The test is carried out by calculating the deviation (error) value between the actual and predicted data. The smaller the error value obtained, the better the model predicts plant growth conditions in the plant factory.

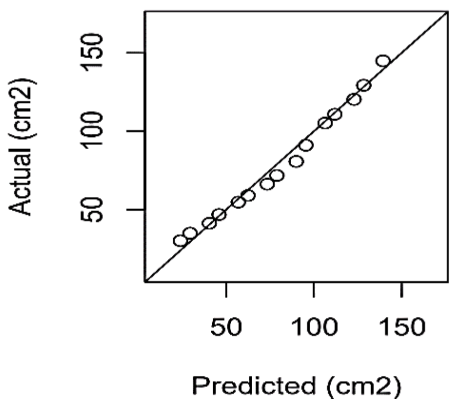
Table 2 shows the calculated errors using the Absolute Deviation (AD) and Absolute Percentage Error (APE) approaches for both artificial light treatments. The compared models are linear regression and polynomial order 4. Meanwhile, Figure 8 shows the relationship between the predicted and actual data in the model validation process for both treatments.

Table 2. Results of the validation of the bok choy plant growth model

No	AD for red-blue LED		AD for white LED		APE for red-blue LED (%)		APE for white LED (%)	
	Linear	Poly4	Linear	Poly4	Linear	Poly4	Linear	Poly4
1	4.76	0.89	5.77	2.29	15.81	2.94	20.85	8.27
2	3.55	0.00	3.60	2.18	10.18	0.00	10.99	6.65
3	2.08	1.19	1.32	2.17	5.04	2.90	3.22	5.30
4	2.48	0.57	2.03	3.34	5.30	1.23	4.71	7.75
5	6.51	0.47	3.10	4.53	11.90	0.86	6.48	9.47
6	8.28	0.36	2.43	3.69	14.04	0.60	4.73	7.18
7	13.00	1.89	3.83	4.62	19.64	2.85	6.86	8.27
8	13.42	1.53	1.58	2.16	18.70	2.13	2.59	3.54
9	16.48	4.00	5.16	5.50	20.43	4.96	8.16	8.69
10	12.09	0.21	1.75	2.06	13.28	0.23	2.51	2.96
11	9.92	1.15	4.22	4.60	9.43	1.09	5.78	6.30
12	10.27	0.20	2.98	3.38	9.27	0.18	3.86	4.38
13	12.75	5.17	5.35	5.45	10.60	4.30	6.64	6.76
14	9.74	3.53	3.72	3.36	7.53	2.73	4.37	3.95
15	6.12	2.59	6.31	3.89	4.23	1.79	7.13	4.40
Mean	**8.76**	**1.58**	**3.54**	**3.55**	**11.69**	**1.92**	**6.59**	**6.26**

Based on Table 2, the MAD value in the red-blue LED treatment is 1.58 using the 4th order polynomial regression model, much smaller than the MAD linear regression of 8.76. While in the white LED treatment, the MAD values for linear regression and 4th order polynomials models are not much different. Further analysis using the MAPE approach showed that the red-blue LED and white LED treatment using 4th order polynomial regression had values below 10%, *i.e.,* 1.92% and 6.26%, respectively. This value indicates that the 4th-order polynomial regression model has an outstanding predictive ability [14], both for red-blue and white LED treatments.

(a)



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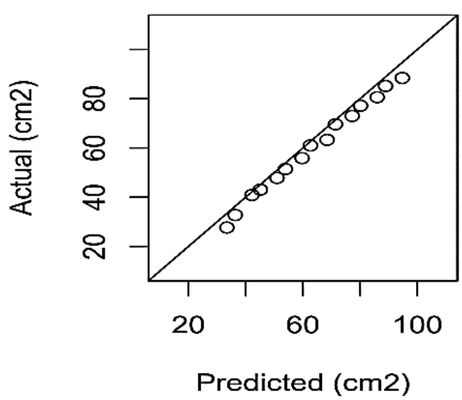
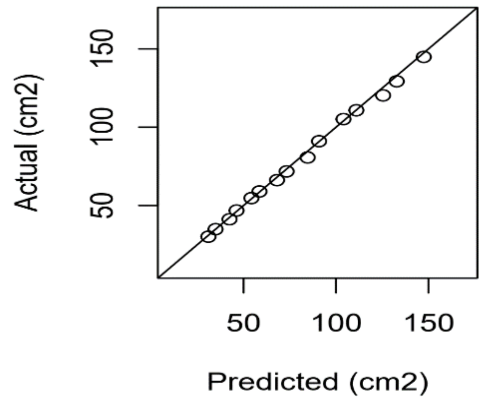


Figure 10 Validation model using linear regression model of (a) red-blue LED and (b) white LED treatment on bok choy plants leave (canopy) area.

(a)



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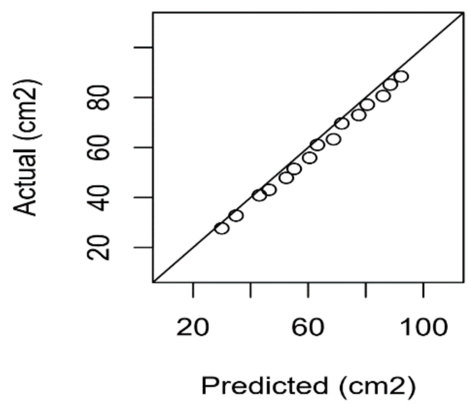

(b)

Figure 11 Validation model using 4th order polynomial regression model of (a) red-blue LED and (b) white LED treatment on bok choy plants leave (canopy) area.

3.3 Prediction of plant growth in the plant factory

Based on the model validation process results, it was determined that a 4th order polynomial regression could be used to predict plant growth in the plant factory. Figure 12 shows the predictions made after the 24th day of observation. Using white LED lamps, Bok choy plants in the growth chamber experienced decreased growth, indicated by the decreasing leaf canopy area.

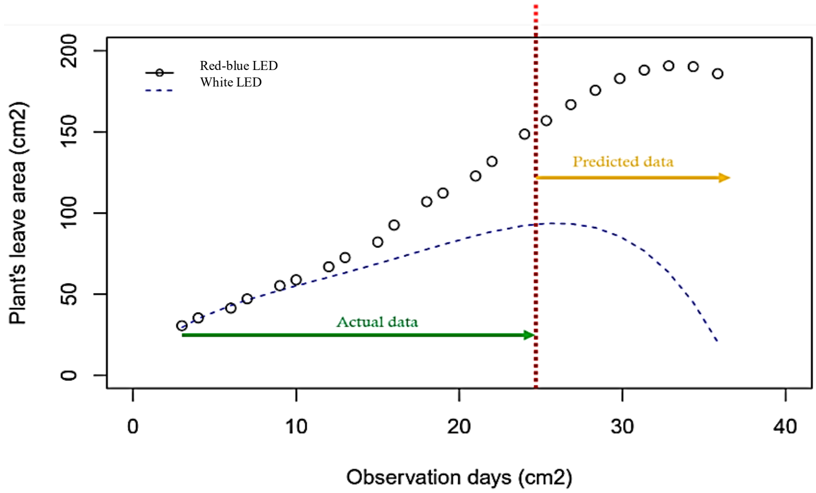

Figure 12 Prediction of leaf canopy area of bok choy plants with red-blue LED and white LED treatment

On the other hand, in the red-blue LED treatment, the leaf canopy area was predicted to increase until the 33rd day and decrease after the 34th day. Based on the prediction in Figure 12, red-blue LED lights can maximize growth and prolong plant life in the plant factory. In line with previous research, LED lights with a combination of red and blue are better at supporting the photosynthesis process of plants in plant factories [16]. This condition may be supported by better stomatal opening in lighting conditions using red-blue LED lamps [17].

4. CONCLUSION

The growth pattern of bok choy plants in red-blue and white LED treatment was best modeled with a 4th-order polynomial equation. The best regression equation for the red-blue LED treatment was $y = -0.0003894x^4 + 0.0212106x^3 - 0.2704279x^2 + 5.0638883x + 17.6728089$ with an R^2 value of 0.9982, while for the white LED treatment, the regression equation is $y = y = -0.0005725x^4 + 0.0327728x^3 - 0.6693752x^2 + 8.5528947x + 9.4850340$ with $R^2 = 0.9966$. Based on the model validation, it is known that the model's accuracy is excellent, indicated by the low MAPE value (below 10%) for both treatments (1.92% and 6.26%). Based on prediction using the preferred model, the result shows that red-blue LED as artificial light sources better support plant growth in plant factories than white LED lamps.

AUTHORS' CONTRIBUTIONS

Diah Ajeng Setiawati collected the experimental data, analyzed the collected data, and prepared the manuscript. Lilik Sutiarso designed the plant factory system. Ngadisih supervised the plant growth monitoring. Murtiningrum supervised the irrigation and plant water requirements. Andri Prima Nugroho developed the regression model using the R program. Guyup Mahardhian Dwi Putra designed and constructed the plant factory using artificial lighting. M. Salman Ibnu Chaer designed and built the plant factory's control and monitoring system.

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