Mathematical Model of Vegetative Growth of Porang (*Amorphophallus muelleri)* with Different Seed Quality

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ABSTRACT
Porang (*Amorphophallus muelleri*) is a tuber plant used in the industrial production of glucomannan. Porang can be cultivated with bulbil (katak tubers) and spontaneously harvested vegetatively. Under certain harvest and storage conditions, infected bulbils can reduce seed quality, viability, and growth. This study developed a mathematical model to predict the vegetative growth of porang with different bulbil seed qualities. The physical properties and plant growth parameters of 90 seeds of non-infected and infected bulbil were measured and divided into the calibration set comprised of 60 samples. The validation set included the remaining 30 samples. Polynomial models were used to predict plant height which was developed based on the calibration set. In contrast, model evaluation was used Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and Means Absolute Percentage Error (MAPE) were used to compare the calibration and validation set with the prediction data of plant height. The mathematical growth model using the polynomial model yielded the coefficient of determination (R^2) of 0.9811 and 0.9824, with RMSE 0.4680 and 2.1504, MAE 0.0111 and 0.6694, and MAPE 0.8661 and 5.3096, for the calibration and validation sets of non-infected seed, respectively. Infected bulbil produced R^2 of 0.9931 and 0.9926, with RMSE 0.5641 and 4.7765, MAE 0.0549 and 1.5163, and MAPE 3.4109 and 4.5561, for the calibration and validation sets, respectively. The R^2 and the validation model showed that the mathematical model was feasible to predict the growth of non-infected and infected porang bulbil to assess the vegetative growth of porang seeds of different qualities.

Keywords: Growth, Quadratic Polynomial, Performance Model, Bulbil.

1. INTRODUCTION

Porang is a valuable commodity due to its high glucomannan content, a water-soluble fiber with multiple industrial applications. In the food and pharmaceutical industries. Porang derivatives and processed products, such as dehydrated chips and konjac flour, are successively exported to Asia, Australia, and several European Union countries [1,2]

Porang is an Araceae plant with bulb-producing leaf stalks. Bulbil of porang is harvested when the plant has reached complete dormancy, as indicated by the petiole's spontaneous detachment [3,4]. This dormancy becomes one of bulbil quality criteria, besides from undamaged seed without rotting, peeling, or fungal attack [5]. In addition, porang seeds aren't available year-round in Indonesia. To fulfill the demand for porang seeds, potesan tubers, harvested before they are fully dormant, are frequently utilized. Low-quality tubers will affect the plant's glucomannan content [6]. On the other hand, incorrect handling and storage can degrade porang seeds' quality. High moisture content, warm temperatures, and high humidity can promote the spread of undetectable infections in newly fallen bulbils, especially those that are not fully dormant [7,8].

A. D. Saputro et al. (Eds.): ICOSEAT 2022, ABSR 26, pp. 245–253, 2023.
https://doi.org/10.2991/978-94-6463-086-2_32

Infected seeds will reduce quality, viability, germination, growth, and yield [7,8,9]. Using superior seeds instead of inferior seeds will result in faster, more uniform growth and greater productivity [10]. Additionally, fully dormant porang seeds of high quality will produce healthy plants. Meanwhile, seeds that are still not fully dormant may not grow if they are planted. Additionally, the presence of pathogens in the form of fungi in porang seeds inhibits plant development. The fungus causes embryo damage, reducing germination, hypocotyl length, root length, fresh weight, and dry weight [11].

In contrast, porang bulbil requires one month from planting to germination [12]. The problem of non-viable seeds reduces the viability of Porang bulbil, which will result in losses if already planted. In addition, the planting test takes a considerable amount of time, whereas the high demand for porang seeds necessitates immediate fulfillment so that planting can occur during the appropriate planting season [13]. A mathematical model is required to predict the growth of porang plants.

The model represents an actual occurrence. The availability of a plant growth model will facilitate the assessment of crop yields and engineering feasibility [14]. Rapid and accurate plant growth modelling is highly anticipated for the success of quality control programs applicable to the seed industry [15]. This research aimed to develop a mathematical model based on the vegetative growth of porang plants. This study focuses on a preliminary data analysis of the seven-week growth of porang grown from different-quality seeds. Without a controlled environment, measurement and expansion were performed manually. The model will be used in the future to precisely estimate porang plant growth in plant factory cultivation.

2. MATERIALS AND METHODS

2.1. Materials

During the final quarter of the tree's vegetative phase, the 90 samples of porang bulbil were collected from porang farmers in Kalasan District, Sleman Regency, Yogyakarta. Non-infected and infected bulbil samples were used for analysis. As shown in Figure 1, non-infected bulbils are free of mechanical, physical, and fungal damage, whereas infected bulbils are moldy, lice-infested, dried, and hollow. The purpose of the contrast qualities sample is to differentiate seed quality. Before use, the porang bulbil was stored for approximately one month, sorted by weight, ranging from 3 to 7 grams, grouped by visual appearance, and planted using polybags filled with soil as planting media.

2.2. Physical Property Evaluation of Bulbils

The weight and dimensions of both classifications of bulbil were measured. The weight was determined using an analytical balance (Fujitsu FS-AR). The water content was measured using the thermogravimetric technique. The spherical volume was measured using a caliper based on the average diameter of the most extended bulbil height and width to calculate the spherical volume based on the average diameter using Equation (1) [16].

$$1.333 \text{ x } \pi \text{x } (\frac{d}{2})^2 \qquad (1)$$

2.3. Measurement of Growth Parameters

Fresh weight, dry weight, root length, root volume, plant height, number of leaves, leaf color including L*, a*, and b* values, and crown cover were measured as growth parameters. Weekly, plant height was measured at once-per-week intervals. The color of the leaves was determined Using a chromometer (Konica Minolta CR-400). The crown cover measurement is based on the leaf's longest diameter, and its value is calculated using Equation (2) [17].

$$\pi \text{ x } (\frac{d1 + d2}{4})^2 \qquad (2)$$

2.4. Measurement of Microclimate Data

Temperature, relative humidity, and light intensity were the environmental factors measured. Temperature and relative humidity were measured with a thermohygrometer, and light intensity was measured with a lux meter (Lutron LM-8000). Throughout the study, daily microclimate measurements were performed.

2.5. Data Analysis and Modelling

Independent sample T-Tests were used to examine the effect of varying quality of porang bulbils on the bulbils' physical attributes and vegetative growth parameters of porang. The probability value of $P \leq 0.05$ was used to indicate statistically significant differences.

(a) (b)

(c) (d)

Figure 1 Quality of bulbil samples was used in the study, (a) non-infected seed; (b) moldy bulbil; (c) dried bulbil; (d) bulbil with lice.

Polynomial Regression was used to create a growth model using plant height data from 90 samples of infected and non-infected porang seeds measured for seven weeks of planted time. Polynomial Regression is linear Regression in which the influence of independent variables is multiplied by a polynomial degree. Multiple linear and polynomial regression models have the same analysis structure. A free variable in a polynomial model can be seen as a non-free variable because each rank or order is a transformation of the initial variable [18]. The equation for a Polynomial regression model is listed in Equation (3) as follows:

$$y = \beta_0 + \sum_{j=1}^{d} \beta_j x_i^j + \varepsilon_i, i = 1, 2, 3, \ldots, n \tag{3}$$

The plant height data for infected and non-infected seeds were separated into calibration sets comprised of two-thirds of the total sample and prediction sets consisting of one-third of the total sample, respectively. The calibration data set (consisting of 30 samples) was used to build the polynomial regression model, while the prediction data set was used to evaluate the model's accuracy.

2.6. Model Evaluation

The prediction error values were examined in both the calibration and prediction sets to evaluate the accuracy of the model's performance. Root mean square error (RMSE), mean absolute error (MAE), mean absolute percentage error (MAPE), and the coefficient of determination (R^2) are used to evaluate models [18], [19]. The equation for model evaluation is listed in Equation (4) – (7), n is the number of samples, $\hat{y}_i$ is the predicted value of plant height at the *i*th point, and y_i represents the actual plant height at the *i*th point.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \tag{4}$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|y_i - \hat{y}_i| \tag{5}$$

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\frac{|y_i - \hat{y}_i|}{y_i} x\ 100 \tag{6}$$

$$R^2 = \frac{\sum_{i=1}^{n}(y_i - \bar{y}_i)(\hat{y}_i - \bar{\hat{y}}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y}_i)^2 \sum_{i=1}^{n}(\hat{y}_i - \bar{\hat{y}}_i)^2} \tag{7}$$

3. RESULTS

3.1. Conditions of the Growing Environment's Microclimate

This study measured temperature, relative humidity, and light intensity daily. Figure 2 depicts the average temperature fluctuations during a porang plant's growth, ranging from 26,4°C to 33,0°C. According to other reports, the microclimate temperature in this study is suitable for the optimal condition. Purnomo et al. (2013) reported that porang plants grow and prosper at temperatures between 25 and 35°C. Above 35°C, the porang plant's leaves begin to burn and curl as necrosis symptoms, whereas the porang plant goes dormant at low temperatures [12]; [20].

Based on Figure 2, the Relative humidity during the plant growth fluctuated with an average value of 72.9% to 86.3%. The research contradicts other reports stating that the optimal humidity for porang growth is 50 - 60 percent [21]. In addition, another study also reported that porang plants thrive in 30 percent shade with 40 to 60 percent humidity [12].

Figure 2 illustrates light intensity fluctuations during indoor porang plants' growth. Based on the graph, the results indicated that the average light intensity during the study varied from 73.34 lux to 881.07 lux. These fluctuations can occur due to the daily variations in cloud cover, affecting daily lux in indoor farming without environmental control. Research on indoor agriculture has not been conducted under optimal light intensity conditions for porang development.

In contrast, other research indicates that porang plants have distinctive characteristics that allow them to tolerate 30 - 60% shade, but that growth is optimal in 30% shaded stands with light intensities between 2512.3 lux and 49225.7 lux. With decreasing light intensity, leaf size and tuber production will increase, but full irradiation will cause necrosis and leaf edge curling. Porang plants exposed continuously to direct sunlight experience wilting, chlorosis, and senescence. The causes of solarization are photosynthesis inhibition and chloroplast pigment decomposition [12], [20].

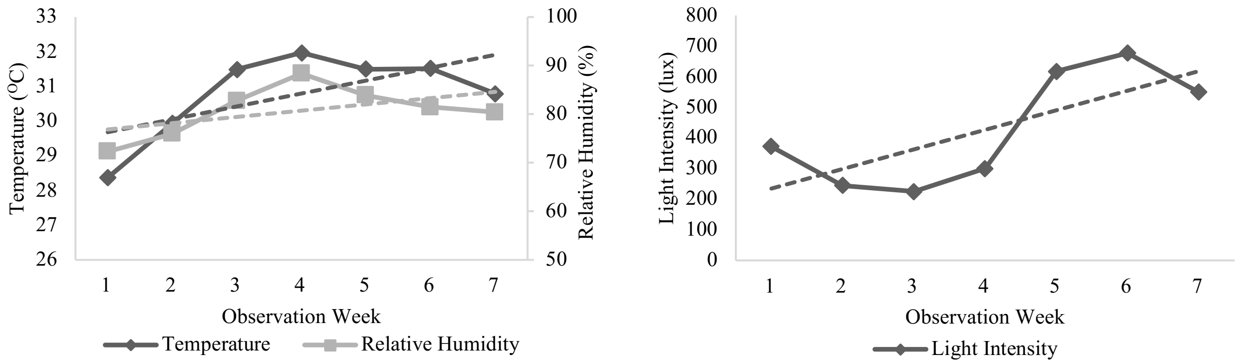


Figure 2 Microclimate conditions observed during the growth of bulbil porang.

3.2. Physical Properties of Bulbil at Different Quality

The weight variable had a statistically significant difference (P<0.05) (Table 1). These results indicated that the weight of bulbil affects its quality. The seed weight of the non-infected seed is greater than the infected seed. The infected seed has structural and fungal damage that decreases the weight volume and can affect the average weight data. Swallowed seeds can occur during depleted endosperm, rotten, and fungi attack the seed's embryo as a food source [22]. A decrease in nutritional quality refers to seed composition, such as amino acids, sugars, proteins, fatty acids, and secondary metabolites when infected seeds are present. Infected seeds will convert carbohydrates into simple sugars, along with a significant breakdown of fat into simple fatty acids [23]. In addition, this will result in yield losses, specifically the weight of seeds whose color and texture have changed, as well as seeds with irregular shapes [24]. The spherical volume and water content variables did not differ significantly in this study.

3.3. Porang Plant Vegetative Growth

There were significant differences (P<0.05) in most wet and dry weight, stem length, and root volume measurements (Table 1). Some of the wet and dry weight of damaged bulbil showed superior growth because the value was more significant than expected. This research contradicts the findings of [11], who discovered that fungal infection could reduce germination, hypocotyl length, root length, fresh weight, and dry weight following planting.

Table 1. Physical seed properties and plant growth parameters of porang

Parameter	Bulbil Quality	
	Normal	Infected
Physical Seed Properties		
Initial Bulb Weight (grams)*	5.72 ± 0.75 a	4.51 ± 0.88 b
Spherical Volume*	5024.13 ± 861.34	4798.66 ± 1121.25
Moisture Content**	75.82 ± 1.54	75.64 ± 1.67
*Plant Growth Parameters**		
Final Bulb Weight (grams)	4,56 ± 2,06 a	2,38 ± 1,74 b
Wet weight of Leaf (grams)	2,48 ± 2,84	2,82 ± 2,17
Wet weight of Stems (grams)	9,95 ± 10,88	9,66 ± 7,26
Wet weight of Root (grams)	0,55 ± 0,53 b	0,81 ± 0,63 a
Wet weight of Plant Canopy (grams)	12,43 ± 13,63	12,47 ± 9,30
Wet weight of Plant in Total (grams)	12,98 ± 14,07	13,28 ± 9,80
Dry weight of Leaf (grams)	0,17 ± 0,19	0,21 ± 0,15
Dry weight of Stems (grams)	0,22 ± 0,24 b	0,28 ± 0,20 a
Dry weight of Root (grams)	0,08 ± 0,07 b	0,12 ± 0,09 a
Dry weight of Plant Canopy (grams)	0,39 ± 0,43 b	0,49 ± 0,35 a

Dry weight of Plant in Total (grams)	0,47 ± 0,49 b	0,61 ± 0,42 a
Root length (cm)	14,31 ± 12,05	16,79 ± 9,98
Root volume (cm^3)	0,67 ± 0,55 b	0,89 ± 0,60 a
Stems lenght (cm)	26,08 ± 26,13 b	33,60 ± 22,31 a
Crown cover (cm^2)	978,25 ± 1109,25	1031,11 ± 825,78
Number of leaves	3,93 ± 4,16	4,80 ± 3,36

a,b The numbers with different letters indicate a statistically significant difference between groups, as determined by the Independent Sample T-Test.

* The data consists of an average of 45 samples.

** The data consist of an average of 5 samples.

The results showed that the infected bulbil grew more rapidly than the non-infected bulbil, despite weighing less on average. The tests were inconsistent with [25], in which larger bulbils produce superior growth because they contain many nutrients. However, other studies have shown that fungus-caused seed diseases do not affect plant growth and yields [23]. Infected seeds were superior to several seed compositions, such as higher protein concentration [29], increased diversity of essential amino acids [23], which influence plant growth, lower carbohydrate content, and no change or increase in oil concentration [29,23,26].

This study was limited to observing the 7-week vegetative growth of porang plants, even though infected bulbil exhibited healthy growth. Seed development has not yet reached the generative phase, which has not yielded in the emergence of new bulbil or achieved fully dormant stages. Infected seeds may transmit devastating seed-borne diseases. The seed-borne disease is also associated with Porang farming, specifically on the bulbil. Other research reported that most seed-borne diseases in bulbil Porang are caused by tuber fungi, such as *Phytophthora colocasiae*, *Sclerotium rolfsii*, *Fusarium oxysporum*, *Fusarium solani*, and *Botrytis cinerea* [27], [8].

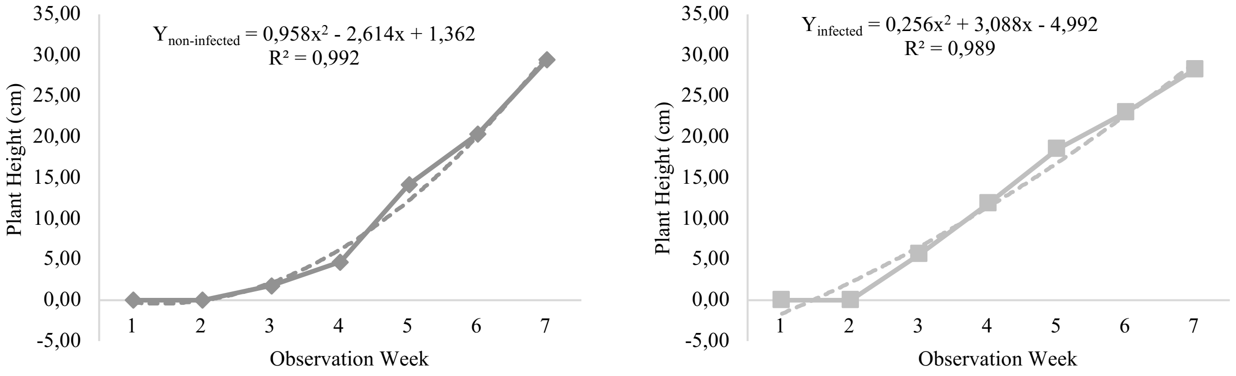
The seed-borne disease is inoculum transmitted by seeds that can inhibit the development of sprouts and causes losses of up to 25 percent, with an infection rate of up to 60 percent during storage. The seed-borne disease will be detrimental during the planting process, causing plant damage, reducing harvest productivity, and becoming a source of additional infection in seeds and neighboring plants. Besides, Fusarium species and other pathogenic fungi are known to produce mycotoxins in food products [28].

3.4. Vegetative Growth Model based on Plant Height

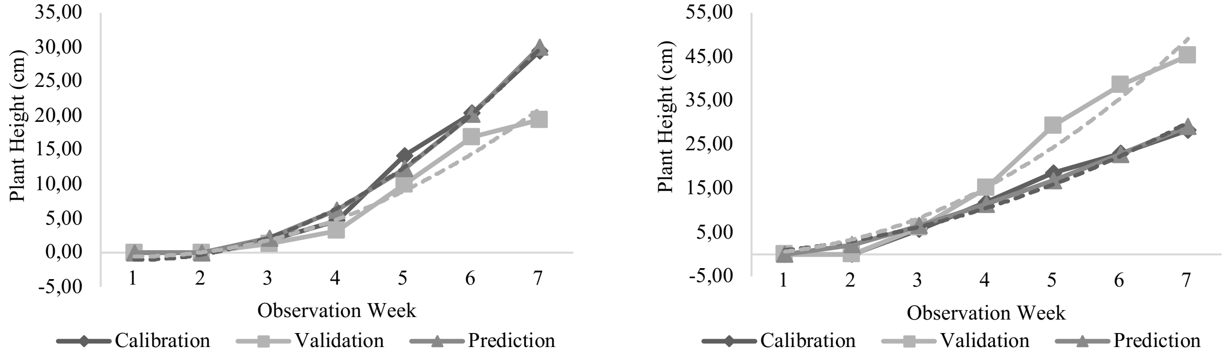
Based on the average yield of 7-week-old porang plant height, a porang vegetative growth model for non-infected and infected seeds was developed. Based on the average porang plant height, infected seeds exhibited faster vegetative growth than non-infected seeds (Figure 3). Equations (8) – (9) are the outcomes of the polynomial model equations for the two growth models.

$$Y_{non-infected} = 0.958x2 - 2.614x + 1.362 \quad (8)$$

$$Y_{infected} = 0.256x2 + 3.088x - 4.992 \quad (9)$$

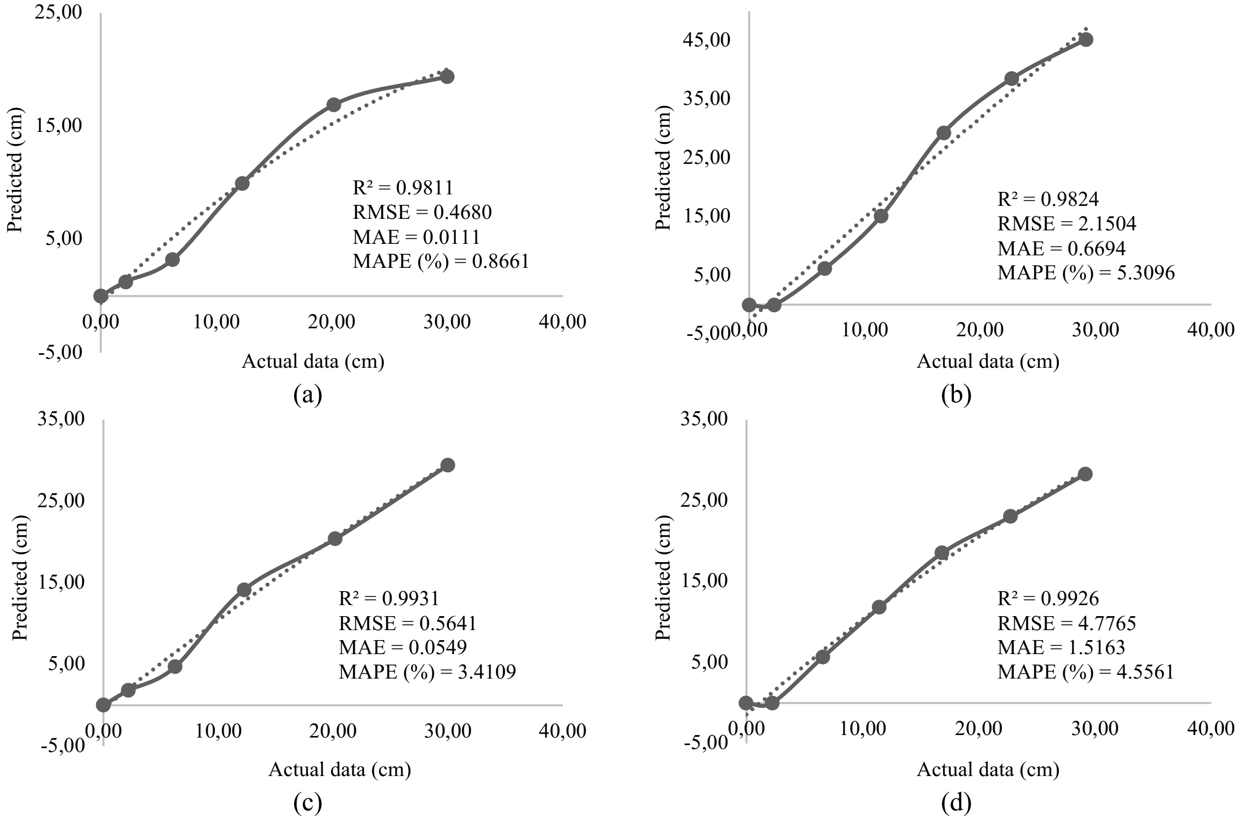


(a) (b)



(c) (d)

Figure 3 Observed plant height during 7 weeks of vegetative growth, the result of the polynomial model on non-infected (a) and infected seed (b), plant height vs. observation week of the calibration, validation, and prediction set on non-infected (c) and infected seed (d).



(a) (b) (c) (d)

Figure 4 Result of the predicted height of polynomial model vs. actual height on a calibration set of non-infected seed (a), a validation set of non-infected seed (b), calibration set of infected seed (c), and validation set of infected seed (d), along with model evaluation by index performance comparisons.

Both models give the coefficient of determination of polynomials, which were R^2 0.9917 and 0.9838 for non-infected and infected seeds, respectively (Figure 3a – 3b). These results indicate a strong relationship between porang plant height and observation week, and both models can be used to predict and validate the model. Furthermore, both models were used to predict the height of each porang plant growth with different qualities.

The plots of plant height against observation week for calibration, validation, and prediction sets showed the same trend, starting from the third week and increasing until the seventh week (Figure 3c – 3d). The actual plant height varies between 0 – 29.42 cm for non-infected seeds and 0 – 45.24 cm for infected seeds, while the predicted height produces data that is close to the plant height in the calibration set as the actual height ranges from 0 – 30.00 cm for non-infected seeds; and 0 – 29.16 cm for non-infected seeds.

As demonstrated by the performance comparison of the model evaluation index in Figure 4, the plot of actual height versus predicted height for various seed qualities resulted in varying degrees. In the non-infected seed, R^2 was 0.9811 and 0.9824, but in the infected seed, it increased to 0.9931 and 0.9926, both models achieving a relatively high degree of the fitting. RMSE, MAE, and MAPE increased the value between a calibration set of non-infected seeds, a validation set of non-infected seeds, a calibration set of infected seeds, and a validation set of infected seeds. RMSE were increased from 0.468, 0.564, 2.150, to 4.776, MAE were increased from 0.011, 0.055, 0.669, to 1.516, while MAPE were also increased from 0.866%, 3.411%, 5.310%, and decreased into 4.556%. Based on the model performance, it can be demonstrated from the analysis that the different bulbil quality resulted in the prediction model of plant height with superior accuracy and robustness.

CONCLUSION

In terms of the physical properties of the seeds, the results showed that the weight of the bulbil had a significant difference, while spherical volume and water content were not. The parameters of the vegetative growth of porang plants during planting showed that the wet weight (bulbil and root), dry weight (bulbil, stem, root, crown, and total), root volume, stem length, and leaf color (L* and a*) showed a significant difference between the two bulbil qualities. This result indicated that weight determines seed quality; furthermore, seed quality affects the vegetative growth parameters of porang plants. The results showed that the growth model developed using the polynomial model is suitable for predicting the vegetative growth of porang plants with different qualities of porang seeds. Both models have significantly low error value between the predicted and the actual plant height and effectively the high value of accuracy of the prediction of porang plant height. In particular, it offers technical assistance for precisely controlling bulbil seed quality. In practical applications, the predictive growth model and its performance will expand to incorporate the entire phase process of plant growth, particularly for predicting plant height in a plant factory.

AUTHORS' CONTRIBUTIONS

Noveria A. Nurrahmah: Conceptualization, Data curation, Methodology, Writing –review & original draft. **Aryanis M. Zahra:** Conceptualization, Supervision, Project administration, Data curation, Formal analysis, Investigation, Methodology, Writing – review & original draft. **Sri Rahayoe and Rudiati E. Masithoh:** Supervision, Methodology, Investigation. **Muhammad F. R. Pahlawan and Laila Rahmawati:** Analytical Method Verification.

ACKNOWLEDGMENTS

We are very thankful for the laboratory facility in Biological Physics Laboratory, Department of Agricultural and Biosystems Engineering, Faculty of Agricultural Technology, Universitas Gadjah Mada, Indonesia. Also, the authors wish to acknowledge bulbil of porang support from Porang Farmer in Kalasan, Yogyakarta, Indonesia.

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