Research Reports

Interactions between Irrigation and Fertilization on Growth Performance of Gesnariad

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ADDITIONAL INDEX WORDS. multiobjective comprehensive evaluation, multiobjective decision-making model, photosynthetic characteristics, *Primulina yungfuensis*, vegetative growth

SUMMARY. Gesnariad (*Primulina yungfuensis*) is a popular houseplant species, native to southwest China. However, stunting frequently occurs as a result of limited knowledge about the growth requirements of this plant. Understanding water and fertilizer requirements of gesnariad are important for effective large-scale greenhouse cultivation. Using a response surface methodology (RSM) based on a rotatable central composite design (RCCD; half implementation), a pot experiment was performed in a natural-light greenhouse from June to Sept. 2014. The study assessed the interaction between irrigation volume (W) and nitrogen (N), phosphorus (P), and potassium (K) fertilizer rates on plant height, crown diameter, number of leaves, single leaf area, and fresh weight. Results showed that W had a significant positive effect on plant height, crown diameter, single leaf area, and fresh weight. Furthermore, P fertilization resulted in increased leaf number. Combined P and K fertilization reduced individual leaf area, whereas combined N and P fertilization reduced fresh weight. By analyzing the multiobjective decision-making model, we found that a combination of 100.2 mL water, 3.6 mmol·L⁻¹ N, 0.10 mmol·L⁻¹ P, and 1.2 mmol·L⁻¹ K could be used to achieve optimum growth of gesnariad.

Gesnariad, belonging to the genus *Primulina* (previously recognized as the genus *Chirita*) from the Gesneriaceae family (Weber et al., 2011), is native to southwest China (Li and Wang, 2004). This small rosette plant with ornamental succulent leaves blooms fully in July and August, with a maximum florescence life of 60 d. It is tolerant to shade and drought, so it can be acclimatized easily to indoor environments. Therefore, gesnariad shows great potential as foliage and a flowering houseplant. Several studies have previously assessed the introduction and cultivation of *Primulina* species,

among which Wen (2008) reported that wild gesnariad plants were introduced successfully from the mountains in southwest China to greenhouses in north China. However, problems such as stunted growth arose as a result of

limited information available about their growth requirements. The only information available regarding greenhouse production of gesnariad was a study by Ai (2013), who found that application of 125 mg·L⁻¹ Hoagland solution every 10 d improved growth performance. Water and fertilizers (mainly N, P, and K fertilizers) are important for the successful growth of potted gesnariad in greenhouse environments, with optimization of form, volume, method, time, and place of application necessary for a maximum increase in growth and development (van Iersel et al., 1998). Therefore, the establishment of an optimal irrigation and fertilization program is of great significance for gesnariad greenhouse production.

Interactions between water and fertilizers refer to the interactions between water and the nutrients supplied to the soil or substrate, resulting in positive or negative influences on plant growth and development (Chen et al., 2018; Dong, 2011; Elmi et al., 2004; Guttieri et al., 2005; Islam et al., 2018). Different experiments have been performed to study the interactions on growth, yield, and quality of ornamental plants. Morvant et al. (2001) reported the effects of varying fertilizer and irrigation systems on geranium (*Pelargonium ×hortorum* ‘Pinto Red’) growth and N retention. Results showed that the plants receiving 100% controlled-release fertilizer produced a greater overall biomass, with less N loss than the plants receiving 100% constant liquid fertilization. Also, microtube irrigation produced the greatest increase in plant growth, and the ebb-and-flow system was the most water efficient. Miller et al. (2011) studied the effects of irrigation methods and fertilizer application rate on growth and development of two shamrock plant species (*Oxalis regnellii* and *O. triangularis*), with results showing that overhead irrigation produced larger plants with increased root mass than subirrigation.

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
29.5735	fl oz	mL	0.0338
3.7854	gal	L	0.2642
2.54	inch(es)	cm	0.3937
6.4516	inch ²	cm ²	0.1550
1	mmho/cm	mS·cm ⁻¹	1
28.3495	oz	g	0.0353
1	ppm	mg·L ⁻¹	1
(°F - 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

Furthermore, low or high fertilizer application rates (50 and 500 mg·L⁻¹ N, respectively) reduced the dry weight of overhead-irrigated plants compared with an intermediate fertilizer application rate, whereas fertilizers containing little or no P also reduced the growth of both plant species significantly. Sun and Zhang (2011a, 2011b) reported the coupled effects of irrigation frequency and fertilization rate on growth and flowering of potted begonia (*Begonia × elation*) and poinsettia (*Euphorbia pulcherrima*) plants, calculating the optimum application rates by regression model construction and optimization. Meng et al. (2014) found that fertilization rate plays a more important role in increasing coleus (*Coleus blumei*) biomass than substrate water content, with coupled application of water and fertilizer having a positive effect on biomass formation. It is of note, that these studies were based primarily on commercialized pot-plant species, whereas little attention has been paid to the water and fertilizer requirements of new floral crops such as gesnariad.

RSM is a collection of mathematical and statistical techniques used to generate three-dimensional plots and statistical analyses of how responses are influenced by process variables (Narsollahzadeh et al., 2007). When multiple factors and their interactions affect the desired response, RSM is an effective statistical tool for process optimization by solving multivariate equations (Poojary and Mugeraya, 2012). The RCCD is the RSM used most commonly to establish a quadratic model for responses and to provide information on the effects of variables based on a minimum number of experiments (Divecha and Tarapara, 2017;

Dong et al., 2011; Ebdon et al., 1999). The RCCD method has been applied to investigate the interactions between water and fertilizers on growth and development of ornamental plants (Meng et al., 2014; Sun and Zhang, 2011a, 2011b). However, to our knowledge, no such studies on gesnariad have been reported. In our study, RCCD was used to analyze the interactions among W and N, P, and K fertilizer rate on growth parameters of gesnariad.

The objectives of this study were 1) to quantify interactions among W, N, P, and K on plant height, crown diameter, number of leaves, single leaf area, and fresh weight of gesnariad; and 2) to develop irrigation and fertilization recommendations to achieve optimal growth.

Materials and methods

EXPERIMENTAL SITE AND PLANT MATERIAL. The experiment was carried out in a natural-light greenhouse located in Xiao Tangshan horticultural fields, affiliated with Beijing Forestry University in Beijing, China (lat. 40°8'57"N to 40°9'11"N, long. 116°26'44"E to 116°26'57"E), from 2 June to 9 Sept. 2014. The greenhouse was oriented east–west. Air temperature (T; measured in degrees Celsius) and relative humidity (RH; measured as a percentage) were recorded using data loggers (HOBO; Onset Computer Corp. Bourne, MA) (Fig. 1).

Gesnariad test plants were propagated from leaf cuttings in a 1:1 peat and perlite (v/v) mixture on 5 Dec. 2013. Young plants were transplanted into black plastic pots (diameter, 8 cm; depth, 10 cm) containing the same medium on 20 May 2014. Last, 600 cuttings with three or four leaves were selected as the experimental materials on 1 June 2014.

RCCD (HALF IMPLEMENTATION) APPLICATION AND MANAGEMENT. The number of trials (NT) required for RCCD (half implementation) is based on the number of variables (x) as follows:

$$\begin{aligned} \text{Number of trials} &= 2^{x-1} + 2x + m_0 \\ &= m_c + 2m + m_0, \quad [1] \end{aligned}$$

where m_c is the number of full-factorial experimental points, $2m$ is the number of star points (the points on the axes at a distance of $\pm\alpha$ from center points),

and m_0 is the number of repeated center points (Dillon, 1966; Dong et al., 2011). For a four-variable RCCD (half implementation), $\alpha = 1.6818$, m_0 is fixed at four to provide an estimate of the experimental error and $N = 20$. Concentrations of each variable (factor) are described by coded values, with five concentrations for each factor: -1.6818 , -1 , 0 , 1 , and 1.6818 (Table 1). Five volumes of W, five concentrations of N, five concentrations of P, and five concentrations of K were applied, for a total of 20 treatment combinations, which were performed according to the design matrix (Table 2). Each treatment contained 30 replicates, with one plant per pot per replicate, in random arrangement in the greenhouse.

Water and fertilizers were applied in form of nutrition solutions according to the experimental design (Table 2), with irrigation once per week and fertilizers supplied in the form of a nutrient solution every second irrigation. Water used in this study was natural well water (pH of 5.5, electricity conductivity = 0.8 mS·cm⁻¹) purified by a reverse-osmosis system (CHINT Group Co., Leqing, China). N, P, and K were applied in the form of calcium nitrate tetrahydrate [$\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ (99%)], ammonium dihydrogen phosphate [$\text{NH}_4\text{H}_2\text{PO}_4$ (99%)], and potassium nitrate [KNO_3 (99%)], respectively. Magnesium (Mg) and trace elements were also included in the fertilizer formula (Table 3). All fertilizers were manufactured by Caibanlv Corp. (Shenzhen, China). In addition, trays were placed under the pots to collect excess water and to avoid water and nutrient losses. All other cultivation practices, such as shading methods, were performed according to the traditional regional practices in the same manner for all plants. Cooling pads and fan ventilation systems were used in the greenhouse to alleviate high temperature stress, between 1 July and 31 Aug. 2014.

GROWTH PARAMETER MEASUREMENT. Plant height (measured in centimeters), crown diameter (measured in centimeters), number of leaves, individual leaf area (measured in square centimeters, excluding the petiole), and fresh weight (measured in grams) of the tested plants were measured on 10 Sept. 2014. Plant height was measured as the vertical distance from the base of the stem to the apex of the plant, crown diameter was measured as the widest diameter of the plant's crown,

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Fig. 1. The gesnariad experiment was carried out in a natural-light greenhouse located in Xiao Tangshan horticultural fields. Air temperature (T) and relative humidity (RH) conditions in the greenhouse from 2 June to 9 Sept. 2014 were recorded using data loggers (HOBO; Onset Computer Corp., Bourne, MA) to monitor the growing environment of gesnariad test plants; $(1.8 \times ^\circ\text{C}) + 32 = ^\circ\text{F}$.

the number of leaves referred to the total number of fully expanded leaves, single leaf area was measured with a leaf area meter (LI-3100C; LI-COR, Lincoln, NE), and fresh

weight was determined with an electronic balance. Ten plants were selected randomly from each treatment and the final measurement was taken as the average of all 10 values.

MATHEMATICAL MODEL. For the four-factor RCCD (half implementation) used in our study, the following quadratic polynomial model shown in Eq. [2] was used to describe the response:

$$y = b_0 + b_1w + b_2n + b_3p + b_4k + b_1b_2wn + b_1b_3wp + b_1b_4wk + b_2b_3np + b_2b_4nk + b_3b_4pk + b_{11}w^2 + b_{22}n^2 + b_{33}p^2 + b_{44}k^2 \quad [2]$$

where y is the response; w , n , p , and k are the coded values of the four variables; and the b coefficients were the model regression coefficients (Bajić et al., 2010). It is of note that the nonsignificant regression coefficients were eliminated when constructing the model. The importance of the variable was determined by the absolute value of its coefficient, and the symbol + or – indicates the functional direction of the variable (Dong et al., 2011; Wang, 2013).

STATISTICAL ANALYSIS. Data were gathered and analyzed using Microsoft Excel 2007 (Microsoft, Redmond, WA) and the SPSS 19.0 software package (IBM SPSS Statistic 19.0; IBM, Armonk, NY). Regression models were constructed by backward elimination with SPSS 19.0. All regression models underwent analysis of variance ($P < 0.05$) nonsignificant variables ($P > 0.05$) were removed via regression coefficient t test analysis in a stepwise manner. Optimal solutions to multivariate models were calculated using Lingo 11.0 (Lindo Systems, Chicago, IL).

Results

REGRESSION MODEL CONSTRUCTION. All five regression models were significant ($P < 0.05$), with relatively high correlation coefficients (except for plant height response), which suggests that these models were adequate to describe the studied responses (Table 4).

MAIN FACTOR EFFECT ANALYSIS. In models y_{PH} , y_{CD} , y_{SLA} , and y_{FW} (where PH is plant height, CD is crown diameter, SLA is single leaf area, and FW is fresh weight), the w coefficient was positive, indicating that W had a significant positive effect on plant height, crown diameter, single leaf area, and fresh weight of gesnariad. In model y_{NL} (where

Table 1. Coded and natural values of factors for rotatable central composite design (RCCD) to analyze the interactions among irrigation volume (W) and nitrogen (N), phosphorus (P), and potassium (K) fertilizer rate on growth parameters of gesnariad. For a four-variable RCCD (half implementation), $\alpha = 1.6818$, m_0 is fixed at four to provide an estimate of the experimental error, and $N = 20$. Concentrations of each variable (factor) are described by coded values, with five concentrations for each factor: -1.6818 , -1 , 0 , 1 , and 1.6818 .

Factors ^z	Interval	Concn of coded and natural values				
		-1.6818	-1	0	1	1.6818
W (mL)	89.19	100.0	160.8	250.0	339.2	400.0
N (mmol·L ⁻¹)	2.32	3.6	5.2	7.5	9.8	11.4
P (mmol·L ⁻¹)	0.238	0.10	0.26	0.50	0.74	0.90
K (mmol·L ⁻¹)	1.07	1.2	1.9	3.0	4.1	4.8

^z1 mL = 0.0338 fl oz, 1 L = 0.2642 gal.

NL is the number of leaves), the p coefficient was positive, indicating that P had a positive effect on the number of leaves on gesnariad. In models y_{SLA} and y_{FW} , the negative coefficients of interaction terms pk and np , respectively, suggest that the interaction of P and K had a negative effect on a single leaf area, whereas the interaction of N and P had a negative effect on fresh weight.

MONOFACTOR EFFECT ANALYSIS. An additional five quadratic models, Eqs. [3] through [7], were obtained

Table 2. Experimental design matrix and application scheme ($n = 20$). Five irrigation volumes (W), five concentrations of nitrogen (N), five concentrations of phosphorus (P), and five concentrations of potassium (K) were applied to gesnariad test plants, with a total of 20 treatment combinations performed according to the design matrix. Each treatment contained 30 replicates, with one plant per pot per replicate, in a random arrangement in the greenhouse. Water and fertilizers were applied in the form of nutrition solutions with irrigation once per week and fertilizers were supplied in the form of a nutrient solution every second irrigation.

Treatment	Matrix				Application scheme ^z			
	W	N	P	K	Irrigation (mL)	N (mmol·L ⁻¹)	P (mmol·L ⁻¹)	K (mmol·L ⁻¹)
1	1	1	1	1	339.2	9.8	0.74	4.1
2	1	1	-1	-1	339.2	9.8	0.26	1.9
3	1	-1	1	-1	339.2	5.2	0.74	1.9
4	1	-1	-1	1	339.2	5.2	0.26	4.1
5	-1	1	1	-1	160.8	9.8	0.74	1.9
6	-1	1	-1	1	160.8	9.8	0.26	4.1
7	-1	-1	1	1	160.8	5.2	0.74	4.1
8	-1	-1	-1	-1	160.8	5.2	0.26	1.9
9	-1.6818	0	0	0	100.0	7.5	0.50	3.0
10	1.6818	0	0	0	400.0	7.5	0.50	3.0
11	0	-1.6818	0	0	250.0	3.6	0.50	3.0
12	0	1.6818	0	0	250.0	11.4	0.50	3.0
13	0	0	-1.6818	0	250.0	7.5	0.10	3.0
14	0	0	1.6818	0	250.0	7.5	0.90	3.0
15	0	0	0	-1.6818	250.0	7.5	0.50	1.2
16	0	0	0	1.6818	250.0	7.5	0.50	4.8
17	0	0	0	0	250.0	7.5	0.50	3.0
18	0	0	0	0	250.0	7.5	0.50	3.0
19	0	0	0	0	250.0	7.5	0.50	3.0
20	0	0	0	0	250.0	7.5	0.50	3.0

^z1 mL = 0.0338 fl oz, 1 L = 0.2642 gal.

Table 3. Composition of nutrient solution, with concentration of magnesium and trace elements. Fertilizers supplied in the form of a nutrient solution were applied every second irrigation to gesnariad test plants, and the rate of different elements applied during the experiment was recorded.

Compound	Formula	Application rate ($\mu\text{mol}\cdot\text{L}^{-1}$) ^z
Magnesium sulfate heptahydrate	$\text{MgSO}_4\cdot 7\text{H}_2\text{O}$	2,000
Edetate disodium iron	$\text{Na}_2\text{Fe}\cdot\text{EDTA}$	76.9
Boric acid	H_3BO_3	46.3
Manganese sulfate tetrahydrate	$\text{MnSO}_4\cdot 4\text{H}_2\text{O}$	9.5
Zinc sulfate heptahydrate	$\text{ZnSO}_4\cdot 7\text{H}_2\text{O}$	0.8
Copper sulfate pentahydrate	$\text{CuSO}_4\cdot 5\text{H}_2\text{O}$	0.3
Ammonium heptamolybdate tetrahydrate	$(\text{NH}_4)_6\text{Mo}_7\text{O}_{24}\cdot 4\text{H}_2\text{O}$	0.02

^z1 L = 0.2642 gal.

EDTA = ethylenediaminetetraacetic acid.

Table 4. Regression models and their F and R^2 values constructed to evaluate their fitness for describing the response of different growth parameters of gesnariad.^z

Response	Regression model	F	R^2
Plant height	$y_{PH} = 2.696 + 0.295w + 0.216w^2$	0.387	5.377
Crown diameter	$y_{CD} = 8.414 + 0.399w + 0.675w^2 + 0.578n^2 + 0.565p^2 + 0.41k^2$	0.816	12.436
No. of leaves	$y_{NL} = 11.199 + 0.488p + 0.883w^2 + 0.476n^2 + 0.458p^2$	0.652	7.012
Single leaf area	$y_{SLA} = 7.249 + 0.333w - 0.338pk + 0.62w^2 + 0.553n^2 + 0.552p^2 + 0.637k^2$	0.874	14.990
Fresh weight	$y_{FW} = 9.048 + 1.381w - 1.781np + 2.304w^2 + 2.258n^2 + 1.716p^2 + 1.859k^2$	0.777	7.534

^zAll regression equations are statistically significant ($P < 0.05$): $F_{PH} > F_{0.05}(2, 17) = 3.59$; $F_{CD} > F_{0.05}(5, 14) = 2.96$; $F_{NL} > F_{0.05}(4, 15) = 3.06$; $F_{SLA} > F_{0.05}(6, 13) = 2.92$; $F_{FW} > F_{0.05}(6, 13) = 2.92$. In the regression models, y_{PH} , y_{CD} , y_{NL} , y_{SLA} , and y_{FW} represent the responses of plant height, crown diameter, number of leaves, single leaf area, and fresh weight, respectively; w, n, p, and k are the coded values of irrigation volume and nitrogen (N), phosphorus (P), and potassium (K) fertilizer rate, respectively. $F_{PH} = F$ test under the null hypothesis for plant height; $F_{0.05}(2, 17) = F$ test under the null hypothesis with 0.05 as the critical value; $F_{CD} = F$ test under the null hypothesis for crown diameter; $F_{NL} = F$ test under the null hypothesis for number of leaves; $F_{SLA} = F$ test under the null hypothesis for single leaf area; $F_{FW} = F$ test under the null hypothesis for fresh weight; y_{PH} = regression model for plant height; y_{CD} = regression model for crown diameter; y_{NL} = regression model for number of leaves; y_{SLA} = regression model for single leaf area; y_{FW} = regression model for fresh weight.

Fig. 2. Monofactor effect of irrigation volume (W) on plant height, crown diameter, single leaf area, and fresh weight of gesnariad. Four corresponding quadratic models [regression model for plant height (y_{PH}), crown diameter (y_{CD}), single leaf area (y_{SLA}), and fresh weight (y_{FW})] were obtained by fixing three factors as the zero levels; the other three factors were set as an explanatory variable. Results showed that the increment of plant height, crown diameter, single leaf area, and fresh weight decreased initially and then increased as irrigation volume increased. All growth parameters displayed parabolic trends; 1 cm = 0.3937 inch, 1 cm² = 0.1550 inch², 1 g = 0.0353 oz.

by fixing three factors as the zero levels, whereas the other three factors were set as an explanatory variable (as shown in Figs. 2 and 3):

$$y_{PH} = 2.696 + 0.295w + 0.216w^2 \quad [3]$$

$$y_{CD} = 8.414 + 0.399w + 0.675w^2 \quad [4]$$

$$y_{NL} = 8.414 + 0.488p + 0.458p^2 \quad [5]$$

$$y_{SLA} = 7.249 + 0.333w + 0.62w^2 \quad [6]$$

$$y_{FW} = 9.084 + 1.381w + 2.304w^2 \quad [7]$$

Results showed that the increment of plant height, crown diameter, single leaf area, and fresh weight decreased initially and then increased as W increased (Fig. 2). The increment of

number of leaves decreased initially and then increased as P increased (Fig. 3). It is of note that all growth parameters displayed parabolic trends.

INTERACTION EFFECT ANALYSIS.

Similarly, another two models were established by fixing the W and N factors as the zero level, and then W and K factors were fixed as the zero level (Figs. 4 and 5):

Fig. 3. Monofactor effect of phosphorus (P) fertilizer rate on the number of gesnariad leaves. One quadratic model [regression model for number of leaves (y_{NL})] was achieved, displaying a parabolic trend. The increment of number of leaves decreased initially, then increased as P increased.

Fig. 4. Interactions between phosphorus (P) and potassium (K) fertilizer application rates on single leaf area (SLA) of gesnariad. When P was fixed, the increment of the SLA value decreased initially, then increased as K increased. When K was fixed, the increment of value decreased initially and then increased as P increased. The SLA value displayed a similar trend as P and K increased simultaneously, indicating that moderate concentrations of P and K reduced SLA. The maximum SLA observed was 11.5680 cm² when P was 1.6818 and K was -1.6818, or P was -1.6818 and K was 1.6818. The minimum SLA value observed was 7.2490 cm², when both P and K were set at zero. Therefore, high P concentration and low K concentration, or low P concentration and high K concentration led to a maximum SLA, whereas low, moderate, or high concentrations of both P and K had a negative effect on leaf expansion; 1 cm² = 0.1550 inch².

$$y_{SLA} = 7.249 - 0.338pk + 0.552p^2 + 0.637k^2 \quad [8]$$

$$y_{FW} = 9.048 - 1.781np + 2.258n^2 + 1.716p^2 \quad [9]$$

When P was fixed, the increment of single leaf area value decreased initially, then increased as K increased (Fig. 4). When K was fixed, the increment of value decreased initially

and then increased as P increased. The single leaf area value displayed a similar trend as P and K increased simultaneously, indicating that moderate concentrations of P and K reduced the single leaf area. The maximum single leaf area observed was 11.5680 cm² when P was 1.6818 and K was -1.6818, or P was -1.6818 and K was 1.6818. The minimum single leaf area value observed was 7.2490 cm² when both P and K were set at zero. Therefore, high P concentration and low K

concentration, or low P concentration and high K concentration led to a maximum single leaf area; whereas low, moderate, or high concentrations of both P and K had a negative effect on leaf expansion of gesnariad.

Similarly, when the N fertilizer rate was fixed, the increment of fresh weight value decreased initially and then increased as P increased. When P was fixed, the increment of value declined initially and then increased as N increased. The increment of fresh weight value displayed a similar trend of an initial decrease, followed by an increase, as N and P increased simultaneously. This suggests that a minimum fresh weight was achieved when both N and P were at moderate concentrations. The maximum fresh weight observed was 25.32 g when N was 1.6818 and P was -1.6818, or N was -1.6818 and P was 1.6818; whereas the minimum fresh weight was 9.05 g when both N and P were set at zero. Therefore, high N concentrations and low P concentrations, or low N concentrations and high P concentrations resulted in the maximum fresh weight; whereas low, moderate, and high concentrations of both N and P resulted in reduced fresh weight of gesnariad.

MULTIOBJECTIVE DECISION-MAKING MODEL ANALYSIS. Regression models Eqs. [3] through [7] were analyzed to determine the optimum values of the five growth parameters by constructing a multiobjective decision-making model to calculate the statistical weight and optimum value of each response variable (Dong, 2011; Han, 2006). The statistical weight and optimum value of each response variable was calculated (Table 5) and an objective function was constructed based on the partial least-square method:

$$y = 0.348454(y_{PH} - 2.81)^2 + 0.234961(y_{CD} - 14.04)^2 + 0.092696(y_{NL} - 15.5)^2 + 0.312118(y_{SLA} - 13.3698)^2 + 0.011771(y_{FW} - 29.74)^2, \quad [10]$$

where the five parameters reached their optimum values when $w = -1.6795$, $n = -1.6818$, $p = -1.6818$, and $k = -1.6818$. The growth performance of gesnariad was optimal when W was 100.2 mL, 3.6 mmol·L⁻¹ N,

Fig. 5. Interactions between nitrogen (N) and phosphorus (P) fertilizer rates on fresh weight (FW) of gesnariad. When the N fertilizer rate was fixed, the increment of the FW value decreased initially, then increased as P increased. When P was fixed, the increment of the value declined initially, then increased as N increased. The increment of the FW value displayed a similar trend of an initial decrease, followed by an increase, as N and P increased simultaneously. This suggests that a minimum FW was achieved when both N and P were at moderate concentrations. The maximum FW observed was 25.32 g when N was 1.6818 and P was -1.6818, or N was -1.6818 and P was 1.6818, whereas the minimum FW was 9.05 g when both N and P were set at zero. Therefore, high N concentrations and low P concentrations or low N concentrations and high P concentrations resulted in the maximum FW, whereas low, moderate, and high concentrations of both N and P resulted in reduced fresh weight; 1 g = 0.0353 oz.

Table 5. Regression models (Eqs. [3] through [7]) were analyzed to determine the optimum values of the five growth parameters of gesnariad by constructing a multiobjective decision-making model and then calculating the statistical weight and optimum value of each response variable. The statistical weight and optimum value of each response variable was calculated, and an objective function was constructed based on the partial least-square method.

Response variable	Statistical wt ^z	Optimum value ^y
Y _{PH}	0.348454	2.81 cm
Y _{CD}	0.234961	14.04 cm
Y _{NL}	0.092696	15.5 leaves
Y _{SLA}	0.312118	13.3698 cm ²
Y _{FW}	0.011771	29.74 g

^zThe statistical weight of each response variable was calculated according to the following formula $w_i = \frac{D_i^{-1}}{\sum_{i=1}^5 D_i^{-1}}$, where i is 1, 2, 3, 4, and 5; and $\sqrt{D_i^{-1}}$ is the reciprocal of the sum of the squared error (SSE) of each response variable.

^y1 cm = 0.3937 inch, 1 cm² = 0.1550 inch², 1 g = 0.0353 oz.

y_{PH} = regression model for plant height; y_{CD} = regression model for crown diameter; y_{NL} = regression model for number of leaves; y_{SLA} = regression model for single leaf area; y_{FW} = regression model for fresh weight.

0.10 mmol·L⁻¹ P, and 1.2 mmol·L⁻¹ K. These conditions resulted in a plant height of 2.81 cm, a crown diameter of 14.04 cm, a leaf number of 15.5, a single leaf area of 13.3698 cm², and a fresh weight of 29.74 g.

Discussion

In our study, W had a significant positive effect on plant height, crown diameter, single leaf area, and fresh

weight of gesnariad, which indicates that water was the single most important factor regulating the growth of gesnariad. This result was similar to the findings of Cao (2010), who observed that water was the most important for improved shrubby bushlover (*Lespedeza bicolor*) plant height. Dong (2011) concluded that water supply was the most important factor for limiting the growth of the chinese white poplar (*Populus*

tomentosa), whereas Liu et al. (2014) suggested that W affected leaf area of coffee (*Coffea arabica*) seedlings significantly. Conversely, Xu (2010) found that P fertilizer was more important for controlling fresh weight of lettuce (*Lactuca sativa*) than irrigation, and N and K fertilizers. Also, Sun and Zhang (2011a, 2011b) reported that fertilizer rate was more important for plant height and crown diameter of potted begonia or poinsettia plants than substrate water content. One possible explanation for these conflicting findings could be the variations in requirements for water and fertilizers among plant species. Water is required for every plant, and it plays many essential roles in plant growth and function. For plants tolerant of low soil fertility, such as gesnariad, water is more important in determining growth performance. However, for plants that have a high fertilizer demand, such as begonia and poinsettia, fertilizers play a more important role in boosting growth, especially when adequate volumes of water have been supplied.

P is an essential nutrient for plant growth and is found in every living plant cell. Its functions cannot be replaced by any other nutrient, and an adequate supply of P is required by plants from the very early stages of growth for optimum growth performance (Grant et al., 2005; Jemo et al., 2017; Li et al., 2010; Sun et al., 2016). In our study, P fertilizer affected positively the number of leaves. An increased rate of P fertilizer application increased the number of leaves relatively. This indicates that P fertilizer rate was the most important factor concerning leaf formation in gesnariad. This result is similar to the results of Balathandayutham et al. (2008) and Ezz El-Din et al. (2010), who found that adequate P fertilizer contributed to the maximum number of leaves. Osman and AboHassan (2010) reported that P application affected positively the number of leaves per mangrove (*Avicennia marina*) plant, whereas Ding (2012) claimed that the number of garden dahlia (*Dahlia pinnata*) leaves increased markedly as P fertilizer rate increased, when all other factors were fixed. This may be because P is required especially in young cells or tissues, such as shoots, in which cell division is rapid and metabolism is

vigorous (Khalid, 2012), with the increased number of leaves being the direct result of rapid cell division.

The negative interactions reported for P and K fertilizers were also observed in our study, in which a high P concentration and low K concentration, or low P concentration and high K concentration led to a maximum single leaf area for gesnariad. Conversely, leaf expansion was inhibited when both P and K concentrations were high, moderate, or low. In addition, a negative interaction between N and P fertilizers was observed when high N concentrations and low P concentrations, or low N concentrations and high P concentrations contributed to the maximum fresh weight of gesnariad; whereas fresh weight was reduced when both N and P concentrations were high, moderate, or low. Xu (2010) found that the interactions between N and P fertilizers had a positive effect on fresh weight of lettuce and that high concentrations of both N and P led to a maximum fresh weight, whereas high N concentrations and low P concentrations led to the minimum fresh weight. Ding (2012) reported that higher concentrations of both P and K fertilizers increased the leaf area of garden dahlia considerably. Conversely, Wallace (2008) reported that the interactive effects of N and P on yields of 'Valencia' sweet orange (*Citrus sinensis*) trees were antagonistic. Therefore, it could be speculated that the interactions between the two factors (P and K on single leaf area, N and P on fresh weight) might be antagonistic when they are fixed at the same concentration; however, these interactions require further exploration.

In conclusion, regression models Eqs. [3] through [7], derived from RCCD (half implementation), represented adequately the relationships between factors and response variables. W had a significant positive effect on plant height, crown diameter, single leaf area, and fresh weight of gesnariad. In addition, P had a significant positive effect on the number of gesnariad leaves. The interactions between P and K and between N and P had negative effects on single leaf area and fresh weight, respectively. By using the multiobjective decision-making model, the optimum combination of nutrient solution volume, as

well as N, P, and K can be recommended as 100.2 mL water, 3.6 mmol·L⁻¹ N, 0.10 mmol·L⁻¹ P, and 1.2 mmol·L⁻¹ K. Ten to 15 d after transplanting, the seedlings should be watered every 7 d, and the nutrient solution should be applied on alternate water applications, which could help growers obtain an optimal growth performance for greenhouse-cultivated gesnariad.

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