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Effects of Different Light Substrate Ratios and Fertilization Treatments on the Growth and Physiology of Potted *Prunus mume* 'Gulihong' Seedlings: Postprint

Authors: Ren Anqi, Wei Linxin, Zhang Ruoxi, Zhang Yuhan, Li Qingwei

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Abstract

To guide rational fertilization of 'Guli Hong' mei seedlings, this study used one-year-old 'Guli Hong' mei cutting seedlings as experimental material to design a three-factor three-level orthogonal experiment, investigating the effects of light substrate raw material ratio (volume ratio), single fertilization amount, and fertilization frequency on the growth and physiology of 'Guli Hong' mei. The QI index for each treatment was obtained through the seedling quality index (QI) formula, principal component analysis was conducted on individual indicators to calculate weight coefficients for each indicator, and the fertilization effect D value was calculated by combining the membership function model, providing a basis for scientific fertilization of 'Guli Hong' mei seedlings. The results showed that: (1) The overall growth of 'Guli Hong' mei seedlings was best under the light substrate volume ratio of pine needle soil:peat:perlite (volume ratio) = 1:2:2, which was superior to the other two substrate ratios. (2) In fertilization treatments, the soluble sugar, soluble protein, chlorophyll content, and photosynthetic parameters of 'Guli Hong' mei seedlings showed an upward trend with increasing fertilization amount, but when the fertilization amount was too high, some indicators no longer increased or slightly decreased. (3) The nutrient content in 'Guli Hong' mei leaves increased with rising fertilization amount. (4) Under the conditions of a 20-day fertilization frequency and 200 mL single fertilization amount, biomass accumulation in 'Guli Hong' mei seedlings was promoted. Considering plant growth indicators, physiological indicators, nutrient content, QI index, membership model, and principal component analysis results comprehensively, a light substrate fertilization scheme suitable for one-year-old 'Guli Hong' mei seedling growth was identified as: nutrient solution with nitrogen concentration of 420 $mg \cdot L^{-1}$, phosphorus concentration of 217 $mg \cdot L^{-1}$, potassium concentration of 273 $mg \cdot L^{-1}$, pine needle soil:peat:perlite (volume

ratio) = 1:2:2, single fertilization amount of 150 mL, and fertilization frequency of 15 days. This conclusion provides technical support for light substrate cultivation of 'Guli Hong' mei and theoretical support for further exploring universal formulas suitable for various mei cultivars, and is of significant importance for scientific fertilization and export of mei.

Full Text

Effects of Different Light Substrate Ratios and Fertilization Treatments on Growth and Physiology of Potted Prunus mume 'Gulihong' Seedlings

REN Anqi, WEI Linxin, ZHANG Ruoxi, ZHANG Yuhan, LI Qingwei*

School of Landscape Architecture, Beijing Forestry University, National Engineering Research Center for Floriculture, Beijing 100083, China

Abstract

To guide rational fertilization of 'Gulihong' seedlings, this study employed one-year-old 'Gulihong' cuttings as experimental material in a three-factor, three-level orthogonal experiment investigating the effects of light substrate composition (volume ratio), single fertilization amount, and fertilization frequency on the growth and physiology of 'Gulihong'. The Quality Index (QI) for each treatment was calculated using a seedling quality index formula, principal component analysis was performed on individual metrics to compute weight coefficients, and a membership function model was used to calculate fertilization effect D-values, providing a foundation for scientific fertilization of 'Gulihong' seedlings. Results showed: (1) The optimal overall growth of 'Gulihong' seedlings occurred with a pine needle soil:grass charcoal:perlite volume ratio of 1:2:2, which outperformed the other two substrate ratios. (2) In fertilization treatments, soluble sugar, soluble protein, chlorophyll content, and photosynthetic parameters of 'Gulihong' seedlings increased with fertilization rate, though some indices plateaued or declined slightly at excessive rates. (3) Leaf nutrient content increased with rising fertilization amounts. (4) A fertilization frequency of 20 days and single application of 200 mL promoted biomass accumulation. Considering plant growth indices, physiological indices, nutrient content, QI values, membership function models, and principal component analysis, the recommended light substrate fertilization regime for one-year-old 'Gulihong' seedlings is: nutrient solution with N=420 $mg \cdot L^{-1}$, P=217 $mg \cdot L^{-1}$, K=273 $mg \cdot L^{-1}$; substrate ratio of pine needle soil:grass charcoal:perlite=1:2:2; single fertilization amount of 150 mL; and fertilization frequency of 15 days. These findings provide technical support for light substrate cultivation of 'Gulihong' and theoretical support for developing universal formulas suitable for various Prunus mume cultivars, with significant implications for scientific fertilization and export of Prunus mume.

Keywords: Prunus mume, light substrate, nutrient solution, formula fertilization, growth and physiological responses

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Prunus mume (mei flower) is a small arbor species in the Rosaceae family native to China. With early flowering, diverse cultivar types, and excellent ornamental value in color, fragrance, form, and charm, Prunus mume holds significant application potential in bonsai decoration and landscape greening (Chen, 1999). To meet market demand for potted Prunus mume, understanding the response mechanisms of mei flower to light substrates and fertilization methods, and identifying approaches to enhance yield and efficiency, represent important production measures.

Light substrate is a lightweight seedling medium composed of mixtures of peat, perlite, vermiculite, and other agricultural/forestry wastes or renewable resources that have undergone fermentation, decomposition, or carbonization (Li, 2019). Due to its light weight, rich nutrient content, and strong water/fertilizer retention capacity, light substrate improves nursery convenience and practicality, leading to increased research interest in recent years (Liu et al., 2022). Current Prunus mume research frequently employs light substrates for cutting propagation, grafting, and cultivation of small-to-medium seedlings. For example, Zhou et al. (2021) incorporated grass charcoal, perlite, and vermiculite in cultivation media when studying the effects of gibberellin and temperature on forcing culture of 'Meiren' mei (P. mume 'Meiren'). Light substrate also facilitates logistics and transportation of nursery stock, serving as a prerequisite for optimizing industrialized seedling production, and has been widely applied in agricultural seedling production and forest container nursery systems (Li, 2019). However, traditional cultivation of Prunus mume, particularly 'Gulihong', remains relatively extensive, primarily using garden soil with problems including soil compaction, nutrient loss, and high cultivation costs, resulting in mediocre growth and low standardization that fails to provide optimal conditions for scientific research. Light substrate cultivation can provide 'Gulihong' seedlings with favorable aeration and drainage while reducing pests and diseases. The lighter medium also facilitates potted plant management and logistics, addressing numerous issues associated with traditional cultivation. Therefore, integrated light substrate cultivation represents the future development trend for Prunus mume nursery production. However, previous research has focused more on other plants, with limited attention to 'Gulihong' mei, and the effects of different light substrate ratios and fertilization methods remain unclear, necessitating research to fill this gap.

Plant nutrients are essential for production, and precise, efficient fertilization represents a hot topic in international agricultural science research. Different growth stages require varying nutrient levels, fertilization amounts, and frequencies. Prunus mume typically receives organic fertilizer as basal dressing once in autumn after new shoot growth ceases, with nitrogen fertilizer applied post-flowering to promote vegetative growth, and phosphorus/potassium fertilizers applied during flower bud differentiation (Li et al., 2020). During vegetative growth, mei flower primarily undergoes morphological development with relatively high nitrogen demand (Su, 2020). However, as cultivar water-use capacity and cultivation techniques improve, plant-plant and plant-environment interactions become increasingly apparent, highlighting the benefits of balanced fertilization over heavy application of single fertilizers. Formula fertilization technology can maintain substrate fertility, reduce nutrient loss, and minimize environmental pollution, representing a core technology in scientific fertilization systems (Savvas & Gruda, 2018). Huang et al. (2022) demonstrated that formula fertilization significantly improved container seedling quality of 'Zi Jing Ling' crape myrtle (Lagerstroemia indica). Long et al. (2022) showed that fertilization promoted growth and biomass accumulation in Camellia huana seedlings. Thus, rational formula fertilization benefits plant cultivation and maintenance. Recent Prunus mume research has focused on cold resistance (Wang et al., 2021), germplasm innovation (Li et al., 2020), and floral fragrance (Yang, 2021), with limited studies on rational fertilization. Fu (2012) indicated that 5% Japanese garden test formula and universal soilless cultivation formula were suitable for 'Kouban Dahong' mei (P. mume 'Kouban Dahong'), but few domestic or international reports address Prunus mume responses to nutrient solution formula fertilization, slowing the development of Prunus mume nutrition research and affecting industrialization theory. Therefore, research on rational light substrate ratios and nutrient solution fertilization technology for potted Prunus mume is needed to understand growth and physiological mechanisms, discover essential growth patterns, and provide scientific basis for industrialized nursery production.

This study utilized one-year-old 'Gulihong' cuttings as material. 'Gulihong' exhibits reddish-green annual branches, red inner bark on older branches, and pink flowers, providing high ornamental value as nursery stock. Employing different light substrate ratios and nutrient solution fertilization orthogonal treatments, we measured plant height, basal diameter, annual branch length and diameter, leaf area, soluble sugar and protein content, photosynthetic parameters, nutrient content, and biomass. Using seedling quality index, principal component analysis, and membership function methods, we investigated effects of different light substrate ratios and fertilization treatments on 'Gulihong' seedling growth and physiology to identify optimal substrate and fertilization regimes, aiming to provide crucial firsthand data for light substrate cultivation and formula fertilization of 'Gulihong' and promote high-quality production and trade of Prunus mume.

1.1 Materials

The experiment was conducted in a semi-slope greenhouse at the Beilin Technology Mei-Ju Nursery, Beijing Forestry University (116°35' E, 40°01' N), located in Haidian District, northwest Beijing. The site experiences temperate monsoon climate with annual average temperature of 9-19°C. During the experiment, the nursery averaged approximately 25.5°C with 65.9% relative humidity.

Uniform one-year-old 'Gulihong' (P. mume 'Gulihong') cuttings were selected in December 2020 with basal diameter of 0.8-1.2 cm, plant height of approximately 50 cm, and free from pests and diseases. These were transplanted into 18 cm diameter polyethylene plastic pots for acclimation. Before potting, the substrate was disinfected with 200× dilution of 20% carbendazim, and cuttings were uniformly sprayed with the same solution immediately after potting. After four months of conventional maintenance, the formal experiment commenced.

1.2.1 Experimental Design

The experiment officially began on April 20, 2021. Nutrient solution composition and concentration followed modified Hoagland formula (specific formulation in Table 1), containing N=420 $mg \cdot L^{-1}$, P=217 $mg \cdot L^{-1}$, and K=273 $mg \cdot L^{-1}$. Three factors were established: different light substrate compositions, single fertilization amounts, and fertilization frequencies, each with three levels, yielding nine orthogonal treatments. Considering Prunus mume's drought tolerance, flood intolerance, and preference for slightly acidic, well-aerated substrates, we incorporated pine needle (high humus, slightly acidic) and perlite (porous, sterile, non-toxic). Substrate ratios were: pine needle soil:grass charcoal:perlite=1:2:1 (A1), 1:2:2 (A2), and 1:3:1 (A3) by volume. Single fertilization amounts were 150 mL (B1), 200 mL (B2), and 250 mL (B3) per pot. Fertilization frequencies were 10 days (C1), 15 days (C2), and 20 days (C3). Experimental design details are shown in Table 2 . Fertilization involved uniform substrate irrigation. Control treatments (CK1, CK2, CK3) corresponded to the three substrate ratios without fertilization. Each treatment comprised 15 pots. Watering was applied according to plant needs and substrate moisture. All other cultivation management measures were identical across treatments. Fertilization ceased after 90 days.

1.2.2 Measurement Methods for Growth and Physiological Indices

One day before experiment initiation and on the final day, we measured plant height, basal diameter, annual branch length and diameter, and leaf area of 'Gulihong' seedlings. Relative growth was calculated as Gn-G0, where Gn represents final measurements and G0 represents initial measurements (0 day) for each parameter.

On the day before nutrient solution treatment (0 day) and final day (100 day), functional leaves from upper-middle portions of current-year branches were collected in ice boxes and immediately transported to the laboratory for physiological measurements, including: soluble sugar content (anthrone colorimetry), soluble protein content (G-250 Coomassie brilliant blue method), chlorophyll content (acetone-ethanol extraction), photosynthetic parameters (portable photosynthesis system LI-6400), total nitrogen (Kjeldahl method), total phosphorus (vanadium molybdate spectrophotometry), and total potassium (atomic absorption spectrophotometry). Methods followed Li (2006) *Principles and Techniques of Plant Physiological and Biochemical Experiments*.

After fertilization concluded, roots, stems, and leaves were harvested separately, washed clean, oven-dried at 80°C to constant weight, and weighed.

1.2.3 Seedling Quality Index Calculation Formula

The seedling quality index (QI) was calculated following Shao et al. (2012):

$$QI = \frac{\text{Total seedling dry weight (g)}}{\text{Plant height (cm)/Basal diameter (mm)} + \text{Aboveground dry weight (g)/Underground dry weight (g)}}$$

1.2.4 Membership Function Calculation Formula

Membership function values were calculated as:

$$u(X_i) = \frac{X_i - X_{\min}}{X_{\max} - X_{\min}}$$

where X_i is the ith comprehensive index, $X_{\min}$ and $X_{\max}$ are the minimum and maximum values of the ith comprehensive index, and $u(X_i)$ is the membership function value.

Weights for each comprehensive index were calculated as:

$$W_i = \frac{P_i}{\sum_{i=1}^{n} P_i}$$

where P_i is the contribution rate of the ith comprehensive index and W_i is its weight among all comprehensive indices.

The comprehensive fertilization effect (D-value) for each plant was calculated as:

$$D = \sum_{i=1}^{n} [u(X_i) \times W_i]$$

where $u(X_i)$ is the membership function value and W_i is the weight of the ith comprehensive index. Higher D-values indicate better fertilization effects.

1.3 Data Processing

Data were processed using MS Office 2019 software. Analysis of variance and multiple comparison tests for significant differences were performed using SPSS 26 software.

2.1 Effects of Light Substrate Fertilization on Growth Characteristics of Prunus mume

As shown in Table 3 , all growth indices were significantly better than unfertilized controls (CK), with different treatment combinations significantly ($P<0.05$) promoting plant height, basal diameter, annual branch length, annual branch diameter, and leaf area growth. Maximum plant height growth occurred under treatment A1B3C3, increasing 225.95% compared to CK1. Maximum basal diameter growth occurred under A3B3C2, increasing 219.44% compared to CK3. These results demonstrate that fertilization measures improve 'Gulihong' seedling growth quality.

2.2 Effects of Light Substrate Fertilization on Physiological Characteristics and Biomass

Effects on leaf soluble sugar, soluble protein, and chlorophyll content are shown in Table 4 . At 100 days, substrate ratio 1:2:2 (volume) produced maximum soluble sugar content, increasing 62.08% from pre-treatment, though not significantly different from other substrate ratios. Soluble sugar content decreased with increasing single fertilization amount, with 150 mL showing the best promotion effect (75.55% increase from 0 day), significantly different from 250 mL but not from 200 mL. Soluble protein content showed a rising then declining trend with increasing fertilization amount, peaking at 200 mL (251.54% increase from 0 day), significantly higher than other treatments. This indicates excessive fertilization causes nutrient loss and reduces energy substance accumulation. Soluble sugar content decreased at overly high fertilization frequencies, reaching maximum at 15-day intervals, suggesting 'Gulihong' cannot absorb excessive nutrients.

At 100 days, chlorophyll content peaked with substrate ratio 1:2:1 (104.34% increase from 0 day). Chlorophyll content rose then fell with increasing single fertilization amount, reaching maximum at 200 mL with significant differences from other levels. Lower fertilization frequency benefited chlorophyll content, with 15-day intervals producing maximum content (98.82% increase from 0 day), not significantly different from 20-day intervals. This indicates fertilization amount is a key factor affecting chlorophyll content—within a reasonable range, increased fertilization raises chlorophyll content, but beyond this range, chlorophyll content declines.

Table 5 shows substrate ratio had no significant effect on Pn or Gs values, indicating it is not a major factor affecting photosynthetic capacity. However, transpiration rate (Tr) reached maximum with substrate ratio 1:2:2, significantly different from 1:2:1. Pn increased with single fertilization amount, reaching maximum at 250 mL (17.34% and 8.61% higher than other levels, respectively, with significant differences). Pn showed a rising then falling trend with decreasing fertilization frequency, peaking at 15-day intervals. Gs and Tr showed similar patterns to Pn, while intercellular CO_2 concentration (Ci) showed opposite trends. This demonstrates that fertilization amount significantly affects photosynthesis, and nutrient solution should be supplemented timely and appropriately according to specific needs.

As shown in Table 6 , leaf N, P, and K contents increased significantly after fertilization, with higher single fertilization amounts producing greater nutrient contents. Maximum N, P, and K contents occurred at 250 mL, significantly different from other levels. This treatment also showed good chlorophyll content and net photosynthetic rate, indicating effective nutrient absorption promoted chlorophyll synthesis and enhanced photosynthetic efficiency. Maximum leaf N (2.872%) and P (0.259%) contents occurred at 10-day fertilization frequency, significantly different from other treatments. K content showed no significant difference between 10-day and 15-day frequencies. These results indicate that N, P, and K contents changed consistently with fertilization amount, with 250 mL significantly promoting nutrient enhancement, while fertilization frequency had less pronounced effects on K content.

Substrate ratio 1:2:2 produced better leaf, stem, and root weight accumulation, though leaf weight showed no significant difference among substrate conditions. Comparison with other indices suggests that this ratio's higher chlorophyll content, maximum Pn values, and greatest soluble sugar and protein accumulation ultimately led to greater biomass accumulation. Stem and root weights peaked at 200 mL single fertilization amount (22.975 g and 10.410 g, respectively), while leaf weight showed no significant difference between 200 mL and 250 mL, both performing well. Thus, 200 mL represents a suitable single fertilization amount. Leaf weight accumulation increased with decreasing fertilization frequency, reaching maximum at 20-day intervals (138.51% and 129.83% of other levels), though frequency showed no significant effect on stem and root weight. This indicates appropriate single fertilization amount effectively promotes biomass accumulation, while fertilization frequency is not a key factor affecting stem and root weight.

2.3 Comprehensive Analysis and Evaluation of Light Substrate Fertilization Regimes

Using total seedling dry weight, plant height, basal diameter, aboveground dry weight, and underground dry weight, QI values were calculated—higher QI indicates better seedling quality. Table 7 shows all fertilization treatments effectively improved QI compared to controls, demonstrating fertilization enhances seedling quality. Treatment A2B2C3 achieved maximum QI (4.267), 49.67% higher than control CK2, followed by A2B1C2, A1B2C2, and A1B3C3. The highest QI occurred with substrate ratio 1:2:2, possibly because 'Gulihong' prefers well-drained conditions, and this ratio's higher perlite content improved substrate permeability.

After extracting comprehensive index eigenvalues through principal component analysis, comprehensive fertilization effect D-values were calculated—higher D-values indicate better fertilization effects. Table 8 shows treatment ranking: A1B3C3 > A2B1C2 > A1B2C2 > A2B2C3. Due to differing correlations between growth and physiological indices and varying reference indices among evaluation methods, some treatments showed slight ranking differences among principal component analysis, fuzzy membership function evaluation, and QI evaluation. Overall, QI evaluation results were consistent with principal component analysis and fuzzy comprehensive evaluation. Integrating all three methods and considering economic benefits, treatment A2B1C2—substrate ratio pine needle soil:grass charcoal:perlite=1:2:2, single fertilization amount 150 mL, fertilization frequency 15 days—represents the most suitable light substrate fertilization regime for 'Gulihong' vegetative growth.

3.1 Effects of Light Substrate Fertilization on Growth Characteristics

In plant cultivation, substrate is a critical factor providing stable water, air, and nutrients. Improper substrate use leads to poor growth, disease, or even plant death (Shao, 2004). Ren and Liu (2018) found that increased perlite reduces composite substrate bulk density, increases the macropore-to-micropore ratio, and improves aeration and drainage. Zhao et al. (2022) demonstrated that different perlite-coconut husk ratios significantly affected clivia seedling growth, with higher perlite ratios showing better development effects. This study found optimal 'Gulihong' seedling growth with pine needle soil:grass charcoal:perlite=1:2:2, where the A2 composite substrate contained more perlite than other ratios, enhancing aeration and drainage beneficial for plant growth. As a drought-tolerant, flood-intolerant plant, Prunus mume benefits from good drainage, with similar results reported by Dong et al. (2016). This indicates that increasing perlite proportion benefits 'Gulihong' seedling growth.

Substrate nutrient status significantly affects seedling growth and nutrient absorption/utilization, with different fertilization frequencies and amounts providing varying nutrient availability. Zhao et al. (2018) found that increased fertilization promoted stem elongation in alfalfa (Medicago sativa). This study suggests that overall, single fertilization amount of 150 mL with 15-day frequency produced the best 'Gulihong' growth, while excessive frequency and amount were detrimental. Chen (2016) found that low fertilization frequency delayed nutrient supplementation, causing concentrated application that reduced nutrient utilization efficiency and inhibited plant growth. Liu (2014) also found that excessive single fertilization amounts decreased water and fertilizer use efficiency, negatively affecting plant growth.

3.2 Effects of Light Substrate Fertilization on Leaf Physiological Indices

Changes in soluble sugar content mark carbohydrate metabolism, and fertilization can increase soluble protein and sugar content while enhancing plant resistance (Lian, 2021). This study found substrate ratio had no significant effect on leaf soluble sugar content, while lower single fertilization amounts and moderate frequency showed better promotion effects. Soluble protein content showed a rising then falling trend with increasing fertilization amount, similar to results from Liu et al. (2019) on birch (Betula platyphylla) nutrients. Excessive nitrogen application increases protease activity, accelerating protein hydrolysis and inhibiting RNA transcription and translation, thereby reducing soluble protein content (Yin et al., 2020).

Chlorophyll plays crucial roles in light energy absorption, transfer, and conversion, with its content affecting photosynthetic capacity (Tian et al., 2022). This study found chlorophyll content decreased with reduced single fertilization amount, as chlorophyll accumulation requires adequate water, and low fertilization reduces water absorption. Zhao (2019) similarly showed that reduced water during tomato (Solanum lycopersicum) cultivation significantly decreased leaf chlorophyll content. Fertilization frequency showed no significant effect on chlorophyll content, possibly because water and fertilizer management during the experiment met chlorophyll accumulation requirements. Substrate A2 with the highest perlite proportion benefited Pn, Gs, and Tr values, consistent with Ma et al. (2010) on black locust (Robinia pseudoacacia) container seedlings. Pn increased with single fertilization amount, as increased nitrogen and phosphorus enhance chlorophyll and protein synthesis and improve photosynthetic capacity and energy conversion, similar to Zhou's (2016) findings on Erythrophleum fordii. In this study, increased nutrients enhanced photosynthetic activity in mesophyll cells, raising Pn and stomatal regulation capacity, reducing intercellular CO_2 accumulation and Ci values (Li et al., 2017).

Nitrogen, phosphorus, and potassium are the three most demanded elements for plant growth. For vegetative-stage Prunus mume, nitrogen level significantly affects growth. Phosphorus content relates to synthesis rates of nucleoproteins, phospholipids, and phosphates, which influence flower bud differentiation, while potassium improves ornamental quality (Wang, 2013). Grass charcoal is a single substrate rich in N, P, and K, and increased grass charcoal proportion enhances composite substrate nutrition and fertilizer supply capacity. This study found substrate A3 (pine needle soil:grass charcoal:perlite=1:3:1) most effectively promoted N, P, and K absorption in 'Gulihong' leaves. Wei et al. (2022) reported that grass charcoal has high nutrient content and appropriate total porosity (>20% aeration porosity) with suitable water permeability and aeration. Chen (2016) found facility radish growth quality closely related to fertilization frequency. 'Gulihong' leaf N, P, and K contents increased with single fertilization amount and frequency, as higher frequency shortened fertilizer supplementation intervals and significantly increased leaf nutrient content. However, while leaf nutrient content increased with fertilization amount and frequency, overall morphological growth did not follow identical trends, suggesting complex nutrient accumulation patterns. This study measured leaf nutrient content only once after fertilization cessation, while nutrient transport patterns vary among growth stages and organs (Ouyang, 2021), causing divergent trends between growth indices and leaf nutrient accumulation under different treatments. Further research is needed on nutrient transport patterns among Prunus mume organs.

3.3 Effects of Light Substrate Fertilization on Biomass

Plant biomass directly reflects growth status. Split fertilization meets plant nutrient requirements, enhances nutrient absorption and digestion, improves fertilizer utilization efficiency, and increases biomass accumulation (Chen, 2019). Wang (2013) showed that fertilization increased biomass accumulation in standard chrysanthemum (Chrysanthemum morifolium). This study found all light substrate fertilization treatments produced higher above- and below-ground biomass than controls, indicating fertilization effectively increases total biomass. Total biomass accumulation peaked with substrate ratio 1:2:2, as perlite's high macropore-to-micropore ratio improved substrate structure and aeration when used in higher proportions, while its good salt buffering capacity reduced salt damage from excess nutrient solution, ensuring good plant growth (Li et al., 2016). 'Gulihong' biomass increased notably under medium nutrient solution application (200 mL), while excessive single fertilization amounts reduced biomass. Increased fertilization frequency negatively affected leaf weight gain, as higher frequency increased leaf transpiration and water/nutrient loss (Li, 2014). Therefore, production should carefully manage fertilization amount and frequency to avoid nutrient waste.

This study incorporated environmentally friendly pine needle soil in the light substrate formulation and, using QI index, fuzzy membership function, and principal component analysis, initially identified the optimal light substrate fertilization regime for 'Gulihong' vegetative growth as pine needle soil:grass charcoal:perlite=1:2:2, single fertilization amount 150 mL, and fertilization frequency 15 days, providing scientific basis for 'Gulihong' cultivation research and commercial potted production. However, this study only measured leaf physiological indices. Future research should integrate physiological indices from stems, roots, and other organs for comprehensive evaluation. Additionally, since this study used a single cultivar and different cultivars or ages have varying nutrient requirements, future research should conduct comparative experiments across different Prunus mume cultivars and ages to provide more reference for promoting light substrate fertilization technology.

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