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Reduction in Chemical Fertilizer Rates by Applying Bio-Organic Fertilizer for Optimization Yield and Quality of *Hemerocallis citrina* Baroni

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Abstract: In this study, we investigated if reducing the amount of chemical fertilizer by combining it with organic fertilizer in *Hemerocallis citrina* Baroni (*H. citrina*) cultivation could improve plant growth and photosynthetic capacity and, consequently, increase yield and quality. A continuous two-year field experiment was conducted at a research farm in Zhangzhou City, China, during 2021–2022. Six fertilization levels with two locally grown *H. citrina* cultivars, "Taidong 6" and "Shibage", were tested. The results showed that 100% of the recommended dose of chemical fertilizer (RDF) with bio-organic fertilizer yielded superior effects in promoting both vegetative and reproductive growth in comparison to RDF alone. However, reducing the application rate of chemical fertilizers, especially by more than 40%, resulted in a significant decline in certain agronomic traits such as plant width, leaf width, and scape length. Compared to RDF, the use of 100% or 80% RDF in combination with bio-organic fertilizer significantly increased chlorophyll content, net photosynthetic rate, and transpiration rate as well as yield production, while excessive reductions in chemical fertilizer rate produced results that demonstrated an opposite trend. The co-application of chemical and bio-organic fertilizer enhanced the contents of soluble sugar and lowered total acidity, whereas excessive chemical fertilizer reduction decreased vitamin C, total flavonoids, and soluble protein levels. Utilizing radar chart analysis for a comprehensive assessment of yield and quality demonstrates that the application of bio-organic fertilizer with 80% RDF could be a better field fertilization regime for *H. citrina* cultivation.

Keywords: bio-organic fertilizer; photosynthetic; yield and quality; radar chart analysis

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1. Introduction

Hemerocallis citrina Baroni (*H. citrina*) is a species of perennial herb belonging to the *Asphodelaceae* family. The fresh and dried unopened flower buds of *H. citrina* are commonly referred to as "Golden Needle" or "Huanghua Cai" in Chinese. It has a long history of use as a highly nutritious vegetable in Asian cuisine [1]. In 2018, the cultivation area of *H. citrina* in China covered approximately 6.04 × 10^4 ha, yielding a total production of about 5.85 × 10^5 t and generating an economic value of RMB 4.32 billion [2]. The cultivation industry of *H. citrina* now benefits farmers by increasing their income and promoting rural revitalization in several regions of China [3].

Fertilizers play a vital role as an indispensable guarantee for national food security and an effective supply of agricultural products. Over the past few decades, the significant escalation in crop production in China has largely been due to the intensive application of fertilizers [4]. China has been the world's greatest utilizer of chemical fertilizers, using 23% of the world's total nitrogen fertilizer, 21% of the world's phosphorus fertilizer, and

26% of the world's total potassium fertilizer [5]. However, the long-term and excessive use of fertilizers has a negative impact on soil health and the sustainability of agricultural practices [6]. Excessive use of chemical fertilizers not only escalates production costs but also diminishes crop quality and leads to considerable nutrient depletion, degradation of soil quality, and exacerbation of pest and disease issues [7–9]. This, in turn, necessitates increased pesticide usage, resulting in residual contamination. The same issues also occur in *H. citrina* production, where the overuse of a single fertilizer leads to soil compaction, a decline in soil organic matter, the destruction of soil aggregate structure, and a diminished fertilizer utilization rate, which causes decreased yields [10,11]. Therefore, identifying effective fertilization strategies that mitigate the detrimental effects of excessive fertilizer application has become an urgent imperative in agricultural production.

In light of the imperative to sustain stable food production over the long term in China, the total cessation of chemical fertilizer utilization is impracticable. Presently, integrated nutrient management emerges as a viable strategy to mitigate the environmental impacts engendered by the overapplication of chemical fertilizers. This approach is not intended to supplant chemical fertilizers in the near term; rather, it aims to diminish their usage through the concomitant application of organic fertilizers. Evidence has demonstrated that such synergistic application notably enhances soil fertility more effectively than the exclusive use of either chemical or organic fertilizers [12,13]. Bio-organic fertilizer is a novel organic fertilizer formed by adding a variety of beneficial microbial communities, in which the unique microbial community can activate soil, enhance its physicochemical properties, increase soil biodiversity, and improve soil enzyme activity [14]. Previous studies have shown that the combined application of bio-organic fertilizer and chemical fertilizer can increase soil organic matter content, improve crop root vitality and resistance, promote crop nutrient absorption and accumulation, and enhance crop yield and quality [15–17]. Qiu et al. [18] reported that the combined application of chemical and bio-fertilizers notably enhanced root growth and optimized nutrient distribution in citrus plants. Shi et al. [19] revealed that reducing the use of chemical fertilizers and appropriately supplementing with bio-organic fertilizers significantly increased soil availability of nitrogen and phosphorus, as well as improved cotton stem diameter and seed yield. Compared to conventional chemical fertilizer application, the total soluble sugars and vitamin C content in tomatoes treated with a 25% reduced application of chemical fertilizer plus *Trichoderma*-enriched bio-organic fertilizer increased by up to 24% and 57%, respectively, while nitrate accumulation decreased by up to 62% [12].

Currently, the *H. citrina* industry and its market scale remain relatively limited, and the increase in market value relies on the improvement of production and quality [20]. Adopting reasonable fertilization management practices is the best method to ensure the quality and yield of *H. citrina*, improve and optimize the industrial structure of *H. citrina,* as well as promote its upgrading and efficiency [10,11]. Although bio-organic fertilizers have been shown to improve both crop growth and quality as discussed above, information is limited on the impact of reducing chemical fertilizer application and adding bio-organic fertilizers on the yield and quality of *H. citrina*. Additionally, a comprehensive evaluation method for the yield and quality of *H. citrina* needs to be perfected. Therefore, this study used locally widely planted varieties ("Taidong 6" and "Shibage") in the southeast *H. citrina* planting region in China as experimental materials, with the recommended dose of chemical fertilizer (RDF) as the control, to explore the effects of reducing chemical fertilizer and applying bio-organic fertilizer on the plant growth, yield, and quality of *H. citrina* and to comprehensively evaluate their yield and quality with the radar chart method. This study provides valuable guidance for the establishment of environmentally friendly green fertilization techniques for *H. citrina* cultivation in subtropical region of China and the promotion of sustainable development in the *H. citrina* industry.

2. Materials and Methods

2.1. Site Description

The experiment was conducted at the experimental base of the Institute of Subtropical Agriculture, Fujian Academy of Agricultural Sciences (117°43′ E, 24°32′ N, 18 m AMSL) from 2021 to 2022. The region has a subtropical monsoon humid climate. The average air temperature and precipitation data over the two-year period were obtained from a nearby weather station (Figure 1). The soil tested was a gray sandy loam with 6.57 pH, 14.2 $g \cdot kg^{-1}$ of organic matter, 68.0 $mg \cdot kg^{-1}$ of alkali-hydrolysable N, 12.8 $mg \cdot kg^{-1}$ of Olsen-P, and 177.2 $mg \cdot kg^{-1}$ of available K in the 0–20 cm soil layer.

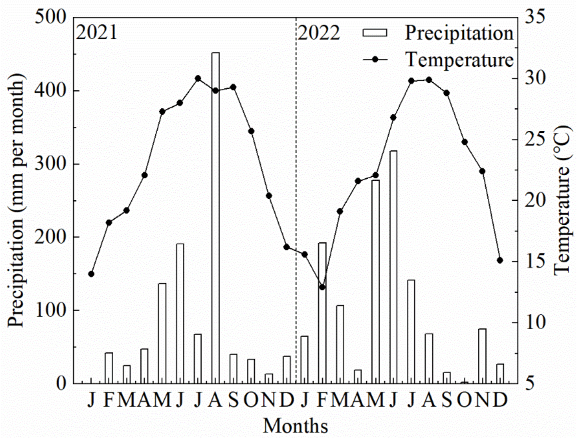

Figure 1. Mean monthly precipitation and temperature in the experimental site from 2021 to 2022.

2.2. Plant Materials and Experimental Design

The cultivars of *H. citrina* examined in this study were "Shibage", a representative cultivar from southern Fujian, and "Taidong 6", which was introduced from Taiwan. A field plot experiment was conducted to evaluate the effects of various fertilization treatments. Six treatments were established: T_0 (no fertilization), T_1 (recommended dose of chemical fertilizer, RDF), T_2 (100% RDF with bio-organic fertilizer), T_3 (80% RDF with bio-organic fertilizer), T_4 (60% RDF with bio-organic fertilizer), and T_5 (40% RDF with bio-organic fertilizer). The fertilizers evaluated in this study were alginate compound fertilizer and alginate bio-organic fertilizer. The compound fertilizer comprised a balance of $N\text{-}P_2O_5\text{-}K_2O$ at a 15:15:15 ratio and contained $\geq$800 $mg \cdot kg^{-1}$ of alginic acid. The bio-organic fertilizer included alginic acid $\geq$ 1000 $mg \cdot kg^{-1}$, organic matter $\geq$ 45.0%, and specific beneficial microbial strains (including *Bacillus subtilis*, *Bacillus licheniformis*, *Bacillus mucilaginosus*, etc.) with an effective viable count $\geq 10^8$ $CFU \cdot g^{-1}$. These products were manufactured by Shandong Enbao Biotechnology Co., Ltd. (Qingdao, China). Details regarding the timing and quantity of fertilizer application are provided in Table 1. Both bio-organic and chemical fertilizers were uniformly broadcast into a trench (width of 20 cm and depth of 10 cm) which was placed 10 cm away from the *H. citrina* plants. Experimental plots each spanned an area of 8 m^2 (1.6 m × 5 m, with a ridge width of 1.2 m and furrow width of 0.4 m). On 26 January 2021, *H. citrina* seedlings were transplanted, with two plants per hole. The row spacing was set at 40 cm and the hole spacing at 30 cm, resulting in a planting density of 62,500 $holes \cdot ha^{-1}$. The experimental design was a randomized complete block with three replicates.

Table 1. Fertilizer application rates to *H. citrina* in different growing periods (kg·ha^{-1}).

Treatment	Basal Dressing	Side-Dressing at Seedling Stage	Side-Dressing at Bolting Stage
T_0	0	0	0
T_1	CF450	CF375	CF375
T_2	CF450 + BOF1200	CF375 + BOF750	CF375
T_3	CF360 + BOF1200	CF300 + BOF750	CF300
T_4	CF270 + BOF1200	CF225 + BOF750	CF225
T_5	CF180 + BOF1200	CF150 + BOF750	CF150

CF, chemical fertilizer; BOF, bio-organic fertilizer; the capital letters followed by numbers are the different levels of fertilizer input.

2.3. Plants Observation, Sampling and Measurement

The agronomic characteristics of each treatment plot at the flowering stage were assessed by selecting six representative plants for measurement. Parameters included plant height and width, leaf length and width, along with scape length, defined as the distance from the base of the main scape to the top of the inflorescence, and floral bud length, measured from the pedicel of the central bud in the inflorescence to the bud's apex. These dimensions were gauged using a ruler. The diameters of the main scape and the floral bud at their widest points were measured with a vernier caliper. Additionally, three uniform, disease-free *H. citrina* plants of comparable size and development were chosen. Measurements of net photosynthetic rate (*Pn*) and transpiration rate (*Tr*) were determined by a portable photosynthesis system (GFS-3000, Heinz Walz, Effeltrich, Germany) and conducted on the central section of the third newest leaf on each plant. The SPAD, indicative of total chlorophyll, was measured by portable chlorophyll meter (SPAD-502 Plus, Konica Minolta, Tokyo, Japan) and calculated using average values from the upper, middle, and lower leaf sections. The yield was determined during the harvest period by demarcating a 2 m^2 central area within each treatment plot and harvesting daily. Records included the fresh weight of floral buds, total fresh yield, and counts of scapes and floral buds. Bud samples were stored at −80 °C for further analysis.

The nutritional analysis of *H. citrina* involved fresh sample assessments. Soluble protein content was determined by the Coomassie brilliant blue G250 method [21]. Soluble sugars were quantified using the anthrone colorimetric method [22]. Vitamin C concentration was measured via the phosphomolybdic acid spectrophotometric method [23]. Total flavonoid content was ascertained with the sodium nitrite–aluminum nitrate spectrophotometric method [24]. The total acid content was determined according to the pH meter potentiometric titration method [25].

2.4. Basic Procedure of Improved Radar Chart Method

Radar chart analysis is a visual technique that translates multidimensional information about an evaluation subject into a two-dimensional space [26]. This method visually represents the strengths and weaknesses of the subject across multiple indicators. To obtain quantifiable results suitable for comparison, Chinese scholars have constructed a comprehensive evaluation function by calculating the area and perimeter of radar chart feature vectors. This function is utilized to compute the scores of the evaluation targets, which are then ranked according to the magnitude of their scores to generate the final evaluation outcome [27,28]. The specific analytical procedures are delineated as follows.

2.4.1. Establishing the Comprehensive Evaluation Index Matrix

The data matrix R, representing the evaluation samples and indexes, was established as follows: there were 2 × 2 × 6 (two years, two cultivars, and six fertilization levels) evaluation samples and nine (scape number, floral bud number, floral bud weight, yield, vitamin C, total flavonoids, total acid, soluble sugar, and soluble protein) evaluation indexes:

$$R = (r_{ij})_{m\times n} \tag{1}$$

where r_{ij} is the original data of the jth evaluation index in the ith sample, with m = 24 and n = 9.

2.4.2. Normalization of Evaluation Index

In order to ensure the comparability of different indicators, considering the potential differences in types and dimensions, it is necessary to standardize the data. The standardization process is typically conducted according to the following equation:

$$r'_{ij} = r_{ij}/\max r_{ij} \tag{2}$$

Here, r'_{ij}, r_{ij}, and $\max r_{ij}$ represent the transformed data, original data, and the maximum value of the jth evaluation index of the ith evaluation sample, respectively. The standardization result transforms the indicator values into the interval [0, 1], where a value closer to 1 indicates a better trait.

2.4.3. Construction of the Evaluation Function and Comprehensive Assessment

In the radar chart consisting of n evaluation indicators, its area is composed of n triangles, and the two sides of each triangle are formed by any two of the n axes, with the angles between them calculated as the average of 360 degrees divided by n indicators. The average area and average perimeter of the radar chart remain invariant with respect to the sequence of evaluation indicators; therefore, these two parameters have been chosen as feature vectors for quantifying the comprehensive evaluation. The calculation formulas of the two are as follows:

$$S_i = \frac{n\sum_{p=1}^{n-1}\sum_{q>p}^{n}\frac{1}{2}r'_{ip}\ r'_{iq}\sin\theta}{C_n^2} \tag{3}$$

$$L_i = \frac{n\sum_{p=1}^{n-1}\sum_{q>p}^{n}\sqrt{r'^2_{ip} + r'^2_{iq} - 2r'_{ip}r'_{iq}\cos\theta}}{C_n^2} \tag{4}$$

where S_i and L_i represent the average area and average perimeter of the closed graph in the radar chart of the ith evaluation sample, respectively; n is the number of evaluation indexes and is also the number of triangles; r'_{ip} and r'_{iq} are the transformed values of the pth and qth evaluation indexes of the ith evaluation sample, respectively; θ is the angle between the two index axes (that is $\theta = 2\pi/n$); and C_n^2 represents the combination number of selecting any two evaluation indexes from n evaluation indicators.

The evaluation vector was constructed based on the average area and perimeter of the radar chart, denoted as $V = (V_{i1}, V_{i2})$. The computation formulas are the following:

$$V_{i1} = S_i/\pi \tag{5}$$

$$V_{i2} = 4\pi S_i/L_i^2 \tag{6}$$

where V_{i1} represents the relative size of the radar chart area of the ith evaluation sample, with higher values signifying a stronger overall advantage possessed and, conversely, smaller values indicating a less competitive position. V_{i2} is employed to reflect the inhomogeneity degree of all indices within the ith evaluation treatment; a higher value indicates better balanced indices, whereas a lower value suggests more poorly balanced indices.

Various methods exist for constructing evaluation functions, with the most common approach involving the calculation of the geometric mean of the evaluation variables. Its formula is as follows:

$$Y_i = \sqrt{V_{i1}V_{i2}} \tag{7}$$

where Y_i is the comprehensive evaluation value of the ith evaluation treatment. It was assumed that the larger the value of Y_i is, the greater the indication of better overall characteristics of the evaluated objective.

2.5. Statistical Analysis

Statistical analyses were conducted using Microsoft Excel 2016 and SPSS 27.0. Graphs were plotted using Origin 2021b. The LSD test was used to assess the differences among all treatments at the $p < 0.05$ level. Spearman's correlation coefficients were used to assess the relationships between plant growth traits and yield parameters of *H. citrina*. The water use efficiency (WUE) was calculated as the ratio of Pn and Tr. In addition, both yield- and quality-related parameters were analyzed using an improved radar chart method; all parameters were normalized through a maximum transformation to ensure consistency in the data representation.

3. Results

3.1. Plant Growth Characteristics

Table 2 presents the results for the effects of various fertilization treatments on the vegetative and reproductive growth indexes of *H. citrina* over a two-year period. Both "Taidong 6" and "Shibage" demonstrated similar trends across the duration of the study. Fertilization significantly enhanced both vegetative growth and reproductive development in *H. citrina* when compared to the non-fertilized control (T_0). Compared with the RDF alone (T_1), all tested agronomic traits showed improvement under T_2 treatment, with increases ranging from 0.1% to 6.2%. Conversely, T_3–T_5 treatments exhibited a descending trend in PH, LL, SL, SD, and FBL, with average reductions of 4.1–9.8%, 1.0–11.2%, 4.7–10.5%, 2.8–9.0%, and 0.2–2.9%, respectively. The mean traits of PW and LW for both *H. citrina* cultivars initially increased and then decreased under treatments T_3–T_5, whereas FBD consistently increased by 1.4–5.9% relative to T_1 results. This suggests that reducing chemical fertilizer application and using bio-organic fertilizer can effectively inhibit the excessive growth of vegetative organs of *H. citrina* and promote the transformation of buds from slender to robust types.

Table 2. Effects of various fertilization treatments on the growth index of *H. citrina*.

Cultivar	**Treatment**	**PH (cm)**	**PW (cm)**	**LL (cm)**	**LW (cm)**	**SL (cm)**	**SD (cm)**	**FBL (cm)**	**FBD (cm)**
2021									
Taidong 6	T_0	45.7 e	45.9 d	33.6 e	1.03 e	35.4 d	0.36 d	9.49 a	1.01 c
	T_1	54.2 b	53.2 a	47.0 a	1.17 b	44.9 a	0.46 a	9.63 a	1.05 bc
	T_2	57.5 a	53.3 a	43.9 b	1.22 a	43.9 a	0.43 b	9.59 a	1.10 a
	T_3	53.8 b	50.3 b	41.2 c	1.16 b	41.7 b	0.40 c	9.24 b	1.09 ab
	T_4	51.7 c	49.5 b	38.9 d	1.12 c	38.9 c	0.40 c	9.19 b	1.09 ab
	T_5	49.5 d	48.6 c	38.1 d	1.08 d	38.3 c	0.38 cd	9.00 c	1.08 ab
Shibage	T_0	72.8 d	62.8 d	46.1 d	1.32 d	61.8 d	0.46 d	9.78 d	0.76 c
	T_1	84.9 a	75.9 b	52.9 b	1.46 b	70.7 a	0.51 c	10.40 ab	0.87 b
	T_2	83.2 ab	80.8 a	57.4 a	1.51 a	69.3 a	0.59 a	10.43 ab	0.95 a
	T_3	81.1 b	75.6 b	54.2 b	1.50 ab	67.3 b	0.56 ab	10.58 a	0.93 a
	T_4	78.2 c	70.8 c	52.5 bc	1.42 c	66.2 bc	0.53 bc	10.27 bc	0.88 b
	T_5	76.6 c	68.4 c	50.5 c	1.41 c	65.3 c	0.51 c	10.13 c	0.86 b
2022									
Taidong 6	T_0	52.6 e	52.4 d	43.9 e	1.17 d	43.1 e	0.42 d	7.94 d	0.76 d
	T_1	62.5 bc	62.6 b	55.5 cd	1.25 c	53.3 b	0.53 a	8.22 c	0.85 c
	T_2	67.1 a	68.5 a	58.7 b	1.30 b	56.5 a	0.54 a	8.44 abc	0.90 ab
	T_3	62.7 b	67.0 a	62.2 a	1.36 a	51.8 bc	0.50 b	8.57 ab	0.90 a
	T_4	61.2 c	63.3 b	57.6 bc	1.25 c	51.1 c	0.48 c	8.67 a	0.87 bc
	T_5	58.2 d	58.6 c	53.2 d	1.22 c	48.2 d	0.47 c	8.39 bc	0.86 c

Table 2. *Cont.*

Cultivar	Treatment	PH (cm)	PW (cm)	LL (cm)	LW (cm)	SL (cm)	SD (cm)	FBL (cm)	FBD (cm)
Shibage	T_0	85.3 d	66.7 d	47.3 d	1.29 d	83.7 e	0.53 e	8.49 d	0.75 d
	T_1	106.3 a	77.1 b	67.0 a	1.44 a	99.1 a	0.61 ab	9.26 ab	0.79 c
	T_2	105.4 a	80.3 a	68.8 a	1.43 a	98.7 a	0.63 a	9.22 ab	0.83 ab
	T_3	97.8 b	77.3 b	62.6 b	1.41 ab	94.7 b	0.59 c	9.06 bc	0.85 a
	T_4	94.0 c	73.7 c	58.6 c	1.37 bc	91.0 c	0.60 bc	9.34 a	0.82 ab
	T_5	93.5 c	72.3 c	55.8 c	1.35 c	88.1 d	0.56 d	8.92 c	0.81 bc

PH, plant height; PW, plant width; LL, leaf length; LW, leaf width; SL, scape length; SD, scape diameter; FBL, floral bud length; FBD, floral bud diameter. T_0–T_5 represent different chemical fertilizer reductions combined with bio-organic fertilizer (see details in Table 1). Different letters within the same column indicate significant differences ($p < 0.05$) according to LSD testing across the different treatments for each cultivar.

3.2. Leaf Chlorophyll Content (SPAD Value)

Compared to the control treatment (T_0), an increase in leaf SPAD values was observed with the application of chemical fertilizer alone (T_1) or in combination with bio-organic fertilizer (T_2–T_5). Specifically, in the T_2 and T_3 treatments, the "Taidong 6" and "Shibage" cultivars exhibited the highest SPAD values, showing an increase of 2.7–7.3% and 2.4–7.1%, respectively, relative to the T_1 treatment. Notably, the "Taidong 6" cultivar demonstrated more remarkable fluctuations in chlorophyll content across different fertilization treatments compared to "Shibage", indicating a greater sensitivity to fertilization (Figure 2).

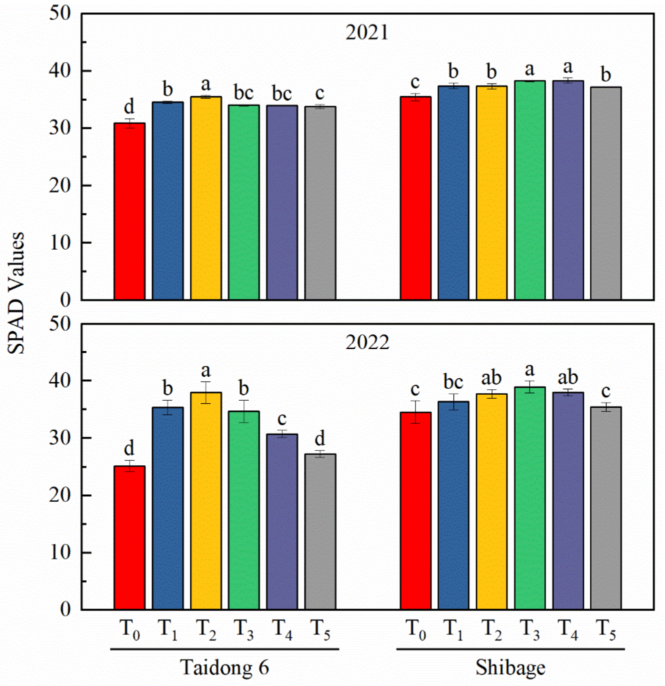

Figure 2. Effects of different chemical fertilizer reductions combined with bio-organic fertilizer on leaf SPAD value of *H. citrina*. T_0–T_5 represent different chemical fertilizer reductions combined with bio-organic fertilizer (see details in Table 1). Vertical bars represent standard deviations. With each cultivar in the trial, vertical bars marked by the different letters are significantly different at $p < 0.05$ according to LSD testing.

3.3. Leaf Photosynthetic Parameters

As shown in Figure 3, significant differences were observed in the *Pn*, *Tr*, and *WUE* of *H. citrina* across all fertilized treatments compared to the unfertilized treatment. The highest values for leaf *Pn* and *Tr* were recorded in the T_2 treatment, followed by T_3 and T_1 treatments, respectively. In the two years of experiments, the "Shibage" cultivar exhibited the highest *WUE* under the T_3 treatment; conversely, the "Taidong 6" cultivar showed the highest *WUE* values under the T_1 and T_2 treatments, respectively. The impact of different fertilization treatments on the *WUE* of the "Taidong 6" cultivar was more significant than that observed in the "Shibage" cultivar.

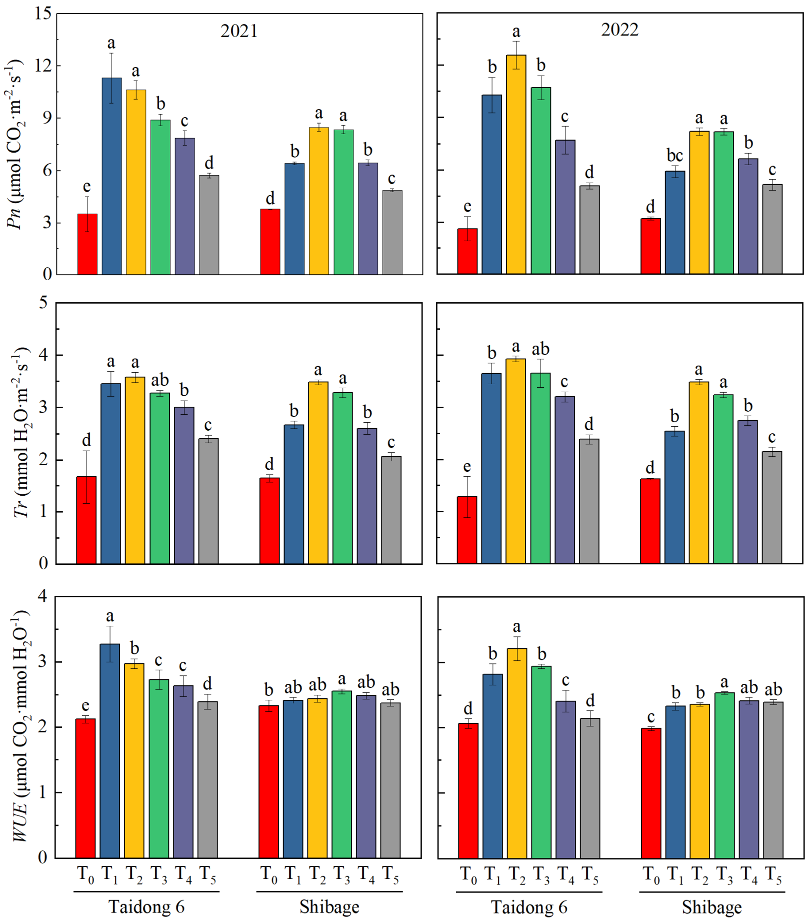

Figure 3. Effects of different chemical fertilizer reductions combined with bio-organic fertilizer on leaf photosynthetic characteristics at the full-flowering stage of *H. citrina*. *Pn*, net photosynthetic rate; *Tr*, transpiration rate; *WUE*, water use efficiency. T_0–T_5 represent different chemical fertilizer reductions combined with bio-organic fertilizer (see details in Table 1). Vertical bars show standard deviations; different letters denote significant differences at $p < 0.05$ according to LSD testing.

3.4. Yield Performance and Correlation Analysis

From Table 3, one can observe that all fertilizer treatments enhanced the yield, scape number, floral bud number and floral bud weight in both *H. citrina* cultivars compared to the treatment with no fertilizer. In detail, the "Taidong 6" cultivar showed increases of 108.9–446.4% in yield, 76.5–250.0% in scape number, 14.9–83.8% in floral bud number, and 3.6–11.9% in floral bud weight following fertilizer application. Similarly, the "Shibage" cultivar exhibited improvements of 109.6–341.2% in yield, 50.0–200.0% in scape number, 21.1–53.3% in floral bud number, and 5.6–18.7% in floral bud weight when fertilized. Overall, fertilization had a more significant effect on yield, scape number, and floral bud number for "Taidong 6", while it had a greater impact on floral bud weight for "Shibage". Compared with the T_1 treatment, the average yield of T_2 and T_3 treatments increased by 14.9% and 17.6%, respectively, whereas the yield of T_4 and T_5 treatments decreased by 10.3% and 34.9%, respectively. The scape number showed a declining trend with the reduction in chemical fertilizer use, while both the floral bud number and floral bud weight first increased, and then decreased, with the changes in the floral bud number being particularly significant. In two years of experimental results, different fertilization treatments showed similar trends in their effects on the yield and its components of *H. citrina*. This suggests that an appropriate reduction in chemical fertilizer combined with the application of bio-organic fertilizer (especially T_3 which contains 80% RDF) can achieve higher yields by increasing the floral bud number while maintaining the scape number.

Table 3. Effects of different chemical fertilizer reductions combined with bio-organic fertilizer on yield and its components of *H. citrina*.

Cultivar	Treatment	SN (Per Cave^{-1})	FBN (Per Scape^{-1})	FBW (g)	Y (g·m^{-2})
2021					
Taidong 6	T_0	0.8 c	8.0 e	2.60 c	182.5 e
	T_1	2.0 b	12.8 b	2.87 a	773.5 b
	T_2	2.8 a	11.7 c	2.84 ab	987.3 a
	T_3	2.0 b	14.7 a	2.91 a	896.3 a
	T_4	1.8 b	11.3 c	2.87 a	625.3 c
	T_5	1.5 bc	10.0 d	2.75 b	434.2 d
Shibage	T_0	1.8 b	9.0 c	2.69 d	466.4 d
	T_1	3.2 a	12.2 b	2.95 b	1194.5 abc
	T_2	3.0 a	13.8 a	2.94 b	1281.0 ab
	T_3	3.2 a	13.2 ab	3.01 a	1316.5 a
	T_4	2.8 ab	12.7 ab	2.85 c	1074.1 bc
	T_5	2.7 ab	12.3 ab	2.84 c	977.8 c
2022					
Taidong 6	T_0	1.7 e	8.7 d	2.23 e	341.9 e
	T_1	4.1 c	14.8 a	2.33 cd	1483.1 b
	T_2	5.3 a	13.2 b	2.39 bc	1749.2 a
	T_3	5.2 ab	14.3 ab	2.39 ab	1868.1 a
	T_4	4.6 bc	10.8 c	2.45 a	1284.8 c
	T_5	3.0 d	10.0 cd	2.31 d	714.3 d
Shibage	T_0	1.4 d	10.9 c	2.62 c	409.0 d
	T_1	3.6 ab	13.8 ab	2.97 b	1553.4 b
	T_2	4.2 a	13.2 b	2.97 b	1732.5 a
	T_3	4.0 a	14.4 ab	2.98 b	1804.4 a
	T_4	3.0 bc	15.4 a	3.11 a	1503.0 b
	T_5	2.6 c	13.9 ab	2.98 b	1130.9 c

SN, scape number; FBN, floral bud number; FBW, floral bud weight; Y, yield. T_0–T_5 represent different chemical fertilizer reductions combined with bio-organic fertilizer (see details in Table 1). Different letters within the same column indicate significant differences ($p < 0.05$) according to the LSD test across the different treatments for each cultivar.

Through the correlation analysis of the agronomic traits and yield parameters (Figure 4), it was found that there were seven growth indexes exhibiting significant ($p < 0.01$) positive correlations with the scape number of *H. citrina*, with leaf length demonstrating the highest correlation coefficient (0.824), followed by transpiration rate (0.692) and photosynthetic rate (0.624). The floral bud number showed significant ($p < 0.01$) positive correlations with eight agronomic traits, with the strongest correlations observed for SPAD value (0.668), transpiration rate (0.665), and scape diameter (0.661). Floral bud weight was positively correlated with four growth parameters; the highest correlation coefficients were associated with floral bud length (0.712), SPAD value (0.680), and plant height (0.570). Furthermore, yield was positively correlated with nine agronomic traits. The strongest correlations were found for leaf length (0.881), scape diameter (0.757), and transpiration rate (0.722).

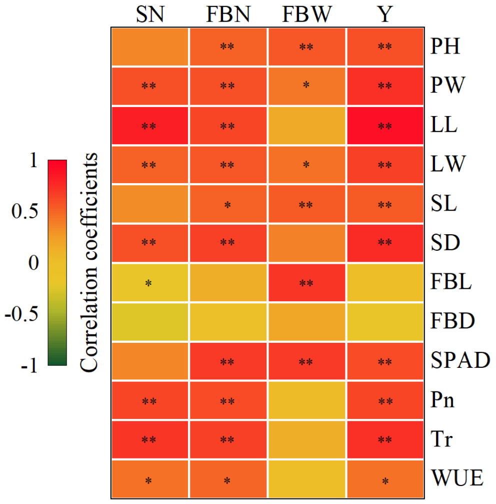

Figure 4. Correlation coefficients between growth and yield parameters of *H. citrina*. PH, plant height; PW, plant width; LL, leaf length; LW, leaf width; SL, scape length; SD, scape diameter; FBL, floral bud length; FBD, floral bud diameter; SPAD, chlorophyll content; *Pn*, net photosynthetic rate; *Tr*, transpiration rate; *WUE*, water use efficiency; SN, scape number; FBN, floral bud number; FBW, floral bud weight; Y, yield. ** and * represent $p < 0.01$ and 0.05 according to Pearson correlation analysis, respectively.

3.5. Quality Analysis

The data reveal that the application of different fertilizer treatments significantly affected all assessed quality parameters over two consecutive growing seasons (Table 4). Bio-organic fertilizer applications exhibited higher values in certain measured indexes than that of chemical fertilizer alone and unfertilized treatments. In general, the combined use of bio-organic fertilizers was associated with an initial increase, followed by a decrease, in the levels of vitamin C, total flavonoids, soluble sugars, and soluble proteins in *H. citrina* as the rate of reduced chemical fertilizer increased. The highest concentrations of these components were predominantly observed under the T_3 treatment, followed by the T_4 and T_2 treatments. Conversely, the total acid content showed a consistent decline across treatments involving bio-organic fertilizers, with reductions ranging from 9.8% to 22.5% compared to the T_1 treatment. The findings indicate that a moderate reduction in chemical fertilizers combined with the use of bio-organic fertilizers improves the nutritional value and taste of *H. citrina*.

Table 4. Effects of different chemical fertilizer reduction combined with bio-organic fertilizer on quality of *H. citrina*.

Cultivar	**Treatment**	**VC ($mg \cdot g^{-1}$)**	**TF ($mg \cdot g^{-1}$)**	**TA ($mg \cdot g^{-1}$)**	**SS ($mg \cdot g^{-1}$)**	**SP ($mg \cdot g^{-1}$)**
			2021			
Taidong 6	T_0	1.285 d	0.611 d	1.08 b	18.54 e	0.498 e
	T_1	1.434 b	0.640 d	1.318 a	22.79 d	0.537 cd
	T_2	1.554 a	0.717 c	1.028 bc	26.03 b	0.561 b
	T_3	1.456 b	0.856 a	0.970 c	27.27 a	0.588 a
	T_4	1.362 c	0.766 b	0.764 d	24.02 c	0.532 d
	T_5	1.335 cd	0.689 c	0.822 d	24.04 c	0.547 c
Shibage	T_0	0.919 d	2.720 d	1.131 c	31.06 d	0.329 c
	T_1	1.005 c	3.137 bc	1.421 a	36.94 bc	0.379 b
	T_2	1.210 b	3.635 a	1.274 b	39.39 b	0.387 b
	T_3	1.361 a	3.674 a	1.163 c	44.35 a	0.410 a
	T_4	1.346 a	3.334 b	1.099 c	42.15 a	0.387 b
	T_5	1.262 b	3.062 c	0.96 d	34.49 c	0.338 c

Table 4. *Cont.*

Cultivar	Treatment	VC (mg·g^{-1})	TF (mg·g^{-1})	TA (mg·g^{-1})	SS (mg·g^{-1})	SP (mg·g^{-1})
		2022				
Taidong 6	T_0	1.286 d	0.336 d	1.792 a	19.11 c	0.277 c
	T_1	1.387 c	0.367 d	1.564 b	21.93 c	0.536 ab
	T_2	1.795 a	0.628 ab	1.479 b	38.67 a	0.570 ab
	T_3	1.617 b	0.556 bc	1.365 c	41.92 a	0.607 a
	T_4	1.365 cd	0.681 a	1.337 c	40.59 a	0.505 b
	T_5	1.354 cd	0.529 c	1.308 c	28.30 b	0.353 c
Shibage	T_0	1.070 d	2.893 d	1.479 a	57.19 d	0.239 c
	T_1	1.492 b	3.860 b	1.337 b	63.55 c	0.458 b
	T_2	1.594 a	3.857 b	1.308 b	67.56 bc	0.593 a
	T_3	1.668 a	3.888 b	1.252 b	68.89 b	0.642 a
	T_4	1.243 c	4.246 a	1.308 b	76.15 a	0.431 b
	T_5	1.321 c	3.465 c	1.28 b	66.52 bc	0.314 c

VC, vitamin C; TF, total flavonoids; TA, total acid; SS, soluble sugar; SP, soluble protein. T_0–T_5 represent different chemical fertilizer reductions combined with bio-organic fertilizer (see details in Table 1). Different letters within the same column indicate significant differences ($p < 0.05$) according to LSD testing across the different treatments for each cultivar.

3.6. Overall Evaluation of *H. citrina* Yield and Quality by Radar Chart

The yield and quality parameters of *H. citrina* cultivars were dimensionless-processed and plotted onto a radar chart (Figure 5), and then the evaluation function was constructed based on the average area and perimeter of the radar chart to comprehensively assess the effects of different fertilization treatments (Table 5). A higher value of the evaluation function result (Y_i) indicates better comprehensive traits of yield and quality in *H. citrina*. From the radar chart, it is evident that several indicators (especially total flavonoids and soluble sugar) for the year 2022 significantly improved compared to 2021, demonstrating enhanced overall advantages and greater balance. Among the different fertilization treatments, the T_3 treatment showed the most significant advantage in indicators, followed by the T_2 and T_4 treatments. The comprehensive evaluation results indicate that, with the exception of the "Taidong 6" cultivar in 2021 (which performed better under the T_2 treatment than the T_3 treatment), all other instances exhibited the highest rankings under the T_3 treatment, followed by the T_2 and then the T_1 or T_4 treatments. These results suggest that a moderate reduction in chemical fertilizers, combined with the application of bio-organic fertilizers, significantly improves both the yield and quality of *H. citrina*.

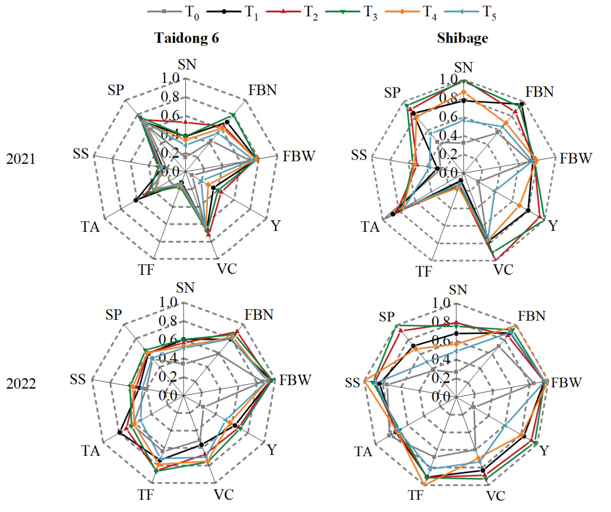

Figure 5. Radar chart showing the overall performance of *H. citrina* yield and quality under different chemical fertilizer reductions combined with bio-organic fertilizer. All variables were normalized using

division by their maximum value. SN: scape number; FBN: floral bud number per scape; FBW: floral bud weight; Y: yield of fresh floral buds.

Table 5. Value of comprehensive assessment of different chemical fertilizer reductions combined with organic fertilizer on yield and quality of *H. citrina*.

Cultivar	Treatment	S_i	L_i	V_{i1}	V_{i2}	Y_i	Rank
				2021			
Taidong 6	T_0	0.568	4.350	0.181	0.377	0.261	6
	T_1	1.002	4.956	0.319	0.513	0.405	3
	T_2	1.080	4.860	0.344	0.575	0.445	1
	T_3	1.083	5.048	0.345	0.534	0.429	2
	T_4	0.813	4.504	0.259	0.504	0.361	4
	T_5	0.725	4.423	0.231	0.465	0.328	5
Shibage	T_0	0.792	3.859	0.252	0.669	0.411	6
	T_1	1.344	4.529	0.428	0.824	0.594	4
	T_2	1.480	4.751	0.471	0.824	0.623	2
	T_3	1.562	4.794	0.497	0.854	0.652	1
	T_4	1.344	4.500	0.428	0.834	0.597	3
	T_5	1.146	4.282	0.365	0.785	0.535	5
				2022			
Taidong 6	T_0	0.620	4.403	0.197	0.402	0.282	6
	T_1	1.316	5.484	0.419	0.550	0.480	4
	T_2	1.691	5.818	0.538	0.628	0.581	2
	T_3	1.708	5.857	0.544	0.626	0.583	1
	T_4	1.285	4.875	0.409	0.679	0.527	3
	T_5	0.833	4.192	0.265	0.596	0.397	5
Shibage	T_0	0.969	4.583	0.309	0.580	0.423	6
	T_1	1.951	5.180	0.621	0.914	0.753	3
	T_2	2.210	5.453	0.703	0.934	0.810	2
	T_3	2.318	5.651	0.738	0.912	0.820	1
	T_4	1.980	5.504	0.630	0.821	0.720	4
	T_5	1.539	4.955	0.490	0.788	0.621	5

S_i, L_i, V_{i1}, V_{i2}, and Y_i denote the average area of radar chart, the average perimeter of radar chart, the relative area radar chart, the inhomogeneity degree of all parameters of radar chart and comprehensive evaluation index, respectively. T_0–T_5 represent different chemical fertilizer reduction combined with bio-organic fertilizer (see details in Table 1).

4. Discussion

Fertilizers play a crucial role in modern agricultural practices, as they are deemed essential for addressing land degradation and food insecurity in densely populated areas [29,30]. By combining the use of chemical fertilizers and organic fertilizers, it is possible to adjust and optimize the fertilizer application structure, thus reducing the amount of chemical fertilizers used [19]. Research has demonstrated that integrating a 10–20% reduction in chemical fertilizer usage with the appropriate application of bio-organic fertilizer can enhance soil fertility, promote the growth and development of plants, and increase the yield of *Brassica campestris* ssp. [31]. In the present study, compared with the RDF alone, reducing chemical fertilizer by 20% combined with an appropriate amount of bio-organic fertilizer was able to increase yield by 10.2–26.0%. However, when the reduction in chemical fertilizer usage exceeded 40%, even when combined with bio-organic fertilizer, the *H. citrina* yield exhibited a downward trend (Table 3). This is consistent with the results of the study by Rose et al. [32], who found that bio-fertilizer could replace 23–52% of nitrogen fertilizer without a loss of yield. The bio-organic fertilizer application in this study used seaweed extract as a carrier and contained multiple plant growth-promoting rhizobacteria (PGPR) strains, including various *Bacillus* species. Among them, *Bacillus mucilaginosus* can decompose potassium feldspar and apatite through mechanisms such as acidolysis, alkaline hydrolysis, capsule adsorption, and comprehensive actions, thus increasing the content of phosphorus (P) and potassium (K) in soil [33]. *Bacillus subtilis* has been documented to significantly enhance nitrogen fixation and induce pathogen resistance in plants [34]. Therefore, PGPR-containing bio-organic fertilizers can improve nutrient availability by activating the soil nutrient system. Since chemical fertilizers have the advantage of rapid nutrient release, the combined application of bio-organic fertilizer and chemical fertilizer can compensate for the slow release of nutrients in bio-organic fertilizer, balancing soil nutrients, and thereby meeting the nutrient demands of crops throughout their entire growth period. This facilitates the formation of crop yields.

The yield components of *H. citrina* include the number of scapes, the number of floral buds per scape, and the weight of floral buds. Experimental analysis of the different fertilization results revealed that increasing the number of floral buds and preserving the number of scapes is crucial for achieving optimal yield. This is similar to the findings of Song et al. [10]. Correlation analysis suggested that the plant width, leaf length, leaf width, transpiration rate, photosynthetic rate, and scape diameter of *H. citrina* were significantly ($p < 0.01$) related to the number of floral buds and the number of scapes (Figure 4). Integrating various parameters, it is evident that the growth of the leaves and the photosynthetic capacity of daylilies are key agronomic traits in yield formation. The application of bio-organic fertilizers can significantly enhance soil microbial activity, leading to the production of various metabolites such as enzymes, vitamins, hormones and growth stimulants during their decomposition, as well as promote root growth and nutrient absorption, which might promote accumulation of photosynthates, reduce ineffective tillering, and facilitate a more efficient distribution of photosynthetic products to reproductive organs [15,35–37]. This was supported by our finding that photosynthetic efficiency, scape number, and floral bud number significantly increased under bio-organic fertilization (Figure 3, Table 3). Furthermore, a comparison between the two *H. citrina* cultivars revealed that "Taidong 6" exhibited higher sensitivity to various fertilization treatments in terms of SPAD values, WUE, and yield compared to the "Shibage" cultivar (Figures 2 and 3, Table 3). This may be explained by the fact that "Taidong 6" bloomed earlier (about 50 days ahead of the "Shibage" cultivar); the bio-organic fertilizer applied was not fully released, and the excessive reduction in chemical fertilizer led to an insufficient soil nutrient supply, thereby affecting the growth and development of "Taidong 6", particularly in the first year. Therefore, the application of bio-organic fertilizers should be appropriately advanced for early-blooming cultivars of *H. citrina*.

Quality refers to the comprehensive set of multi-level quality characteristics of crops and is the direct factor determining their economic benefits [38]. The enhancement of fruit and vegetable quality primarily encompasses three key aspects: visual appeal, nutritional value, and taste and flavor [39,40]. Previous studies have demonstrated that the appropriate application of bio-organic fertilizers in combination with chemical fertilizers enhances soil properties and alters bacterial and fungal communities, so that the quality of banana crops is yet to be improved [34]. The present study showed that in *H. citrina*, the levels of vitamin C, total flavonoids, soluble sugars, and soluble proteins increased to varying degrees in the T_2–T_4 treatment groups (Table 4). Similar results have also been found in lettuce [41] and edible *Roses* [42]. Compared to chemical fertilizers, the application of bio-organic fertilizer significantly increased the nutritional content of purslane, including soluble sugars and total flavonoids, while reducing the levels of antinutritional compounds such as nitrates and soluble oxalic acid [43]. In this study, we observed a continuous decline in the total acid content of *H. citrina* as the amount of chemical fertilizer decreased across all treatments involving the application of bio-organic fertilizer (Table 4). Bio-organic fertilizers that provide organic nutrients are more efficient than nutrients from chemical sources in supporting plant functions, such as protein and enzyme synthesis [44]. Moreover, their slow-release properties may help prevent excessive nitrogen uptake, which could lead to increased levels of amino acids and polyphenols at the expense of reduced sugars in *H. citrina*, thereby contributing to the improvement of flavor [45]. The application of *Bacillus*-based bio-organic fertilizer has been reported to significantly increase the levels of tea polyphenols and amino acids, which are crucial indicators for assessing tea quality [33]. It is interesting to note that these microorganisms might induce the production of hormones such as gibberellins (GAs) due to the high carbon/nitrogen ratios in the soil [46]. In addition, the PGPR strains can prevent some soil-borne diseases through the coordinate release of antibiotics, and the production of minute active substances can also stimulate and induce crop resistance, thus effectively improving quality [47]. Consequently, future investigations should primarily focus on the impact of the combination of bio-organic fertilizers with reduced chemical fertilizers on the rhizosphere ecology of *H. citrina*, with the aim of further elucidating the underlying mechanisms governing their relationship with both yield and quality.

Radar chart analysis is increasingly used in the natural sciences, especially within the fields of agricultural and biomedical research [26]. Huang et al. [28] employed radar charts to effectively visualize the resistance characteristics of various rice varieties against the white-backed planthopper, providing a clear distinction of their resistance performances. Xin et al. [48] visually represented and quantitatively analyzed the synergistic interactions between roots, water, and soil nutrients by utilizing radar charts, intuitively revealing that root development is a limiting factor for improving soil moisture and nutrient supply efficiency. When plotting a radar chart, the shape of the chart varies with the order of the indicators, consequently affecting the area and perimeter of the radar chart. Given the one-to-one correspondence between the combination of indicators and the radar chart, Wang [49] introduced the concepts of "average area" and "average perimeter", that is, exhausting all possible combinations of indicator arrangements, plotting all potential radar charts, and then calculating their average area and perimeter. We used the improved radar chart method to provide an integrated analysis of *H. citrina* yield and quality. Results showed that a moderate reduction in chemical fertilizer combined with the application of bio-organic fertilizer enhanced both the yield and quality of *H. citrina*, and the T_3 treatment demonstrated superior comprehensive performance, with the highest Y_i value of 0.820 in the radar chart evaluation (Table 5). This indicates that a 20% decrease in chemical fertilizer usage complemented by bio-organic fertilizer not only conserves resources and decreases fertilizer costs but also stimulates crop growth, resulting in both quality improvement and increased production, thereby maximizing economic benefits. Based on these findings, we identified the T_3 treatment (80% RDF with bio-organic fertilizer) as the optimal fertilization strategy.

5. Conclusions

A moderate reduction in the use of chemical fertilizers, especially by 20%, combined with the application of bio-organic fertilizer, can significantly promote plant growth, improve photosynthetic efficiency, and increase both the yield and quality of *H. citrina* production. This integrated fertilization approach, as opposed to the exclusive use of chemical fertilizers, is environmentally sustainable and increases the economic value of *H. citrina*. The T_3 treatment, which involves applying 80% of the recommended dose of chemical fertilizer plus bio-organic fertilizer, has been identified as the optimal fertilization management practice, particularly for the "Taidong 6" and "Shibaige" cultivars of *H. citrina*. This finding provides a theoretical basis for selecting rational fertilization techniques to boost both the production and quality of *H. citrina* and paves the way for further research on the effects of reduced chemical fertilizer rates by applying bio-organic fertilizers on nutrient uptake, utilization, and the rhizospheric soil ecosystem of *H. citrina*.

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