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Effect of Substrate Flow Rate on Nutrient Uptake and Use Efficiency in Hydroponically Grown Swiss Chard (*Beta vulgaris* L. ssp. *cicla* 'Seiyou Shirokuki')

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Abstract: Unlike in soil culture, a substrate (nutrient solution) in a hydroponics system can flow, and this can affect both nutrient uptake and plant growth. In this study, we hydroponically cultivated Swiss chard (*Beta vulgaris* L. ssp. *cicla*) under different flow rates to analyze changes in the growth, nutrient uptake, and nutrient use efficiency. When the flow rate was intensified from 2 to 4 L/min, leaf area, the fresh weight, dry weight, and root length increased. However, when the flow rate was increased from 4 to 8 L/min, values of these growth parameters decreased. The nutrient uptake had a similar trend relative to the growth parameters and nutrient use efficiency of macronutrient elements, increased as the flow rate increased. This indicates that the flow rate affects plant growth by influencing the nutrient uptake, and an increase in the flow rate can aid in improving nutrient use efficiency. In hydroponics, regulating the flow rate at a reasonable volume is recommended to increase yield by enhancing nutrient use efficiency, but too intensive a flow rate may cause excessive physical stimulation to plants and inhibit their growth. Therefore, it is important to choose an appropriate substrate flow rate for optimal hydroponics production.

Keywords: hydroponics; flow rate; nutrient uptake; nutrient utilization efficiency; nutrition management; plant growth; controlled environment agriculture; artificial light cultivation; nutrient solution; dryland agriculture

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1. Introduction

Drought and soil degradation in drylands can severely hinder the existing agricultural production [1]. Therefore, drylands need a high yield production mode that saves water and resources [2]. Hydroponic culture, as a mode of agricultural production practice, has been proven to be effective at addressing these challenges [3] by saving resources and providing high yield [4]. It is widely used in many environments that are not suitable for field production, especially in drylands [5].

Hydroponic culture is a kind of agriculture with a controlled environment [6]. Since the cultivation environment affects plant growth [7], hydroponics, unlike soil cultivation, requires the use of nutrient solution and intensive environmental control (pH, electrical conductivity (EC), dissolved oxygen (DO), temperature, etc.) to ensure normal growth of crops [8]. The key difference between hydroponic culture and soil culture is that a cultivation substrate in hydroponics can flow, which implies that a change in flow rate may affect plant growth in a hydroponic culture [9].

Researchers have recently studied the effect of the nutrient solution flow rate on crop yield in hydroponics. Dalastra et al. [10] studied the lettuce nutrient content and biomass production based on nutrient solution flow in hydroponic cultivation. The evaluated treatments included nutrient solution flow rates of 0.5, 1, 2, and 4 L/min, each applied to a separate cultivation channel. The highest yield was obtained with a nutrient solution flow rate of 1 L/min. Al-Tawaha et al. [11] investigated the effect of three different flow rates of nutrient solution (10 L/min, 20 L/min, and 30 L/min) on lettuce growth. They found that the 20 L/min flow rate increased lettuce biomass production. Obviously, the results of previous studies indicate that the flow rate considerably affects plant growth in hydroponic cultivation. Many researchers have proven that the flow rate has an impact on production in hydroponic culture, and in a series of flow rates, there is a certain value or range of values that can make plants absorb more nutrient particles and maximize the yield.

Baiyin et al. [9] performed hydroponic cultivation of the vegetable Swiss chard (*Beta vulgaris* L. ssp. *cicla*) under different flow rates (0, 2, 4, 6, and 8 L/min) in a natural light greenhouse. The appearance of the roots under different flow rates was described by fluid visualization technology. The authors also pointed out that the flow rate could impact the nutrient absorption of hydroponic plants by affecting the vorticity distribution of the flow field in the container. The flow rate of 6 L/min had the best results for fresh weight, dry weight, leaf area, and nitrogen uptake in that study. In addition, in another study [12], the authors carried out floating hydroponics cultivation experiments (also with Swiss chard) under artificial light conditions and investigated the root morphology of plants growing under different flow rates. It was concluded that excessive flow brought excessive physical stimulation, which would make the roots compact and reduce nutrient absorption, thus affecting plant growth.

In hydroponic cultivation for vegetable production, increasing the yield by regulating the flow rate is recommended [11]. Furthermore, it should be mentioned that the contents of nutrients in plants growing at different flow rates are different [10]. It is indicated that the ability of plants to use nutrients is different under different flow rates, which makes the growth of plants different at different flow rates. However, previous studies have discussed the effect of the flow rate on crop growth, but rarely mentioned the change of nutrient use efficiency. Generally, agricultural producers aim to maximize yield [13]. However, in favor of areas with restricted resources, they also focused on maximizing resource utilization [14]. In drylands particularly, the balance between input and output in agriculture is a crucial challenge and the utilization efficiency of plant nutrition is a very important topic [15]. Increasing nutrient utilization efficiency through reasonable management has always been the goal of dryland agriculture [16]. In hydroponics, an increased understanding of the influence of the flow rate on nutrient use efficiency may identify economic ways of improving yield. Low availability of nutrition often limits crop growth and production potential in agricultural systems because most of the crops are sensitive to nutrient deficits in certain periods. On the other hand, production costs can be increased and the environment polluted by the overuse of fertilizers. As such, enhancing the nutrient use efficiency in agriculture is very important [17]. Nutrient management in cultivation systems is an essential factor for controlling the production quality, especially in arid and semi-arid regions [2].

This study aimed to analyze changes in plant growth parameters and nutrient uptake by employing hydroponic cultivation under different flow rates of a substrate. Correlation among these growth parameters and nutrient uptake was analyzed. In addition, authors also discuss the utilization efficiency of various nutrient elements under each flow rate. This paper explores a nutrient management method based on flow regulation for usage in hydroponic culture, which can not only maximize the yield but also makes the nutrient utilization efficiency as high as possible.

2. Materials and Methods

2.1. Cultivation System and Elemental Analysis

The hydroponics cultivation experiment was performed under artificial lighting in an indoor cultivation room. Environmental data such as the air temperature, air pressure, wind speed, and relative humidity in the cultivation room were recorded during the experiment period (Supplementary Data Table S1). This study used the same cultivation device, LED lamp, and nutrient solution as the literature [12]. The details of the cultivation device, operation, and the setting status of the LED light have been described in detail in the literature [12].

Plants cultivated in each container were harvested after 14 days and subsequently separated into shoots and roots. The fresh weight and dry weight of shoots and roots, leaf area, and root length were measured using the method described in the literature [12] (Supplementary Data Table S2). Next, dried plant parts were crushed to measure the nutrient content. The total nitrogen content in either shoot or root samples was measured using an organic elemental analyzer (CN corder JM1000CN, J-SCIENCE GROUP, Tokyo, Japan). The contents of phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S) were measured using an inductively coupled plasma-mass spectrometer (ICP-MS Agilent 8900, Agilent Technologies Inc., Santa Clara, CA, USA) [18]. Then, the nutrient uptake by the whole plant was calculated according to the dry weight of a plant and the content of each nutrient element (Supplementary Data Table S3). The nutrient use efficiency of each nutrient element was calculated by dividing values of dry weight by the nutrient uptake of a whole plant.

2.2. Data Analysis

Statistical analysis software (SPSS 25, IBM) was used to analyze the data. The statistical analysis method used in this study was one-way analysis of variance, followed by Duncan's multiple range test at the significance of $p < 0.05$. Four treatments (flow rate) were established with four replications (cultivation container). The value of each replication was obtained by calculating the average value of all the plants in the same cultivation container. The results were expressed as means ± standard error ($n = 4$) and correlations among plant growth parameters and their nutrient uptake were analyzed by Pearson's correlations.

3. Results

3.1. Plant Growth under Different Flow Rates

The leaf area of plants grown under different flow rates is shown in Figure 1a. The results show that with an increased flow rate from 2 to 4 L/min, the leaf area increased by 12.8%, but with a further increase in the flow rate from 4 to 8 L/min, the leaf area decreased. Compared with the rate of 4 L/min, the leaf area decreased under the rates of 6 L/min and 8 L/min by 27.1% and 45.9%, respectively.

As Figure 1b shows, the results of the fresh weight of plants grown under different flow rates show that with an increased flow rate from 2 to 4 L/min, the fresh weight increased by 26.7%. Conversely, with an increased flow rate from 4 to 8 L/min, the fresh weight decreased. In comparison to the rate of 4 L/min, the fresh weight of plants grown under the flow rate of 6 L/min and 8 L/min decreased by 36.2% and 51.4%, respectively.

Figure 1c shows the dry weight of plants grown under different flow rates. The mean dry weight increased with an increased flow rate from 2 to 4 L/min and decreased with an intensified flow rate from 4 to 8 L/min. The mean plant dry weight showed a significant decrease at the rate of 8 L/min in comparison to the other flow rates and was 30.0% lower as compared to 4 L/min.

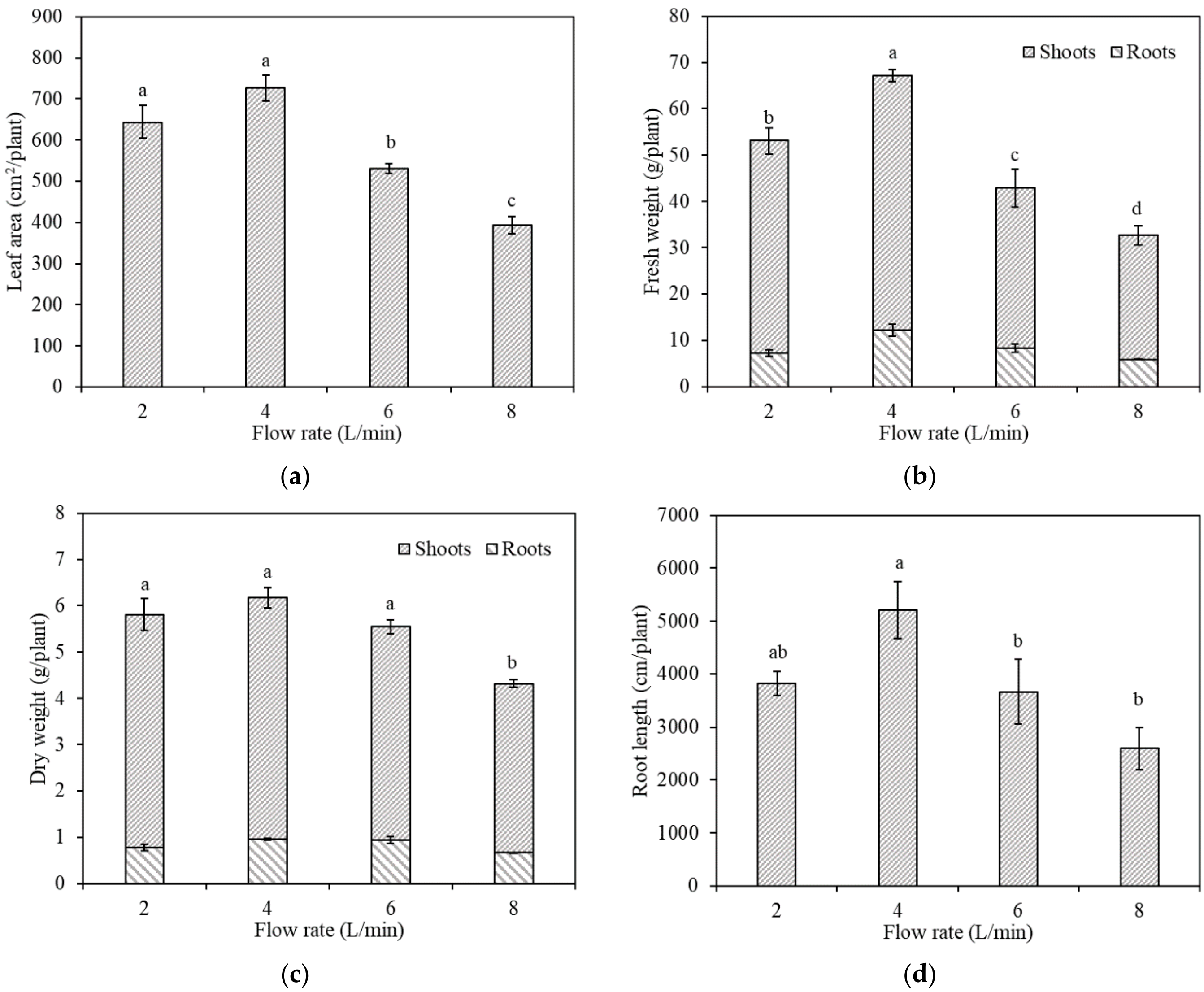

Figure 1. Growth parameters of the plants growth under different flow rates in this study. (**a**) Leaf area; (**b**) fresh weight; (**c**) dry weight; (**d**) root length. There were significant differences in the bars marked with different letters ($p < 0.05$). Data are expressed as means ± standard error ($n = 4$).

The root length of plants grown under different flow rates is shown in Figure 1d. It is evident that with an increased flow rate from 2 to 4 L/min, the root length increased by 36.4%. However, with an increased flow rate from 4 to 8 L/min, the root length decreased. Compared with the flow rate of 4 L/min, the root length in the treatments of 6 L/min and 8 L/min decreased by 29.6% and 50.3%, respectively.

As shown in Figure 1, in this study, we achieved a similar result to our previous research [9,12]. That is, in a certain range, with the increase in flow, the growth of plants is enhanced. However, when the flow is too fast, increasing the flow continuously is not beneficial to the growth of the plant. In addition, in this article, the authors will use the dry weight (Figure 1c) and nutrient uptake (Figure 2) of plants under different flow rates to discuss the nutrient utilization efficiency.

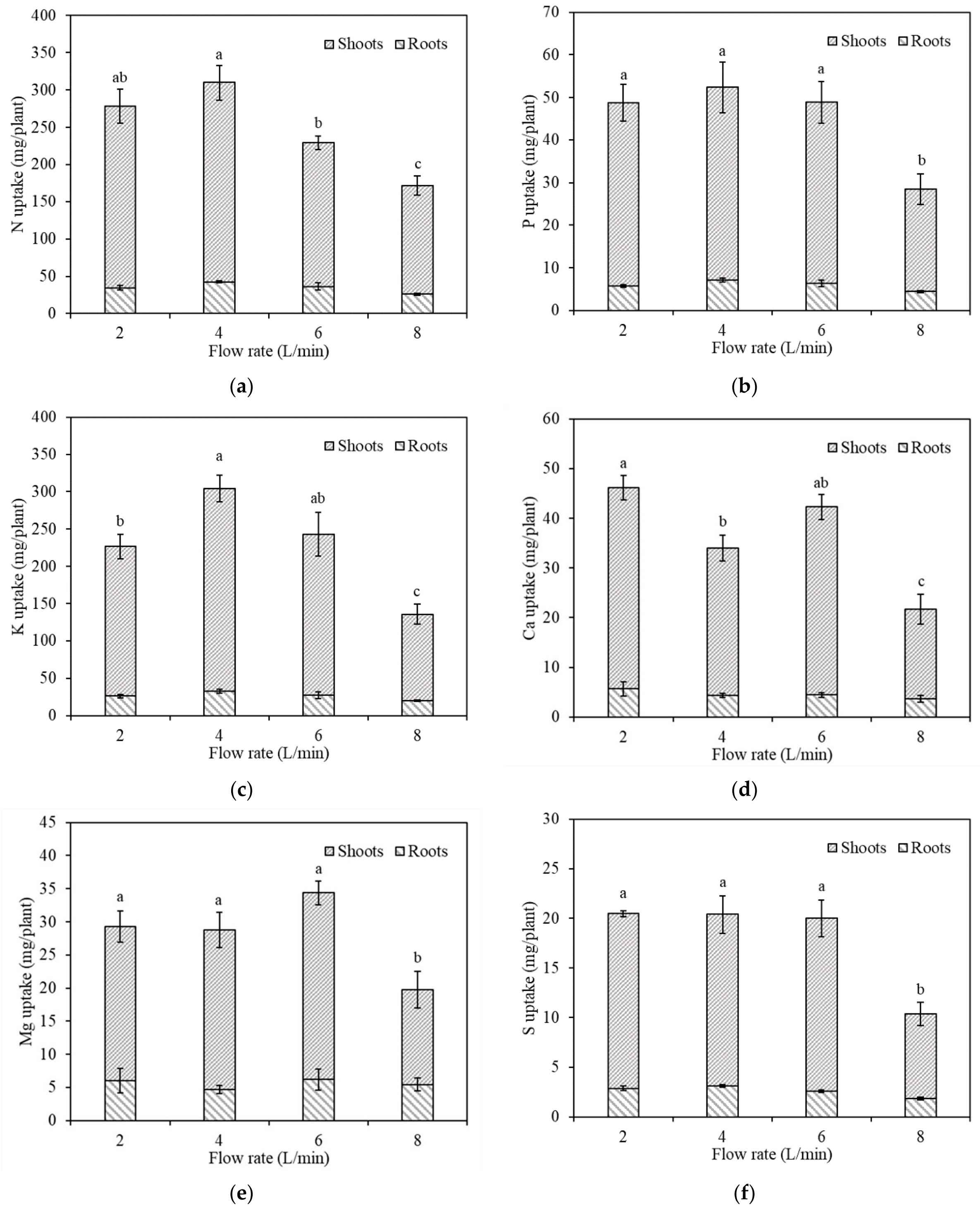

Figure 2. Nutrient uptake of plants under different flow rates. (**a**) Nitrogen uptake by a whole plant; (**b**) phosphorus uptake by a whole plant; (**c**) potassium uptake by a whole plant; (**d**) calcium uptake by a whole plant; (**e**) magnesium uptake by a whole plant; (**f**) sulfur uptake by a whole plant. There were significant differences in the bars marked with different letters ($p < 0.05$). Data are expressed as means ± standard error ($n = 4$).

3.2. Nutrient Uptake of Plants Grown under Different Flow Rates

The nutrient uptake of plants grown under different substrate flow rates is shown in Figure 2. As can be seen in Figure 2a, with an increased flow rate from 2 to 4 L/min, the rate of N uptake by a whole plant increased by 8.3%, and with an increased flow rate from 4 to 8 L/min, the N uptake decreased. As compared with the rate of 4 L/min, the nitrogen uptake of plants under the treatment of 6 L/min and 8 L/min decreased by 23.6% and 42.6%, respectively.

As can be seen in Figure 2b, with the increase in the flow rate from 2 to 6 L/min, there was no significant difference in the rate of P uptake by the plants, while there was a significant decrease at 8 L/min compared to the other flow rates. In comparison to 6 L/min, the P uptake by plants in the 8 L/min treatment decreased by 41.8%.

With an increased flow rate from 2 to 4 L/min, the K uptake of the whole plant increased by 34.3% (Figure 2c), and with an increased flow rate from 4 to 8 L/min, the K uptake decreased. As compared with the rate of 4 L/min, the K uptake of the plants grown at the rates of 6 L/min and 8 L/min decreased by 20.3% and 55.34%, respectively.

Figure 2d shows that with an increased flow rate from 2 to 4 L/min, the rate of Ca uptake of a whole plant decreased by 26.2%. With an enhanced flow rate from 4 to 6 L/min, the Ca uptake of a whole plant increased by 24.2%. Further increasing the flow rate to 8 L/min resulted in a decrease in Ca uptake by 36.2%.

Figure 2e displays that the Mg uptake rate had no significant difference during the increase in the flow rate from 2 to 6 L/min, but it showed a significant decrease at the rate of 8 L/min as compared with other flow rates. Compared to 6 L/min, the plant Mg uptake at the rate of 8 L/min decreased by 42.5%.

As can be seen from Figure 2f, with an increased flow rate from 2 to 6 L/min, the S uptake of the whole plant showed no significant difference, while it significantly decreased at the rate of 8 L/min as compared with other flow rates. The S uptake of plants cultivated under the flow rate of 8 L/min decreased by 48.2% in comparison to a flow rate of 6 L/min.

3.3. Correlation between Plant Growth and Nutrient Uptake

Correlations between plant growth and their nutrient uptakes are shown in Figure 3. There was a positive correlation between the growth parameters and nutrient uptake. Among them, the leaf area had a significantly positive correlation with plant fresh weight, dry weight, root length, and nutrient (N, P, K, Ca, and S) uptake. Root length had a strong positive correlation with plant fresh weight, leaf area, and nutrient (K and P) uptake. Fresh weight had a significantly positive correlation with nutrient (N, P, K and S) uptake, and dry weight was significantly correlated with all nutrient absorption, especially with N uptake (Pearson's correlation coefficient: 0.849).

	Leaf area	Fresh weight	Dry weight	Root length	Mg uptake	K uptake	P uptake	S uptake	Ca uptake	N uptake
Leaf area	1									
Fresh weight	0.916**	1								
Dry weight	0.829**	0.781**	1							
Root length	0.640**	0.769**	0.429	1						
Mg uptake	0.418	0.334	0.627**	0.085	1					
K uptake	0.698**	0.814**	0.704**	0.714**	0.646**	1				
P uptake	0.721**	0.720**	0.627**	0.740**	0.539*	0.742**	1			
S uptake	0.639**	0.650**	0.792**	0.468	0.818**	0.851**	0.698**	1		
Ca uptake	0.506*	0.339	0.698**	0.049	0.743**	0.394	0.434	0.759**	1	
N uptake	0.847**	0.773**	0.849**	0.439	0.488	0.664**	0.588*	0.739**	0.561*	1

Figure 3. Correlations among plant growth parameters and plant nutrient uptake. Pearson's correlation coefficients are presented. "*" denotes $p < 0.05$ and "**" denotes $p < 0.01$.

3.4. Nutrient Use Efficiency under Different Flow Rates

The nutrient use efficiency under different substrate flow rates is shown in Figure 4. Figure 4a shows that with an increased flow rate from 2 to 4 L/min, the nitrogen use efficiency (NUE) decreased by 3.5%, while with an increase from 4 to 6 L/min and from 6 to 8 L/min, the NUE increased by 19.3% and 26.0%, respectively.

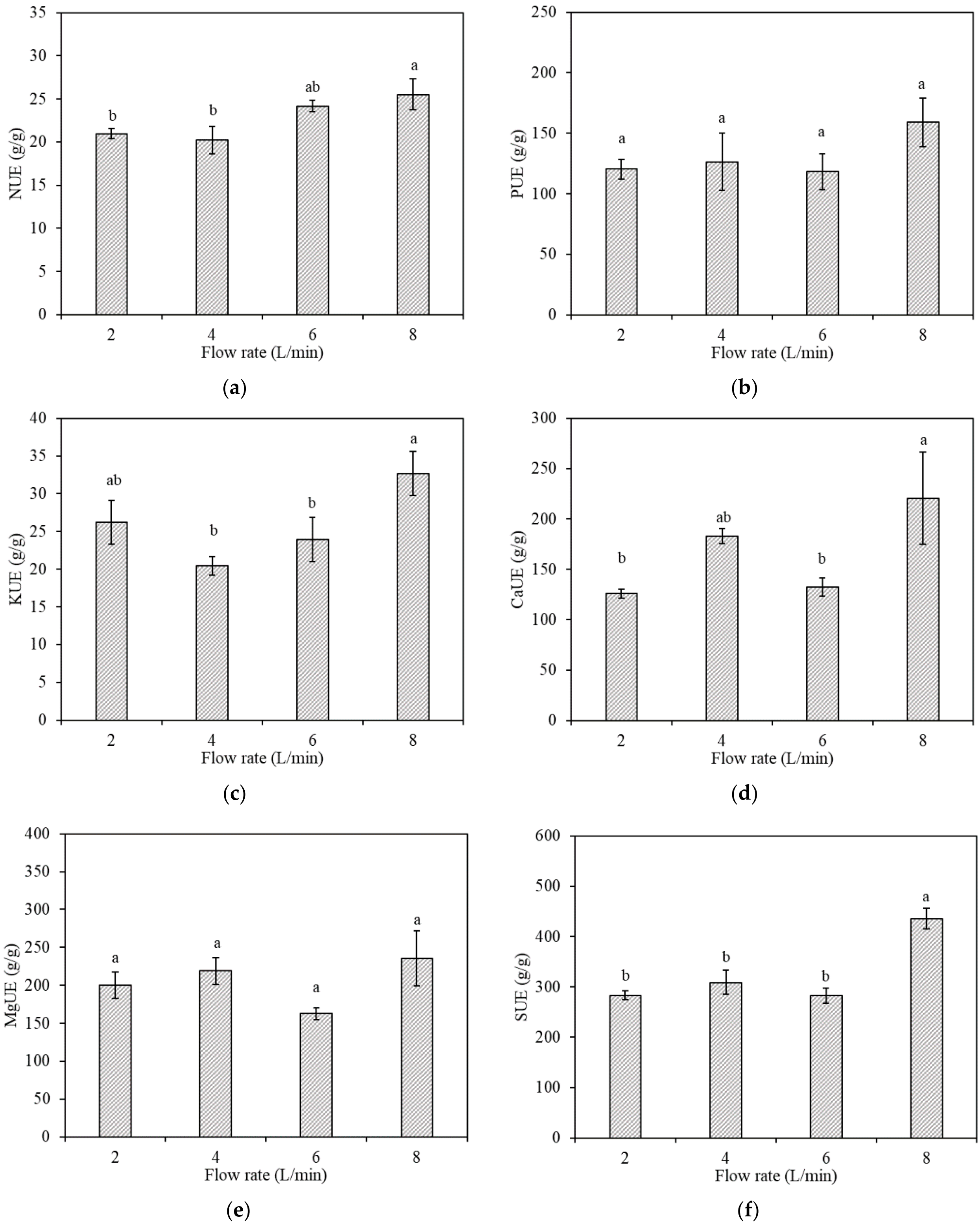

Figure 4. Nutrient use efficiency under different flow rates (values are calculated by dry weight/nutrient uptake of a whole plant). (**a**) Nitrogen use efficiency (NUE); (**b**) phosphorus use efficiency (PUE); (**c**) potassium use efficiency (KUE); (**d**) calcium use efficiency (CaUE); (**e**) magnesium use efficiency (MgUE); (**f**) sulfur use efficiency (SUE). There were significant differences in the bars marked with different letters ($p < 0.05$). Data are expressed as means ± standard error ($n = 4$).

Figure 4b,e, show that the phosphorus use efficiency (PUE) and magnesium use efficiency (MgUE) did not significantly differ among the flow rates.

Figure 4c displays that with an increased flow rate from 2 to 4 L/min, the potassium use efficiency (KUE) decreased by 22.0%, while further intensification of the flow rate to 6 L/min and 8 L/min resulted in increases in KUE by 17.1% and 36.6%, respectively.

With an increased flow rate from 2 to 4 L/min, the calcium use efficiency (CaUE) increased by 45.2% (Figure 4d), while with an increased flow rate from 4 to 6 L/min, CaUE decreased by 27.6%. Further increasing the flow rate from 6 to 8 L/min induced the CaUE to increase by 76.7%.

As can be seen from Figure 4f, with an increased flow rate from 2 to 4 L/min, the sulfur use efficiency (SUE) increased by 9.2% and further increasing the flow rate to 6 L/min resulted in a decrease in the SUE by 8.5%. The SUE values were similar at all flow rates except for a significant 54% increase at 8 L/min.

4. Discussion

Root extension, mass flow, and diffusion are the main forms of plant nutrients in soil moving to the root surface [19]. Unlike soil, the culture substrate (nutrient solution) of hydroponics is flowable. This also means that the way that nutrient ions are transported to the root surface in a hydroponic culture is different from that in a soil culture. Since a cultivation substrate (nutrient solution) in hydroponics can flow, the mechanism of nutrient transport to the root surface also has turbulent diffusion. Turbulent diffusion is referred to as the transfer of nutrient ions in a turbulent fluid to the root surface by means of irregular motions of fluid particles. This turbulent diffusion is affected by the flow rate of a fluid in a container [20]. It makes the flow rate affect both the circulation and diffusion of nutrient ions in a container, consequently affecting both the nutrient uptake and plant growth [9].

In recent years, many researchers have intensively studied the impact of substrate flow on plant growth in hydroponic systems [9–12] and their results suggest that crop yield can be improved by regulating flow rate. The ideal flow rate provides sufficient contact time and collision frequency for roots and nutrient ions in a nutrient solution. This can promote nutrient absorption and thus increase plant growth. Conversely, although an increased flow rate can promote turbulent diffusion and affect the transport of nutrient ions to the root surface, a flow rate that is too fast may represent excessive physical stimulation that may have a negative impact on plant growth [12].

The leaf is the vital structure for plants to convert light to chemical energy by means of photosynthesis. The photosynthetic capacity, affected by leaf area, is closely related to plant growth [21]. Both fresh and dry weights of plants are considered the main parameters to measure yield [22]. Root length is considered to be related to plant's nutrient uptake capacity [23]. All plants require 17 essential elements to ensure their normal growth. Among those 17 elements, 14 are absorbed through the soil, while the remaining 3 are obtained from the air and water [24]. In hydroponics, the fertilizer containing these essential elements is provided as a nutrient solution to ensure the growth of the plants [25].

The results of this study suggest that the increase in the flow rate from 2 to 4 L/min improved growth parameters (leaf area, fresh weight, dry weight, and root length) (Figure 1). When the flow rate was further intensified from 4 to 8 L/min, the measured growth parameters decreased. Nutrient uptake rates had a similar trend, especially those of N, P, and K that increased with an amplified flow rate from 2 to 4 L/min and decreased with a further rise to 8 L/min (Figure 2). At the same time, when comparing the correlation relationships among the growth parameters and nutrient uptake, there was a strong positive correlation between N, P, and K uptake and plant growth (Figure 3). This indicates that the flow rate affects plant growth by influencing the plant nutrient uptake. However, at a high flow rate (8 L/min), plant growth was inhibited due to excessive physical stimulation initiated by high flow substrate.

Generally, agricultural production is mainly focused on obtaining the maximum yield. Regarding the dry weight, the optimal flow rate in this study was 2–6 L/min. However, in drylands, the main focus of agriculture, besides yield, is on how to use fewer resources to produce as much food as possible and to improve the utilization of resources through cultivation management methods [14–16].

From the results of this study, the utilization efficiency of N, P, and K, as the main plant macronutrients, increased with an increase in the substrate flow rate (Figure 4). The highest nutrient utilization efficiency appeared at 8 L/min, while the minimum was at flow rates of 2 and 4 L/min. This indicates that the increase in flow rate may be helpful in the improvement of the nutrient utilization efficiency.

If the optimal flow rate is determined from the perspective of taking into account both the production and nutrient utilization efficiency, the results from this study suggest that an optimal flow rate would be 6 L/min. However, it should be mentioned that this flow rate may not be optimal for all hydroponic systems. Plant growth is a complex process that is affected by the cultivation environment [26]. In addition to investigating the nutrient utilization efficiency, the physiological processes from primary metabolism (e.g., photosynthesis) and secondary metabolism (e.g., bioactive compounds) will be evaluated in a future study. These processes are of major importance in the context of mechanisms underlying the crop response (e.g., fresh mass increase and root morphology and architecture). In addition, the nutrient utilization efficiency of plants is also affected by many factors (both genetic and environmental) [27]. Determination of the optimal flow rate is also related to the size of cultivation container and root characteristics [9]. Moreover, both the plant growth and nutrient utilization efficiency are also linked to features other than the flow rate, such as the plant species [28], nutrient solution composition [29], pH [30], salinity [31], light intensity [32], and temperature [33]. A comprehensive understanding of the impact of environmental factors on plant growth and nutrient use efficiency in hydroponics will also be examined in a future study.

5. Conclusions

Hydroponics is a water-saving cultivation method that is often used in dryland areas. Unlike in soil culture, a substrate (nutrient solution) in a hydroponics system can flow. This means that the change in flow rate can affect plant growth and nutrient uptake in hydroponic culture. In agriculture, particularly in drylands, the balance between input and output is of pivotal importance. Therefore, in this study, in addition to investigating how to increase production to the greatest extent, we also investigated how to economize resource utilization. Increasing the nutrient utilization efficiency through a reasonable management has always been the goal of dryland agriculture.

In this study, the authors cultivated Swiss chard plants in a hydroponic system under different flow rates of a substrate to analyze changes in the plant growth, nutrient uptake, and nutrient use efficiency. We found that an increase in the flow rate from 2 to 4 L/min resulted in an increase in the leaf area, fresh weight, dry weight, and root length. With an intensified flow rate from 4 to 8 L/min, the growth parameters decreased. Likewise, a similar decrease was recorded for nutrient uptake values, especially for N, P, and K. Comparison of the correlation relationships among the growth parameters and nutrient uptake showed that there is a strong positive correlation between N, P, and K uptake and plant growth, which implies that the flow rate is able to influence plant growth by affecting the plant nutrient uptake. The utilization efficiency of N, P, and K were the main plant macronutrient elements that increased with the amplification of flow rate, indicating that an increase in the flow rate can help improve the nutrient utilization efficiency. In hydroponic production, it is advocated to improve the yield and nutrient use efficiency through flow rate regulation. However, from the influence of flow rate regulation on the growth and nutrient use efficiency, a slow flow rate may have little effect on the nutrient use efficiency. Although an excessive flow rate is beneficial to improve the nutrient use efficiency, it is unfavorable to plant growth. The reasonable regulation of flow rate can not only produce more harvest but also ensures nutrient use efficiency. It is necessary to find a suitable flow rate in actual production. In addition, it should be mentioned that the regulation of the optimal flow rate is also related to the types of plants and the shape of cultivation containers [9]. The influence of these factors on the regulation of optimal flow rate will be further studied in our future research.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/agronomy11102050/s1, Table S1: The environment data of the cultivation room during the experiment, Table S2: The plant growth under different flow rates, Table S3: The nutrient contents of the plant under different flow rate.

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