agronomy

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# Cucumber (*Cucumis sativus* L.) Growth and Productivity under Solar Radiation-Based Quantitative Nutrient Management in Hydroponic System

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**Abstract:** Grafted cucumber plants were grown in a new hydroponic system ("Kappa Land", Mitsubishi Chemical Aqua Solutions, Co., Ltd., Tokyo, Japan). Two different nutrient management methods were applied to the plants as treatments: Electrical Conductivity-based Management (ECM) and Quantitative Nutrient Management (QNM). During the growth period, we examined plant growth characteristics and productivity, fruit growth characteristics and quality, and nutrient use characteristics. The results revealed that the QNM technique significantly reduced the nutrient supply rate per plant for $Ca^{2+}$, $SO_4^{2-}$, and N by 28.5%, 25.5%, and 23.3%, respectively. Similarly, the absorption rates per plant of $SO_4^{2-}$, $K^+$, and $PO_4^{3-}$ were reduced by 17.8%, 11.9%, and 10.9%, respectively. However, N, $Ca^{2+}$, and $Mg^{2+}$ absorption rates slightly increased in the QNM treatment. The nutrient wastes generated per kilogram of produced fruits were also reduced by 66.4%, 60.7%, and 30.2% for N, $Ca^{2+}$, and $SO_4^{2-}$, respectively. Although the QNM technique reduced the plant's leaf area, it significantly increased its total length by 9.4%. The total and marketable yields were not significantly different between the ECM (9.0 and 8.0 kg plant$^{-1}$) and QNM (9.1 and 8.2 kg plant$^{-1}$) treatments. However, the QNM treatment produced the highest total dry matter of 617 g plant$^{-1}$, surpassing the ECM treatment by 6.9%. On the other hand, differences in nutrient management methods did not significantly affect fruit quality, including total soluble solids, water content, skin color, size, and shape. These results suggest that with the QNM method, it is possible to produce quality cucumbers with high nutrient use efficiency while protecting the environment from nutrient wastes.

**Keywords:** electrical conductivity; environment; leaf area; nutrient use efficiency; nutrient wastes; total soluble solids; water use efficiency

**Citation:** Samba, N.; Nunomura, O.; Lu, N.; Johkan, M.; Nakano, A.; Tsukagoshi, S. Cucumber (*Cucumis sativus* L.) Growth and Productivity under Solar Radiation-Based Quantitative Nutrient Management in Hydroponic System. *Agronomy* **2024**, *14*, 296. https://doi.org/10.3390/agronomy14020296

Academic Editors: Giuseppe Colla, Pradeep Kumar, Mariateresa Cardarelli and Pratapsingh Khapte

Received: 31 December 2023
Revised: 24 January 2024
Accepted: 26 January 2024
Published: 29 January 2024



## 1. Introduction

The world's population is expected to reach 9.4 to 10.1 billion by 2050 [1]. This increasing population, climate change, and natural resource scarcity make meeting the increased food demand a global challenge for humanity [2,3]. To sufficiently feed these people, the total food production must increase by 70% [4]. However, several scientific publications noted the scarcity of natural resources used in agriculture. According to several authors, fresh water [5], agricultural land [6,7], rock phosphate [8–11], and potash resources [12] are diminishing in many locations of the earth. Considering these alerts, creative and technologically advanced food production methods must be adopted to maximize diminishing natural resources [2]. Moreover, experts suggested increasing food production by improving natural resource use efficiency and reducing negative environmental impacts [13–15]. Lal [16] reported that soilless culture (aquaponics, aeroponics, and hydroponics) is an innovative agricultural strategy that produces more with less to meet the increasing demand for food. Hydroponics is a soil-free technique used to cultivate plants with mineral nutrient solutions [17]. It helps to address climate change challenges and manage production systems to utilize natural resources in a more sustainable way [18]. For illustration, high-value vegetables can be grown with less water [19], land [20], and nutrients [21,22] in controlled hydroponics compared to traditional soil-based production.

Cucumber (*Cucumis sativus* L.) is one of the most extensively cultivated and consumed vegetable crops worldwide [23]. It is the top four most cultivated vegetables in the world, following tomatoes, brassicas, and onions [24]. Cucumbers are cultivated in both soil and hydroponic systems.

In general, in hydroponics, a conventional nutrient supply method known as Electrical conductivity-based management (ECM) is used to supply highly concentrated nutrient solutions to plants. This method can cause an excessive uptake of ions, which disrupts the balance between vegetative and reproductive growth, resulting in a decrease in both yield and quality (e.g., fruit vegetables may have low sugar content while leaf vegetables may have high nitrate content) [25].

In a long-term cultivation system with the ECM technique, plants may selectively absorb nutrients, leading to an imbalance in the nutrient solution. For example, when fertilizers are constantly supplied to keep the EC of the nutrient solution at a constant level, vegetables tend to absorb certain nutrient ions, such as $PO_4^{3-}$, $NO_3^-$, and $K^+$, excessively, surpassing their need [26,27]. On the other hand, some ions, such as $Ca^{2+}$ and $Mg^{2+}$, will accumulate in the root zone [28]. This indicates that the remaining nutrient solution of the ECM, at the end of a growth cycle, contains high ion concentrations. The remaining nutrient solution containing imbalanced nutrients and root exudates should be recycled for future use in hydroponics. However, even when the remaining nutrient solution is recycled, regular nutrient composition analysis to maintain nutrient balance is required. Regarding the high costs involved in recycling the effluent, most farmers prefer to discharge it into the environment. This process is wasteful and has negative environmental impacts [29,30].

To enhance nutrient utilization efficiency and minimize the environmental impact of nutrient wastes, a new approach known as Quantitative Nutrient Management (QNM) has been proposed [29,31]. In the QNM approach, nutrients are supplied in a quantitative and periodic manner regardless of the nutrient solution EC value. This method prevents excess delivery and uptake of nutrients. It also reduces the accumulation of nutrient ions in the root zone.

The QNM has been used to regulate and optimize the growth and productivity of various vegetables, including tomatoes [29,32], melon [33], spinach [34], and basil [31]. Applying the QNM on these crops permitted increased nutrient use efficiency without lowering the yield and quality of harvested products. It also eased plant vegetative and reproductive growth regulation. Plants grown under QNM conditions could prevent excessive vegetative growth, contributing at some level to increased light interception by the canopy and higher fruit yields per unit area [29].

The QNM method has not yet been applied to cucumber production. This indicates that the effect of the QNM method on cucumber plant growth characteristics and productivity remains unknown. In our approach, we considered the solar radiation received in the greenhouse as an index to supply the nutrients to the plants in the QNM treatment. This approach is supported by Samba et al. [35], who found a significant correlation between cucumber water uptake and solar radiation. Moreover, Gislerod and Adams [36] have demonstrated that cucumber crops exhibit a significant increase in the absorption of both water and potassium in response to solar radiation.

This study aimed to examine cucumber's growth characteristics and productivity under QNM and ECM conditions in the Nutrient Film Technique (NFT) hydroponic system.

## 2. Materials and Methods

### *2.1. Trial Location and Experimental Facility*

The research was conducted in a greenhouse (20 m length × 8 m width × 5 m height, North–South oriented) located at the Kashiwa-no-ha campus of Chiba University. The greenhouse ventilation and heating systems were set to turn on at 25 and 14 °C, respectively. The greenhouse daytime internal relative humidity was adjusted to a set value (70%) via an automatic activation of the fogging system (Ikeuchi Co., Ltd., Osaka, Japan). The greenhouse received carbon dioxide ($CO_2$) every morning at 4, 5, 6, and 7 a.m. when all windows were closed. To monitor the internal changes of the greenhouse environmental parameters, an agricultural production support system, Midori Cloud (SERAKU Co., Ltd., Tokyo, Japan), was used to record air temperature, relative humidity, $CO_2$ concentration, and solar radiation intensity every two minutes.

### *2.2. Plant Materials and Cultivation Method*

Cucumber (*Cucumis sativus* L., cv. "Nina Z") and squash (*Cucurbita maxima*, cv. "Yu Yu Ikki) seeds were obtained from a seed company, Saitama Progenitor Breeding Society Co., Ltd., Saitama, Japan. The cucumber cultivar used in this study, "Nina Z," has a stable fruit shape and is resistant to brown spots and powdery mildew. It also has a good branching ability and a nearly 100% female flowering rate on the main stem.

In 2022, on August 29 and 31, respectively, squash and cucumber seeds were sown into 128 cell trays filled with commercial substrate (Na-Terra; Mitsubishi Chemical Aqua Solutions, Co., Ltd., Tokyo, Japan). The seeded cell trays were placed in a germination chamber, having no light and a temperature of 28 °C. Germinated seedlings were grown under fluorescent lamps in a growth chamber (Nae Terrace, Mitsubishi Chemical Aqua Solutions, Co., Ltd., Tokyo, Japan) for five days. The growth chamber had a $CO_2$ concentration of 1000 μmol $mol^{-1}$, a daily light period of 14 h, and a temperature of 24 and 18 °C in light and dark conditions, respectively. A hydroponic technique named ebb-and-flow used a nutrient solution (1.4 dS $m^{-1}$) to water the seedlings. The nutrient solution was constituted with 202 mg $L^{-1}$ $KNO_3$, 236 mg $L^{-1}$ Ca $(NO_3)_2{\cdot}4H_2O$, 38 mg $L^{-1}$ $NH_4H_2PO_4$, 123 mg $L^{-1}$ $MgSO_4{\cdot}7H_2O$, 3.0 mg $L^{-1}$ Fe, 0.5 mg $L^{-1}$ B, 0.5 mg $L^{-1}$ Mn, 0.05 mg $L^{-1}$ Zn, 0.02 mg $L^{-1}$ Cu, and 0.01 mg $L^{-1}$ Mo. On September 7, the hole insertion approach grafting method was used to graft cucumber scions onto squash rootstocks. Our previous work detailed the grafting procedure [35].

On September 26, grafted seedlings were transplanted into a new Nutrient Film Technique (NFT) hydroponic system specially developed for cucumber production ("Kappa Land", Mitsubishi Chemical Aqua Solutions, Co., Ltd., Tokyo, Japan). Our previous work described the hydroponic system [35]. The distance between transplanted seedlings within a cultivation bed was 45 cm, with 180 cm between the cultivation beds. The cultivated plants were trained following the lowering training method (Figure S1).

The plant's main stem was grown vertically with support and pinched at the 16th node. All flowers and laterals of the first five nodes were removed.

Three lateral vines were selected and trained onto overhead wires at 2.5 m above the ground. The three lateral vines were consistently lowered throughout the growth period after reaching the overhead wires. The other side shoots were pruned on a regular basis. The growing lateral vines were spaced to 30 cm [35]. The flowers emerging from the lateral branches' nodes were removed to promote the lateral vines' growth.

### *2.3. Treatments*

Cucumber plants' growth and productivity were examined under two nutrient management methods: Electrical Conductivity-based Management (ECM) and Quantitative Nutrient Management (QNM). Four nutrient solutions (A, B, C, and D), formulated and stored in different tanks, were used to feed cultivated plants. The compositions of the nutrient solutions are listed in Table 1.

**Table 1.** Composition of the nutrient solutions.

| Solution | Components and Concentrations (g $L^{-1}$) | | | | | | |
|---|---|---|---|---|---|---|---|
| | $Ca(NO_3)_2\cdot 4H_2O$ | $KNO_3$ | $NH_4H_2PO_4$ | $MgSO_4\cdot 7H_2O$ | $K_2SO_4$ | $KH_2PO_4$ | Pre-Mixed Micronutrients |
| A | 0 | 0.81 | 0.17 | 0.51 | 0.05 | 0 | 0.05 |
| B | 1.30 | 0 | 0 | 0 | 0 | 0 | 0 |
| C | 0 | 1.96 | 0.21 | 1.22 | 0 | 0.27 | 0.14 |
| D | 2.86 | 0 | 0 | 0 | 0 | 0 | 0 |

Electrical Conductivity-based Management (ECM): First, the nutrient solutions A and B were diluted 100 times to form a starter circulating nutrient solution. Next, the two nutrient solutions (A and B) were injected into the circulating nutrient solution tank according to a set value of the EC from the beginning to the end of the growth cycle. This treatment was considered as the control treatment.

Quantitative nutrient management (QNM): From transplanting the seedlings to pinching the plants' main stems and removing all unnecessary lateral branches (28 days after transplantation), nutrient solutions A and B were supplied following the ECM method. The circulating nutrient solution was renewed after pinching the plants' main stems. First, the nutrient solutions C and D were diluted 300 times to form a starter nutrient solution. Next, the same nutrient solutions (C and D) were injected into the cultivation system based on the amount of solar radiation received in the greenhouse. For each 1 MJ $m^{-2}$ of solar radiation received, 10 mL of each nutrient solution was supplied.

The quantity of the nutrient solutions supplied (10) mL was determined based on the significant correlation observed between solar radiation and the nutrient uptake of a previous experiment [35]. Figure 1a shows the nutrient application scheme.

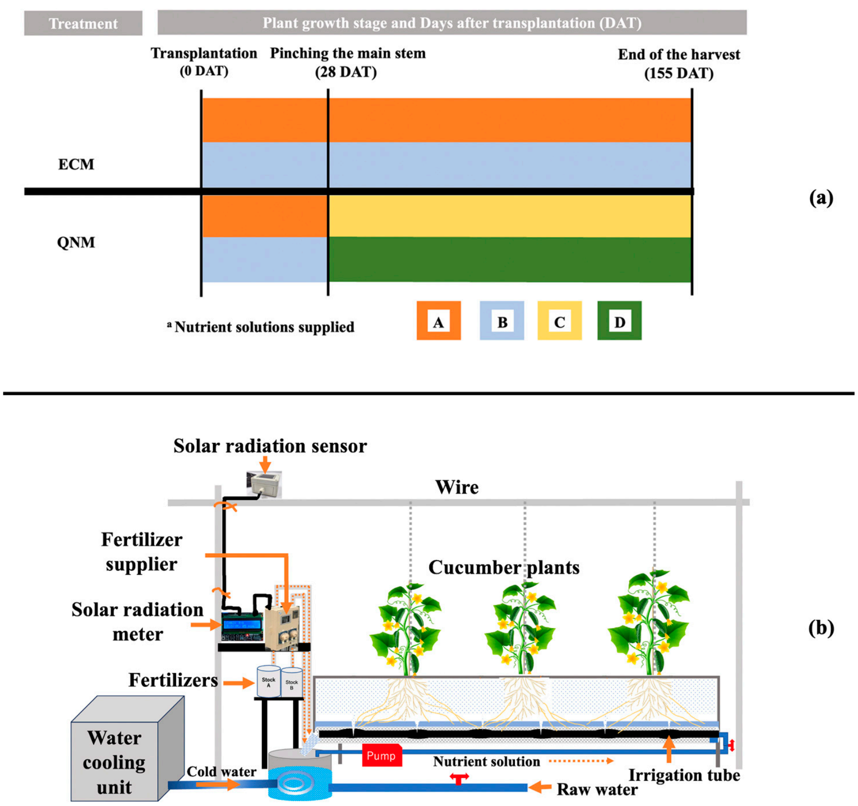


**Figure 1.** Nutrient solution supply scheme (**a**) and schematic diagram of the cultivation system (**b**). [a] The details of the nutrient solutions are in Table 1.

For each treatment, a cultivation bed (7.17 m length, 0.45 m width, 12 cm depth) containing 17 plants was used to perform the experiment.

In the QNM treatment, a solar radiation sensor was placed on an overhead wire above the plants' canopies at 2.5 m above the ground. That sensor was connected to a solar irradiation meter. Once the solar irradiation meter recorded 1 MJ $m^{-2}$ of solar radiation, the fertilizers' pumps injected 10 mL of the nutrient solutions into the cultivation system. Figure 1b shows the schematic diagram of the cultivation system connected to nutrient supply control tools.

### 2.4. Measurements

#### 2.4.1. Water and Nutrient Consumptions

The electrical conductivity (EC) and the temperature of the circulating nutrient solutions were recorded every 30 min with EDGE EC HI2003 Hanna (Hannah Instruments Japan Co., Ltd., Chiba, Japan). The nutrient solution's pH was maintained between 5.5–6 by continuously injecting an acid solution ($NO_3^-$) to keep the $NO_3^-$ concentration in the groundwater at 18–27 mg $L^{-1}$.

The ionic content of the circulating nutrient solution was monitored weekly by sampling 50 mL of the solution and analyzing its content using Dionex ICS1100 ion chromatography (Thermo Fisher Scientific Inc., Waltham, MA, USA). The following formula was used to calculate the average daily ion uptake rates:

$$\frac{(\text{Initial concentration} \times \text{Initial solution volume}) - (\text{Final concentration} \times \text{Final solution volume})}{\text{Time interval in days}}$$

The quantity of water injected into the cultivation system was recorded using a water flow meter. Plant water uptake was estimated by dividing the amount of water injected into the cultivation system by the number of plants.

The crop water and nutrient use efficiencies were calculated according to the formulas described by Jovicich et al. [22]:

$$\text{Water use efficiency } (\text{L kg}^{-1}) = \frac{\text{Total water volume delivered } (\text{L plant}^{-1})}{\text{Marketable fruit yield } (\text{kg plant}^{-1})}$$

$$\text{Nutrient use efficiency } (\text{g kg}^{-1}) = \frac{\text{Total weight of nutrient used } (\text{g plant}^{-1})}{\text{Marketable fruit yield } (\text{kg plant}^{-1})}$$

The nutrient waste was calculated as follows:

$$\text{Nutrient waste } (\text{g kg}^{-1}) = \frac{\text{Nutrient waste generated } (\text{g plant}^{-1})}{\text{Marketable fruit yield } (\text{kg plant}^{-1})}$$

#### 2.4.2. Vegetative Growth Characteristics

Data on leaf growth characteristics were collected on five selected plants of each treatment.

A chlorophyll meter (SPAD-502 Plus, Konica Minolta Inc., Tokyo, Japan) was utilized to determine the relative chlorophyll contents of cucumber leaves every two weeks. Moreover, on each selected plant, the lengths and widths of 10 randomly selected leaves were measured with a ruler following the method described by Robin and Pharr [37]. The leaf area (LA, $cm^2$) was estimated using a linear regression obtained from data collected in a pilot experiment (r = 0.9407): LA = 0.785 (L × W) + 43.6, where L and W represent leaf length and width, respectively. The leaf area index (LAI, $m^2$ $m^{-2}$) was estimated using the following formula:

$$\text{LAI} = \frac{\text{Average single leaf area} \times \text{Average number of leaves per plant}}{\text{Planted area per plant}}$$

The five selected plants' main stem diameters were measured 35 days after transplantation (DAT). The measurements were carried out in the middle of the first 10th internodes using a digital caliper. The stem diameter was estimated as the average value of the measured data.

#### 2.4.3. Plant Physiology

At the cropping period's middle (20 December) and late (20 February) stages, the cucumber plants' gas exchange parameters were measured with a gas exchange system LI-6400 (LI-COR, Lincoln, NE, USA). Data were collected from five plants selected in each treatment. Each plant's mature leaves at the 5th, 10th, and 15th node positions were inserted into an integrated fluorescence chamber connected to the gas exchange system. In the leaf chamber, the $CO_2$ concentration of the flow-in air, the photosynthetic photon flux density, the temperature, and the relative humidity were set at 400 μmol $mol^{-1}$, 1000 μmol $mol^{-1}$, 25 °C and 70%, respectively.

#### 2.4.4. Plant Productivity

Cucumber fruits were harvested and weighed once their weights and lengths reached approximately 100 g and 22 cm (Japanese standards) [38]. Plant yield components were expressed in terms of total and marketable fresh fruit weights, marketable number of fruits, and the percentage of non-marketable fruits.

During the cultivation period, the fresh weights of all pruned leaves were recorded. On the final day of the experiment, five plants were randomly chosen from each treatment and were separated into their respective roots, leaves, and stems. Stems and leaves were immediately weighed to obtain their fresh weights. Plant roots were dehydrated by centrifugation using a centrifugal dehydrator (HS-S60A high-speed dehydrator dry cyclone, High Smart Japan Co., Ltd., Utsunomiya, Japan) for one minute to obtain the fresh root weights. All plant parts and sample fruits were oven-dried at 80 °C until reaching a constant weight to obtain their dry weights. Recorded data were used to estimate dry matter distribution into roots, leaves, stems, and fruits.

#### 2.4.5. Fruit Growth and Fruit Quality

At the flowering stage, all pistillate flowers were tagged with their flowering dates using paper tags (11 mm × 22 mm, Heiko No. 22; Shimojima Co., Ltd., Tokyo, Japan). The paper tags were collected during harvest to register the fruit growth duration.

The length and diameter of the harvested fruit were measured. The fruit shape index, which represents the degree of fruit curvature, was estimated using the ratio of the fruit's arc length and chord length. Sample fruits harvested from the same node positions in each treatment were used to determine fruit Total Soluble Solids (TSS) concentration. Each fruit was cut into small pieces, and an electric blender was used to prepare a well-mixed sample, filtered with a tea filter bag [39]. The collected juice's brix value was measured with a portable refractometer (PAL-BX Acid F5, Atago Co., Ltd., Tokyo, Japan). In addition, the selected fruits' color was evaluated monthly. The fruit color was measured at the fruit's stalk, mid, and blossom regions, and results were averaged [40]. Measurement was carried out with a portable spectrophotometer Konica Minolta (Nippon Denshoku Ind., Ltd., Tokyo, Japan) calibrated on the CIE Lab scale: red share, a*; yellow share, b*; and brightness, L* [41].

### *2.5. Data Analysis*

The collected data underwent normality testing using the Shapiro–Wilk test and was then analyzed using Analysis of Variance (ANOVA). In cases where significant differences were observed, Tukey's multiple comparison tests were used to distinguish treatment means using XLSTAT software Ver. 2022.4.1.

## 3. Results

### *3.1. Water and Nutrient Consumptions*

The water consumption rate per plant is shown in Figure 2a. In total, 135.3 and 136.5 L of water were consumed by a single plant during the entire growth cycle in the ECM and QNM treatments, respectively. Moreover, Figure 2b shows the electrical conductivity (EC) changes of the circulating nutrient solutions. In the ECM treatment, the daily average EC value was kept above 2 dS $m^{-1}$. In the QNM treatment, the daily average value of the EC significantly increased immediately after the beginning of the treatment (28 DAT). It reached 4.0 dS $m^{-1}$ at 40 DAT and then progressively decreased to the lowest level of 0.4 dS $m^{-1}$. The daily average temperature values of the nutrient solutions were kept between 19–21 °C in the two treatments.

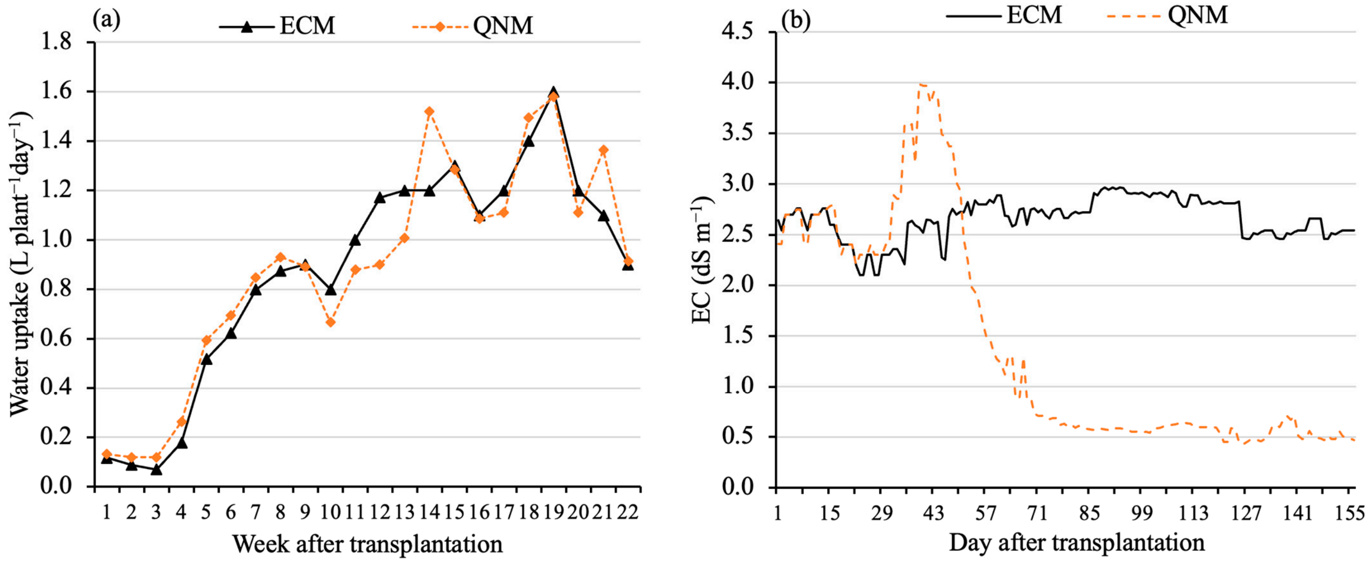


**Figure 2.** Daily water uptake (**a**) and Electrical Conductivity (EC) daily average values of the circulating nutrient solutions (**b**). Data represent the average of plant daily water uptake over the past week (**a**) and the daily average of the nutrient solution EC recorded every 30 min.

The amounts of all nutrient elements supplied per plant were lower in the QNM treatment than in the ECM treatment. The reduction rate ranged from 8.2% for $PO_4^{3-}$ to 28.5% for $Ca^{2+}$ (Table S1). However, the total nutrient uptake rate in the QNM was slightly greater for N, $Ca^{2+}$, and $Mg^{2+}$ than in the ECM, while it was lower for $PO_4^{3-}$, $K^+$, and $SO_4^{2-}$ (Table S1).

Figure 3 presents the weekly nutrient supply, nutrient uptake, and the concentration of the nutrient elements in the nutrient circulating tanks. $K^+$, $NO_3^-$, and $Ca^{2+}$ were the most supplied and absorbed nutrients in both treatments. The nutrient absorption trend followed the nutrient supply trend in both treatments. The nutrient supply and uptake progressively increased from the transplanting stage to 6–7 weeks after transplantation. After that period, the two variables decreased in both treatments to some extent and fluctuated for the rest of the growth period.

In the nutrient circulating tanks, the concentrations of nutrient elements were relatively higher and constant in the ECM treatment compared to the QNM treatment. In the QNM treatment, the concentrations of nutrient elements were like those of the ECM treatment at the beginning of the transplantation. Four weeks after transplantation, the concentrations increased for a few weeks before decreasing to a low level. From 9 weeks after transplantation to the end of the growth period, the concentrations of the nutrient elements in the tanks were lower in the QNM treatment than in the ECM treatment.

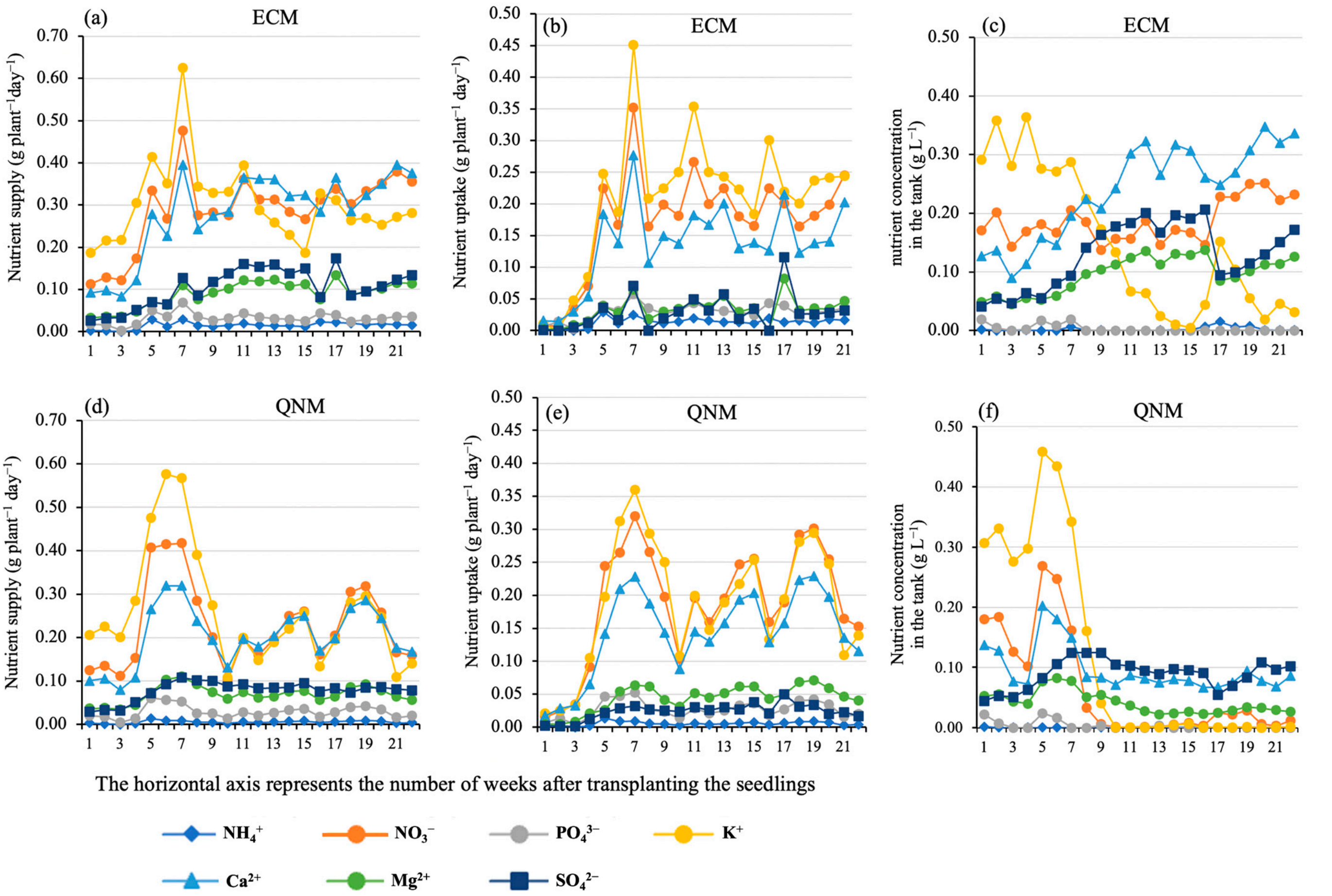


**Figure 3.** Nutrient supply (**a**,**d**), uptake (**b**,**e**), and element concentration in the circulating tanks (**c**,**f**). Data represent the average of the daily quantity of nutrients supplied per plant (**a**,**d**), plant nutrient uptake (**b**,**e**) over the past week, and nutrient solution concentration in the tank (**c**,**f**).

The two treatments' nutrient use efficiency (NUE) significantly differed (Table 2). The quantity of nutrients used to produce a kilogram of marketable fruit in the QNM treatment was significantly smaller. The reduction rate ranged from 3.2% for $PO_4^{3-}$ to 30.4% for $Ca^{2+}$. On the other hand, the water use efficiency was not significantly different between the two treatments. In addition, the quantity of nutrient wastes generated per kilogram of marketable fruit was significantly smaller in the QNM treatment for all nutrient elements except for $PO_4^{3-}$ (Table 2). The QNM treatment reduced the nutrient wastes by 21.2% for $K^+$ and 66.4% for N.

**Table 2.** Water, nutrient use efficiencies, and nutrient wastes generated to produce a kilogram of marketable fruit at 155 DAT.

| Treatment | Nutrient Use Efficiency (NUE) (g Nutrient kg$^{-1}$ Fruit) | | | | | | Nutrient Waste (NW) (g Nutrient kg$^{-1}$ Fruit) | | | | | | WUE (L kg$^{-1}$ Fruit) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **N** | **$PO_4^{3-}$** | **$K^+$** | **$Ca^{2+}$** | **$Mg^{2+}$** | **$SO_4^{2-}$** | **N** | **$PO_4^{3-}$** | **$K^+$** | **$Ca^{2+}$** | **$Mg^{2+}$** | **$SO_4^{2-}$** | |
| ECM | 6.0 ± 0.2 | 0.62 ± 0.02 | 5.9 ± 0.2 | 5.6 ± 0.2 | 1.8 ± 0.06 | 2.1 ± 0.07 | 2.2 ± 0.08 | 0.038 ± 0 | 1.8 ± 0.06 | 2.8 ± 0.1 | 0.23 ± 0.02 | 0.27 ± 0.02 | 17.3 ± 0.6 |
| QNM | 4.4 ± 0.2 | 0.60 ± 0.01 | 5.0 ± 0.2 | 3.9 ± 0.1 | 1.3 ± 0.05 | 1.5 ± 0.05 | 0.8 ± 0.03 | 0.040 ± 0 | 1.4 ± 0.04 | 1.1 ± 0.03 | 0.17 ± 0.01 | 0.19 ± 0.01 | 16.9 ± 0.6 |
| Significance | ** | * | ** | ** | ** | ** | ** | NS | ** | ** | ** | ** | NS |
| Reduction (%) | 26.7 | 3.2 | 15.3 | 30.4 | 27.8 | 28.6 | 66.4 | 0 | 21.2 | 60.7 | 27.9 | 30.2 | 2.3 |

Data are presented as mean ± standard error (n = 5). NUE = Total weight of nutrient used (g plant$^{-1}$)/Marketable fruit yield (kg plant$^{-1}$); NW = Nutrient waste generated (g plant$^{-1}$)/Marketable fruit yield (kg plant$^{-1}$); Water use efficiency (WUE) = Total water volume delivered (L plant$^{-1}$)/Marketable fruit yield (kg plant$^{-1}$). Treatment effects were significant at 5% (*), 1% (**) probability level, according to Tukey's test, or were not significant (NS).

*3.2. Vegetative Growth Characteristics*

The SPAD (Soil Plant Analysis Development) value was not significantly different between the two treatments from the beginning of transplanting to ten (10) Weeks After Transplantation (WAT) (Figure 4a). From 12 WAT to the end of the experiment, the SPAD value was significantly greater in the ECM treatment.

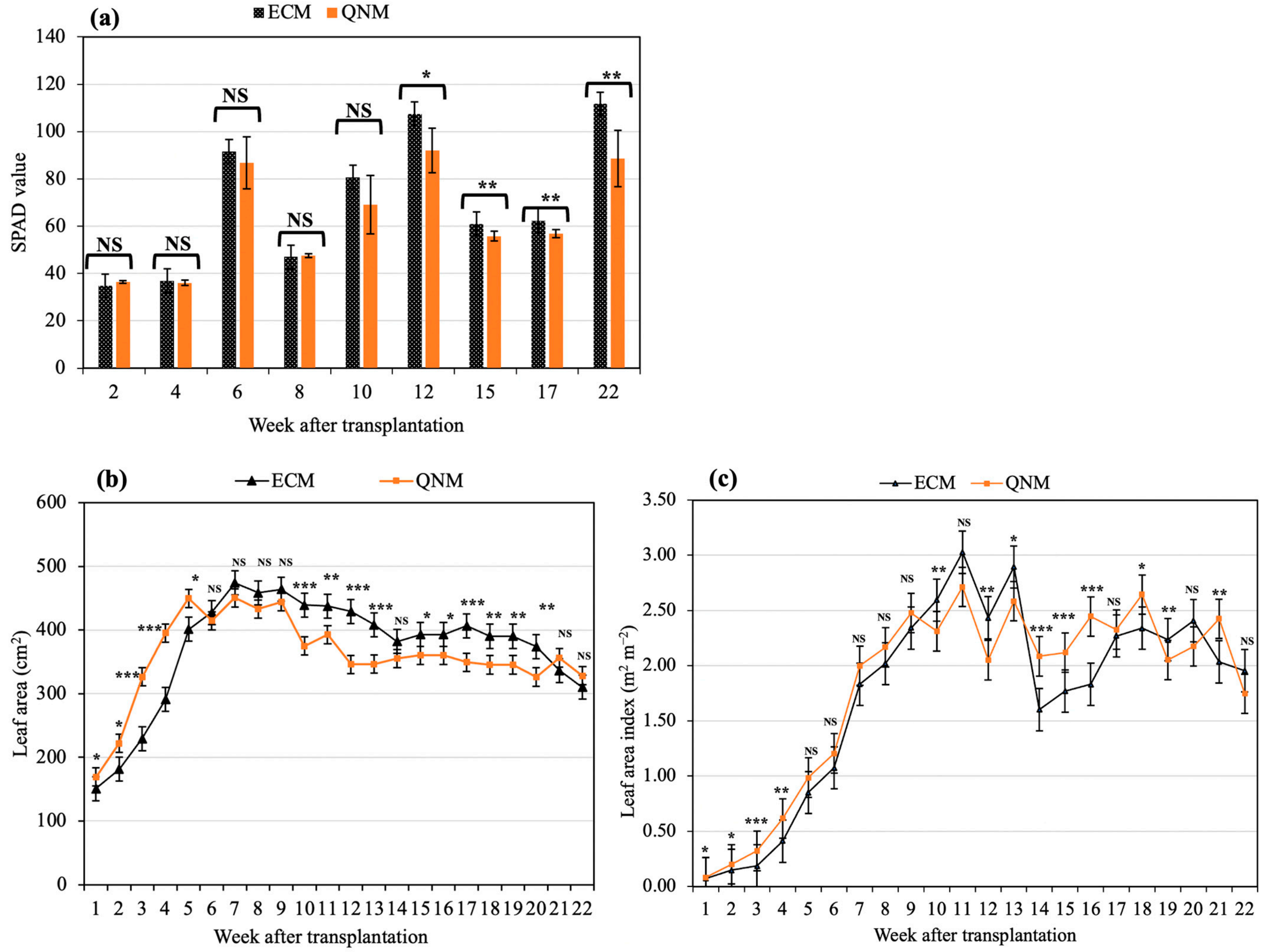


**Figure 4.** Effects of nutrient management methods on leaf SPAD value (**a**), leaf area (**b**), and leaf area index (**c**). Data represent means of 5 selected plants. Error bars indicate the standard error. Treatment effects were significant at 5% (*), 1% (**), and 0.1% (***) probability levels, according to Tukey's test, or were not significant (NS).

The changes in the leaf area and the leaf area index are presented in Figure 4b,c. The application of the QNM treatment affected the plant's leaf area. From 10 WAT to 18 WAT, the leaf size was significantly smaller in the QNM treatment. In addition, the leaf area index was significantly reduced in the QNM treatment during the middle stage of the growing period (12–13 WAT). However, it tended to be greater in the QNM treatment or similar in both treatments for the rest of the growth cycle.

*3.3. Plant Physiology*

At the middle stage of the growing period (20 December), plant physiological parameters were not significantly different between the treatments. However, at the late stage of the growth period (20 February), the individual leaf photosynthetic rate (Pn), stomatal conductance (Gs), and transpiration rate (Tr) significantly decreased in the QNM treatment (Figure 5).

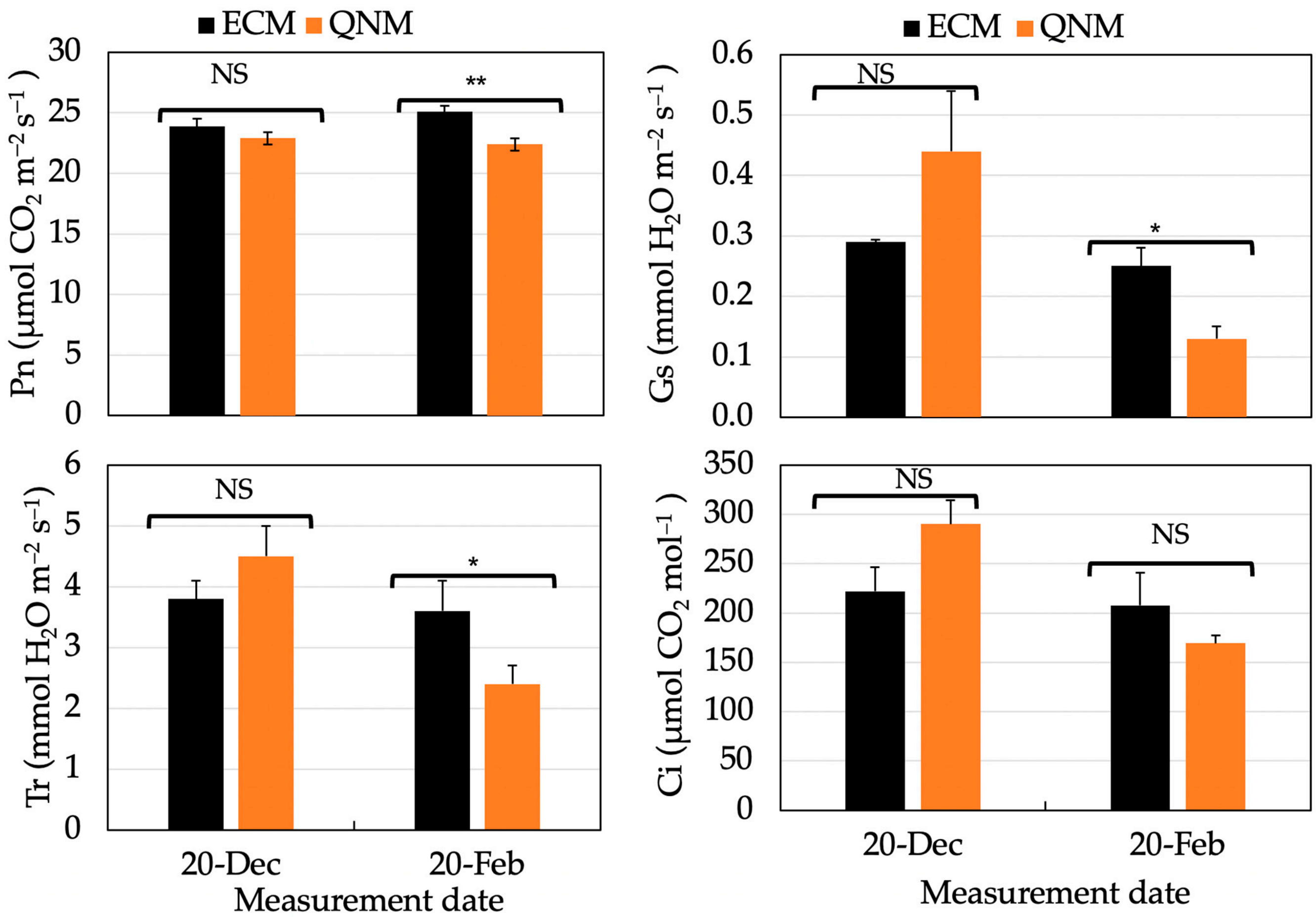


**Figure 5.** Effect of nutrient management methods on plant physiology. Data represent means of 5 selected plants. Error bars indicate the standard error. Pn: Individual leaf photosynthetic rate; Gs: stomatal conductance; Ci: intercellular $CO_2$; Tr: transpiration rate. Treatment effects were significant at 5% (*) 1% (**) probability levels, according to Tukey's test, or were not significant (NS).

### *3.4. Plant Productivity and Dry Matter Partitioning*

The fruits were harvested from November 2 and 6 in the QNM and ECM treatments, respectively, to February 28 in both treatments. All variables linked with plant productivity, such as the total yield per plant and the number of fruits produced per plant, were not significantly different between the treatments (Table 3). Similarly, the marketable yield per plant and the number of marketable fruits produced per plant were not significantly different between the treatments. In addition, the percentage of non-marketable fruits per plant was not significantly different among the treatments. On the other hand, the plant's main stem diameter was not affected by the nutrient management methods. However, the number of nodes per plant and total plant length were significantly greater in the QNM treatment (Table 3).

The total dry matter production significantly increased in the QNM treatment (Table 4). Moreover, leaf and stem dry matters were significantly greater in the same treatment. In contrast, nutrient management methods did not affect root and fruit dry matters. The dry matter partitioned to fruits was significantly greater in the ECM treatment (54.5%) compared to the QNM treatment (50.1%).

**Table 3.** Effects of nutrient management methods on fruit yields, number of fruits, non-marketable fruit rate, and plant growth characteristics.

| Treatment | Total Yield (kg plant$^{-1}$) | Marketable Yield (kg Plant$^{-1}$) | Total Fruits Number (Fruits Plant$^{-1}$) | Marketable Fruits Number (Fruits Plant$^{-1}$) | Non-Marketable Fruits Rate Per Plant (%) | Node Number Plant$^{-1}$ | Total Plant Length (m Plant$^{-1}$) | Main Stem Diameter (mm) |
|---|---|---|---|---|---|---|---|---|
| ECM | 9.0 ± 0.3 | 8.0 ± 0.3 | 91.4 ± 3.1 | 76.0 ± 2.6 | 16.8 ± 1.1 | 147 ± 2.6 | 18.1 ± 0.5 | 5.68 ± 0.05 |
| QNM | 9.1 ± 0.3 | 8.2 ± 0.2 | 86.5 ± 2.7 | 73.7 ± 2.1 | 14.6 ± 0.1 | 178 ± 6.1 | 19.8 ± 0.5 | 5.72 ± 0.06 |
| Significance | NS | NS | NS | NS | NS | * | * | NS |

Data are presented as mean ± standard error (n = 5 for yields, total fruit number, number of nodes, total plant length, and main stem diameter). Treatment effects were significant at a 5% (*) probability level, according to Tukey's test, or were not significant (NS).

**Table 4.** Effects of nutrient management methods on dry matter production and partitioning.

| Treatment | Leaf DW (g Plant$^{-1}$) | Fruit DW (g Plant$^{-1}$) | Stem DW (g Plant$^{-1}$) | Root DW (g Plant$^{-1}$) | TDM (g Plant$^{-1}$) | Dry Matter Partitioning (%) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Leaves | Stem | Fruits | Root |
| ECM | 194.1 ± 1.2 | 316.1 ± 10.4 | 56.0 ± 0.1 | 11.2 ± 0.8 | 577.4 ± 11.8 | 33.7 ± 0.5 | 9.8 ± 0.2 | 54.5 ± 0.7 | 2.00 ± 0.04 |
| QNM | 228.5 ± 3.0 | 309.9 ± 9.9 | 65.8 ± 0.2 | 12.8 ± 0.8 | 617.0 ± 12.5 | 37.1 ± 0.4 | 10.7 ± 0.2 | 50.1 ± 0.7 | 2.09 ± 0.05 |
| Significance | *** | NS | *** | NS | * | *** | ** | *** | * |

Data are presented as mean ± standard error (n = 5 for leaf DW, Fruit DW, TDM, stem DW, and root DW). DW: Dry weight; TDM: Total Dry matter. Treatment effects were significant at 5% (*), 1% (**), or 0.1% (***) probability level, according to Tukey's test, or were not significant (NS).

### 3.5. Fruit Growth and Fruit Quality

Figure 6a shows the growth duration of the harvested fruits and their weights. Recorded data of all fruits indicated a significant reduction in fruit growth duration from flowering to harvest in the QNM treatment. However, fruit growth duration was not significantly different between the two treatments for fruits harvested in November, December, and January. This fruit growth duration was significantly reduced in the QNM treatment for fruits harvested in February. Moreover, the fruit growth duration increased progressively from November to January and decreased in February in both treatments.

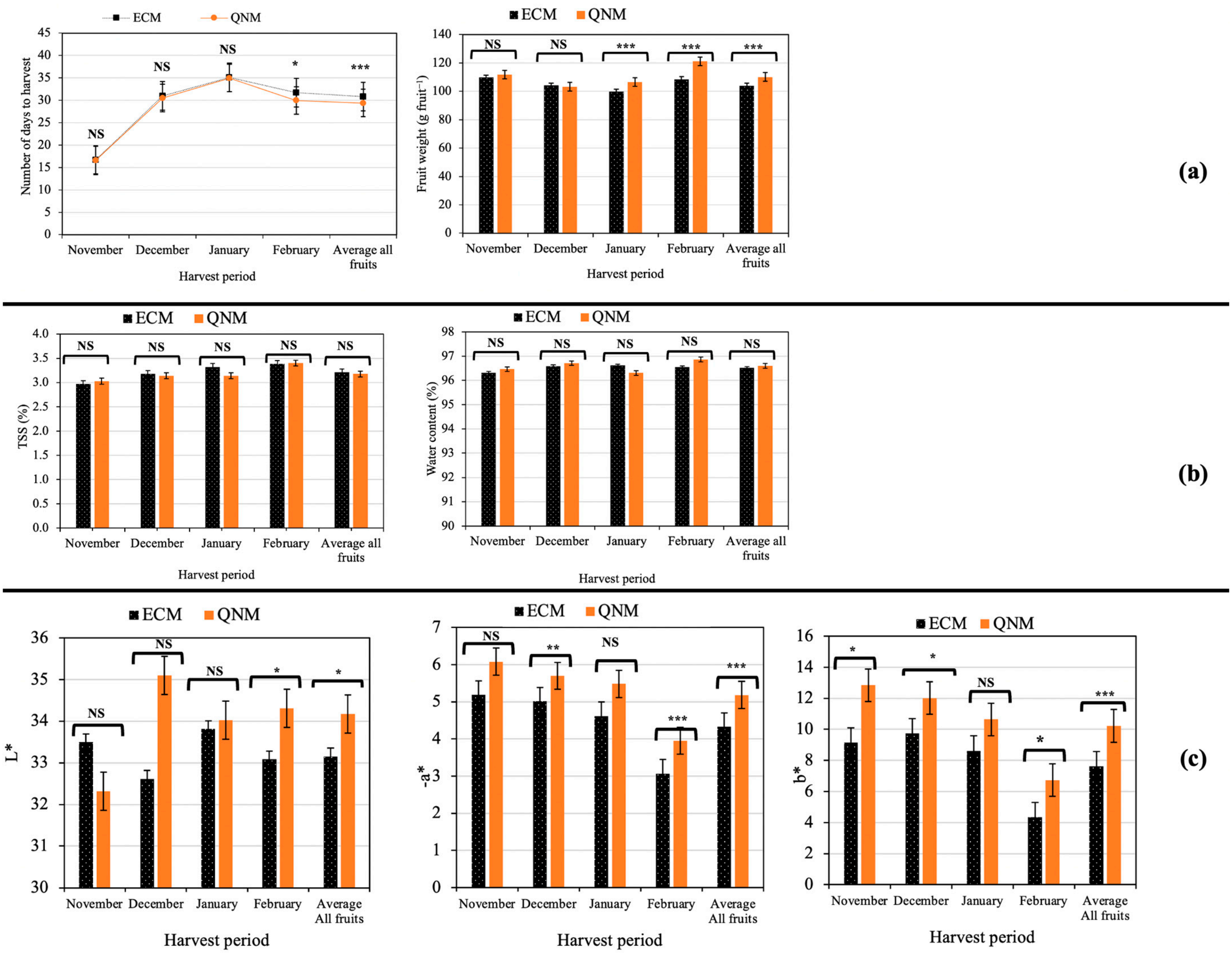


**Figure 6.** Effect of nutrient management methods on fruit growth duration and fruit weight at harvest (**a**), fruit total soluble solids and fruit water content (**b**), and fruit color parameters (**c**). Data represent means of marketable fruits (**a**) and sample fruits (**b**,**c**). Error bars indicate the standard error (n = 135, 155, 344, 251, and 885 for the number of days to harvest in November, December, January, February, and all fruits, respectively. For fruit fresh weight, n = 885. n = 5 for TSS and fruit color parameters in November, December, January, and February and 20 for all fruits. For fruit water content, n = 14 in November, December, January, and February and 56 for all fruits). Treatment effects were significant at 5% (*), 1% (**), and 0.1% (***) probability levels, according to Tukey's test, or were not significant (NS).

The harvested fruits weighed, on average, 110.1 ± 0.6 and 104 ± 0.5 g in the QNM and ECM treatments, respectively. Considering all fruits' weights, harvested fruits were significantly heavier in the QNM treatment. The differences in harvested individual fruit weights were recorded in January and February.

The nutrient management methods did not influence the fruits' total soluble solids (TSS) and water content (Figure 6b). However, the fruit's color at harvest was affected by the difference in nutrient management methods. Considering all evaluated fruits' data, L*, −a*, and b* values significantly increased in the QNM treatment (Figure 6c).

Nutrient management methods did not affect fruit length, shape index, and diameter (Table 5).

**Table 5.** Effect of nutrient management methods on fruits length, shape index, and diameter.

| Treatment | Fruit Length (cm) | Fruit Shape Index | Fruit Diameter (mm) |
|---|---|---|---|
| ECM | 23.3 ± 0.06 | 0.939 ± 0.001 | 27.38 ± 0.06 |
| QNM | 22.4 ± 0.09 | 0.941 ± 0.001 | 27.29 ± 0.07 |
| Significance | NS | NS | NS |

Data are presented as mean ± standard error (n = 885). Treatment effects were not significant (NS).

## 4. Discussion

### 4.1. Nutrient Wastes and Nutrient Use Efficiency

Brunelle et al. [42] predicted that the cost of fertilizers could rise from 0.8% to 3.6% every year between 2005 and 2050. Therefore, it is important to explore cultivation methods that can optimize fertilizer usage. In the current experiment, the QNM treatment significantly improved the nutrient use efficiency. The QNM technique resulted in 26.7% less nitrogen, 30.4% less calcium, and 27.8% less magnesium used to produce one kilogram of cucumber fruits compared to the conventional ECM technique. The higher nutrient use efficiency of the QNM treatment can be attributed to the combination of low nutrient supply rate and low dry matter nutrient concentration [43]. By adopting the QNM technique, farmers can cope with increasing fertilizer prices without negatively impacting crop yields and harvested product quality.

The QNM technique is also effective in generating minimal nutrient wastes. Our data indicated that the QNM treatment showed a significant reduction of 66.4% and 21.2% in nitrogen and potassium wastes per kilogram of cucumber fruits, respectively, when compared to the ECM treatment (Table 2). These findings indicate that the QNM technique is a practical method that can be used to prevent groundwater pollution [44,45].

### 4.2. Vegetative Growth Characteristics

The QNM technique was developed for plant growth control, which has proven to be effective in regulating leaf size [30] and optimizing the leaf area index. Ten weeks after transplantation, the leaf area began to significantly decrease (Figure 4b) in the QNM treatment because of a reduced nutrient supply rate. In contrast, during the experiment, it was observed that the Leaf Area Index (LAI) did not decrease for an extended period in the QNM treatment. This was due to a higher number of leaves that remained on the plants in that treatment. These results indicate that reducing the leaf size in the QNM treatment had no significant negative impact on the LAI, which is a key factor in collecting sunlight and contributing to plant fruit yield.

The total plant length and number of nodes per plant significantly increased in the QNM treatment. These findings align with those of Chartzoulakis [46] and Helal et al. [47]. The relatively high root zone's nutrient concentration observed in the ECM treatment (Figure 3c) might be the reason for the total plant length reduction. According to Helal et al. [47], both root and shoot growth were reduced due to an increased osmotic pressure from nutrient element accumulation in the root zone. Figure 7 displays photographs of plants at different growth stages.

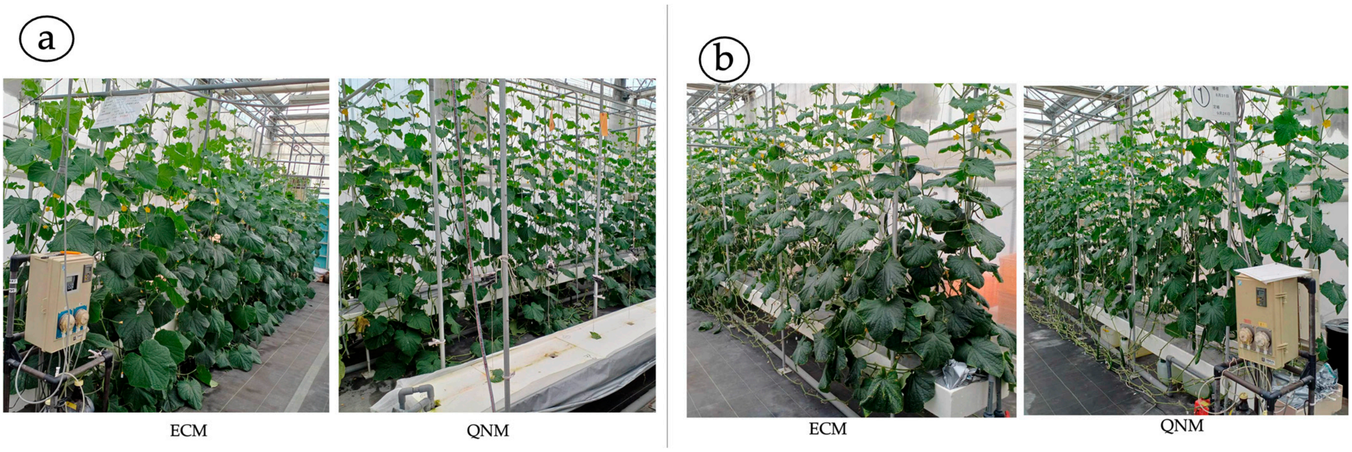


**Figure 7.** Photographs of plants at 93 DAT (**a**) and 130 DAT (**b**).

### 4.3. Plant Physiology

The Pn, Gs, and Tr were significantly reduced in the QNM treatment at the late stage of the experiment. This was probably caused by the reduction in the leaf area and the leaf chlorophyll content in that treatment. Evans [48] found a positive correlation between leaf N content and photosynthetic capacity per leaf area in $C_3$ plant species. Moreover, there is a correlation between leaf longevity, specific leaf area, tissue nitrogen concentration, and leaf gas exchange [49,50]. Considering those remarks, Matsuda et al. [30] suggested adjusting the nutrient application rate in QNM to a level that does not limit dry matter production due to low leaf N content per unit leaf area.

### 4.4. Plant Productivity

Applying the QNM treatment did not reduce the total and marketable fruit yields even though the amount of nutrients supplied was reduced. This means that in the QNM treatment, the plant efficiently used the nutrients supplied by reducing the individual leaf size and increasing the number of leaves (plant length), optimizing the LAI. The small leaf size has probably enhanced the distribution of light across the plant canopy [29]. In contrast, the plants treated with ECM produced a small number of larger leaves, which could not increase the yield due to shading effects within and between plants [51]. In addition, it is well known that when the amount of nutrients absorbed by plants exceeds a threshold, the yield no longer increases with the nutrient application. This indicates that in the ECM treatment, plants were probably exposed to luxury nutrient consumption, leading to excessive vegetative growth [31].

### 4.5. Fruit Growth and Quality

The changes observed over time in the fruit growth duration were probably caused by the changes in the greenhouse's internal temperature and the solar radiation intensity (Figure S2) [52]. Considering the average growth duration of all fruits, the QNM treatment significantly reduced the growth duration. This could be due to reduced leaf area and improved light distribution across the plant's canopy in that treatment.

Cucumber's fruit length, shape index, and diameter were not affected by the nutrient management methods. These characters are controlled by genes [53,54], hormones [55], and leaf area index [56] and were likely not significantly affected by the difference in the nutrient management methods. In addition, fruit total soluble solids (TSS) and water contents were not significantly different between the treatments. However, fruit color significantly improved in the QNM treatment. Several previous studies reported that the QNM technique did not reduce the quality of harvested products [29,31]. Chaverria et al. [57] examined the effect of nitrogen concentration in the nutrient solution on cucumber fruit color parameters. They reported that perceived color intensity decreased with higher N concentrations, depending on the cultivars used and cultivation seasons.

## 5. Conclusions

This study used electrical conductivity-based management (ECM) and quantitative nutrient management (QNM) to grow cucumbers in the nutrient film technique hydroponic system. The results showed that the QNM treatment reduced nutrient supply without reducing total and commercial yields and fruit quality. Cucumbers grown under the QNM treatment required 26.7% less nitrogen, 30.4% less calcium, and 27.8% less magnesium to produce a kilogram of fruit compared with cucumbers grown under the ECM treatment. Moreover, the nutrient wastes generated to produce a kilogram of fruit were significantly reduced in the QNM treatment by 66.4%, 60.7%, and 21.2% for nitrogen, calcium, and potassium, respectively. Regarding these results, the QNM method can be adopted by cucumber growers to maximize fertilizer utilization and protect the environment against nutrient waste pollution. We suggest applying the QNM treatment at the beginning of the growth cycle instead of 28 DAT (in the current study) to increase the nutrient use efficiency.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy14020296/s1, Figure S1: Lowering training method; Figure S2: Daily mean temperature and cumulative irradiation (a), and daily average relative humidity and carbon dioxide ($CO_2$) concentration (b) in the greenhouse; Table S1: Total nutrients supplied and absorbed during the cultivation period.

**Author Contributions:** Conceptualization, N.S., S.T., M.J. and A.N.; methodology, N.S., S.T., A.N. and O.N.; software, N.S.; formal analysis, N.S.; investigation, N.S., S.T. and A.N.; resources, S.T. and O.N.; data curation, N.S.; writing—original draft preparation, N.S.; writing—review and editing, N.S., S.T., N.L., M.J. and A.N.; visualization, S.T.; supervision, S.T.; project administration, S.T., M.J. and A.N.; funding acquisition, S.T. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Data Availability Statement:** Data are contained within the article.

**Acknowledgments:** The authors are grateful to the Japan International Cooperation Agency (JICA) for supporting this study.

**Conflicts of Interest:** The authors declare no conflicts of interest.

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