A DISSERTATION FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Improvement of Utilization Efficiency and Ion Balance of Recycled Nutrient Solution in Closed Soilless Culture of Paprika (*Capsicum annuum* L.)

BY

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ABSTRACT

Although closed soilless culture is useful for saving water and fertilizers with minimizing environmental pollution, adequate management of nutrient solutions is still not stabilized in greenhouse cultivation. However, ion imbalance in recycled nutrient solution and the accumulation of nutrients in root medium are serious problems affecting plant growth. For efficient nutrient management, an adjustment of the recycled nutrient solution at an appropriate analysis interval is required considering the nutrient and water demands of plants.

The aims of this study are to compare the ion balance, yield, and use of water and fertilizers between the closed and open soilless culture systems, to find out the proper renewal period reducing ion imbalance in the recycled nutrient solution, to investigate the nutrient and water uptake and the yield and mineral contents of the plants by the renewal period of recycled nutrient solution, and to determine the effect of renewal pattern on ion balance in the recycled nutrient solution and substrate, and nutrient uptake of paprika plants.

Yield reduction by 19% was observed in the closed system compared with that in the open system after four harvests. Water use efficiency (WUE) and fertilizer use efficiency (FUE) were 68% and 78% higher in the closed system than those in the open system. The ion imbalance in the recycled nutrient solution appeared after 4 weeks even though the EC and pH were maintained within acceptable ranges.

Among the different renewal periods, the changes in cation and anion ratios in the recycled nutrient solution could be reduced by renewing every 4 weeks. Although 50 to 51% WUE and 61 to 67% FUE were higher in the closed system using different renewal periods than those in the open system, the lowest fruit yield was observed in the closed system at a 12-week renewal period. Considering nutrient balance and yield, an adequate renewal period of the recycled nutrient solution was suggested as 4 weeks, but it can be extended to 8 weeks practically.

The ion balances change in the recycled nutrient solution was reduced at the renewal pattern of 4-4-4 weeks, and followed by 6-4-2 and 8-2-2 weeks. Particularly the accumulation of Ca^{2+} and Mg^{2+} was reduced as the same trend as above. No significant differences in nutrient uptake, yield and plant growth were observed among all the renewal patterns. Chemical analysis indicated that paprika needs less Ca and Mg in the fruits than in the leaves during fruit growth.

It can be concluded that renewal period and pattern play important roles in the ion balances of the recycled nutrient solution and root medium and the uptakes of water and nutrients by plants in closed soilless culture. For more efficient management of nutrient solution in closed soilless culture, adjustment (or renewal) of recycled nutrient solution considering growing stage and environmental conditions are required as further study.

Key words: closed rockwool culture, ion imbalance, recycled nutrient solution, renewal period, water and nutrient uptake,

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CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

Soilless culture is a modern plant production method which requires no arable lands, allows the possibility of a year-round production, and has a faster growth cycle. Soilless culture is classified into two types of open and closed systems. Open system is the common practice under commercial conditions with the supply of fresh nutrient solution every irrigation include 20%-30% drain out which causes the wastes of water and nutrients, causing the pollution of the soil and underground water (Incrocci et al., 2006).

It is known that closed system increases water and fertilizer use efficiency compared with the open system (Zekki et al., 1996) although a slightly yield reduction due to ion imbalance and accumulation of unwanted ions (like Na^+ and Cl^-) in the recycled nutrient solution and root medium (Carmassi et al., 2005). In the closed system, nutrient management remains the primary difficulty due to the imbalance of nutrient ions in the recycled nutrient solution when the nutrient solutions was continuously re-used although it is preferable for saving water and nutrients. It is important to know the conceptual nutrient management technology of closed soilless culture may be an important for sustainable greenhouse production (Pardossi et al., 2002). Nutrient solution composition, volume of supplied nutrient solution, electrical conductivity (EC) and pH of the nutrient solution and root-zone, growth stage, and environmental conditions (temperature, light intensity and relative humidity) are implied for the effective management of crop production in the closed system. Management of the nutrient solution in the closed systems is mostly based on EC control (Savvas and Manos, 1999; Sonneveld, 2000a) because the EC value is closely associated with the total macro-cation (K^+, Ca^{2+}, Mg^{2+}, and Na^+) level (Sonneveld, 2000a). However, possible consequences of salt accumulation can occur at the root-zone when the ion concentration in the recycled nutrient solution is higher than the plant uptake concentration (Carmassi et al., 2005; Savvas et al., 2005). Frequently replenishment of the recycled nutrient solution in the closed system is needed due to the increasing salinity levels in the root-zone (Savvas et al., 2007a).

The optimization of nutrient solution management requires the knowledge of how changes in concentrations of wanted and unwanted ions like Na^+ and Cl^- in the closed system during the cultivation period. Recent studies (Baas et al., 1995; Brun et al., 2001; Bugbee, 2004; Carmassi et al., 2007; Ehret et al., 2005) have showed that the unbalances between water and nutrients supply were responsible for accumulation of unwanted ions in the recycled nutrient solution and root medium, resulting in yield losses. Although fluctuations in total ion uptakes can be corrected by the adjustment of EC, specific nutrients uptake cannot be. It is important to monitor the nutrient availability or equilibrium between the recycled nutrient solution and root medium. Therefore, in order to reduce the constraints of the closed system like operational costs, environmental protection without reduction of yield and quality, frequent analysis or adjustment of mutual ion ratio is required in the recycled nutrient solution and root medium (Grattan and Grieve, 1998; Incrocci et al., 2006; Lopez et al., 2003; Rouphael and Colla, 2009; Savvas et al., 2005).

Changes in total and specific ion concentrations in the recycled nutrient solution due to growth and development should be considered. Regular analysis of drainage water is used as a safety management for the recycled nutrient solution even though Bugbee (2004) indicated that the monitoring ions in solution is not always necessary. Although uptake volume-based continuous nutrient supplementing systems are cost-effective, they still need to be equipped with high-cost nutrient sensors and dispensers etc. (Gieling et al., 2000). Periodical flushing of the recycled nutrient solution is related to increase the water and fertilizers use efficiency and crop yield (Massa et al., 2010; Pardossi et al., 2002). However the proper renewal or analysis period for better nutrient application management in the closed system is still needed to study.

The objectives of the thesis are:

1) To investigate the problems occurred in the closed soilless culture of paprika compared with the open system in terms of ion balance, fruit yield, water and fertilizer use efficiency
2) To find out the proper renewal period reducing ion imbalance in the recycled nutrient solution
3) To investigate the nutrient and water uptakes of the plants and to measure the yield and mineral contents in plants as influenced by renewal period of the recycled nutrient solution in the closed system compared with the open system
4) To determine the effect of renewal pattern on the distribution of nutrients in the recycled nutrient solution and root medium that subsequently affected the nutrient uptake of the plant

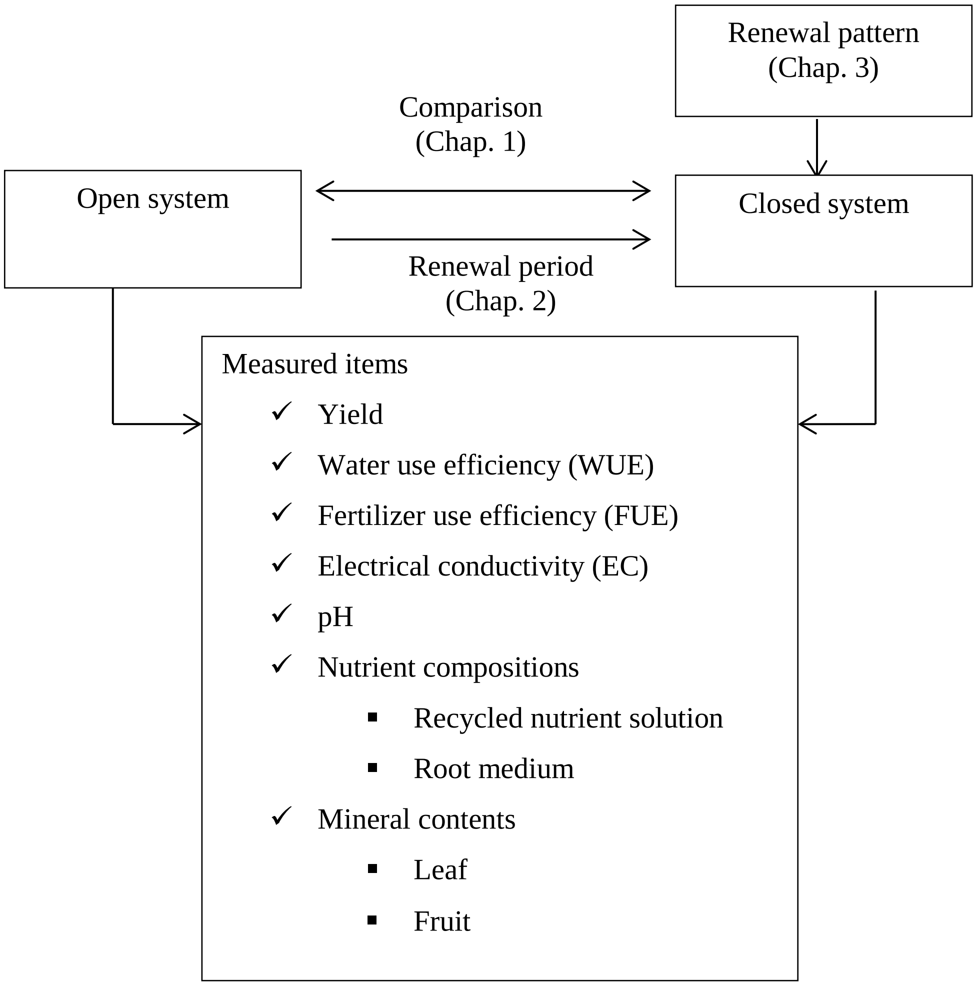

Fig. 1.1. Schematic diagram for describing the experimental approach in each chapter and measure items.

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2. LITERATURE REVIEW

2.1. Nutrient management in closed system

2.1.1. pH management

As the pH value determines the nutrient availability for plants, its adjustment must be done daily due to the lower buffering capacity of soilless culture system (Urrestarazu and Mazuela, 2005). The changes in the pH of the nutrient solution depend on the differences in magnitude of nutrient uptake by the plants. When the anions are taken up higher than cations, the plant excretes OH^- or HCO_3^- anions, to balance the electrical charges inside, which produces increasing in the pH value (Marschner, 1995). Regulating of pH is normally carried out by using nitric, sulfuric or phosphoric acid. When acid is applied, the CO_3^{2-} ion is transformed to HCO_3^- and then HCO_3^- is converted into H_2CO_3 which is partially dissociated to H_2O and CO_2 (De Rijck and Schrevens, 1997) since pH is closely related to the concentration of HCO_3^- and CO_3^{2-}.

Usually the pH is the lowest at the spots of the drippers because of the rapid NH_4^+ absorption and the intensive rooting at these spots. Between drippers the pH will be highest because of a lack of NH_4^+ and accumulation of HCO_3^-, due to root respiration (Voogt, 1995). The pH of drainage water is the result of a leachate from all sites in the root environment and will be affected most by the strongest buffer. The lower the drainage rate, the higher the pH will be. As a consequence, the concentrations of P and Mn will be reduced since both nutrients will precipitate in the root environment at spots with high pH values.

2.1.2. EC management

EC is defined as the total ion concentration in the nutrient solution. A decrease in some ions concentration is tended to increase the concentration of others which is observed simultaneously, both in closed and open systems. It was observed that the concentration of Fe decreased very fast, while that of Ca^{2+}, Mg^{2+}, and Cl^{-} increased; moreover, concentrations of K^{+}, Ca^{2+}, and SO_4^{2-} did not reach critical levels in a closed hydroponic system with a rose crop (Lykas et al., 2001). Instead, an increase in the EC value due to the accumulation of high level of some ions like bicarbonates, sulfates, and chlorides with recycling of nutrient solution was observed (Zekki et al., 1996). In fact, the rapid depletion of some nutrients often causes the accumulation of some nutrients to the recycled nutrient solution. Carmassi et al. (2007) developed a simple model for the changes in ion concentration and EC of recycled nutrient solution on the basic of balance equation for nutrient uptake by hydroponically grown tomato by refilling the mixing tank with complete nutrient solution to compensate crop evapotranspiration.

In addition there is a shift in the mutual ratios of nutrients in the drainage where the EC in the drainage water is increased while compare to the initial supply. If not adequately adjusted, reuse of drainage water results in high EC which is characterized by relatively high concentrations of Ca^{2+}, SO_4^{2-}, and Mg^{2+} and low concentrations of NH_4^{+}, K^{+}, and NO_3^{-} (Voogt and Sonneveld, 1997).

2.2. Nutrient uptake

Application of plant nutrients need to be carried out according to the requirement of nutrients by the plants since the composition and concentration of the nutrient solution are dependent on culture system, crop development stage, and environmental conditions. The ions in the nutrient solution are transported to the root through mass flow, which is driven by the transpiration rate (Mengel and Kirkby, 2001). Absorption of ions by plant is influenced by three processes: diffusion of ions to the root as the result of either concentration or electrical gradients, mass flow of water as the result of transpiration, selective absorption by the plant.

In general, increasing the frequency of irrigation reduces the variations in nutrient concentration, thereby increasing their ability to plants (Silber and Bar-Tal, 2008; Sonneveld and Voogt, 2009; Urrestarazu and Mazuela, 2005). However, frequent irrigation leads to always wet to the surface of the substrate to continuous evaporation, which cause accumulation of nutrient ions at the top layer of the substrate that may reduce the nutrient uptake by the roots (Rouphael and Colla, 2009; Savvas et al., 2007b; Sonneveld and Voogt, 2009; Uronen, 1995). In addition, long irrigation events increase the leaching fraction (Lieth and Oki, 2008), which reduces the availability of nutrients to the roots. Some ions in excess can cause nutrient deficiencies in plants by interfering with the uptake of other ions due to the antagonistic effect of ions (Mengel and Kirkby, 2001).

Cations and anions may be absorbed independently and not in equal quantities. Monovalent ions are taken up more readily than divalent ions and ions with small diameter will be absorbed faster than ions with large diameter. The total uptake is more or less determined by the growth, but the uptake of specific nutrient depends on plant age. K^+ uptake increases strongly 8 weeks after planting together with reduced uptake of Ca^{2+} and Mg^{2+} which is connected with an increased fruit load and restriction of the vegetative growth and root development (Voogt, 1993). The decrease in nutrient uptake rate of bell pepper mainly in the winter season with too low temperature delayed fruit ripening and decreased the rate of fruit DW accumulation (Tzipilevitz et al., 1996).

2.3. Ion competition and antagonism

The relationship between ion uptake and plant development could be the basis for developing nutrition programs in response to changes in plant nutrient demand over time, enhancing fertilizer use efficiency and reducing fertilizer losses (Bugbee, 2004; Cabrera et al., 1995). The presence of several ions in solution can cause competition between cations and anions. For either cations or anions, an increased concentration of one will often competitively inhibit the uptake of others especially on ions of similar sizes (Marschner, 1995). Moreover, extensive application of potassium and calcium fertilizers can depress Mg^{2+} uptake since the binding strength is rather low of the highly hydrated Mg^{2+} at the exchange sites in the cell wall. It has been reported that NH_4^+ absorption depress the uptake of other cations and NO_3^- uptake depress that of anions (Kirkby and Mengel, 1967). High NH_4^+: NO_3^- ratio reduce the uptake Ca^{2+} and K^+ that have negative effect on dry matter production, fruit quality and the incidence of blossom end rot (BER) due to unbalance of cations uptake (Bar-Tal et al., 2001). Ca^{2+}

uptake is in the root tip region whereas K^+ and $H_2PO_4^-$ absorption and movement to the shoots takes place readily throughout the root length. NO_3^-, $H_2PO_4^-$, and K^+ are usually transported rapidly to the upper parts of the plant, depending upon uptake and transpiration rates, while Ca^{2+}, Mg^{2+}, and SO_4^{2-} are transported at lower rates (Silber and Bar-Tal, 2008). The uptake can be altered not only by concentration but also by the irrigation treatment (Lieth and Oki, 2008). With the increased EC of recycled nutrient solution mainly resulted from the accumulation of bivalent ions like sulfate and bicarbonate can reduce uptake or transport of Ca^{2+} (Lopez et al., 2002). Reduced transpiration by raising humidity inhibited the uptake of K^+, Ca^{2+}, and Mg^{2+} in tomato (Sonneveld and Welles, 2005). Since nutrient and non-nutrient concentration may largely influence ion and water uptake kinetics (Le Bot et al., 1998; Parida and Das, 2005), frequent nutrient replenishments of recycled nutrient solution is the required management for keeping the equilibrium of nutrient concentration in the supplied solution and at the root medium.

2.4. Morphology, growth, and quality of paprika

Paprika is annual or perennial, dicotyledonous indeterminate plant and originated from Central and South America. Plant growth is largely influenced by genotypes and environmental conditions. The main developmental stages of paprika are juvenile stage, flower differentiation, and fruit developmental stage. Plant development and flowering are affected by light intensity and temperature. Paprika is indeterminate and it can grow continuously as long as the growth conditions are favorable. It has tap root system with evenly distributed lateral roots. Greenhouse production of peppers is based on indeterminate cultivars in which the plants continually develop and grow from new meristems that produce new stems, leaves, flowers and fruits. It grows in a single stem before the appearance of the first flower. Indeterminate cultivars require constant pruning to manage their growth. In order to optimize yield, a balance between vegetative (leaves and stems) and generative (flowers and fruit) growth must be established and maintained (Jovicich et al., 2004; Research center of fruit vegetables for export, 2010).

Paprika transplants generally require 6 to 8 weeks from seeding to transplant size. It is sensitive to low temperatures and relatively slow to establish. Optimum growth temperature is 18 to 27°C and the optimum vegetative growth temperature is 21 to 23°C. Fruit set is sensitive to extreme temperatures and will not set fruit above 32°C during the day or below 16°C at night. Best yields occur when temperature during fruit set are between 18 to 27°C. The first fruit harvest for paprika is typically ready 8 to 10 weeks after transplanting. Target temperature for the root medium is 18 to 21°C. The optimum humidity for the growth of paprika is 75%. The flower and fruit set and development of paprika is very sensitive to the environmental conditions, although paprika is cultivated in controlled environment under greenhouse. The differential environmental conditions and the shift in plant growth from vegetative to reproductive stage might alter nutrient requirement of paprika (Decoteau, 2000).

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3. CHAPTER I. Comparisons of Ion Balance, Fruit Yield, Water and Fertilizer Use Efficiencies in Open and Closed Soilless Culture System

ABSTRACT

Although closed soilless culture is useful for saving water and fertilizers with minimizing environmental pollution, adequate management of nutrient solutions is still not stabilized in greenhouse cultivation. In order to investigate the problems occurred in closed soilless culture of Paprika (*Capsicum annuum* L., cv. Fiesta), compared ion balance, fruit yield, and the water and fertilizer use efficiencies in closed system with those in open system. The plants were grown in rockwool culture with a nutrient solution of the electrical conductivity (EC) 2.5 $dS{\cdot}m^{-1}$. 4 weeks after recycling the nutrient solution, individual ratio of NO_3^-, K^+, Ca^{2+}, and Mg^{2+} to total ion concentration ($meq{\cdot}L^{-1}$) decreased from the initial value, especially the biggest decrease was observed in K^+, and on the other hand SO_4^{2-}, Cl^-, and Na^+ were accumulated in the closed system. Yields after four-time harvests were 19% higher in the open system than the closed one. Total volume of water and fertilizer used per unit area (m^2) was 73% and 81% higher in the open system than closed system. Hence, water and fertilizer use efficiency was increased 68% and 78% in the closed system. Amount of marketable fruits was not significantly different between the two systems. The ion imbalance in recycled nutrient solution was more pronounced after 4 weeks even though maintaining within the acceptable range of the EC 2.5 $dS{\cdot}m^{-1}$ and pH 5.5-6.5. It can

conclude that it is needed to renew recycled nutrient solution beginning from 4 weeks to prevent imbalance or depletion of nutrients in close soilless culture of paprika plants to get more balanced nutrient composition during whole cultivation period.

Key words: ratio of nutrient composition, recycled soilless culture, reused nutrient solution

3.1. Introduction

The management of nutrient solution is required in soilless culture which is divided into two systems, open and closed system. In the open system, the drainage solution containing considerable amount of nutrients causes the pollution of ground water and soil, while closed soilless culture may overcome this problem by reusing water and nutrients with improving water and nutrient use efficiencies (Van Os, 1999). However, recycling of drainage leads to imbalance of nutrient solution, resulting in the change of nutrient ratios (Savvas and Gizas, 2002b).

As a reason for nutrient imbalance, it is reported that each nutrient is absorbed by plants though different mechanisms resulting in variations in uptake efficiency (Sonneveld, 2000b; Sonneveld and Voogt, 1985; Wild et al., 1987). Moreover, uptakes of water and nutrients are influenced by growth stage, climatic conditions (Sonneveld and Van Den Bos, 1995) and other environmental variables during the growing period (flowering and fruit developing). Therefore, water and nutrients should be adequately supplied considering the demand of plants in order to avoid an accumulation or depletion of nutrients in the closed system. To solve this problem, total nutrient strength and individual nutrient concentration in the recycled solution should be adjusted by using water and stock solutions. Estimation of daily replenishment needs by using indirect measurements of nutrient availability is an optional strategy (Weerakkody et al., 2007).

In general, the management of nutrient solution based on electrical conductivity has a difficulty in adjusting the ratio of individual ion concentration. For efficient management of nutrient solution, Savvas and Gizas (2002) tried to adjust individual ion ratio by chemical analysis every two weeks. Some reports indicated that recirculation of nutrient solution had no effect on harvested parameters during the first 8 weeks but had a negative impact in average over the entire harvest (Ehret et al., 2005; Hao and Papadopoulos, 2002; Raviv and Blom, 2001). Since adjustment frequency of recycled nutrient solutions based on chemical analysis is related to stability and operational cost in closed soilless culture, determination of an appropriate analysis period is important in commercialized farms.

The aim of this study was to investigate the changes in ion concentrations, its effect on fruit yield, and the water and fertilizer use efficiencies in closed soilless culture of paprika plants by comparing with those in the open system.

3.2. Materials and Methods

3.2.1. Plant materials and experimental conditions

The paprika seedlings (*Capsicum annuum* L. cv. Fiesta) planted on rockwool cube (10 cm × 10 cm × 6.5 cm) was bought from the commercial farm. The experiment was started two months after transplanting to the rockwool slabs (90 cm x 15 cm x 7 cm) at the beginning of fruiting, with a density of 3 plants/m^2. It was conducted in a venlo-type glasshouse at the experimental farm of Seoul National University (Suwon, Korea, Latitude 37.3°N, Longitude 127.0°E) from end of June to end of August 2011. Environmental conditions during the growing period were shown in Fig. 3.1. Average outside radiation was ranged 0.7 to 20.7 MJ·m^{-2}·d^{-1} and average inside greenhouse temperature was controlled at 24 to 31.2 °C. Three slabs were installed for each system and placed in each gutter. In the closed system, reservoir tank (52 cm × 26 cm × 26 cm) containing nutrient solution volume 20 L was used. The supplied nutrient solution was prepared in a mixing tank using two stock solutions adjusting desired EC and pH at 2.5 dS·m^{-1} and 5.5 to 6.5, respectively. Compositions of fresh nutrient solution (meq·L^{-1}) were 14.17 NO_3^-, 1.14 $H_2PO_4^-$, 5.92 K^+, 8.85 Ca^{2+}, 3.17 Mg^{2+} and 3.2 SO_4^{2-}. A pump connected to drip emitters (having a capacity of 3L·h^{-1}) controlled by a timer was used for irrigation. Drainage ratio was maintained within 20 to 50% at each irrigation event. Nutrient solution was supplied four times per day (7:00, 10:00, 14:00 and 16:00) for 5 to 10 min each. The plants were pruned to form two main stems, which were vertically trellised to a “V” canopy system (Jovicich et al., 2004b) and the additional plant management of pruning and training were carried out every week.

3.2.2. Measurements

The entire quantity of drainage directly returned to the reservoir tank. The EC, pH, and volume of recycled nutrient solution in the tanks of the closed system were measured every three days and the tanks were refilled with water and fresh nutrient solution until EC of the solution reaching 2.5 dS·m^{-1}. The nutrient solution volume in the tank was kept constant every three day. The EC and pH of recycled nutrient solution were measured by using a conductivity meter (D-54, Model-352734-1, Horiba, Japan). Every two weeks, nutrient solutions from all the reservoir tanks were sampled and analyzed: NO_3^-, $H_2PO_4^-$, Cl^- and SO_4^{2-} by an ion chromatography (ICS-3000, Dionex, Sunnyvale, CA, USA) and K^+, Ca^{2+}, Mg^{2+} and Na^+ by an inductively coupled plasma-atomic emission spectrometry (ICP-730 ES, Varian, Inc, USA). At each harvest (harvested four times), fruit number, fruit fresh and dry weights were measured. Fruits were dried in a thermo-ventilated oven at 70°C until reaching a constant weight. Fruits were divided into marketable and not marketable (fruits with cracks on the epicarp or small size (less than 100 g) and miss-shaped) and blossom end rot. Harvesting started on mid-July and ended at the end of August.

3.2.3. Water and fertilizer use efficiencies

In the closed system, the reduced volume of nutrient solution inside the reservoir tank and the added volumes of water and nutrient solution were measured. Total volume of water used was calculated using the total volume of water supplied to the plants. Following formula was used to estimate the water and fertilizer use efficiencies (Jovicich et al., 2007).

For open system, used water ($L \cdot kg^{-1}$ fruit) and used fertilizer ($g \cdot kg^{-1}$ fruit) is by dividing total water volume delivered (including drainage) ($L \cdot m^{-2}$) and total fruit yield ($kg \cdot m^{-2}$).

For closed system, used water ($L \cdot kg^{-1}$ fruit) is the sum of initial 20L nutrient solution and additional nutrient solution and water to the reservoir tank divided by the total fruit yield ($kg \cdot m^{-2}$). Used fertilizer ($g \cdot kg^{-1}$ fruit) is the sum of initial 20L nutrient solution and additional nutrient solution divided by the total fruit yield ($kg \cdot m^{-2}$).

3.2.4. Statistical analysis

The experiment was conducted by the simple comparison between the two systems, open and closed. The two systems with three replications (slabs) were compared with the time and three plants were grown in each slab. Data were subjected to single factor analyses of variance using SAS 9.2 (SAS Institute, Cary, NC, USA) and means were separated by Duncan's multiple range tests at ($p < 0.05$). Treatment means of ion concentration changes in open and closed systems were performed using Sigma-Plot 10 (SPSS, Inc., Chicago, IL, USA).

3.3. Results and Discussion

3.3.1. EC and pH in recycled nutrient solution

The EC in recycled nutrient solution significantly increased from the initial set value of 2.5 $dS{\cdot}m^{-1}$ for 74 to 102 days after transplanting (DAT), (14 to 42 days after treatment) and then decreased (Fig. 3.2A). It might be due to the uptake of more water than nutrients by plants during 14 to 42 days. In fact, depleted volume was supplemented with water and fresh nutrient solution for adjusting EC and constant volume three times a week. The changes in EC and composition of recycled nutrient solution were supposed to from the imbalance in uptake ratio of water and nutrient. Lopez et al. (2003) reported that when the nutrient solution is recycled, sulfate, bicarbonate and chloride ions may accumulate resulting in a significant increase of EC. Although the pH of drainage solution in the closed system was observed within 5.5-6.5, it was a little higher than that in the open system (Fig. 3.2B). It might be caused by more anion uptake in the closed system as reported by Savvas and Gizas (2002).

3.3.2. Nutrient composition in the recycled nutrient solution

No significant change in ion ratio was observed in cation (Fig. 3.3), while significant change observed in anion in recycled nutrient solution (Fig. 3.4). In fact, nutrient and non-nutrient concentration may largely influence on nutrient and water uptake kinetics (Le Bot et al., 1998; Parida and Das, 2005). After 4 weeks of treatment (88 DAT), individual ratio of NO_3^-, K^+, Ca^{2+} and Mg^{2+} to total ion concentration ($meq \cdot L^{-1}$) in recycled nutrient solution decreased from the initial value, especially the biggest decrease was observed in K^+, (Fig. 3.5). For a reason, Marcussi et al. (2004) reported that NO_3^- and K^+ were the most required macronutrients in sweet peppers, followed by Ca^{2+}, Mg^{2+}, SO_4^{2-} and PO_4^{3-} in decreasing order. Climate and growth variables during the entire cultivation cycle were also related to nutrient absorption patterns (Silberbush and Lieth, 2004). Meanwhile, accumulation of SO_4^{2-} as well as a progressive increase in Cl^- and Na^+ were observed in the closed system (Figs. 3.5 and 3.6). This condition is generally found in recycled nutrient solution due to relatively poor absorption of those ions by plants (Savvas and Gizas, 2002). Although the set EC value of 2.5 $dS \cdot m^{-1}$ was controlled by adding water and fresh nutrient solution, sum of each cation (K^+, Ca^{2+}, Mg^{2+} and Na^+) and anion (NO_3^-, $H_2PO_4^-$, SO_4^{2-} and Cl^-) concentration ($meq \cdot L^{-1}$) in recycled nutrient solution increased rather than the initial value (Fig. 3.7). It might be due to the significant reduction of NO_3^-, K^+, Ca^{2+} and Mg^{2+}

and the accumulation of SO_4^{2-}, Cl^- and Na^+ as shown in Figs. 5 and 6. Ionic contributions of NO_3^- and K^+ to EC reading were the greatest and followed by Ca^{2+}, SO_4^{2-} and Mg^{2+} in the order (Ahn and Son, 2011). On the other hand, ion uptakes became lower than expected and led to ion accumulation in the closed system. This tendency was more pronounced by anion accumulation 4 weeks after treatment. Therefore, frequent nutrient replenishments should be required every 4 weeks to maintain constant ion ratio in the closed system.

3.3.3. Fruit yield

Total number of fruits and yields per m^2 were 22% and 19% less in the closed system than the open system, respectively (Table 3.1). Mean fruit weight was relatively higher in the closed system. Since adjustment of the reused nutrient solution in the closed system was based on pH and EC instead of instantaneous renewal or mineral analysis, nutrient imbalance in the solution was expected to affect both crop yield and quality. When the drainage solution was reused, the highest yield was obtained with the supply of highest ratio of $K^+ : (K^+ + Ca^{2+} + Mg^{2+})$ than those recommended in open system (Savvas and Gizas, 2002). This seems to be true that the decrease of $K^+ : (K^+ + Ca^{2+} + Mg^{2+})$ ratio in reused nutrient solution with the time Fig. 3.3 and resulted 19% yield reduction was observed in this study. The accumulation of SO_4^{2-} in recycled nutrient solution is a common phenomenon in closed soilless culture, which has been implicated to restrict the yield of tomatoes grown in nutrient film technique (NFT) (Lopez et al., 1996; Zekki et al., 1996).

3.3.4. Water and fertilizer use efficiencies

Water and fertilizer use efficiencies in the open and closed systems were given in (Table 3.2). Total volume of water used in the open system was 132.3 $L \cdot m^{-2}$ while that in the closed system was 35.5 $L \cdot m^{-2}$ with a 73% saving of nutrient solution. Total volume of water delivered per kg of fruit was 68% less in the closed system (20.1 $L \cdot kg^{-1}$) than the open system (63.4 $L \cdot kg^{-1}$). Total fertilizer used (42.5 $g \cdot m^{-2}$) was 81% less in the closed system than the open system (227.3 $g \cdot m^{-2}$). As results, average fertilizers used for per kg of fruit were 78% lower in the closed system than the open system. Giuffrida and Leonardi (2011) reported that a strong improvement of water and fertilizer efficiencies using lower nutrient concentration was observed on peppers grown in a closed soilless culture system as I observed.

In this study, the nutrient balance, fruit yield, water and fertilizer use efficiencies were compared in open and closed soilless culture of paprika plants. The ion imbalance in recycled nutrient solution was more pronounced after 4 weeks even though the EC and pH were maintain within the acceptable range. It can conclude that it is needed to renew recycled nutrient solution beginning from 4 weeks to prevent imbalance or depletion of nutrients in close soilless culture of paprika plants to get balanced nutrient composition during whole cultivation period. It is possible to increase the water and fertilizer use efficiencies without yield reduction and quality by renewing or adjusting ions of the recycled nutrient solution in closed soilless culture.

Table 3.1. Growth and yield of paprika plants in open and closed soilless culture systems.

	Number of fruits (m^{-2})	Yield ($g \cdot m^{-2}$)	Fruit wt. (g / fruit)	Number of marketable fruits (m^{-2})
Open system	18 ± 4[z]	2180.0 ± 512	102.5 ± 7.9	13 ± 2
Closed system	14 ± 4	1771.1 ± 112.7	129.8 ± 16.3	10 ± 3
% reduction in closed system	22	19		23
Significance	n.s.[y]	n.s.	n.s.	n.s.

[z]Each value represents mean ± standard deviation (n=9).

[y]ns means non-significant by Duncan's multiple range test at $p < 0.05$.

Table 3.2. Total used amounts and use efficiencies of water and fertilizer in open and closed soilless culture systems.

	Water used ($L \cdot m^{-2}$)	Fertilizer used ($g \cdot m^{-2}$)	Used water ($L \cdot kg^{-1}$fruit)	Used fertilizer ($g \cdot kg^{-1}$fruit)
Open system	132.3 a[y]	227.3 a	63.4 ± 17.2 a	108.9 ± 29.5 a
Closed system	35.5 ± 3.2[z] b	42.5 ± 1.7 b	20.1 ± 1.4 b	24.0 ± 0.9 b
% reduction in closed system	73	81	68	78

[z]Each value represents mean ± standard deviation (n=3). In open system, the total amount of water and fertilizer used are the same in 3 replications.

[y]Means with different letter shows significant difference by Duncan's multiple range test at $p < 0.05$.

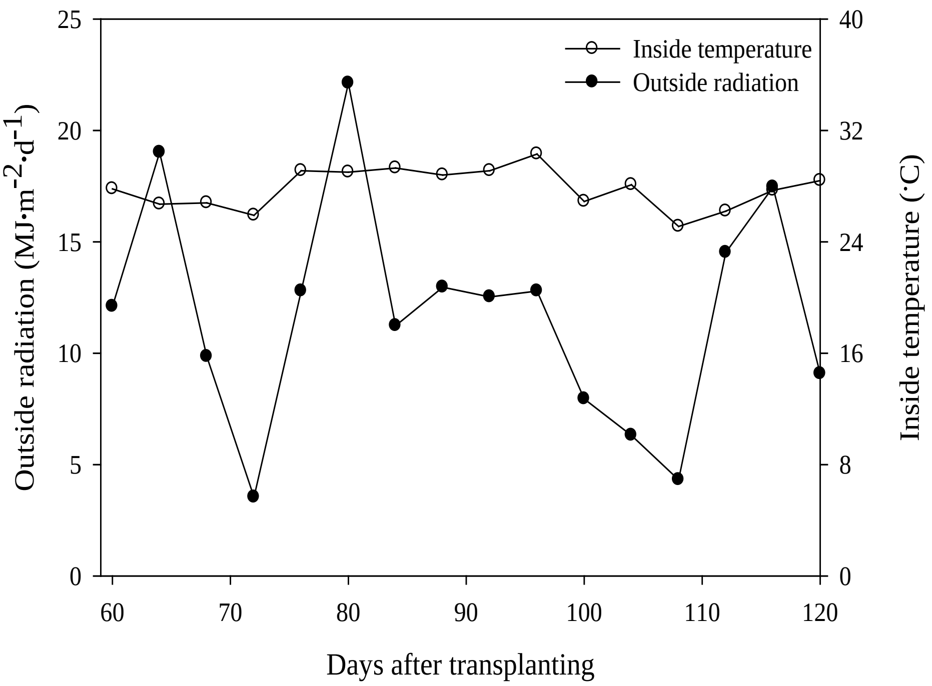

Fig. 3.1. Average outside radiation and inside greenhouse temperature during experimental period from June to August, 2011.

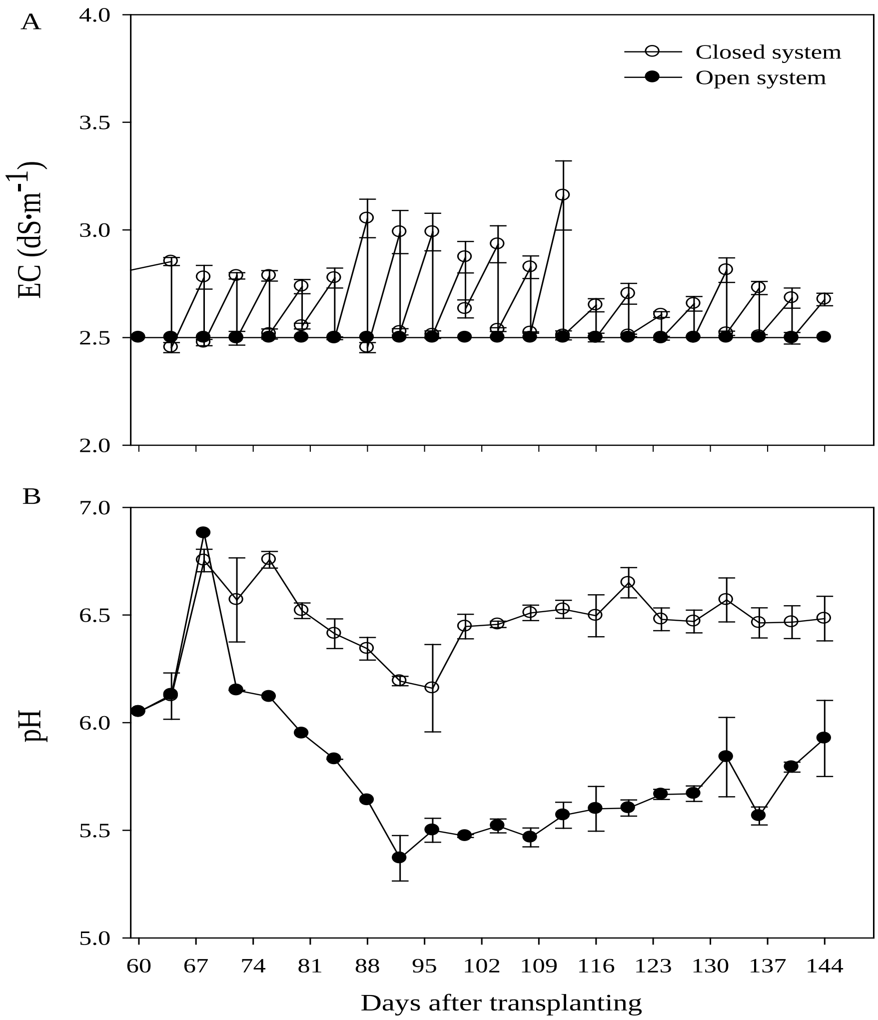

Fig. 3.2. Change of EC in recycled nutrient solution of the closed system (A). Periodical decline of EC is due to adding of fresh nutrient solution and water for adjusting EC. Change of pH in the open system drainage and recycled nutrient solution of the closed system (B). Vertical bars indicate ± SE of the mean (n=3).

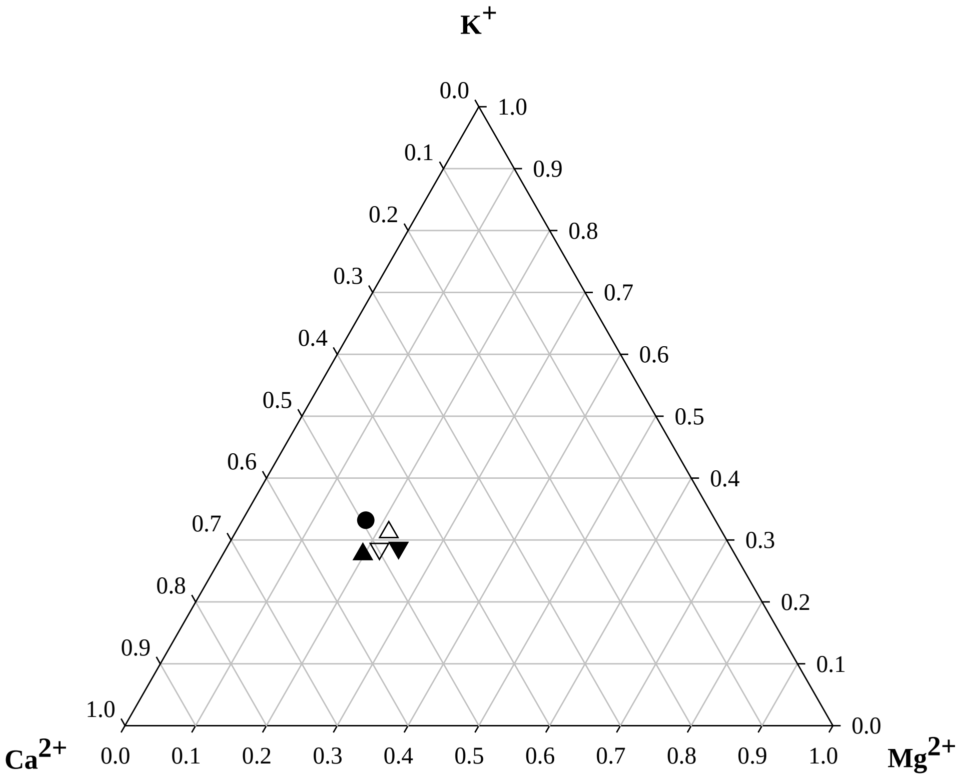

Fig. 3.3. Change in cation ratio of individual ion concentration (meq·L^{-1}) of recycled nutrient solution with time in closed soilless culture systems (● initial, △ week 2, ▲ week 4, ▽ week 6, and ▼ week 8) under a constant EC of 2.5 dS·m^{-1}.

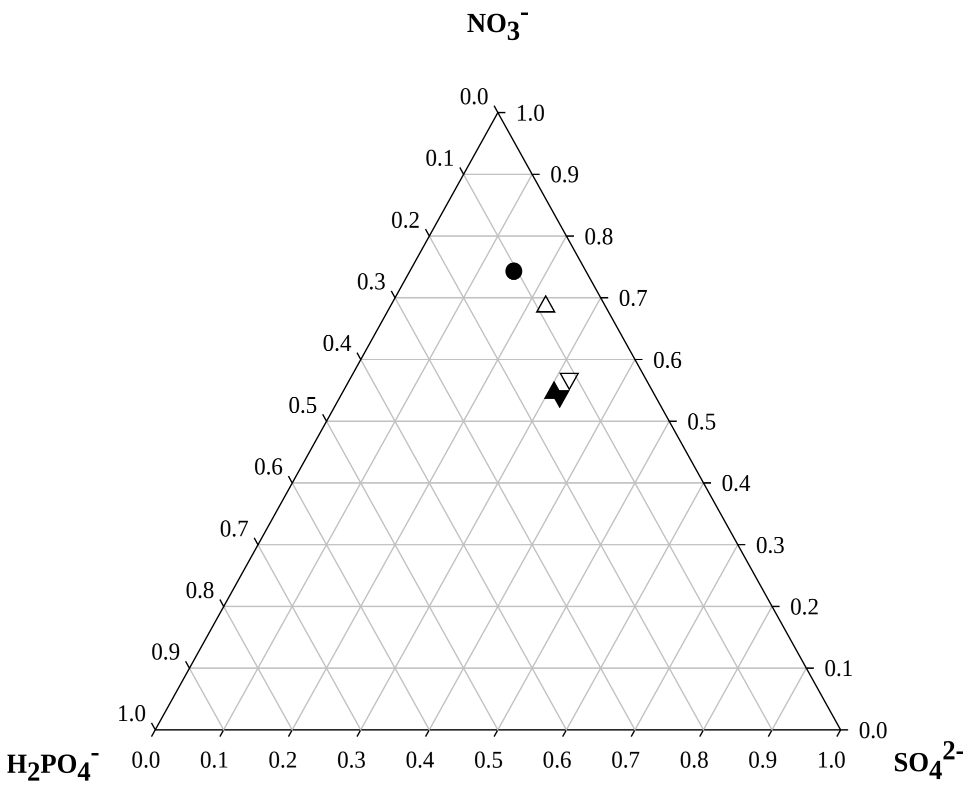

Fig. 3.4. Change in anion ratio of individual ion concentration ($meq \cdot L^{-1}$) of recycled nutrient solution with time in closed soilless culture systems (● initial, △ week 2, ▲ week 4, ▽ week 6, and ▼ week 8) under a constant EC of 2.5 $dS \cdot m^{-1}$.

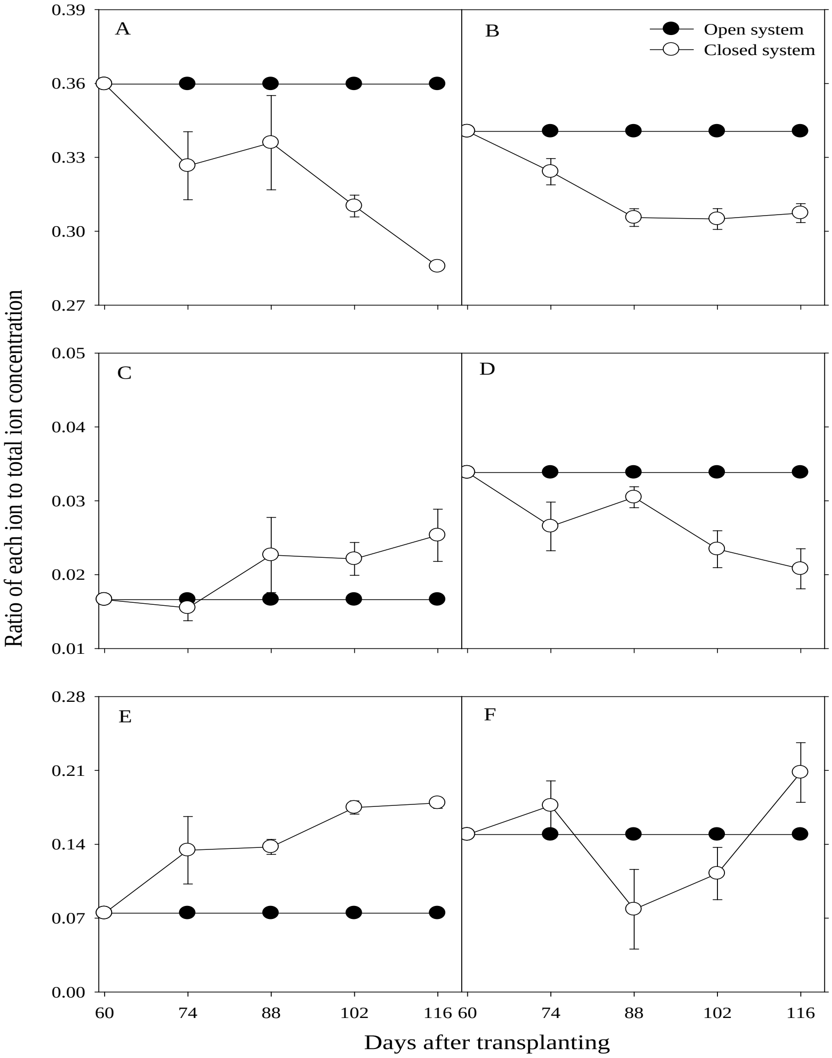

Fig. 3.5. Change in ratio of individual ion concentration to the total ion concentrations ($meq \cdot L^{-1}$) in recycled nutrient solution of closed soilless culture systems. In the open system, ion concentration was the same as the initial value. A, B, C, D, E, and F indicate NO_3^-, K^+, $H_2PO_4^-$, Ca^{2+}, SO_4^{2-}, Mg^{2+}, respectively. Vertical bar indicate ± SE of the mean (n = 3).

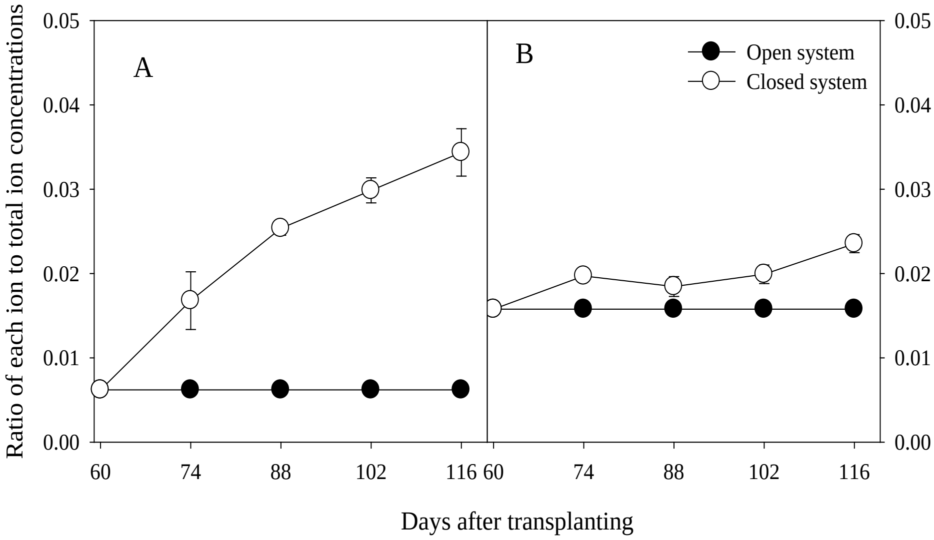

Fig. 3.6. Change in ratio of Cl^- (A) or Na^+ (B) concentration to the total ion concentrations ($meq \cdot L^{-1}$) in recycled nutrient solution of closed soilless culture systems. In the open system, ion concentration was the same as the initial value. Vertical bar indicate ± SE of the mean (n = 3).

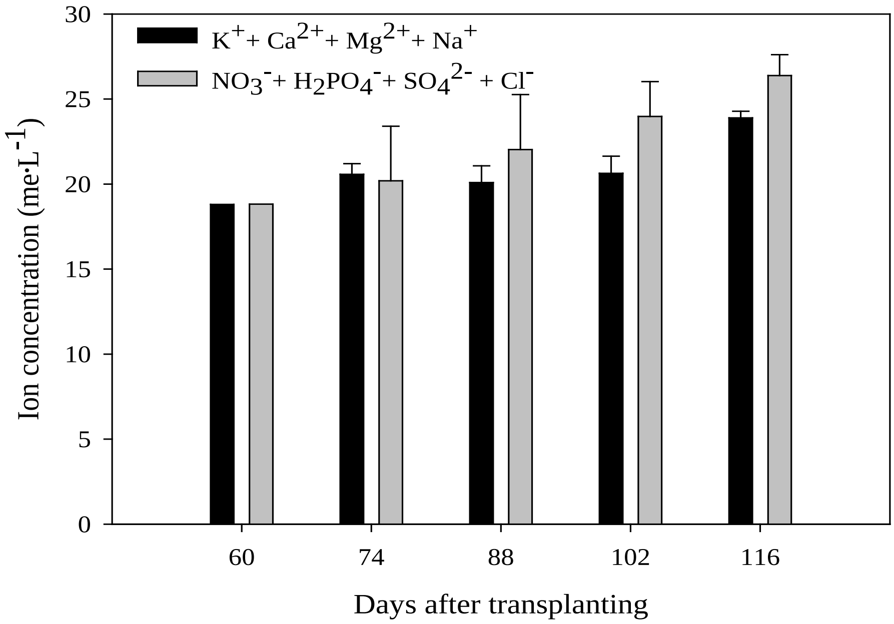

Fig. 3.7. Change in sum of (■) cation ($K^+ + Ca^{2+} + Mg^{2+} + Na^+$) and (□) anion ($NO_3^- + H_2PO_4^- + SO_4^{2-} + Cl^-$) concentrations in recycled nutrient solution after adjusting EC by adding water and fresh nutrient solution. Vertical bar indicate ± SE of the mean (n = 3).

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4. CHAPTER II. Nutrients and Water Uptake of Paprika (*Capsicum annuum* L.) as Affected by Renewal Period of Recycled Nutrient Solution in Closed Soilless Culture System

ABSTRACT

One of the problems in closed soilless culture is to find the solution reducing ion imbalance in recycled nutrient solution when drained nutrient solution is re-used. To reduce ion imbalance in recycled nutrient solution, determination of renewal period is required since individual ion uptake by plants changes throughout the growing period. The aims of this study are to find out the proper renewal period reducing ion imbalance in the recycled nutrient solution and to investigate the nutrient and water uptakes of paprika plants and to measure fruit yield and mineral contents in plant as influenced by renewal period of recycled nutrient solution in closed soilless culture. Paprika plants were grown in closed rockwool culture systems under 4-, 8-, and 12-week renewal periods comparing with the open system (control). The electrical conductivity (EC), pH, and volume of the nutrient solutions were measured every three days. The nutrient solution in the reservoir tank was constantly maintained at EC 2.5 dS·m^{-1} and pH 5.5-6.5. As results, closed system using different renewal period was 50 to 51% higher in water use efficiency (WUE) and 61 to 67% higher in fertilizer use efficiency (FUE), respectively, compared to control (open system). Changes of cation and anion ratio in the recycled nutrient solution could be smaller by discharging every 4 weeks uptake of

K^+ was significantly influenced. The lowest fruit yield was significantly observed in a closed system using 12-week renewal period. Regarding the ion balance in the recycled nutrient solution, renewing every 4 weeks was more effective within this study. However, considering the yield along with water and nutrient uptake, it can be extended to 8 weeks.

Key words: drained nutrient solution, ion imbalance, mineral content, rockwool culture.

4.1. Introduction

Application of balanced nutrient solutions to plants is necessary in closed soilless culture. This process is more attractive than open system in regards to saving nutrients and water as well as reducing surface and ground water pollution through greenhouse effluents. Continuous reuse of the entire quantity of drainage solution may, however, lead to gradual nutrient imbalances of recycled nutrient solution (Ahn and Son, 2011; Lopez et al., 1996; Zekki et al., 1996). Moreover the accumulation of unwanted ions increases the salinity in nutrient solution and root medium (Baas et al., 1995), resulting in negative effects on the nutrient and water uptake of plants. Differences in water and nutrient uptake as well as changes in nutrient concentration during plant growth period can cause the changes in EC and composition of recycled nutrient solution again (Pardossi et al., 2005), and thereby leads to the nutrient imbalance with inadequate nutrient ratios (Savvas and Gizas, 2002).

In closed soilless culture, it is important to monitor whether accumulation or depletion of particular ions occur. Most growers frequently drain nutrients and water to prevent nutrient imbalance since the recycled nutrient solution is managed by controlling the level of total salt concentration with EC rather than the concentration of individual nutrient. Accumulation of unwanted ions like Na^+ and Cl^- which occurs in the closed system may require a partial discharge of the recycled nutrient solution (Carmassi et al., 2007). Therefore, to improve water and nutrient use efficiencies, appropriate strategies for managing the recycled nutrient solution is essential (Raviv and Blom, 2001).

Previous studies indicated that the accumulated salts in recycled nutrient solution should be frequently flushed out for maintaining better root-zone environments (Incrocci et al., 2006; Savvas et al., 2005). In particular, to avoid mineral deficiency, toxicity or nutrient imbalance, periodical renewal of the recycled nutrient solution is required. The aims of this study were to find out the proper renewal period reducing ion imbalance in the recycled nutrient solution and to investigate the nutrient and water uptakes of paprika plants and to measure the fruit yield and nutrient contents in plant as affected by renewal period of the recycled nutrient solution in closed soilless culture while compare to open soilless culture system.

4.2. Materials and Methods

4.2.1. Cultivation and environmental conditions

This experiment was carried out in a venlo-type glasshouse at the experimental farm of Seoul National University (Suwon, Korea, Latitude 37.3°N, Longitude 127.0°E) from October 1, to December 25, 2011. Average inside radiation and temperature during the experimental period were shown in Fig. 4.1. The average inside radiation ranged from 1.46 to 4.29 $MJ \cdot m^{-2} \cdot d^{-1}$ and the average inside temperature was controlled at 18.5 to 24.1°C during the experimental period. Thirty days after planting on the rockwool cube (10 cm × 10 cm × 6.5 cm), paprika (*Capsicum annuum* L. 'Fiesta') plants were transplanted to rockwool slabs (90 cm × 15 cm × 7 cm) with spacing of 30 cm plant to plant at a density 3 plants/m^2. The experiment was started 20 days after transplanting (DAT) on the rockwool slabs (65 days after planting) when average plant height and number of leaves were 80 cm and 20, respectively with starting fruit initiation. Total twelve slabs were installed for paprika plants and placed in each gutter (100 cm × 20 cm × 10 cm). Three slabs each of which has three plants were used for each open or closed system. The plants were pruned to form two main stems, which were vertically trained to a “V” canopy system (Jovicich et al., 2004a) and the additional plant management of pruning and training were carried out every week.

4.2.2. Management of nutrient solutions

Compositions of the nutrient solution used in this experiment were 14.17 NO_3^-, 1.14 $H_2PO_4^-$, 5.92 K^+ , 8.85 Ca^{2+} , 3.17 Mg^{2+}, and 3.2 SO_4^{2-} (in $meq{\cdot}L^{-1}$) as macro elements, and 1.05 Fe^{2+}, 0.64 Zn^{2+}, 0.09 Cu^{2+}, 0.57 Mn^{2+}, and 0.05 Mo^{6+} (in ppm) as micro elements based on the PBG nutrient solution of Netherlands. The fresh nutrient solution was prepared in a reservoir tank (52 cm × 26 cm × 26 cm) with the same amounts from two stock solutions A and B (100% concentrated) and adjusted to the desired EC 2.5 $dS{\cdot}m^{-1}$ and pH 5.5 to 6.5. In the recycled system, fresh nutrient solution was added to the tank which was placed under each gutter. At every irrigation event, the drainage was returned to the tank. EC and pH levels in the tank were monitored every three days by using an EC meter (D-54, Model-352734-1, Horiba, Japan). To maintain the initial EC of 2.5 $dS{\cdot}m^{-1}$, fresh water (EC 0.17 $dS{\cdot}m^{-1}$ and pH 7.11) containing the nutrient composition in ($meq{\cdot}L^{-1}$) 0.21 Na^+, 0.29 Cl^- , 0.04 K^+, 0.71 Ca^{2+}, 0.21 Mg^{2+}, 0.19 SO_4^{2-}, 0.39 NO_3^-, and 0.04 PO_4^{3-} was added to the tank. Then, the fresh nutrient solution was added to reach the original nutrient solution volume (20 L) in the tank. To adjust the pH, 1N of nitric acid was used. Total nine tanks were used for nutrient recycling.

4.2.3. Nutrient supply

Fertilizer was applied through drip irrigation, with one emitter per plant having a capacity of $3L \cdot h^{-1}$. A pyranometer (SQ-110-L10, Apogee, USA) was placed inside the greenhouse at a height of 2 m from the ground and was connected to a data-logger (CR-1000, Campbell Scientific, USA) to measure total solar radiation ($W \cdot m^{-2}$) at every 10 s. Irrigation began whenever cumulative radiation measured inside the greenhouse reached the preset value of solar radiation integrals (SRI). The SRI set point was not kept constant throughout the crop season because it requires adjustments considering plant growth, light, temperature, EC of the drainage (Schelford et al., 2004). In this study, the SRI set point was adjusted by the measurements of EC of the substrate and the drainage within the range of 30 to 50% of the volume irrigated. The SRI set ranged 50 to70 $J \cdot cm^{-2}$ and the irrigation lasted 3 to 5 minutes per event. The irrigation frequency was checked every day online and all the plants were supplied between 5 to 8 times per day.

4.2.4. Measurements of growth and fruit yield

Plant height and leaf area were measured every two weeks. Leave area was calculated by using leaf length and width (Tai et al., 2009). Forty days after treatment (62 DAT), first harvest of fruits was carried out. At each harvest, fruit number and fruit fresh weight were measured from three plants per treatment with three replications. Harvesting started on November 8, and finished on December 25, 2011. The fruits were dried in a thermo-ventilated oven at 70°C until reaching a constant dry weight.

4.2.5. Estimation of water and nutrient uptakes

The consumption of water and nutrient solution, the EC and pH, and volume of nutrient solution in the reservoir tanks were measured every three days in the morning. The water uptake for the open system was estimated with the difference between the amounts of irrigation and drainage. The amount of water uptake per culture area ($L \cdot m^{-2}$) for the closed system was estimated with the difference between initial and final volumes in each tank every three days. The loss of nutrient solution by evaporation from the tank was prevented and the evaporation for the rockwool cube was not considered. Every two weeks, 50 mL of nutrient solution from the tank was collected and analyzed. NO_3^-, $H_2PO_4^-$, Cl^-, and SO_4^{2-} were measured with a portable spectrophotometer (photoLab, 6100 (VIS), Germany) and K^+, Ca^{2+}, Mg^{2+}, and Na^+ were measured with an inductively coupled plasma optical emission spectrometer (ICP-730ES, Varian Australia Pty Ltd., Australia). Nutrient uptakes by the plants were calculated every two weeks with the following equations (Pardossi et al., 2005).

Ratio of cation or anion = cation or anion / sum of total cations or anions……. (1)

Nutrient uptake ($meq \cdot d^{-1}$/plant) =($C_0V_R + C_WV_W + C_SV_S – C_1V_{R1}$) /14d / 3 plants(2)

Water uptake ($L \cdot d^{-1}$/plant) = (water uptake ($L \cdot m^{-2}$)/ 3 d) / no. of plants……….. (3)

where, C_0 and C_1 are ion concentrations ($meq \cdot L^{-1}$) in recycled nutrient solution at the beginning, at the end of every two weeks, C_W and C_S are ion concentrations ($meq \cdot L^{-1}$) in irrigation water and in added fresh nutrient solution, respectively. V_R and V_{R1} are volumes of recycled nutrient solution at the beginning, at the end of every two weeks, V_W, and V_S are volumes of irrigation water and added fresh nutrient solution used for the replenishment, respectively.

WUE was determined in terms of gram shoot biomass (including fruits, leaves and stems) fresh weight per liter water transpired and FUE was determined in terms of gram shoot biomass fresh weight per gram of nutrients absorbed, respectively.

4.2.6. Analysis of nutrient contents in leaves and fruit

At 56 days after renewal treatment (70 DAT), recently fully-matured leaves at the 4^{th} and 5^{th} nodes from the top of the stem were collected. Each sample consisted of 9 to 10 leaves (including petiole) from each treatment. Leaves were washed in tap water and dried for 48 h at 70°C. For analysis of the nutrient content in fruit, matured fruits (three fruits per treatment) at the second harvest were sampled and dried at 70°C until constant weight. The dried leave and fruit sampled were grinded. 0.5 g of each grinded sample was digested by using concentrated nitric acid. 1 ml of concentrated perchloric acid was added to maintain a set solution temperature of 180°C and to accelerate the digestion process by placing on hotplate at 90°C for about one hour until clear color solution was obtained. After the digestion, cool the tube, fill up 25 ml of deionized, and the total nutrient contents of K, Ca, Mg, P, and S from fruits and leaves were determined by the ICP-730ES. Total-N was measured using the Kjeldahl (Kjeltec

8400, Foss, Sweden).

4.2.7. Experimental management and statistical analysis

Experiments were conducted under the three different renewal periods of 4, 8, and 12weeks (4, 8, 12 WR, respectively) as treatments comparing to the open system (control). The schematic diagrams of experimental systems were shown in Fig. 4.2. Treatments were arranged in randomized complete block design. There were three plants per slab and three replications (slabs) per treatment. Total twelve slabs were used for the treatments and control. Data were subjected to analysis of variance by using one-way ANOVA; the SAS 9.2 (SAS Institute, Cary, NC, USA) and Sigma-Plot 10 (SPSS, Inc., Chicago, IL, USA). Treatment means were analyzed and compared using Duncan's multiple range tests. Values of $P < 0.05$ were considered statistically significant.

4.3. Results and Discussion

4.3.1. Changes in EC and pH of recycled nutrient solution

The pH was maintained at 5.5 to 6.5 by adding 1 N nitric acid, while the EC increase from 2.5 to 3.3 $dS{\cdot}m^{-1}$ from 76 DAT (at the time of the 2nd fruit harvest to final harvest) (Fig. 4.3). It might be related to the accumulation or depletion of a certain ions in the recycled nutrient solution which probably due to the reduced nutrient uptake at the reproductive stage since nutrient absorption have been related to growth variables (Silberbush and Lieth, 2004). Marti and Mills (1991b) stated that a decline in Ca^{2+}

uptake occurs when fruits approach the mature green stage. The pH became higher at the later stage and it might be due to the reduced uptake or accumulation of cations (except K^+) than those of anions during reproductive stage.

4.3.2. Uptake of water and nutrients by plants

An increase in accumulated uptake of water and nutrients was clearly observed, while a gradual decrease in nutrient uptake was observed during reproductive stage although there were no significant differences at $p<0.05$ in all the treatments (Fig. 4.4). Beginning from the 1st fruit harvest (60 DAT), the plant height slightly increased and the leaf area expansion became relatively lower (76 DAT) (Fig. 4.5). There was no difference in plant growth in all treatments. To maintain EC, pH, and the volume of the recycled nutrient solution in all renewal period, no additional fresh nutrient solution was required 8 weeks after treatment (76 DAT). That is because the nutrient uptake was relatively lower than the nutrient supply, resulting in nutrient accumulation in the recycled nutrient solution. Voogt and Sonneveld (1997) stated that lower nutrient uptake was observed during heavy fruit bearing of sweet pepper. The reduction of nutrient uptake at fruit maturity is possibly due to a competition for energy between nutrient uptake and fruit growth (Marti and Mills, 1991a).

Although there was no significant difference in plant growth (Fig. 4.5), the accumulated uptakes of NO_3^-, $H_2PO_4^-$, K^+, Ca^{2+}, Mg^{2+}, and SO_4^{2-} significantly increased in the control at $p<0.05$ after 76 DAT since the fresh nutrient solution was always supplied every irrigation time (Fig. 4.6). There was no significant difference in accumulated nutrient uptake of each nutrient by using different renewal period; however, uptake of K^+ significantly increased in 4 WR than other renewals of 8 WR and 12 WR after 76 DAT. N and K were the most extracted macronutrients followed by Ca, Mg, S, and P in decreasing order (Marcussi et al., 2004).

4.3.3. Changes in cation and anion ratios in recycled nutrient solution

The difference in cation ratio between initial and recycled nutrient solutions started to appear 4 weeks after treatment (48 DAT). The longer the renewal period was, the more the deviation from initial values was observed (Fig. 4.7). K^+ decreased, however Ca^{2+}, Mg^{2+}, and Na^+ increased with time as the renewal period became longer. K^+ depletion in the recycled nutrient solution was reduced by renewing the solution every four weeks, resulting in increased K^+ uptake in 4 WR (Fig. 4.6).

NO_3^- and $H_2PO_4^-$ decreased and SO_4^{2-} and Cl^- increased as the renewal period became longer (Fig. 4.8). Although 1N nitric acid was used to adjust pH of the recycled nutrient solution, there was no increase in NO_3^- concentration from the initial. The longer the renewal period was, the more the accumulation of Ca^{2+}, Mg^{2+}, Na^+, SO_4^{2-}, and Cl^- and the depletion of NO_3^-, K^+, and $H_2PO_4^-$ were observed. However gradual increases in accumulated uptakes of NO_3^-, K^+, $H_2PO_4^-$, Ca^{2+}, Mg^{2+}, and SO_4^{2-} were observed with decreasing order. Although the concentrations of Ca^{2+}, Mg^{2+}, and SO_4^{2-} increased in the recycled nutrient solution, the uptake of those ions were lower than NO_3^-, K^+, and $H_2PO_4^-$. It might be related to the results that the growth of the plants slightly decreased at the reproductive stage (Fig. 4.5) and the uptake of Ca^{2+} and Mg^{2+}

became lower during fruit developmental stage. However these results were also observed in rose plants at different nutrient solution temperature, indicating that the nutrient concentration was not the only factor affecting nutrient uptake (Calatayud et al. (2008).

Giuffrida and Leonardi (2012) stated that the renewal of nutrient solution with time will be reduced by shortage of nutrients below optimum level. It was evident in our study that 4 WR reduced the change in ion ratio compared to those in 8 WR and 12 WR in the nutrient solutions. In fact, adjusting the irrigated nutrient solution according to crop demand and environmental conditions will help to prevent periodic nutrient disorders during crop cycle (Hamlin and Mills, 2001b) and consequently lead to the increase in fruit yield.

4.3.4. Yield, water and fertilizer use efficiencies

Water use efficiencies (WUE) and fertilizer use efficiencies (FUE) and yields for the open and closed systems under different renewal periods are shown in (Table 4.1). WUE and FUE were significantly higher in the closed system than that of open system. Among 4, 8, and 12 WR, no significant differences in WUE and FUE, however, 50 to 51% WUE and 61 to 67% FUE was higher in closed system (4, 8, and 12 WR) than open system. The yield was significantly lower in 12 WR that any other treatments including the opens system. It might be due to the accumulation of SO_4^{2-}, Na^+, and Cl^- in the recycled nutrient solution in 12 WR (Figs. 4.7 and 4.8).

Accumulation of SO_4^{2-} in the recycled nutrient solution is a common phenomenon in closed soilless culture, which has been implicated to restrict the yield of tomatoes grown in nutrient film technique (NFT) (Lopez et al., 1996; Zekki et al., 1996). According to some reports with tomatoes and roses (Raviv and Blom, 2001; Zekki et al., 1996), growth and yield did not seem to be inferior in the closed system during the first 8 week compared to the open system. It was in agreement with in this study that there was no nutritional problem and no significant yield reduction was observed until 8 weeks in the plants while maintaining EC and pH at adequate levels.

4.3.5. Mineral content in leaves and fruit

Total-N and K were the highest in the leaves, followed by Ca, Mg, S, and P (Table 4.2), while Ca and Mg were the lowest in the fruits, followed by S, P, N, and K (Table 4.3). There were no significant differences in mineral contents of the leaves and fruit in all treatments. Although plant analysis may not provide a precise nutritional diagnosis, there was no deficiency or toxicity in all different renewal periods under controlled EC and pH in the recycled nutrient solution compared to the open system. Hence it reveals that with possible pH adjustments in the recycled nutrient solution that improves in uptake rate and subsequent growth and yield increase (Weerakkody et al., 2007). By a proper renewal of the recycled nutrient solution under the control of EC and pH, there could be no nutritional problem.

To optimize ion balance in recycled nutrient solution for paprika plants grown in rockwool closed soilless culture, it is recommended to adjust (or renew) the recycled nutrient solutions every 4 weeks. Even though the adequate renewal period of the recycled nutrient solution was 4 weeks within this study, by considering uptakes of water and nutrients and yield of paprika, it can be extended to 8 weeks with an adjustment of EC and pH every three days. Nutrient concentrations in the root media could be altered with time depending on the concentration of supplied nutrient solution. This solution, in turn, is able to influence nutrient uptake by plants in recycled soilless culture. For practical purpose, in the future, further research is warranted investigating the effect of nutritional status of root environment on yield and nutrient uptake of plants in closed soilless culture with the renewal period extended beyond 8 weeks.

Table 4.1. Fruit yield, water use efficiency (WUE) and fertilizer use efficiency (FUE) of paprika in closed rockwool culture during the growing period.

Treatment[z]	WUE ($g \cdot L^{-1}$)	FUE ($g \cdot g^{-1}$)	Total fruit yield ($g \cdot m^{-2}$)
Control	16.6 b[y]	19.2 b	1613.35 a
4 WR	32.9 a	49.7 a	1682.20 a
8 WR	33.4 a	52.5 a	1672.69 a
12 WR	34.1 a	57.4 a	1407.15 b

[z]Control, 4, 8, and 12 WR represent non-recycled, 4-, 8-, and 12-week renewals of recycled nutrient solutions, respectively.

[y]Means with different letter shows significant difference by Duncan's multiple range test at $p < 0.05$.

Table 4.2. Leaf mineral content of paprika grown in closed rockwool culture as affected by renewal period.

Treatment[z]	Leaf mineral contents (%)					
	T-N	P	K	Ca	Mg	S
Control	4.25	0.32	4.79	1.85	0.65	0.51
4WR	4.50	0.36	5.22	2.04	0.71	0.59
8WR	4.17	0.40	4.97	1.76	0.61	0.57
12WR	4.49	0.32	4.83	2.03	0.66	0.51
Significance	n.s.[y]	n.s.	n.s.	n.s.	n.s.	n.s.

[z]Control, 4, 8, and 12 WR represent non-recycled, 4-, 8-, and 12-week renewals of recycled nutrient solutions, respectively.

[y]ns means non-significant difference at $p < 0.05$ by Duncan's multiple range test.

Table 4.3. Mineral contents of paprika fruit grown in closed rockwool culture as affected by renewal period.

Treatment[z]	Fruit mineral contents (%)					
	T-N	P	K	Ca	Mg	S
Control	2.77	0.46	3.02	0.06	0.13	0.22
4WR	2.53	0.44	3.03	0.06	0.12	0.21
8WR	2.58	0.46	3.08	0.06	0.13	0.21
12WR	2.64	0.47	3.12	0.06	0.12	0.21
Significance	n.s.[y]	n.s.	n.s.	n.s.	n.s.	n.s.

[z]Control, 4, 8, and 12 WR present non-recycled, 4-, 8-, and 12-week renewal of recycled nutrient solutions, respectively.

[y]ns means non-significant difference by Duncan's multiple range test at $p < 0.05$.

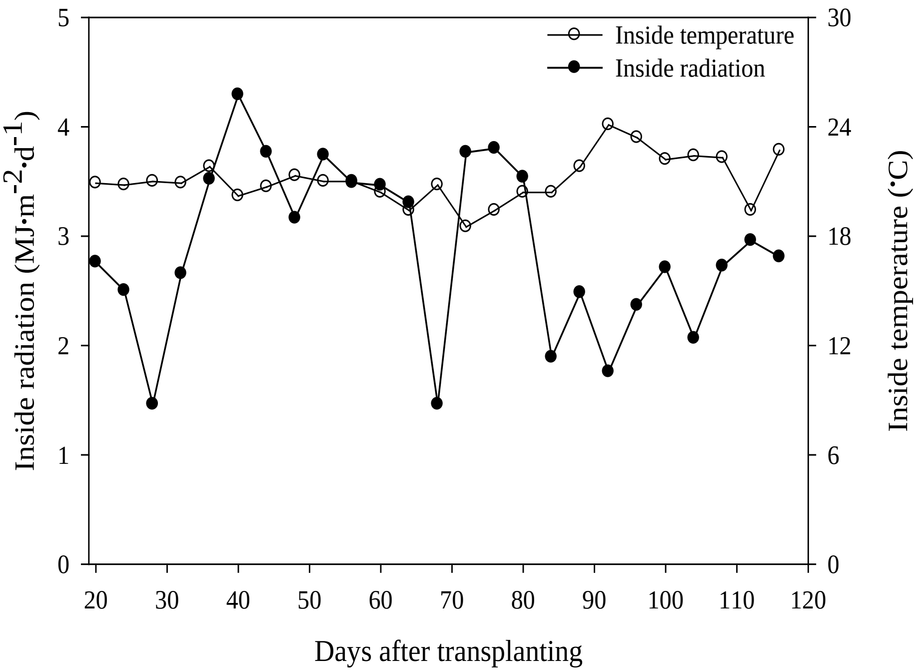

Fig. 4.1. Average inside greenhouse radiation and temperature during experimental period from October to December, 2011.

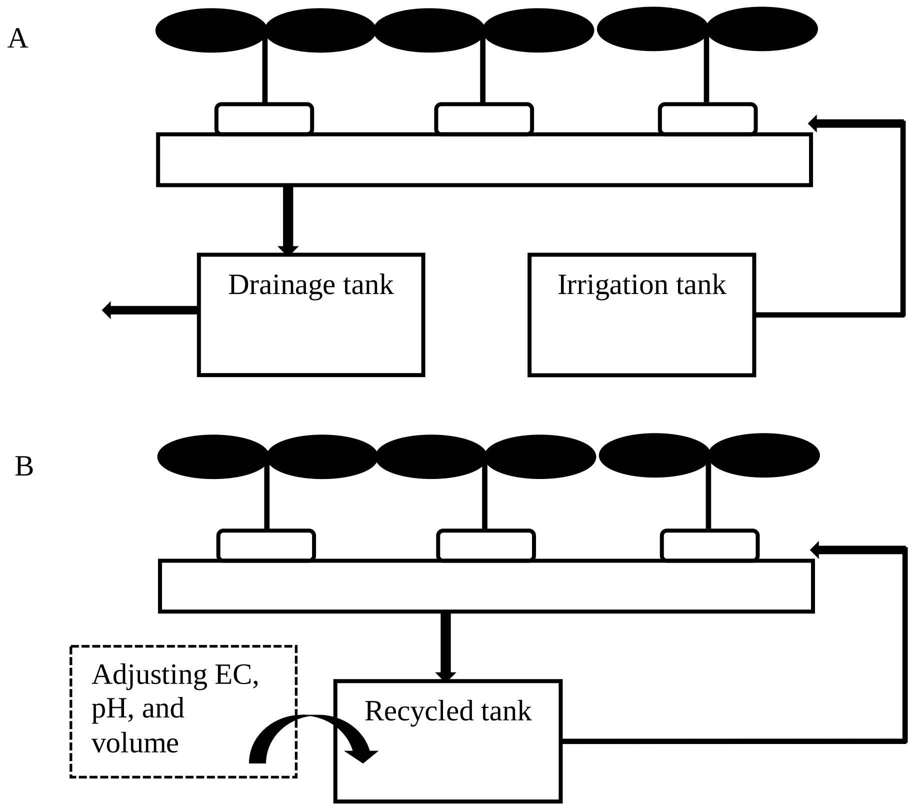

Fig. 4.2. Schematic diagrams of experimental systems. A and B indicate open (without recycled nutrient solution) and closed (with recycled nutrient solution) systems with 4-, 8-, and 12-week renewal periods under the control of EC, pH, and volume of the recycled tank every three days.

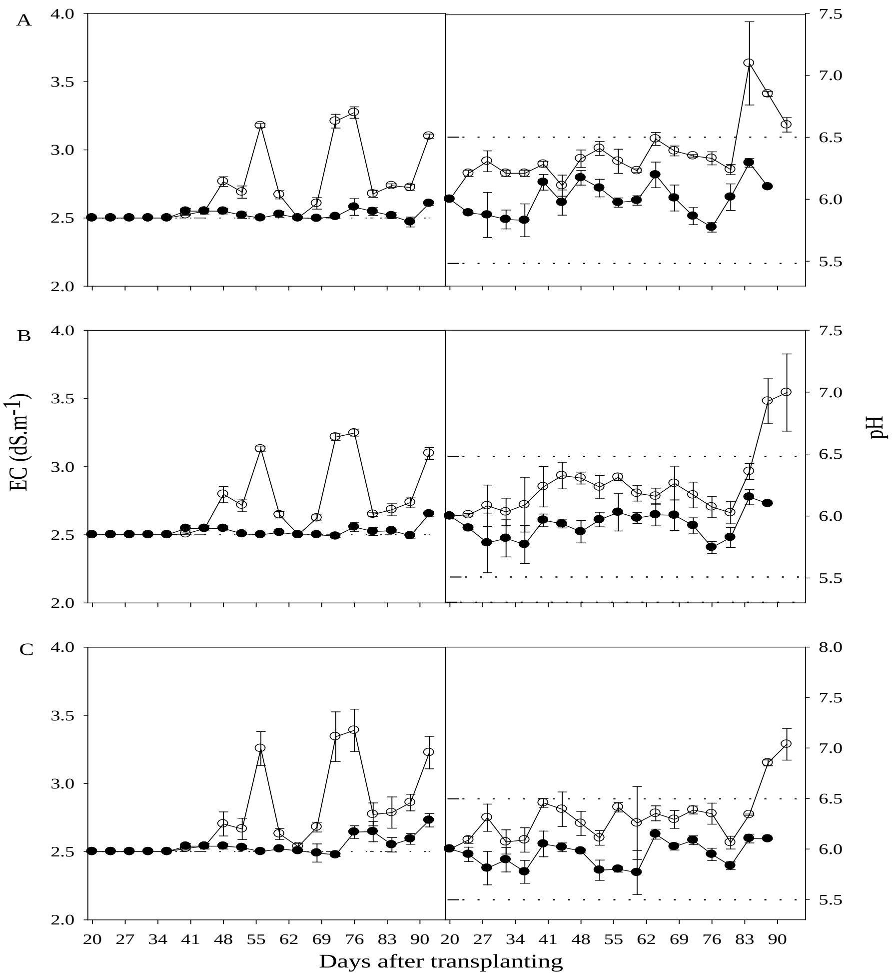

Fig. 4.3. Change in EC and pH of the recycled nutrient solution throughout the treatment period. Open and closed circles mean before and after adjusting reused nutrient solution, respectively. Line represents the set value for EC (2.5 dS·m^{-1}) and pH range of (5.5- 6.5) in the open system (control). A, B, and C indicate 4-, 8-, and 12-week renewals of recycled nutrient solution, respectively. Vertical bars indicate standard error of the means (n = 3).

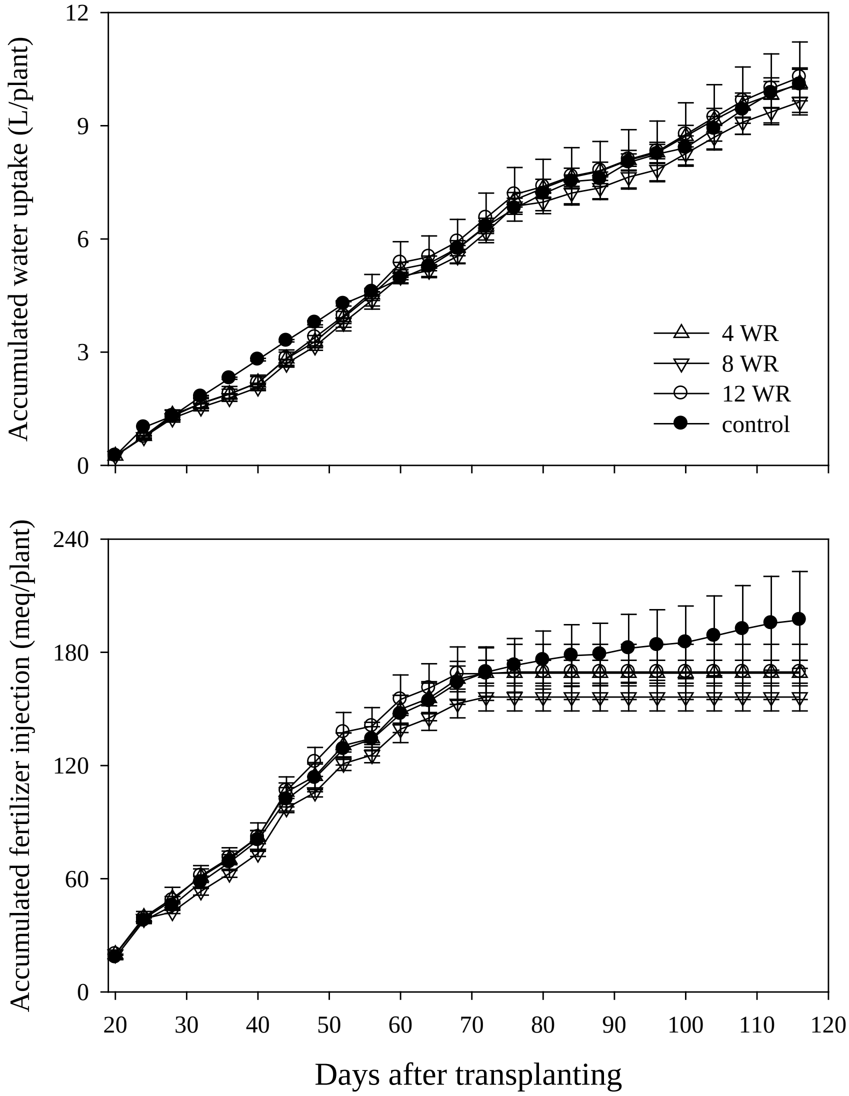

Fig. 4.4. Accumulated water and nutrient uptake throughout the treatment period under the control of EC, pH, and recycled nutrient solution volume. WR is the renewal period (weeks) under recycling conditions while control means the open system. Vertical bars indicate standard error of the means (n = 3).

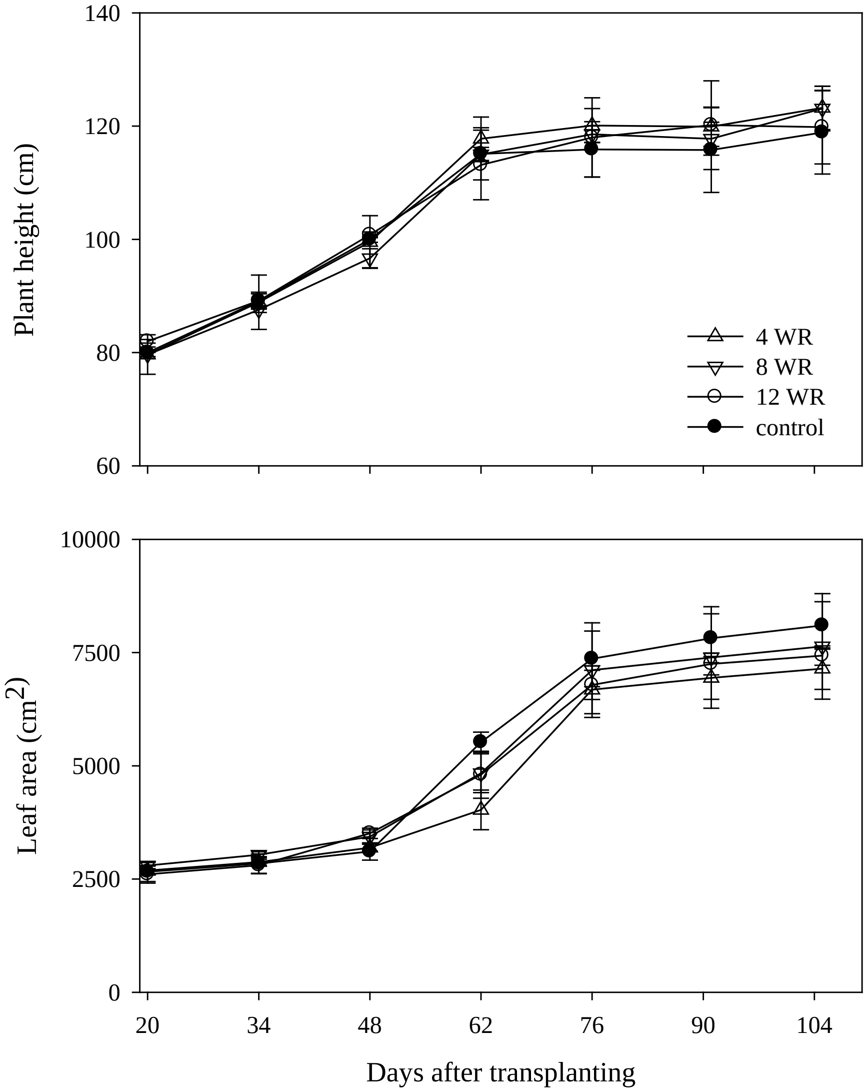

Fig. 4.5. Plant growth throughout the experimental period. WR is the renewal period (week) under recycling conditions while control means the open system. Vertical bars indicate standard error of the means (n = 3).

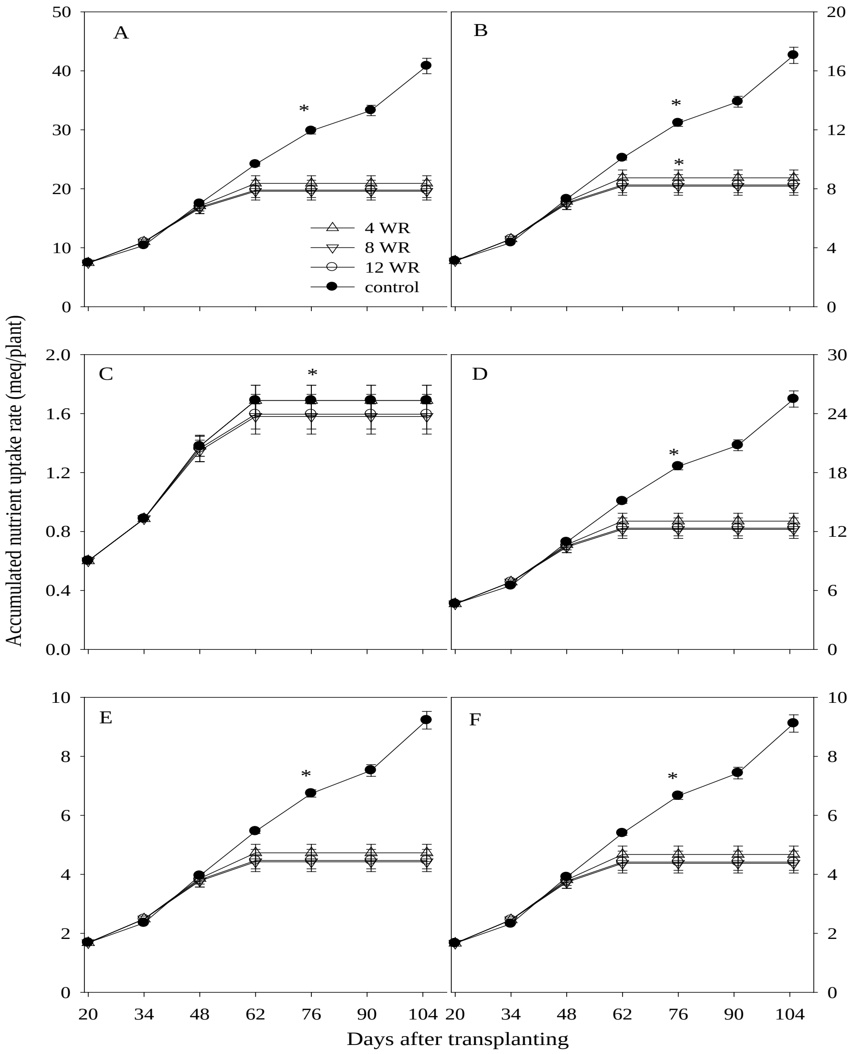

Fig. 4.6. Accumulated individual nutrient uptake rate as affected by different renewal period on recycled nutrient solution. WR is the renewal period (week) under recycling conditions while control means the open system. A, B, C, D, E, and F indicate NO_3^-, K^+, $H_2PO_4^-$, Ca^{2+}, SO_4^{2-}, Mg^{2+}, respectively. Vertical bars indicate standard error of the means (n = 3). *Significant at $p < 0.05$.

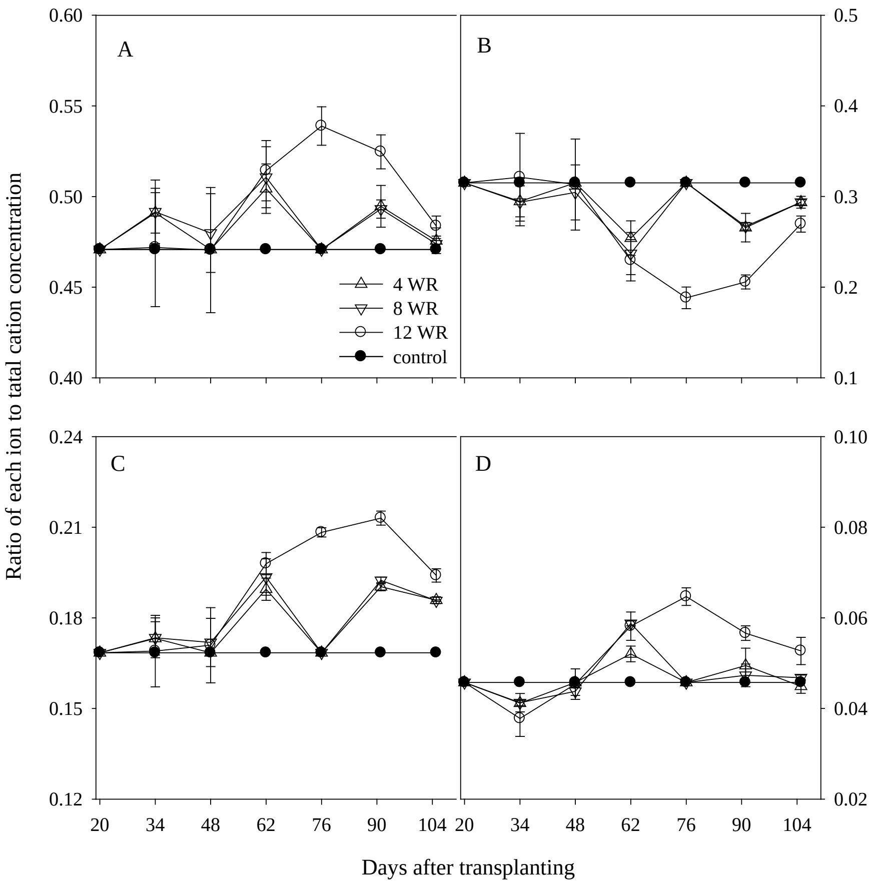

Fig. 4.7. Changes in cation ratios in the recycled nutrient solution under recycling conditions. WR is the renewal period (week) after adjusting EC and pH of the re-used nutrient solution while control means open system. A, B, C, and D indicate Ca^{2+}, K^{+}, Mg^{2+}, and Na^{+}, respectively. Vertical bars indicate standard error of the means (n = 3).

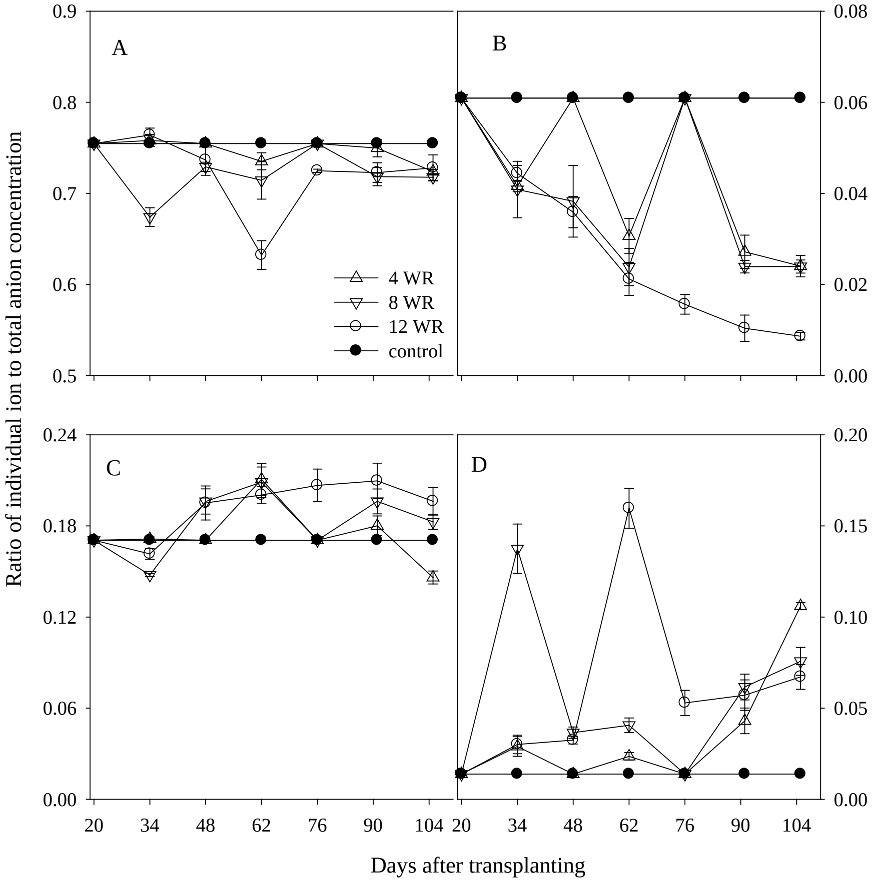

Fig. 4.8. Changes in anion ratios in the recycled nutrient solution under recycling conditions. WR is the renewal period (weeks) after adjusting EC and pH of the re-used nutrient solution while control means the open system. A, B, C, and D indicate NO_3^-, $H_2PO_4^-$, SO_4^{2-}, and Cl^-, respectively. Vertical bars indicate standard error of the means (n = 3).

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5. CHAPTER III. Nutrient Balance and Nutrient Uptake at Different Renewal Patterns of Recycled Nutrient Solution in Closed Soilless Culture System

ABSTRACT

To keep the ion balance in both nutrient solution and root medium is important particularly in closed soilless culture system. Considering that water and nutrient uptake by plants changes with growth stage, adequate adjustment of recycled nutrient solution is necessary. The aim of this study were to investigate the ion balance in both recycled nutrient solution and root medium at different renewal patterns with growth stage of paprika, and to analyze its subsequent effect on water and nutrient uptake. For total 12 weeks, the plants were grown at three different renewal intervals of 4-4-4, 6-4-2, and 8-2-2 weeks in closed rockwool culture systems. The electrical conductivity (EC), pH, and nutrient solution volume were measured every three days. The nutrient solution in the reservoir tank was constantly maintained at EC 2.5 dS m^{-1} and pH 5.5-6.5. The depletion or accumulation of ions in the recycled nutrient solution was lower at 4-4-4 weeks, and followed by 6-4-2 and 8-2-2 weeks. Particularly the accumulation of Ca^{2+} and Mg^{2+} were reduced with the same trend. Less Ca^{2+} and Mg^{2+} were demanded in the fruits than in the leaves during fruit growth. However no significant differences were observed in nutrient uptake, yield, and growth of the plants among all the renewal patterns. The change in ion balance of recycled nutrient solution was smaller at 4-4-4 weeks than others. For precise management of nutrient solution, the renewal patterns considering nutrient requirements with growing stage and environmental conditions are required.

***Key words*:** electrical conductivity, ion ratio, mineral contents, root medium, yield.

5.1. Introduction

Nutrient uptake by plants is closely affected by the ion balance in both nutrient solution and root medium in soilless culture. For maintaining the ion balance reliably in closed soilless culture, adequate renewal of recycled nutrient solution is required. According to Ko et al. (2013b), the longer the renewal period was, the greater the accumulation of Ca^{2+}, Mg^{2+}, Na^{+}, SO_4^{2-}, and Cl^{-} and the depletion of NO_3^{-}, K^{+}, and $H_2PO_4^{-}$ occurred in a closed soilless culture of paprika. For preventing periodic nutrient disorders by supplying right amounts of nutrients to plants (Hamlin and Mills, 2001a), the demand and supply of nutrients at each growth stage should be synchronized (Ahn and Son, 2011; Klaring et al., 1997; Ko et al., 2013a; Savvas and Manos, 1999). For instance, high concentrations of nutrients in root medium did not always result in high nutrient uptake by plants due to nutrient imbalance (Medina et al., 2009). Concentrations of wanted and unwanted nutrients may largely influence the uptake kinetics of nutrients and water (Le Bot et al., 1998; Parida and Das, 2005). As the depletion or accumulation of nutrient ions in recycled nutrient solution is a common phenomenon, frequent replenishments enables to keep the nutrient balance in root medium (Incrocci et al., 2006; Savvas et al., 2005).

Baas et al. (1995) stated that the accumulation of unwanted ions increases the salinity in nutrient solution and root medium, resulting in negative effects on the nutrient and water uptake of plants. Differences in water and nutrient uptake as well as changes in nutrient concentration during plant growth period can cause the changes in EC and composition of recycled nutrient solution again (Pardossi et al., 2005). Thereby the nutrient imbalance with inadequate nutrient ratios occurs (Savvas and Gizas, 2002). According to Marcussi et al. (2004), absorption of PO_4^{3-}, Mg^{2+} and SO_4^{2-} by paprika increased only after 80 days after transplanting (DAT), while absorption of NO_3^-, K^+ and Ca^{2+} increased after 60 DAT.

Although previous research reported that the feasible renewal time for the recycled nutrient solution could be extended until 8 weeks considering the yield (Ko et al., 2013b), more suitable renewal time and pattern considering growing stage is desirable to avoid the accumulation or depletion of nutrients in the recycled nutrient solution as well as the root medium. The aim of this study was to investigate the ion balance in both recycled nutrient solution and root medium at different renewal patterns with growth stage of paprika, and its subsequent effect on water and nutrient uptake.

5.2. Materials and Methods

5.2.1. Experimental conditions

This experiment was conducted in a venlo-type greenhouse at the experimental farm of Seoul National University (Suwon, Korea, Latitude 37.3°N, Longitude 127.0°E). Paprika (*Capsicum annuum* L. cv. Fiesta) seedlings were planted on the rockwool cube (10 cm × 10 cm × 6.5 cm) at the beginning of April, 2012. One month after planting on rockwool cubes, plants were transplanted in rockwool slabs (90 cm × 15 cm × 7 cm) at a density of 3 plants/m^2. The experiment started 30 DAT when average plant height and number of leaves were 90 cm and 40, respectively, with starting fruit initiation. Average radiation and temperature in the greenhouse during the experimental period was shown in Fig. 5.1. The average inside radiation ranged from 2.6 to 5.5 $MJ \cdot m^{-2} \cdot d^{-1}$ and the average inside temperature was controlled at 24.6 to 31.6°C. All the plants were supplied with the nutrient solution of EC 2.5 $dS \cdot m^{-1}$ and pH 5.5 to 6.5. Nine slabs each of which have three plants and placed in each gutter (100 cm × 20 cm × 10 cm). Additional plant management of pruning and training was carried out every week.

5.2.2. Management of nutrient solutions

Compositions of the nutrient solution was based on the PBC nutrient solution of Netherlands: 14.17 NO_3^-, 1.14 $H_2PO_4^-$, 5.92 K^+, 8.85 Ca^{2+}, 3.17 Mg^{2+}, and 3.2 SO_4^{2-} (in $meq \cdot L^{-1}$) as macro elements; and 1.05 Fe^{2+}, 0.64 Zn^{2+}, 0.09 Cu^{2+}, 0.57 Mn^{2+}, and 0.05 Mo^{6+} (in ppm) as micro elements. After irrigation event, the drainage was returned to the reservoir tank (52 cm × 26 cm × 26 cm). EC and pH levels in the reservoir tank were monitored every three days by using a conductivity meter (WTW, Multi 3420 SET C, TC 925, S 940, Germany). EC and water content of the root medium were measured by using a TDR sensor (Grodan, WCM-control, Model- Sensor 300 Baud, Serial nr.-2007481320s3). To maintain the set EC of 2.5 $dS\ m^{-1}$, fresh water (EC 0.17 $dS\ m^{-1}$ and pH 7.11) containing 0.21 Na^+, 0.29 Cl^- , 0.04 K^+, 0.71 Ca^{2+}, 0.21 Mg^{2+}, 0.19 SO_4^{2-}, 0.39 NO_3^-, and 0.04 PO_4^{3-} (in $meq \cdot L^{-1}$) was added. Then fresh nutrient solution was added to reach the original nutrient solution volume (20 L) in the tank. Total nine tanks were used for nutrient recycling. To adjust the pH, 1N nitric acid was used.

5.2.3. Nutrient solution supply based on solar radiation

Nutrient solution was supplied by drip irrigation with one emitter (a capacity of $3L \cdot h^{-1}$) per plant based on solar radiation integral (SRI). Solar radiation ($W \cdot m^{-2}$) inside the greenhouse was measured every 10 s by a pyranometer (SQ-110-L10, Apogee, USA) at a height of 2 m from the ground and was connected to a data-logger (CR-1000, Campbell Scientific, USA). Whenever SRI inside the greenhouse reached the set value, irrigation started. Drainage was controlled within 30 to 50%. SRI was set 50 $J \cdot cm^{-2}$ and the irrigation lasted 4 to 5 min per event depending on the drainage amount. The irrigation frequency was checked every day online and all the plants were supplied between 8 to 10 times per day.

5.2.4. Analyses of plant growth and nutrient solution

Plant height and leaf area were measured at the time of beginning (30 DAT) and the end (115 DAT) of the experiment. Leaf area was calculated by using leaf length and width (Tai et al., 2009). Recently fully-matured leaves at the 4th and 5th nodes from the top of the stem were collected two weeks before first fruit harvest, 6 weeks after treatment (70 DAT) and 11 weeks after treatment (110 DAT). Each sample consisted of 9 leaves from each treatment. Leaves were washed in tap water and dried for 48 h at 70°C. Fruits were harvested two times at 87 DAT (8 weeks after treatment) and 115 DAT (at the end of experiment). At each harvest, fruit number, fruit fresh and dry weights were measured. Matured fruit (three fruits per treatment) were dried in a thermo-ventilated oven at 70°C until they reached a constant weight. The leaf and fruit samples were grinded and digested by using concentrated nitric acid until clear color solution was obtained. The digested clear solution was filled up by 20 mL of deionized water and the nutrient contents of K, Ca, Mg, P, and S were determined by the inductively coupled plasma optical emission spectrometer (ICP-730ES, Varian Australia Pty Ltd., Australia). Total-N was measured by Kjeldahl (Kjeltec 8400, Foss, Sweden).

5.2.5. Estimation of water and nutrient uptake

The changes of water and nutrient solution, the EC and pH, and the volume of the recycled nutrient solution in the reservoir tanks were measured every three days. The water uptake ($L \cdot m^{-2}$) was estimated using the difference between the initial and final volumes in each reservoir tank (20 L) with the change in water content of root medium every two weeks. The losses of nutrient solution by evaporation or leakage from the tank were prevented and the evaporation from the rockwool cube was not considered. Water contents in the root media were maintained at 60% - 70%. Every two weeks, 50 mL of nutrient solution from the reservoir tanks and root medium was collected and analyzed. NO_3^-, $H_2PO_4^-$, Cl^-, and SO_4^{2-} were measured with a spectrophotometer (photoLab, 6100 [VIS], Germany), and K^+, Ca^{2+}, Mg^{2+}, and Na^+ were measured with ICP-730ES.

Ion in recycled nutrient solution ($meq \cdot L^{-1}$) = $(C_rV_r + C_wV_w + C_fV_f) /(V_r + V_w + V_f)$ (1)

Water uptake (L, WU) = $\{(V_w + V_f) + (V_{r1} - V_{r2})\}$ (2)

Nutrient uptake (meq·L^{-1})=$[C_fV_f-\{(V_{r1}C_r - V_{r2}C_{r2})+V_s(C_{s1}-C_{s2})\}]$/ WU (3)

where, C_r, C_w, C_f, and C_s are ion concentrations (meq·L^{-1}) in recycled nutrient solution, added water, added fresh nutrient solution, and remained nutrient solution in the root medium, respectively. V_r, V_w, V_f, and V_s are volumes of recycled nutrient solution, added water, added fresh nutrient solution, and remained nutrient solution in the root medium, respectively. 1 and 2 mean the beginning and the end of every two weeks.

Individual cation (or anion) ratio was expressed by dividing cation (or anion) concentration by sum of cation (or anion) concentrations.

5.2.6. Experimental management and statistical analysis

Different renewal patterns of recycled nutrient solution with 4-4-4, 6-4-2, and 8-2-2 weeks were compared in the closed system. There were three plants per slab and three slabs per treatment. A randomized block design with three replications was used. The levels of nutrient accumulation or depletion in the recycled nutrient solution and root medium, and the nutrient uptake by the plants were analyzed by using the software Sigma-Plot 10 (SPSS, Inc., Chicago, IL, USA). Data were subjected to analysis of variance (ANOVA) using SAS 9.2 (SAS Institute, Cary, NC, USA). Means and standard errors were analyzed for each nutrient. Values of $p < 0.05$ were considered statistically significant by using Duncan's multiple range tests.

5.3. Results and Discussion

5.3.1. Changes in individual ion concentrations in the recycled nutrient solution

The deviation of ion concentration in the recycled nutrient solution from the initial supply was clearly observed in all the patterns and the renewal pattern of 4-4-4 weeks reduced the ion imbalance than the patterns of 6-4-2 and 8-2-2 weeks (Fig. 5.2). Particularly, the imbalance of Ca^{2+} and Mg^{2+} in the recycled nutrient solution was more affected by renewal pattern. The longer the renewal time 8-2-2 weeks, the more accumulation of Ca^{2+} was observed. Under management of the nutrient solution based on EC and pH, it is needed to estimate the accumulation or depletion of K^+, Ca^{2+}, Mg^{2+}, and Na^+ concentrations in the nutrient solution (Savvas and Manos, 1999; Sonneveld, 2000b).

The depletion in NO_3^- concentration in the recycled nutrient solution was observed, while those in $H_2PO_4^-$, SO_4^{2-} and Cl^- concentrations in the recycled nutrient solution were nearly the same within 8 weeks despite of the renewal patterns. Rouphael and Colla (2005) stated that accumulation of bivalent ion like Ca^{2+} and depletion of NO_3^- and K^+ are well-known alterations occurring in the composition of nutrient solutions when recycled. Based on the results, renewing the recycled nutrient solution with the pattern of every 4 week can reduce the accumulation of Ca^{2+} and the depletion of K^+.

5.3.2. Changes in individual ion concentration in the root medium and nutrient uptake

Ion concentrations in the root medium were the highest in NO_3^- and the lowest in $H_2PO_4^-$ decreasing with Ca^{2+}, Mg^{2+}, K^+, SO_4^{2-}, Cl^- and Na^+ in the order (Fig. 5.3). The longer the renewal pattern was, the more the accumulations of Ca^{2+} and Mg^{2+} in the root medium were observed. NO_3^- concentration in the root medium decreased with time. While certain nutrient ions in the root medium are depleted due to uptake by the plants, on the other hand, certain nutrients which are less absorbed by the plant may lead to accumulate due to transpiration (Silberbush, 2002). The changes in other ion concentrations in the root medium were not different among the different renewal patterns of 4-4-4, 6-4-2, and 8-2-2 weeks.

The amount of added volume of water and fresh nutrient solution to maintain EC, pH and nutrient solution volume in the recycled tank was shown in (Fig. 5.4). There was no significant difference in water content in the root medium and water uptake among all the renewal patterns. Since the plants cannot use all the nutrients supplied, some nutrients were accumulated and caused the EC increase in the root medium EC. Depending on the chemical compositions of the recycled nutrient solution, increases in the amounts of total dissolved solutes with time can lead to accumulation of salts in the root medium (Mmolawa and Or, 2000). Although water uptake and volume of water content in the root medium were not significantly different under different renewal patterns, a reduction in water uptake occurred due to the osmotic potential of nutrient concentrations between the root cell and root environment. Li et al. (2001) reported that the increase in EC with the accumulation of nutrients in the root medium caused a reduction in water uptake due to osmotic effect.

Changes in individual uptake concentration for 2 weeks at 4-4-4, 6-4-2, and 8-2-2 week renewal time were observed in (Fig. 5.5). The uptake of NO_3^- by paprika was the highest and followed by Ca^{2+}, K^+, Mg^{2+}, SO_4^{2-}, and $H_2PO_4^-$ using the recycled nutrient solution with different renewal times. Marcussi et al. (2004) indicated that NO_3^- and K^+ were the most extracted macronutrients by paprika and followed Ca^{2+}, Mg^{2+}, $SO_4^{2-}$and $H_2PO_4^-$. In this study, it was observed that $NO_3^- > Ca^{2+} > K^+ > Mg^{2+} > SO_4^{2-} > H_2PO_4^-$. It might be due to the depletion of K^+ when the nutrient solution was reused.

5.3.3. Changes in ion ratios in the recycled nutrient solution, root medium and nutrient uptake

The uptake of K^+ was the highest, causing the depletion of K^+ concentration in the recycled nutrient solution and the root medium at all the renewal patterns even though it was not different among the renewal patterns (Fig. 5.6). The uptake in Ca^{2+} by the plant and its accumulation in the recycled nutrient solution and root medium were the same among the different renewal patterns while Mg^{2+} was relatively less absorbed by the plant and more accumulated in the root medium at the renewal pattern of 8-2-2 weeks than any others.

Mg^{2+} concentration in the root medium was higher than the supplied nutrient solution due to the K^+ and Ca^{2+} compete quite effectively with Mg^{2+} and strongly depress the uptake rate of Mg^{2+} (Marschner, 1995). The nutrient solution supplied and remained in the root medium could not be the same since nutrient absorption have been related to growth variables as well as climate variables during the cultivation cycle (Silberbush and Lieth, 2004). In fact, Ca^{2+}, and Mg^{2+} concentrations in the root medium were higher than those in the recycled nutrient solution while K^{+} concentration in the root medium was lower than in the recycled nutrient solution. Voogt (1993) stated that the actual uptake ratios of K^{+}, Ca^{2+}, and Mg^{2+} can change dramatically the actual nutrient concentration of the root environment.

There were no differences in anion ratio change in the recycled nutrient solution, root medium and the uptake of NO_3^{-}, $H_2PO_4^{-}$, and SO_4^{2-} under different renewal patterns within 8 weeks (Fig. 5.7). However, SO_4^{2-} was more accumulated in the root medium under the renewal pattern of 8-2-2 weeks causing the reduction in Ca^{2+} uptake. Similar trend was observed by Lopez et al. (2003) indicated that high sulfate concentration in the nutrient solution reduced relative calcium activity.

The accumulation of Cl^{-} in the root medium was higher than those in the recycled nutrient solution however the Na^{+} concentration was not consistently changes in recycled nutrient solution and root medium from the initial (Fig. 5.8). The longer the renewal pattern was the more the accumulation of Cl^{-} occurred. Since nutrient and non-nutrient concentration may largely influence ion and water uptake kinetics (Le Bot et al., 1998; Parida and Das, 2005), nutrient replenishment with adequate patterns can reduce the variations in cation and anion ratios in the recycled nutrient solution and the root medium.

5.3.4. Growth and yield of paprika plants

There were no differences in growth and yield of paprika by renewing different patterns of 4-4-4, 6-4-2, and 8-2-2 weeks (Table 5.1). According to Nukaya et al. (1991), yields will not be affected by the accumulation of Cl^- and SO_4^{2-} in the recycled nutrient solution when the EC in the root medium is maintained within the acceptable range. The specific ion-toxic effects of Na^+ and/or Cl^- were not related to the decrease in yield, while the accumulations of Na^+ and Cl^- were linearly related to the concentration of major elements in the nutrient solution (Baas et al., 1995).

5.3.5. Tissue mineral analysis

The concentrations of leaf and fruit mineral contents were not significantly different among different renewal pattern. K content in leaf increased during fruit development period at the renewal patterns of 4-4-4 and 6-4-2 weeks, but decreased at the renewal pattern of 8-2-2 weeks (Table 5.2). Meanwhile, the opposite trend was observed in fruit (Table 5.3). However, Ca and Mg contents in fruit and leaf appeared to be higher by renewing constant patterns of 4-4-4 weeks than the other renewal patterns of 6-4-2 and 8-2-2 weeks (Tables 5.2 and 5.3), while those in fruit decreased during fruit development. Marti and Mills (1991a) observed that a decline in Ca^{2+} uptake occurred when fruits approach the mature green stage. Because Ca^{2+} is relatively immobile in the plant and its movement into the fruit is dependent upon transpiration from the fruit. Hanger (1979) suggested that the amount of water entering the fruit from the xylem would decline as the fruit matures when a waxy surface was developed with the fruit maturity.

Renewing recycled nutrient solution using adequate renewal patterns can reduce the ion imbalance in recycled nutrient solution and root medium without any detrimental effect on yield and plant growth. It was confirmed that the feasible management was adjusting ions ratio with the pattern of 4-4-4 week. For efficient management of nutrient solution to avoid the accumulation or depletion of nutrients in the recycled nutrient solution, the cation changes with growth stage and environmental conditions should be considered as further study.

Table 5.1. Growth and yield of paprika in closed rockwool culture during the growing period.

Renewal time [z] (week)	Leaf area (cm^2/plant)	Yield ($g \cdot m^{-2}$)	Shoot fresh weight (g/plant)
4-4-4	7550.63	2841.63	1601.41
6-4-2	8596.25	2441.23	1522.24
8-2-2	7091.25	2705.87	1608.26
Significance	n.s.[y]	n.s.	n.s.

[z] 4-4-4, 6-4-2, and 8-2-2 present the renewal of nutrient solution at week 4, 8, 12; week 6, 10, 12; and week 8, 10, and 12, respectively.

[y] n.s. means non-significant by Duncan's multiple range test at $p < 0.05$.

Table 5.2. Leaf mineral contents with harvest stage as influenced by renewal time of recycled nutrient solution.

	Renewal time (week)	Leaf mineral contents (%) T-N	P	K	Ca	Mg	S
70 DAT[z]	4-4-4[y]	4.72 ±0.42[x]	0.24 ±0.03	3.72 ±0.21	2.12 ±0.49	0.54 ±0.16	0.48 ±0.07
	6-4-2	5.01 ±0.44	0.19 ±0.03	3.30 ±0.49	1.82 ±0.33	0.41 ±0.06	0.37 ±0.06
	8-2-2	4.60 ±0.81	0.21 ±0.01	3.77 ±0.86	1.86 ±0.17	0.45 ±0.05	0.42 ±0.04
	Significance	n.s.[w]	n.s.	n.s.	n.s.	n.s.	n.s.
110 DAT	4-4-4	4.13 ±0.19	0.18 ±0.02	4.14 ±0.17	2.26 ±0.24	0.56 ±0.16	0.43 ±0.02
	6-4-2	4.37 ±0.35	0.23 ±0.03	3.95 ±0.73	1.86 ±0.45	0.54 ±0.06	0.44 ±0.03
	8-2-2	4.07 ±0.12	0.16 ±0.03	3.25 ±0.78	1.93 ±0.07	0.50 ±0.01	0.43 ±0.02
	Significance	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

[z]DAT means days after transplanting.

[y]4-4-4, 6-4-2, and 8-2-2 means the renewal of nutrient solution at week 4, 8, 12; week 6, 10, 12; and week 8, 10, and 12, respectively.

[x]Each value represents Mean ± SD (n=3).

[w]n.s. means non-significant by Duncan's multiple range test at $p < 0.05$.

Table 5.3. Fruit mineral contents with harvest stage as influenced by renewal time of recycled nutrient solution.

		Fruit mineral content (%)					
	Renewal time (week)	T-N	P	K	Ca	Mg	S
80 DAT[z]	4-4-4[y]	2.99 ±0.25[x]	0.42 ±0.01	1.98 ±0.47	0.08 ±0.02	0.15 ±0.01	0.22 ±0.08
	6-4-2	2.89 ±0.25	0.38 ±0.08	2.15 ±0.80	0.06 ±0.01	0.14 ±0.02	0.22 ±0.05
	8-2-2	2.76 ±0.38	0.34 ±0.05	1.80 ±0.44	0.06 ±0.02	0.12 ±0.01	0.20 ±0.03
	Significance	n.s.[w]	n.s.	n.s.	n.s.	n.s.	n.s.
115 DAT	4-4-4	2.67 ±0.25	0.38 ±0.03	1.86 ±0.52	0.06 ±0.01	0.12 ±0.01	0.22 ±0.03
	6-4-2	2.24 ±0.35	0.33 ±0.06	2.41 ±0.40	0.07 ±0.01	0.12 ±0.01	0.21 ±0.04
	8-2-2	2.57 ±0.16	0.39 ±0.09	2.56 ±0.74	0.05 ±0.01	0.12 ±0.01	0.24 ±0.05
	Significance	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

[z]DAT means days after transplanting. [y]4-4-4, 6-4-2, and 8-2-2 means the renewal of nutrient solution at week 4, 8, 12; week 6, 10, 12; and week 8, 10, and 12, respectively.

[x]Each value represents Mean ± SD (n=3).

[w]n.s. means non-significant by Duncan's multiple range test at $p < 0.05$.

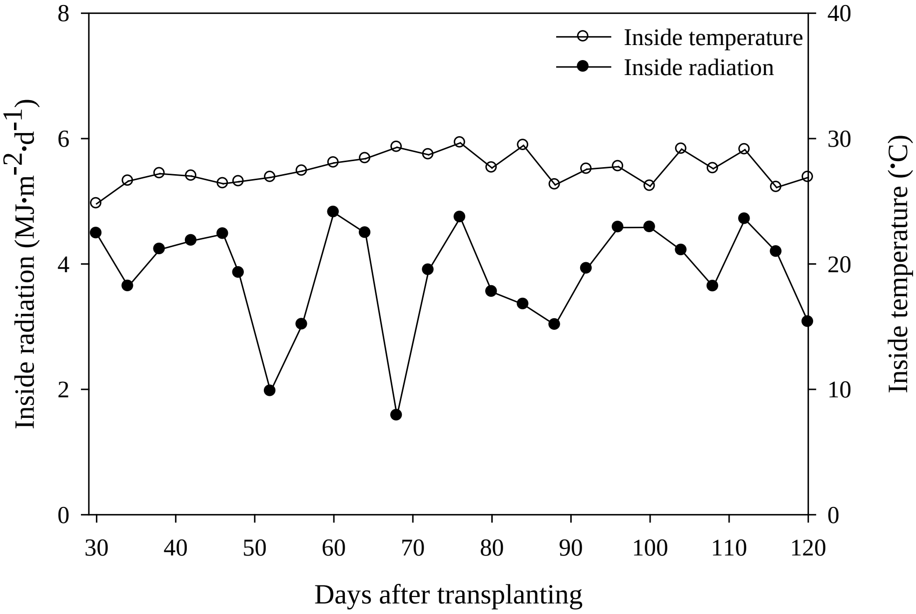

Fig. 5.1. Average inside greenhouse radiation and temperature during the experimental period from June to August, 2012.

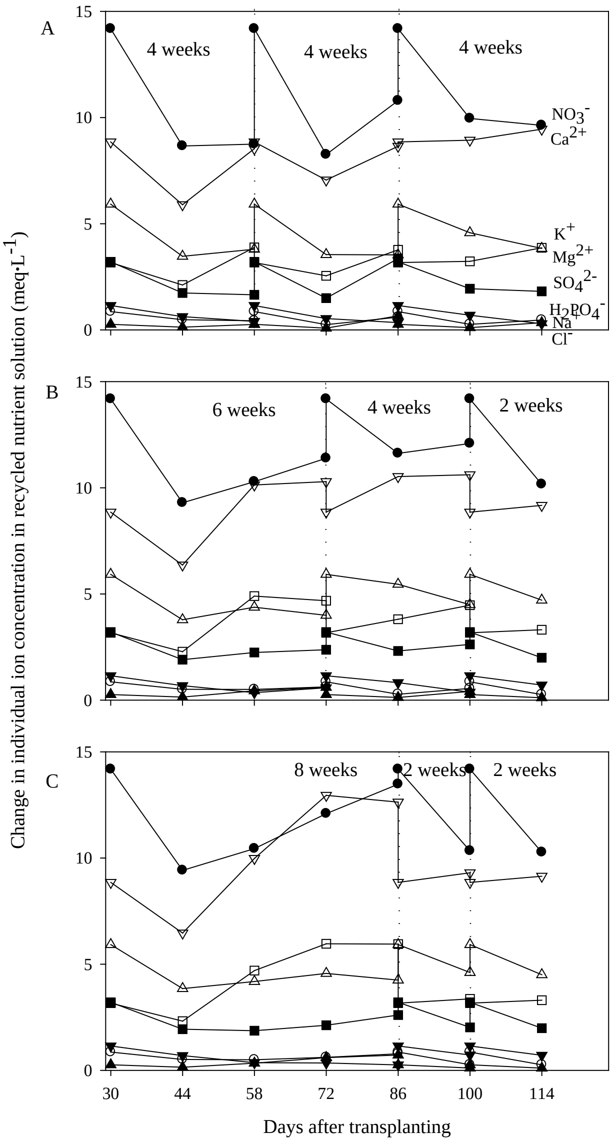

Fig. 5.2. Change in individual ion concentration in the recycled nutrient solution after adjusting EC and pH every three days. Dashed-lines represent the renewal time of recycled nutrient solution. A, B, and C indicate the renewal times of 4-4-4, 6-4-2, and 8-2-2 weeks, respectively.

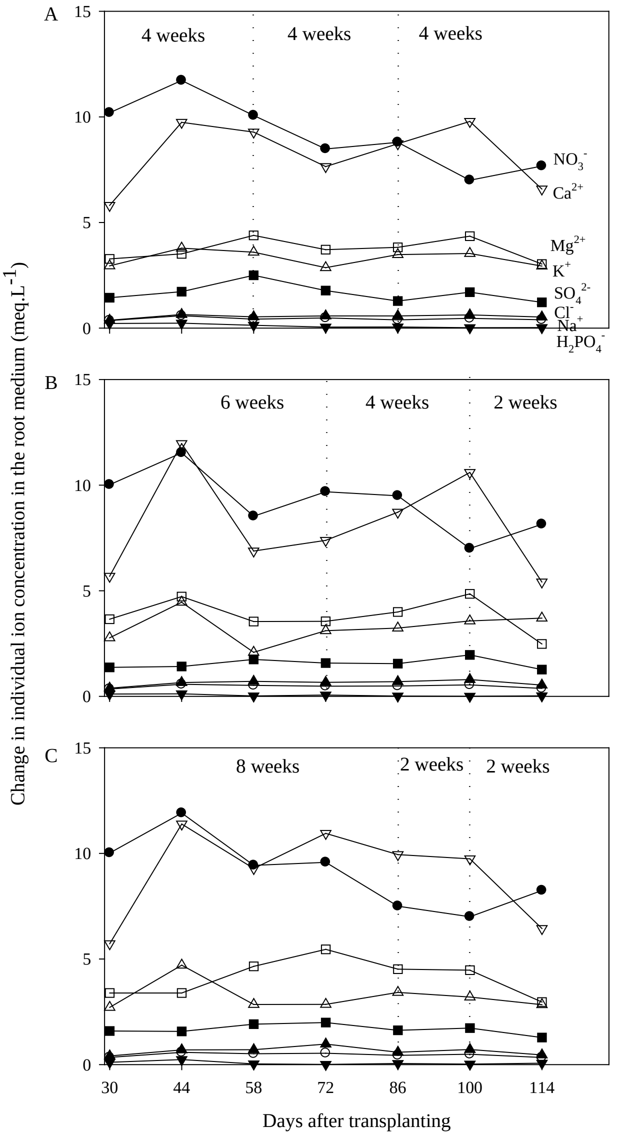

Fig. 5.3. Change in individual ion concentration in the root medium at different renewal times. Dashed-lines represent the renewal time of recycled nutrient solution. A, B, and C indicate renewal times of 4-4-4, 6-4-2, and 8-2-2 weeks, respectively.

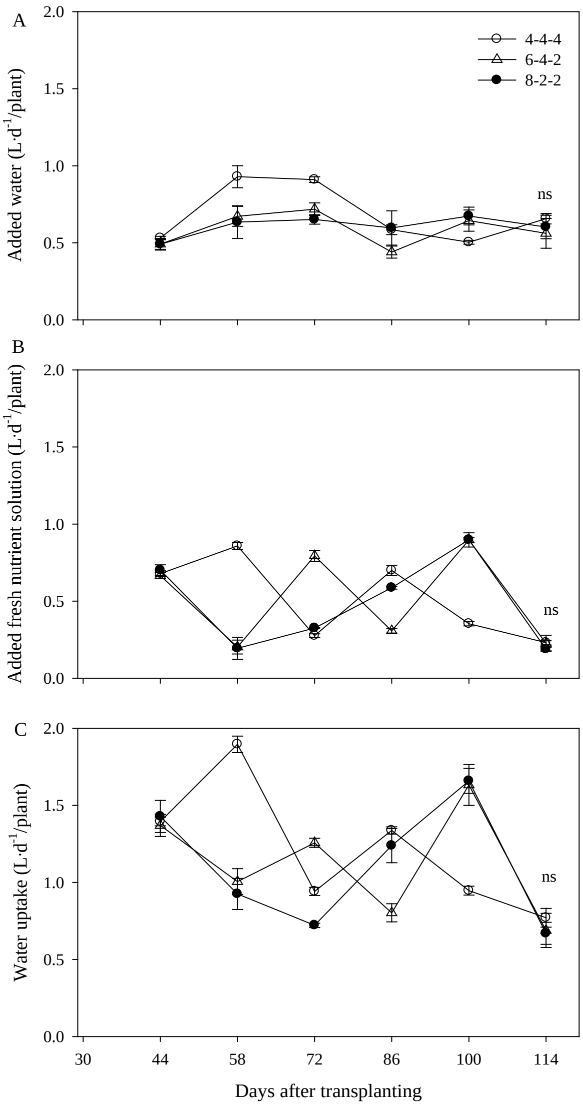

Fig. 5.4. Changes in volume added water (A), fresh nutrient solution (B), and water uptake (C) during the experimental period. 4-4-4, 6-4-2, and 8-2-2- indicate the renewal times of 4-4-4, 6-4-2, and 8-2-2 weeks, respectively. Vertical bars indicate Mean ± SE of the mean (n=3). ns means non-significant difference at $p < 0.05$ by Duncan's multiple range test.

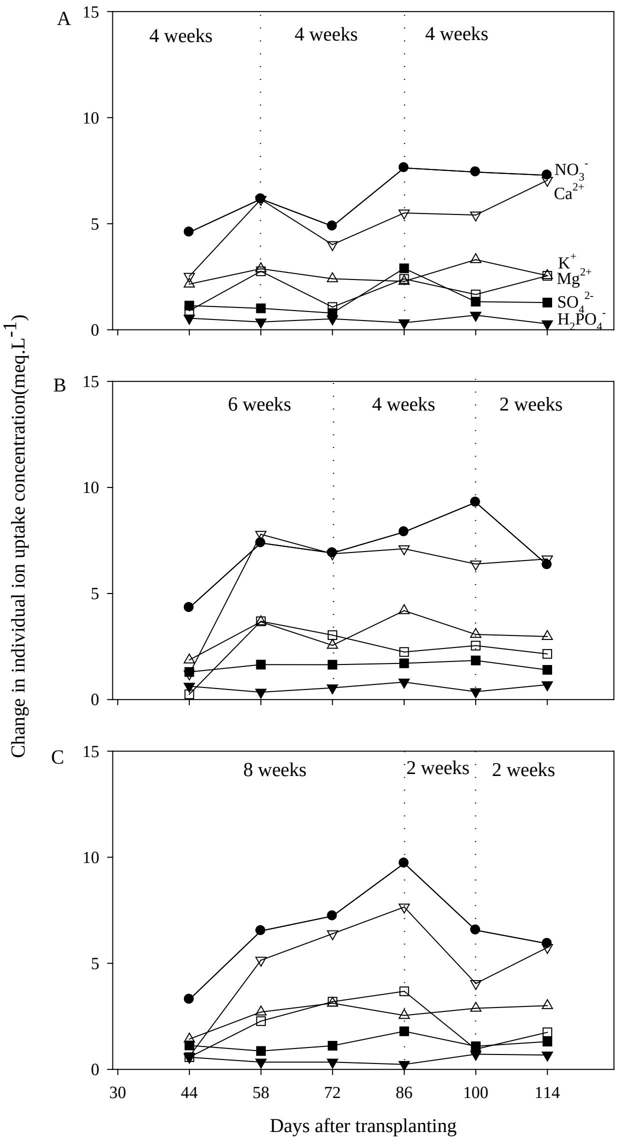

Fig. 5.5. Change in individual ion uptake concentration at different renewal times. Dashed-lines represent the renewal time of recycled nutrient solution. A, B, and C indicate renewal times of 4-4-4, 6-4-2, and 8-2-2 weeks, respectively.

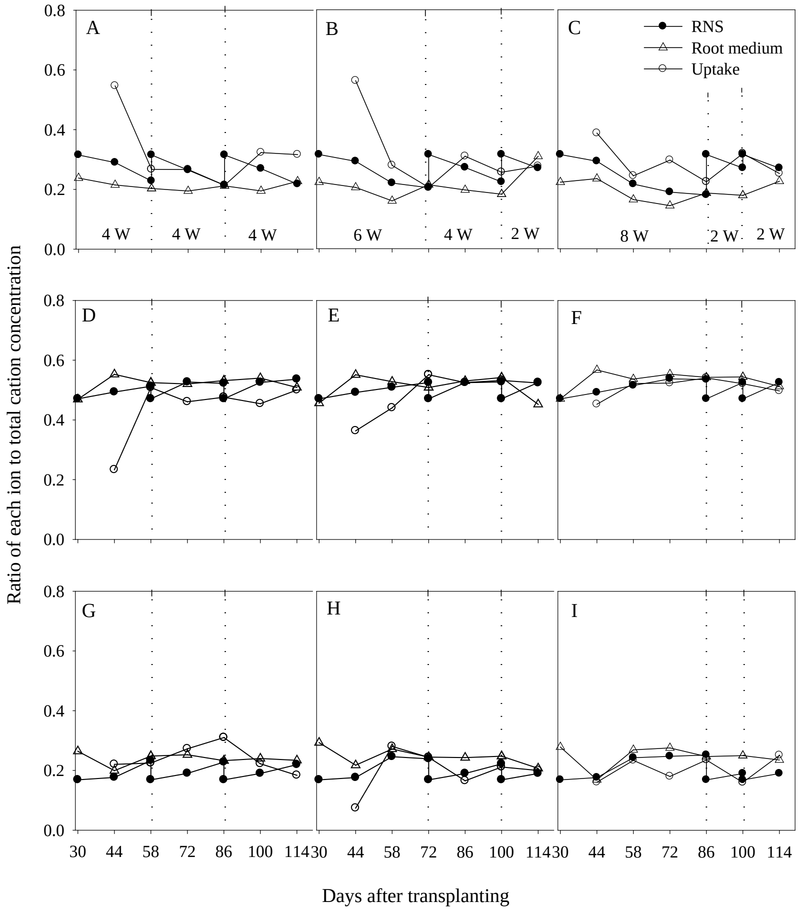

Fig. 5.6. Change in individual ion ratio to total cations in the recycled nutrient solution (RNS), root medium, and ion uptake. Dotted lines represent the renewal time of recycled nutrient solution. The upper (A, B, and C) figures indicate the change in K^+ ratio at the renewal times of 4-4-4, 6-4-2, and 8-2-2 weeks, respectively. The middle (D, E, and F) and the bottom (G, H. and I) figures are corresponding to Ca^{2+} and Mg^{2+}, respectively.

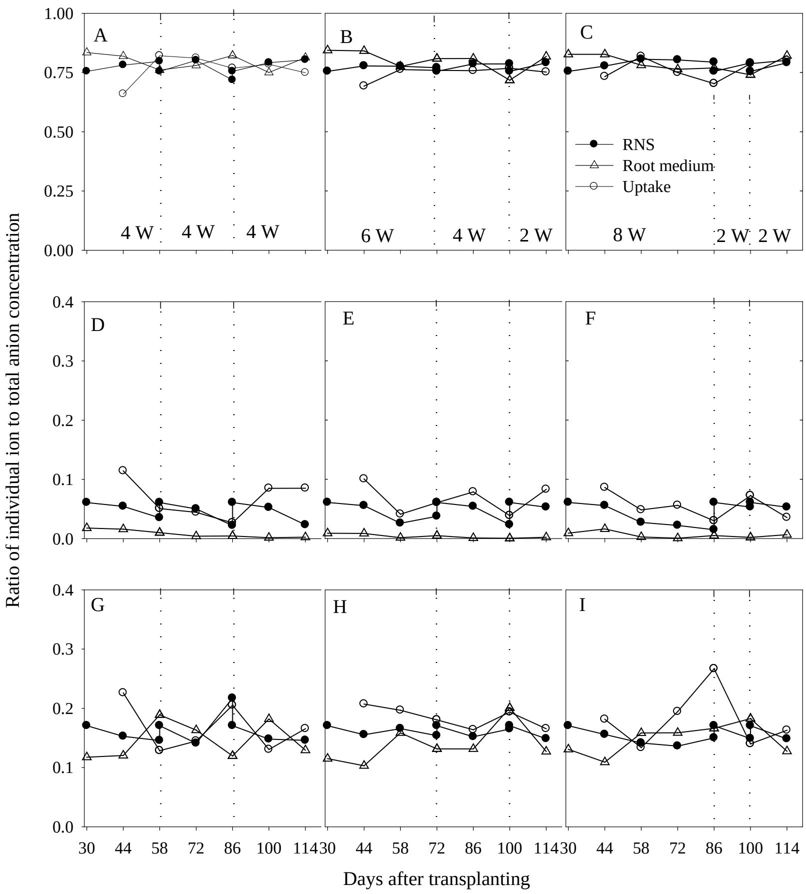

Fig. 5.7. Change in individual ion ratio to total anions in the recycled nutrient solution (RNS), root medium, and ion uptake. Dotted lines represent the renewal time of recycled nutrient solution. The upper (A, B, and C) figures indicate the change in NO_3^- ratio at the renewal times of 4-4-4, 6-4-2, and 8-2-2 weeks, respectively. The middle (D, E, and F) and the bottom (G, H. and I) figures are corresponding to $H_2PO_4^-$ and SO_4^{2-}, respectively.

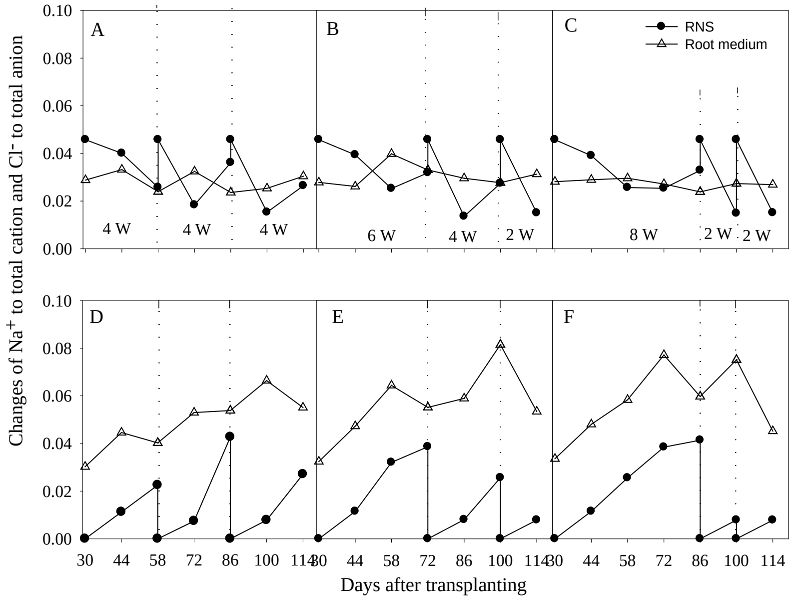

Fig. 5.8. Change in Na^+ ratio to total cations (upper) and Cl^- ratio to total anions (bottom) in the recycled nutrient solution (RNS), root medium, and ion uptake. Dotted lines represent the renewal time of recycled nutrient solution. The renewal times are 4-4-4 weeks in A and D, 6-4-2 weeks in B and E, and 8-2-2 weeks in C and F.

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6. CONCLUSIONS

Soilless culture is classified into two types of open and closed systems. Main advantage of the closed system over the open one is to reduce the wastes of water and fertilizers, resulting in improvement of resource use efficiency. On the other hand, a disadvantage of the closed system is the difficulty in supplying the nutrient solution with right nutrient compositions.

When the nutrient solution is continuously re-used throughout the growing period of paprika, some ions like NO_3^- and K^+ are depleted and the others like Ca^{2+}, Mg^{2+}, Na^+, SO_4^{2-}, and Cl^- are accumulated in the recycled nutrient solution. In fact, 19% reduction in yield was observed in the closed system compared with that in the open system after four harvests. Although water and fertilizer use efficiency were 50% and 67% higher in the closed system than those in the open system, the ion imbalance in the recycled nutrient solution appeared after 4 weeks under acceptable ranges of EC and pH. To manage the nutrient solution cost-effectively in the closed system, renewal of the recycled nutrient solution every 4 weeks is desirable because the change in cation and anion ratios in the recycled nutrient solution was minimized and the yield was not different from that in the open system. However, by considering water and nutrients uptake and the yield, it can be extended to 8 weeks with an adjustment of EC and pH.

In the recycled nutrient solution and root medium, NO_3^- and K^+ were depleted by active plant uptake, and the ion balances were reduced at the renewal pattern of 4-4-4 weeks, and followed by 6-4-2 and 8-2-2 weeks. Particularly the accumulation of Ca^{2+}

and Mg^{2+} was reduced as the same trend as above. No significant differences in nutrient uptake, yield and plant growth were observed among all the renewal patterns. Chemical analysis indicated that paprika needs less Ca and Mg in the fruits than in the leaves during the fruit growth, and hence these nutrients should be reduced during fruit developing period in the renewed nutrient solution to prevent the accumulations in the recycled nutrient solution.

It can be concluded that renewal period and pattern play important roles in the ion balances of the recycled nutrient solution and root medium and the uptakes of water and nutrients by plants in closed soilless culture. For more efficient management of nutrient solution in closed soilless culture, adjustment (or renewal) of recycled nutrient solution considering growing stage and environmental conditions are required as further study.

ABSTRACT IN KOREAN

파프리카 순환식 수경재배에서 재사용 양액의 이용 효율 및 이온 균형의 개선

순환식 수경재배 방식은 양수분의 절약과 환경오염원 발생을 최소화할 수 있어 유용하지만, 온실 재배에서의 적절한 양액 관리를 위한 기술은 아직 안정화되어 있지 않다. 그러나 재사용 양액 내 이온의 불균형과 배지 내 양분의 집적은 식물의 생육에 영향을 미치는 중요한 요인이다. 효율적인 양분관리를 위해는 작물의 양수분 요구량을 고려한 적절한 분석주기에서의 재사용 양액의 양분 조정이 필요하다. 본 연구는 순환식과 비순환식 수경재배 방식의 이온균형, 수량, 양분 및 수분 이용량 비교와 이온의 불균형을 최소화할 수 있는 적절한 재사용 주기를 결정하고, 양액의 재사용 주기에 따른 파프리카의 양분 및 수분 흡수량과 이온 함량을 조사하고, 양액의 재사용 주기의 패턴에 따른 배지 및 재사용 양액 내 이온 균형과 양분 흡수량의 변화를 조사하기 위해 수행하였다. 순환식 처리가 비순환식 처리에 비해 4회의 수확량에서 19%의 감소가 관찰되었다. 순환식 처리의 양분과 수분의 이용효율은 비순환식 처리에 비해 각각 68%와 78% 높게 나타났다. 재사용 양액의 EC와 pH는 일정 범위 내에서 유지되었으나 이온의 불균형은 4주 이후부터 나타나기 시작했다. 양액의 재사용 주기에 따른 처리 중 4주 간격 교체 처리에서 재사용 양액 내 양이온과 음이온의 비율 변화가 감소하였다. 과실 수확량은 12주 간격 교체 처리에서 가장 낮게 나타났다. 양분의 균형

과 수확량을 고려해봤을 때 적절한 양액의 재사용 주기는 4주로 판단되지만, 실질적으로 8주까지 연장 할 수 있다. 양액 재사용 주기의 패턴별 배지와 재사용 양액 내 NO_3^-와 K^+의 감소 수준은 4-4-4, 6-4-2, 8-2-2 처리의 순으로 나타났으며, 같은 순서로Ca^{2+}, Mg^{2+}, SO_4^{2-}, Na^+, Cl^-의 집적이 관찰되었다. 그러나 각 양액 재사용 주기의 패턴별 수확량과 생육에서 유의적인 차이는 관찰되지 않았다. 본 연구 결과 파프리카 순환식 수경재배에서 양액의 재사용 주기와 그 패턴은 재사용 양액과 배지 내 양분의 균형과 파프리카의 양분 흡수에 중요한 요인으로 작용하는 것으로 판단할 수 있다. 더 효율적인 양액 관리를 위해서는 생육단계와 환경조건을 고려한 양분의 조정 방법에 대한 추가적인 연구가 필요하다.

주요어 : 순환식 암면 수경재배, 재사용양액, 이온불균형, 양수분흡수, 재사용 주기, 배지이온집적

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