EFFECT OF SPLIT ROOT FERTIGATION ON THE GROWTH AND YIELD OF GREENHOUSE STRAWBERRY CV. ELSANTA

Wenjun Ran
Master’s thesis
University of Helsinki
Department of Agricultural Sciences
Horticulture
2014
The application of the split root fertigation (SRF) on strawberry cv. Elsanta (*Fragaria × ananassa* Duch.) was tested in a greenhouse. Responses of strawberry plants under SRF treatments were evaluated by investigating plant water use, plant vegetative growth, berry yield, and berry quality. In this experiment, strawberry plants had their roots separated evenly into two parts and grown in containers with two compartments in peat. In the traditional fertigation (TF), the control in the experiment, irrigation water with equal electrical conductivity (EC) (1.4 mS/cm) was applied to both root compartments. Three levels of SRF treatments with low, medium, and high mean EC in irrigation water were designed for the experiment. In these SRF treatments, half of roots received the irrigation solutions with lower EC value of 0.7 mS/cm, the other half of roots received irrigation solutions with EC values of 1.4 mS/cm (SRF1), 2.8 mS/cm (SRF2), and 4.2 mS/cm (SRF3). For plant growth, leaf number, petiole length, runner number and dry weight, plant dry weight, leaf nutrient contents, and flowering date were examined. For yield and berry quality, total fresh yield, total berry number, average berry fresh and dry weight, shelf life, contents of total soluble solids (TSS), titratable acid (TA), total phenolics, and ascorbic acid were measured. For plant water use, substrate water content (θ) and EC, leakage amount and EC were recorded; water use efficiency (WUE) and water uptake percentage were calculated to investigate the water use. Compared to TF, plants under SRF treatments showed differences in some parameters. Plants grown under SRF2 had highest total leaf area, although no differences in total plant dry weight were observed; leaf Mg was improved by SRF treatments, leaf N increased by SRF with high EC (SRF3), and leaf B and Mn decreased in SRF with low EC (SRF1). More lateral roots were found of plants under SRF treatment. Plant flowering was accelerated in the medium SRF treatment. For fruit quality, berry size was reduced in SRF3, which was in consistent with the response of strawberry grown under salinity stress. TSS/TA decreased in SRF3. In all SRF treatments, more water was taken up from root compartment with the lower EC value. However, the total water uptake amount had no differences. As a conclusion, SRF treatments affected the plant water uptake distribution, plant vegetative growth, yield and yield quality in some parameters, but results were not consistent in this experiment. Treatments with more EC combinations in a wider range are recommended for further studies.
# CONTENTS

Effect of Split root fertigation on the growth and yield of greenhouse strawberry cv. Elsanta ................................................................................................................................. 1

Contents ........................................................................................................................................ 1

Abbreviations .................................................................................................................................. 2

1 Introduction .................................................................................................................................. 5

2 Literature review ......................................................................................................................... 6

  2.1 Strawberry plant ....................................................................................................................... 6

  2.2 Strawberry production .............................................................................................................. 7

  2.3 Strawberry fruit quality .......................................................................................................... 8

  2.4 Split root fertigation and partial root drying .......................................................................... 10

  2.5 Effects of EC and salinity on strawberry growth and yield .................................................. 12

3 Research objectives .................................................................................................................... 15

4 Materials and methods .............................................................................................................. 16

  4.1 Plant material and growing conditions .................................................................................. 16

  4.2 Fertigation and the treatments ............................................................................................... 17

  4.3 Monitoring of water use ......................................................................................................... 19

  4.4 Observation on vegetative growth .......................................................................................... 20

  4.5 Berry yield and analysis of yield quality ............................................................................... 20

  4.6 Experimental design and data analysis ................................................................................... 22

5 Results ......................................................................................................................................... 23

  5.1 Substrate and leaching water ................................................................................................. 23

  5.2 Growth of the plants .............................................................................................................. 27

  5.3 Berry yield and quality .......................................................................................................... 32

6 Discussion .................................................................................................................................... 38

  6.1 Plant water use ......................................................................................................................... 38

  6.2 Growth and yield of strawberry plants .................................................................................... 39

7 Conclusion .................................................................................................................................... 43

8 Acknowledgements .................................................................................................................... 44

References ....................................................................................................................................... 45

Appendix 1 ....................................................................................................................................... 51
## ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DI</td>
<td>Deficient irrigation</td>
</tr>
<tr>
<td>EC</td>
<td>Electrical conductivity</td>
</tr>
<tr>
<td>PRD</td>
<td>Partial root zone drying</td>
</tr>
<tr>
<td>SRF</td>
<td>Split root fertigation</td>
</tr>
<tr>
<td>TA</td>
<td>Titratable acids</td>
</tr>
<tr>
<td>TF</td>
<td>Traditional fertigation</td>
</tr>
<tr>
<td>TSS</td>
<td>Total soluble solids</td>
</tr>
<tr>
<td>WUE</td>
<td>Water use efficiency</td>
</tr>
</tbody>
</table>
1 INTRODUCTION

Strawberry is the most commonly grown soft fruit crop throughout the world. The plant area of strawberry in Finland was 3,386 ha, and 12,764 t fresh fruit were produced in 2011 (FAOSTAT 2013). Strawberry production in Finland as well as in other Nordic countries has a limited protected cultivation in greenhouse (Lieten et al. 2004). In 2013, the protected greenhouse culture area for strawberry was estimated to be 20 to 30 ha in Finland.

Under great impact of environmental pressure like global warming, protected culture can be a solution to water shortage, and restricted agricultural waste regulations (Lieten et al. 2004). Substrate culture as an important method in protected culture was developed mainly in the Netherlands and Belgium for strawberry cultivation because of its advantages: contamination by root diseases, high plant density and better control of nutrient and pH, and out of season production (Lieten et al. 2001).

The split root fertigation (SRF) was developed to improve greenhouse production efficiency of crops. Plants in split root fertigation (SRF) have their roots separated to several compartments; root compartments are treated with variable fertilizers with different electrical conductivity (EC) values (Jokinen et al. 2011), or supplied with uneven water amounts in partial root zone drying (PRD) (Shao et al. 2008).

Agrifood Research Finland (MTT) had conducted tests about application of SRF treatments on greenhouse cucumber and greenhouse tomato production (Mononen 2011, Karhula 2012, Mäkelä 2012). The potential of applying the SRF system on greenhouse strawberry production to obtain higher berry yield, better berry quality, or higher water use efficiency has not been studied earlier.

The aim of this thesis was to examine the effect of SRF on strawberry yield and yield quality to complement previous study of SRF conducted by MTT.
2 LITERATURE REVIEW

2.1 Strawberry plant

(Darrow 1965) The commercial strawberry *Fragaria × ananassa* Duch. is an octoploid hybrid species obtained by cross-breeding of *F. chiloensis* (L.) Duch. and *Fragaria virginiana* (L.) Duch. The earliest use of strawberry plant can be traced back to the 1400’s when it was used as an ornamental. In the 1700’s the modern strawberry with large berry size was produced for the first time by the crossing of different cultivars. Production and consumption of strawberry grew with the increased global trades in modern history. The delightful taste and aroma of strawberry made it one of the most popular fruits for both fresh consumption market and for processing food industry.

The commercial octoploid strawberry is a shallow rooted plant, with an average root system length of 20-35 cm (Childer 1981). Roots of strawberry are quite vulnerable; they can be damaged by cold stress and water stress easily (Krüger et al. 1999).

![Figure 1. Structure of a strawberry plant.](image-url)
The aboveground parts of strawberry include a crown, leaves, inflorescences and runners (Figure 1).

The crown is actually the short stem of the strawberry plant with the pith in its central part (Childer 1981). Trifoliate leaves arise from the crown in a 2/5 spiral. The growths of leaves always take 2-3 weeks to reach the full size. Axillary buds have the potential to develop into runners, branch crowns, or stay in dormancy, which will be triggered by different environmental stimulators. Runner (stolon) is an axillary bud that turned into a reproductive organ to produce daughter plants at every second node. Flowers of most commercial cultivars have 5 sepals, 5 petals and 20-35 stamens. Wind pollination and insect pollination is combined to obtain the best yield in strawberry production in fields. The berries of strawberry are aggregates where one ‘fruit’ is consisting of many fruitlets in a single receptacle. The flesh of strawberry fruit is derived from the receptacles. The number of pistils in a flower determines the final size of the berry fruit, and the quality of fertilization or the uniformity of pollination determines the shape of the berry. Number of leaves, total leaf area, number of flowers, and even the number of branch crowns are fundamental for the final yield. The density of stomata on strawberry leaves is higher than other fruit crops, which means a higher water-loss through transpiration, or higher water consumption in cultivation.

### 2.2 Strawberry production

Strawberry world production has been increasing in the last few decades. Until 2011, strawberry plant area was 242,371 ha in the world with a production of 4,308,179 t; in Finland, strawberry culture area was 338,6 ha with a production of 12,764 t (FAOSTAT 2013). Major producers are U.S.A., Spain, Japan, Poland, Italy, Korea, Mexico and Turkey. Public and private companies together have released totally nearly 500 strawberry cultivars by various breeding programs with different aims so far (Faedi et al. 2002).

The combination of greenhouses, polyethylene tunnels and field culture supply strawberry throughout almost the whole year (Kempler et al. 2002). The soilless
system for commercial strawberry production had advantages like no contamination by root diseases, nematodes and insects, year-round production, and intensive production (Lieten et al. 2004a, Lieten 2013). The substrate systems were developed in the Netherlands and Belgium, and introduced by skilled growers, researchers and substrate appliers. In 2010, soilless strawberry production in Western Europe exceeded 1,600 ha and with increasing restrictions on the use of soil fumigants and herbicides, it is expected that substrate culture will continue to expand (Lieten 2013). Cv. Elsa ntalong with cv. Sonata can be successfully grown in soilless culture (Lieten 2013). But in Northern Europe, the substrate culture received limited interests; in Finland, substrate culture was applied only for 4 ha among 4500 ha cultivation surface in 2002 (Lieten et al. 2004a)

Strawberry cultivation in the greenhouse or polyethylene tunnels has the potential to help to adapt to the changing climates and maintain strawberry production. Under the impact of the changing climates, strawberry is considered to be the most vulnerable small fruit crop because of the emerging new pests; the Spanish slug is a new invading pest and has been considered to have a great influence on the production of strawberry (Tuovinen et al. 2009).

In soilless culture, the main substrate material in Europe is peat because of its high water holding capacity, low nutrient and pH levels (Lieten 2004). Alternative substrate materials include coir, rockwool, perlite, wood fibers and cork.

2.3 Strawberry fruit quality

2.3.1 Carbohydrates

Carbohydrates in strawberry fruit are known to participate in many pathways related to fruit ripening, flavor development and color development (Souleyre et al. 2004). Strawberry fruits contain sucrose, fructose and glucose as the three major sugar types that consist 99% of the total sugar (Bood and Zabetakis 2002). Inositol and sorbitol are the minor sugar types. While total sugar contents of different strawberry cultivars vary, the ratio of each specific sugar to total sugars is constant (Bood and Zabetakis 2002). Content and composition of sugars affect the ratio of sugar and acids, which is
widely used in sensory evaluation of fruits and beverages, and it is also believed to be a resource of the precursors of the aroma compound (Perez et al. 1997). Content of sugars may be measured as the content of total soluble solids (TSS) by refractometer.

2.3.2 Titratable acids (TA)

Content of organic acids in strawberry fruit is not a constant feature; various environmental factors can cause fluctuation, as reviewed by Wysocki et al. (2012). The main forms of organic acids are citric acid (90%) and malic acid (10%). They are important factors that influence the consumer preference and processing values.

Wozniak et al. (1997) found a correlation between sugar/acid ratios with the sensory preference. Recent instrumental analysis has also confirmed that low sweetness in sensory evaluation is caused by either the low TSS content or high TA content (Jouquand et al. 2008).

2.3.3 Antioxidants

Strawberry is an good source of phenolics. The beneficial phenolics function as antioxidants and are highly valued in the human diet for their role in prevention of cardiovascular disease (CVD) and cancer (Kris-Etherton et al. 2002). Strawberries produced for fresh consumption contain antioxidants at a range from 6.67 to 7.01 mmol/100g, which make it the fifth plant among berries arranged by antioxidant content (Halvorsen et al. 2002).

Ascorbic acid is an important component in strawberry that functions as an antioxidant. Its content is affected by many factors such as genotype, climate conditions and cultivation condition (Lee and Kader 2000). Ellagic acid exists in large amount in strawberry and raspberries in a form conjugated with various sugars, and it is the main phenolic compound in strawberry (Häkkinen et al. 1999). Content of ellagic acid changes with the developmental stages: it is highest in green fruit, intermediate in mid-ripen fruit and lowest in full-ripen ones (Williner et al. 2003).
Distribution of the antioxidants varies and they are produced in plant parts that are susceptible to injury (Atkinson et al. 2005).

Genotype has been found to be the most important factor affecting the content of ascorbic acid, phenolic compounds and antioxidant capacity (Atkinson et al. 2006, Tulipani et al. 2010). However in the study by Pincemail (2012), harvesting time appeared to be more important than other factors, such as genotype, culture condition and environment factors.

Strawberry fruits have short shelf life that is limited to 1-2 days in room temperature because of their susceptibility to mechanical injury and post harvest diseases.

2.4 Split root fertigation and partial root drying

Motivated by the changes of environment like the increasing temperature and decreasing available irrigation water, various irrigation and fertigation strategies have been investigated to improve the fruit production or to promote the water use efficiency (WUE).

SRF technique divides the root system of a plant into two separate parts; treat them with two different fertigation solutions that vary in electrical conductivity (EC) (Sonneveld and Kreij 1999). The split root system was used firstly for testing the response of tomatoes (*Lycopersicon esculentum*) under unequal distribution of nutrition (Sonneveld and Voogt 1990), after that several experiments were carried out using the same technology focusing on tomatoes (Tabatabaie et al. 2003) and cucumbers (*Cucumis sativus L.*) (Sonneveld and Kreij 1999, Mavrogianopoulos et al. 2012).

Yield was reduced when both root parts received high EC (6.0 mS/cm for cucumber and 5 mS/cm for tomato) (Sonneveld and Kreij 1999 and Sonneveld and Voogt 1990, respectively). Cucumber suffering from salinity stress had higher sugar and acid content (Sonneveld and Kreij 1999). The disadvantage on yield caused by high EC could be eliminated when half of the root received irrigation water with lower EC.
However, it was based on the premises that: firstly the high EC was not too high (below 7 mS/cm), and secondly, low EC value should be under the EC threshold (for example 4.8 mS/cm in cucumber) (Sonneveld and Kreij 1999). Total water and nutrient uptake didn’t differ with different EC combinations (Sonneveld and Kreij 1999). However, water was taken up preferentially from the low EC side (Sonneveld and Kreij 1999, Mavrogianopoulos et al. 2012). Nutrient uptake was highest in root parts supplied with the standard nutrient solution with EC value of 2.0 mS/cm, and decreased with the increasing of EC values (Sonneveld and Kreij 1999).

Recent tests of SRF was designed to reduce the impact of the changing greenhouse environment in crop production or to minimize the effects caused by fluctuating nutrients and water supply, or to stable the environment for better yield (Jokinen et al. 2011). Compared with controls grown in traditional fertigation conditions, cucumber plants in SRF had increased yield by 21% in the open, and 17% in the semi-closed greenhouse compared to traditional fertigation (TF) in the corresponding greenhouses (Jokinen et al. 2011). The same result was obtained by Mononen (2011) when cucumber plants under SRF gained 16% more yields compared to TF. However, no significant differences were found in neither the vegetative structure of plants nor the NUE. However, opposite results were obtained by Mäkelä (2012): when were no significant differences were observed in cucumber total yield, while the proportion of first-class fruits was greater in SRF.

Both yield and yield quality of tomatoes in a greenhouse were reduced under SRF compared to TF, while WUE exhibited no differences between TF and SRF (Karhula 2012). However, the SRF technique has not been tested for strawberry so far.

In partial root drying (PRD) system, amount of irrigation is withheld in some parts of the plant while the remaining parts are well watered (Jensen et al. 2009). Similarly to the SRF system, roots of a plant under PRD system are divided into two parts. However, different amounts of irrigation water are provided to the two sides instead of fertigation solution with different EC values.
PRD system applied to strawberry cultivation increased WUE although it decreased the berry yield and yield quality (Liu et al. 2007). As Liu pointed out, it was the decreased water consumption that attributed to the increase of WUE, instead of the increase in crop yield.

For fruit quality, Dodds et al. (2007) found that although yield of strawberries was reduced under PRD (60% amount of water in fully irrigation), the antioxidants like ascorbic acid (AsA) and ellagic acid increased in strawberry fruits under PRD.

2.5 Effects of EC and salinity on strawberry growth and yield

Lieten and Misotten (1993) studied the nutrient uptake of strawberry cv. Elsanta under protected production for the first time. They concluded that dry matter accumulation of the whole plants reached a peak during the green fruit stage; after that, dry matter kept growing in leaves and petioles, but decreased in roots and crowns because of the transfer into fruits. They found that uptake of macronutrients including nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) reached the peak at the flowering stage. For micronutrients, iron (Fe) consumption was highest in the early development stage of plant and it occupied the largest percentage of strawberry micronutrients. Manganese (Mn) uptake was constant during the whole experiment, and the uptake of boron (B) occurred mainly during flowering because of its important role in receptacle development. Zinc (Zn) and copper (Cu) were found in low concentration and were consumed mainly in fruit developing stage.

Previous studies suggested irrigation water with EC of 1.3 mS/cm for cv. Elsanta in greenhouse production (Lieten and Misotten 1993). Substrate supplier recommended EC ranging from 1.2 mS/cm to 2.0 mS/cm for different plant development stages (Appendix 1). In Alpine strawberry (Fragaria vesca L.), nutrient content in irrigation water expressed by EC had effects on vegetative growth characteristics, and an EC about 1.2 mS/cm was recommended for growing for summer-spring culture cycle (Caruso et al. 2011).
Osmotic stress is one of the potential stresses that the plants might suffer from in SRF. Since the studies on high EC caused by high fertilizer are limited, I also reviewed the effects of high EC caused by NaCl on strawberry plants.

It is the sodion (Na+) that mainly attributes to salinity stress in fertigation solution, and the NaCl was always added to adjust the EC for salinity stress studies (Bisko et al. 2007). Fresh berry yield of strawberry cv. Rapella grown in rockwool decreased with the increasing salinity (from EC=2.5 to EC=8.5 mS/cm) in fertigation solution (Awang et al. 1995). Fresh berry yield of strawberry cv. Elsanta decreased when 2 mmol/l NaCl was added to the irrigation solution (Lieten et al. 2006b). Cv. Elsanta grown on coconut coir obtained the highest fresh yield under EC 2.5 mS/cm irrigation solution adjusted by NaCl (D’Anna et al. 2003).

Beside of the effects on berry fresh yield, high EC caused by 2mmol/l NaCl also reduced the berry size and fruit number of cv. Elsanta (Lieten et al. 2006b). Sugar content and titratable acid content in fruit were increased along with the increase of NaCl from 0.5, 1, 2, 3, 4 to 5 mmol/l (Lieten et al. 2006b). Fruit firmness was found to be improved by the increasing NaCl concentration (D’Anna et al. 2003; Lieten et al. 2006b). Keutgen (2003) found that cv. Elsanta was more sensitive to salinity than cv. Korona. The titratable acid content and sugar content were reduced under salinity stress (under 80 mmol/l NaCl), while the content of ascorbic acid remained stable. According to Keutgen (2007), the content of phenolics increased but the content of ascorbic acid decreased less than 40 mmol/l NaCl.

Plant growth responses to environmental stress are always interfered by stress adaptation. A functional link between morphological and physiological traits was established to understand plant growth and stress adaptation (Orsini et al. 2012). Under salinity, cv. Elsanta maintained larger leaf area compared to cv. Elsinore. Higher tolerance to salinity of cv. Elsanta was thought to attribute to the lower stomatal density, which resulted into lower transpiration rate of Elsanta (14.7 g H$_2$O plant$^{-1}$ h$^{-1}$) compared to Elsinore (17.7 H$_2$O plant$^{-1}$ h$^{-1}$) and the delayed accumulation of toxic ions that enabled plant to adjust more effectively to hyperosmotic environment.
Keutgen and Pawelzik (2009) observed that under NaCl stress, K in fruit and petiole increased, Ca, Zn and Cu were unaffected; Mg, Mn and Fe were decreased slightly in leaves, and N content increased in every part of the plant. Reduction of fruit yield caused by salinity was also observed in experiments carried out by Saied et al. (2004).
3 RESEARCH OBJECTIVES

The aim of this study was to examine the responses of strawberry cv. Elsanta (Fragaria × ananassa Duch.) under the split root fertigation (SRF) in a greenhouse. General parameters will be estimated for plant vegetative growth, yield and berry quality, and plant water use in the experiment.

The hypothesis of the experiment was that strawberry plants would take up water with the roots in the low EC side without suffering from drought stress, and would obtain adequate nutrients from the high EC side. The system was believed to reach an optimal balance between water uptake and nutrient absorption and to obtain a higher WUE. Growth would be unaffected. Further more, yield and berry quality of strawberry would be improved or unaffected.
4 MATERIALS AND METHODS

4.1 Plant material and growing conditions

The experiment was carried out in the greenhouse at the University of Helsinki (60°22’N, 25°02’E, Viikki, Helsinki, Finland) from Feb 15th to May 28th, 2013. Four split root fertigation lines were installed in a greenhouse compartment.

Strawberry (Fragaria × ananassa Duch. cv. Elsanta) frigo A⁺ plants (Neesen Aardbeienplanten & Aspergeplanten, Netherland) were planted on Feb 15th, 2013. Containers with two compartments (Figure 2 A, figure 3; ‘Kekkilä Duo’, 31.5 cm × 50 cm × 13 cm, 18 l, Kekkilä, Tuusula, Finland) were used as the container for splitting the root system of plants. Unfertilized peat (Kekkilä, Tuusula, Finland) was chosen as the substrate. Three plants were planted in one container and formed an experimental unit. Ten containers formed a row, where the distance between the plants was 0.19 m. There were in total six rows with a distance of 0.6 m between the rows. The final density was 2.78 plants/m². There were 32 experimental units; the outermost rows and the pots at the end of each row being buffer plants (Figure 2 B).

![Figure 2](image_url)

Figure 2. ‘Kekkilä Duo’ containers with compressed peat (A), and experimental greenhouse compartment (B).
For the establishment of plant material, fertigation was conducted based on the recommendation provided by the fertilizer producer (Kekkilä, Tuusula, Finland). Fertigation solutions with equal EC 1.2 mS/cm and 1.6 mS/cm were used in the establishment period (from Feb 15th to Feb 20th) and the early fast-growing period (from Feb 21st to Mar 1st), respectively. After 2 weeks of cultivation when there were on average 5 to 6 leaves on plants, different fertigation treatments were applied to plants on Mar 1st.

Air temperature was controlled by the Priva greenhouse system (Priva, De lier, The Netherlands) was kept at 19.7±2.0 °C. Artificial light was provided when natural irradiation was not adequate by high-pressure sodium lamp (SON-T 400W Philips); light intensity was controlled above the value of 80 µmol m⁻² s⁻¹.

4.2 Fertigation and the treatments

The drip irrigation system was used for fertigation. Two drippers were inserted for each side of the container. The fertilizers (Superex, Kekkilä Oy, Tuusula, Finland) and water were added as a complete fertigation solution. Four types of fertigation solutions that differed in EC values (mS/cm) were prepared: EC 0.7, EC 1.4, EC 2.8
and EC 4.2. Ratios between nutrients in four fertigation solutions were kept same. Recipes of fertilizers changed depending on the growth stage of strawberry plants, as recommended by the producer of fertilizers (Appendix 1).

Four different fertigation treatments were applied. In TF treatment, the EC values were same in both sides of the container (1.4/1.4). Three levels of SRF treatments with low, medium, and high mean EC in irrigation water were designed for the experiment. In these SRF treatments, half of roots received the irrigation solutions with lower EC value of 0.7 mS/cm, the other half of roots received irrigation solutions with EC values of 1.4 mS/cm (SRF1), 2.8 mS/cm (SRF2), and 4.2 mS/cm (SRF3).

Same amounts of fertigation solution were provided to both sides of a container. Considering that the water up-take might be different between the two sides treated with different fertigation solutions, excessive fertigation solution was applied. Records of the fertigation system settings are shown in Figure 4. Irrigation was conducted by pumps (BILTEMA, Art.17-961, PA 800W, Helsingborg, Sweden) under systematic control in the experiment.

![Irrigation Frequency Chart](image)

**Figure 4.** Record of the irrigation frequency (times/day) during the experiment. Pumps were operated for 2 minutes for each irrigation action.
4.3 Monitoring of water use

Fertigation solution provided by a single dripper from each fertigation line was collected and recorded weekly. Weekly fertigation water flow was calculated by the following equation:

\[ V = 2 \times (v1 + v2), \]

where:

- \( V \) = total weekly water flow per container (ml)
- \( 2 \) = number of drippers per compartment
- \( v1 \) = water provided weekly per dripper in low-EC side (ml)
- \( v2 \) = water provided weekly per dripper in high-EC side (ml)

Leakage was collected and recorded weekly. Two holes were made at the outer corners of each compartment in containers. Dripping tips installed upright through holes were used for drainage. Plastic bottles that hang under the table collected water dripping down from 16 experimental units including one replicate under four treatments in four blocks. The leakage collecting system was improved in the middle of the experiment period. Larger plastic containers placed on the ground were chosen, while tubes that were connected to funnel form pipette tips (10 ml) transported leakage water into containers. Weekly total amount of leaching was calculated by summing up volumes of leaching water from both sides of a container.

Water up-take percentage was calculated by dividing the difference value between the amount of fertigation solution provided and the amount of leakage by the amount of solution provided. WUE was determined by dividing the total fresh yield (FY) by the total amount of solution used over the whole experiment period and was expressed as g fruit/l water.

About 50 ml leakage was collected for the weekly measurement of pH by pH meter (UltraBasic Benchtop Meters, Denver Instrument, NY, USA) and electrical conductivity (EC) by conductivity meter (4010, JENWAY, Bibby Scientific Limited, UK).
To characterise the conditions in substrate, water content (WC) and EC were measured weekly by WCM-control device (Grodan WCM, Grodan BV, the Netherlands).

### 4.4 Observation on vegetative growth

Leaf number per plant, petiole length and number of runners were recorded every two weeks. Runners were removed and their dry weight (DW) measured twice, on Apr 5th and May 3rd. Fully stretched leaves of a whole plant were counted for the leaf number; petiole length of the third youngest leaf of each plant was measured; runners that longer than 5 cm were counted. At the end of the experiment, fresh weight (FW) and dry weight (DW) of the aboveground parts of the plants were measured. Total leaf areas (TLA) of 16 plants were measured by the Leaf Area Meter (LI-3000A portable Leaf area meter, LI-COR. Inc, Nebraska USA); samples for the analysis of leaf nutrient contents were harvested at the same time. Photographs of the root system in substrate and out of substrate were taken. DW of leaves and runners were measured by digital balance (PJ3000, Mettler-Tledo, LLC, Columbus USA) after in oven (model UFE 800, Memmert, Schwabach, Germany) at 80 °C.

Leaf nutrient contents were analyzed by Viljavuuspalvelu Oy (Mikkeli, Finland) based on the measurement methods made by the Finnish Accreditation Service (FINA) in accordance with ISO/IEC 17025 accreditation process. The recommended macronutrient contents of strawberries are (g/kg DW): N 25-32, P 2.5-4.0, K 15-25, Ca 8-15, Mg 2.5-6.0; and the recommended micronutrient contents (mg/kg DM): B 30-70, Cu 7-15, Mn 40-100, Zn 20-70.

### 4.5 Berry yield and analysis of yield quality

The date for the beginning of flowering was defined as the date when the first fully open flower was observed in a plant. The total number of fully opened flowers per plant was recorded on the date when the first fully ripened berry was obtained. The berry was regarded as fully ripened when the whole berry surface was covered by red color.
Berries were harvested twice a week during the harvesting period starting on Apr 15th (9 weeks after planting) always at a same time in the morning. Number and fresh weight of berries harvested were counted or measured immediately. Berry samples were collected and stored at +5 °C for quality measurements.

For fruit quality, berry dry weight, vitamin C and total phenolics were measured once in the middle of the harvest season (on May 5th, May 8th and May 17th, respectively). TSS and TA content of fresh berry was measured at two time points during the harvesting season (on Apr 30th and May 10th respectively). Pressed fruit juice was filtered for all the analyses.

Content of berry vitamin C was determined by the iodometric titration method using eight to ten fresh berries. Two ml of strawberry juice or standard ascorbic acid solution (100 mg/100 ml) and 1 ml of starch solution (10 g/l) were added to a 10 ml Erlenmeyer flask. Sample was stirred with a magnetic stirrer and titrated by Iodine-potassium iodide (KI-I₂) solution (10 mmol/l) using a burette until the iodine blue-black colour is visible. Three parallels were conducted. The content of vitamin C in strawberry was expressed as g ascorbic acid/100ml juice.

Total phenolic content was assessed using the Folin-Ciocalteu method (Lester et al. 2012). Six to eight fresh strawberries from each treatment in each block were used for analysis.

Dry matter content was measured in +70 °C oven for 2 d (UFE 800, Memmert, Schwabach, German). Ten weighed berries from each treatment of each block were cut into two pieces and placed on large culture dishes.

Six berries from each block for four treatments were used for the measurement of TSS. Pressed fruit juice was filtered and TSS measured by refractometer (Master-α, ATAGO, Japan). Three parallel readings were conducted.
Eight fresh berries were used for determining the TA content in pressed and filtered strawberry juice. 0.1 N NaOH was used for the titration until pH reached 8.1. TA content was expressed as citric acid equivalent (g citric acid / 100 ml juice).

Sugar and acid ratio is calculated as:

\[
\text{Sugar acid ratio} = \frac{\text{°Brix value}}{\text{concentration of acid (g/L acid)}}
\]

For fruit shelf life assessment, 16 to 20 berries from each treatment in each block were randomly divided and packed in two ventilated plastic containers (Kit for 250 g, PET, ventilation slits, 143 X 96 X 50 mm, 1/2 liter, Järvenkylä Oy, Finland). Half of the strawberries were used for the analysis of fresh fruit firmness, total soluble solids (TSS) and titratable acid (TA); the other half of the strawberries were weighed and stored in a +5 °C cold room for one week before the same measurements. Fruit firmness was determined as maximum penetration force by texture analyzer (TA-XT2i, Stable Micro systems Ltd, UK). All berries were cut into two pieces for the measurement of firmness. Speed of 10 mm/s, penetration distance of 5 mm, and probe with a diameter of 0.6 mm were used. Weight loss was defined as the percentage of weight lost during storage. Fruit firmness, TSS and TA were also assessed at the end of the storage experiment.

4.6 Experimental design and data analysis

The experiment was carried out as a nested design, where four blocks were nested within four fertigation treatments. There were 2 replicates in each block. An experimental unit consisted of 3 plants (a container). The data was analyzed using a model: \( y = \mu + T + b + e \), where \( \mu \) = overall mean, \( T \) = fixed effect of fertigation treatment, \( b \) = random block effect nested in \( T \), and \( e \) = random error term. Data were subjected to the analysis of variance (ANOVA) by SPSS (version 21, SPSS Inc., Chicago, IL, USA). A two-way-ANOVA was used for the analysis of TSS, TA and firmness in the storage experiment. Tukey’s Studentised Range (HSD) was applied to compare the treatment means.
5 RESULTS

5.1 Substrate and leaching water

5.1.1 Substrate conditions

Volumetric soil water content ($\theta$) in substrate of TF was above 50% (v/v) during the experiment (Figure 5 A). $\theta$ values in substrates under all treatments showed an increasing trend during the experiment. Compared with the TF, $\theta$ of the low-EC sides of the 3 levels of SRF treatments were lower. Except for SRF1, $\theta$ of the high-EC sides of SRF treatments were higher than in the TF treatment. Differences in $\theta$ between the high-EC sides and low-EC sides in SRF treatments increased with the increasing EC difference of the irrigation solution. $\theta$ values in high-EC sides and low-EC sides were significantly different in SRF1 and SRF2.

EC in substrate under different treatments was comparable to the EC of the corresponding irrigation solution (Figure 5 B). In TF plants, EC of the substrate increased from 1.4 mS/cm to 2.3 mS/cm during the experiment. EC in low-EC sides of the SRF treatments fluctuated between 1.0 and 2.0 mS/cm. EC of high-EC sides showed different trends of changing: EC of the high-EC side of SRF1 (1.4 mS/cm) was similar with TF; EC of the high-EC side of SRF2 (2.8 mS/cm) increased to 3.0 mS/cm; EC of the high-EC side of the SRF3 (4.2 mS/cm) increased to 3.7 mS/cm during the experiment.
Figure 5. Substrate volumetric soil water content ($\theta$) (A) and EC (B) of pot-grown strawberries under TF treatment and SRF treatments with three different EC combinations. For SRF treatments, root compartments with low EC values are indicated as SRF1_0.7, SRF2_0.7, and SRF3_0.7, while the root compartments with high EC values are indicated as SRF1_1.4, SRF2_2.8 and SRF3_4.2. Vertical bars present ± S.E. (n=8).

5.1.2 Amount and EC of leakage

During the experiment, weekly leakage volume increased with the increasing of the irrigation frequency. Less leakage was collected from the low-EC sides in SRF
treatments compared to the high-EC sides, and the difference increased with time (Figure 6 A). The differences in leakage volumes between the two sides increased with the increasing difference in EC values.

Figure 6. Weekly amounts of leakage (A) and EC (B) of fertigation solution of pot-grown strawberries under TF treatment and SRF treatments with three different EC combinations. For SRF treatments, root compartments in low EC sides are indicated as SRF1_0.7, SRF2_0.7, and SRF3_0.7 while the root compartments with high EC values were indicated as SRF1_1.4, SRF2_2.8 and SRF3_4.2. Vertical bars present ± S.E. (n=8).
EC in leaching water from TF and high-EC sides of the SRF treatments was similar to the values of EC in irrigation solutions (Figure 6 B). EC values in leakage from low-EC sides of SRF1 and SRF2 were almost the same, and lower than in SRF3.

5.1.3 Water uptake and WUE

Total water uptake was on an average 65 l per container (21.7 l per plant) during the experiment. Water uptake percentage was 70.3 on average. There were no significant differences between the treatments in total water uptake and water uptake percentage (Table 1, Figure 7). The calculated water use efficiency (WUE) over the whole production period was on average 15.2 g fruit/l water. There were no significant differences in WUE between the treatments.

Table 1. Water uptake and calculated water use efficiency (WUE) of strawberry under traditional fertigation (TF) treatment and split root fertigation (SRF) treatments with three different EC combinations during the experiment. Values are means of four replicates. P=0.05.

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Water uptake (l/plant)</th>
<th>Irrigation (l/plant)</th>
<th>Water uptake (%)</th>
<th>Total yield /pot (g)</th>
<th>WUE (g Fruit/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TF(1.4/1.4)</td>
<td>21.1</td>
<td>30.23</td>
<td>69.9</td>
<td>308</td>
<td>14.6</td>
</tr>
<tr>
<td>SRF1 (0.7/1.4)</td>
<td>22.3</td>
<td>30.34</td>
<td>73.7</td>
<td>345</td>
<td>15.5</td>
</tr>
<tr>
<td>SRF2 (0.7/2.8)</td>
<td>22.3</td>
<td>31.88</td>
<td>69.9</td>
<td>341</td>
<td>15.3</td>
</tr>
<tr>
<td>SRF3 (0.7/4.2)</td>
<td>21.0</td>
<td>31.03</td>
<td>67.8</td>
<td>319</td>
<td>15.2</td>
</tr>
<tr>
<td>P-value</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
</tbody>
</table>
Figure 7. Percentage of water uptake of pot-grown strawberries under TF treatment and SRF treatments with three different EC combinations during the experiment. Data are means of four replicates. Error bars show S.E.

5.2 Growth of the plants

5.2.1 Vegetative growth

There were no obvious differences in plant structure or appearance between the treatments as observed visually. There were no significant differences in the number of leaves, petiole length, or dry weight of the aboveground parts of plants between the treatments (Figure 8, Table 2). However, differences occurred in the total leaf area (TLA), where plants under SRF2 had the highest total leaf area that increased up to 41% compared to TF (Table 2). There were no significant differences in the number of runners, fresh weight (FW), runner dry weight (DW), and DM/FW ratio of the runners between the treatments (Table 2).
Figure 8. Number of leaves per plant (A) and petiole length (B) of pot-grown strawberries under TF treatment and SRF treatments with three different EC combinations during the experiment. Data are means of eight replicates. Vertical bars present ± S.E. (n=8).
Table 2. Runner number, fresh weight, dry weight, and the dry matter content (DM/FW), DW of aboveground plant parts, and the total leaf area (TLA) of pot-grown strawberries under traditional fertigation (TF) treatment and split root fertigation (SRF) treatments with three different EC combinations. Data are means of eight replicates. Values marked with same letter within columns are not significantly different using Tukey’s Test at P=0.05.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>No of runners</th>
<th>Runner FW (g)</th>
<th>Runner DW (g)</th>
<th>DW/FW (%)</th>
<th>Plant DM (g)</th>
<th>TLA (cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TF (1.4/1.4)</td>
<td>8</td>
<td>113</td>
<td>13.8</td>
<td>23.5</td>
<td>55.5</td>
<td>3425 b</td>
</tr>
<tr>
<td>SRF1 (0.7/1.4)</td>
<td>7</td>
<td>106</td>
<td>11.1</td>
<td>20.6</td>
<td>53.6</td>
<td>3541 b</td>
</tr>
<tr>
<td>SRF2 (0.7/2.8)</td>
<td>7</td>
<td>95</td>
<td>11.1</td>
<td>21.1</td>
<td>61.0</td>
<td>4831 a</td>
</tr>
<tr>
<td>SRF3 (0.7/4.2)</td>
<td>8</td>
<td>96</td>
<td>10.8</td>
<td>22.0</td>
<td>58.4</td>
<td>2946 b</td>
</tr>
</tbody>
</table>

5.2.2 Leaf nutrient contents and

The nutrient content of strawberry leaves was affected by the treatments (Table 3). Leaf N was increased by SRF treatments, being higher in SRF3 than in TF or SRF1. Leaf Mg was also increased in all SRF treatments compared to TF. Leaf B was lower in plants under SRF1 treatment than in the other treatments. Leaf Mn in plants under SRF1 treatments was significantly lower than in TF or SRF3.

Table 3. Leaf nutrient contents of pot-grown strawberries under traditional fertigation (TF) and split root fertigation (SRF) treatments with three different EC combinations. Data are means of two replicates. Values marked with same letter within columns are not significantly different using Tukey’s Test at P=0.05.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>N  (g/kg DW)</th>
<th>P  (mg/kg DW)</th>
<th>K  (g/kg DW)</th>
<th>Ca (g/kg DW)</th>
<th>Mg (g/kg DW)</th>
<th>S  (g/kg DW)</th>
<th>Fe (mg/kg DW)</th>
<th>B  (mg/kg DW)</th>
<th>Cu (mg/kg DW)</th>
<th>Mn (mg/kg DW)</th>
<th>Zn (mg/kg DW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TF (1.4/1.4)</td>
<td>21.7 b</td>
<td>5.5</td>
<td>26</td>
<td>6.5</td>
<td>2.9 b</td>
<td>1.5</td>
<td>96</td>
<td>69 a</td>
<td>6.5</td>
<td>200 a</td>
<td>62</td>
</tr>
<tr>
<td>SRF1 (0.7/1.4)</td>
<td>22.3 b</td>
<td>5.1</td>
<td>28</td>
<td>7.9</td>
<td>3.1 a</td>
<td>1.5</td>
<td>93</td>
<td>56 b</td>
<td>6.1</td>
<td>140 b</td>
<td>45</td>
</tr>
<tr>
<td>SRF2 (0.7/2.8)</td>
<td>23.4 ab</td>
<td>5.1</td>
<td>26</td>
<td>8.9</td>
<td>3.2 a</td>
<td>1.5</td>
<td>94</td>
<td>79 a</td>
<td>6.1</td>
<td>180 ab</td>
<td>47</td>
</tr>
<tr>
<td>SRF3 (0.7/4.2)</td>
<td>24.1 a</td>
<td>5.4</td>
<td>28</td>
<td>7.9</td>
<td>3.1 a</td>
<td>1.5</td>
<td>99</td>
<td>75 a</td>
<td>7.2</td>
<td>185 a</td>
<td>51</td>
</tr>
<tr>
<td>P-value</td>
<td>0.02</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>0.01</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
</tbody>
</table>
5.2.3 Flowering

Plants in all the treatments started to flower within 6 days. Flowering time of plants in SRF treatments seemed to concentrate on earlier days compared with plants under TF treatment. The difference was significant between plants in SRF2 and TF on Mar 15th: more plants in SRF2 had produced flowers compared to TF plants (Figure 9). Flowering in SRF2 and SRF3 seemed to be accelerated compared to TF.

Figure 9. Effect of fertigation method on the time of flowering for strawberry under traditional fertigation (TF) and split root fertigation (SRF) treatments with three different EC combinations. Cumulative percentage of plants that had produced the first fully opened flower were counted. Means marked with same letters are not significantly different by Tukey’s Test at P=0.05.

5.2.4 Visual evaluation of root system

In substrate, the distributions of roots in two compartments of four fertigation treatments at the end of the experiment are shown in Figure 10. No visual differences in root system between low-EC and high-EC sides could be observed. Form the figure of root system separated from substrate, the two parts of the root system for a
single plant from each of the treatments are shown in Figure 11. Roots in low EC sides of three SRF treatments contained more lateral roots.

Figure 10. Photos of the distribution of root system in container at the end of experiment. TF= traditional fertigation; SRF1, SRF2 and SRF3 are split root fertigation treatments with three different EC combinations.

Figure 11. Photos of root systems of strawberry plants under four fertigation treatments at the end of the experiment. TF= traditional fertigation; SRF1, SRF2 and SRF3 are split root fertigation treatments with three different EC combinations.
5.3 Berry yield and quality

5.3.1 Berry yield

Each plant produced on average 27 berries and fresh yield of 328.4 g in this experiment; average berry weight was 12.5 g. There were no differences in total berry yield between the treatments, but the average berry weight was lower in SRF3 than in other treatments (Table 4).

In all the treatments harvesting of fully ripened strawberries started 9 weeks after planting and reached a peak 12 weeks after planting (Figure 12 A). There were no differences in weekly yield between the treatments. Average berry weight decreased during the harvesting season (Figure 12 B). In all the treatments, cumulative number of harvested berries and berry yield showed a similar trend (Figure 13).

Table 4. Total fresh berry yield (FY), berry number and average berry weight of pot-grown strawberries under traditional fertigation (TF) treatment and split root fertigation (SRF) treatments with three different EC combinations. Data are means of eight replicates. Values marked with same letters within columns are not significantly different by Tukey’s Test at P=0.05.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>FY/plant (g)</th>
<th>Berry weight (g)</th>
<th>No. of berries/plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>TF (1.4/1.4)</td>
<td>308.0</td>
<td>12.3 a</td>
<td>25</td>
</tr>
<tr>
<td>SRF1 (0.7/1.4)</td>
<td>345.4</td>
<td>12.7 a</td>
<td>28</td>
</tr>
<tr>
<td>SRF2 (0.7/2.8)</td>
<td>341.5</td>
<td>13.0 a</td>
<td>27</td>
</tr>
<tr>
<td>SRF3 (0.7/4.2)</td>
<td>318.8</td>
<td>11.9 b</td>
<td>27</td>
</tr>
<tr>
<td>P-value</td>
<td>ns</td>
<td>0.03</td>
<td>ns</td>
</tr>
</tbody>
</table>
Figure 12. Weekly fresh yield per plant (A) and the average berry weight (B) of pot-grown strawberries under traditional fertigation (TF) treatment and split root fertigation (SRF) treatments with three different EC combinations. Data are means of eight replicates. Vertical bars present ± S.E. (n=8).
Figure 13. Cumulative number of harvested berries (A) and cumulative fresh berry yield per plant (B) of pot-grown strawberries under traditional fertigation (TF) treatment and split root fertigation (SRF) treatments with three different EC combinations. Data are means of eight replicates. Vertical bars present ± S.E. (n=8).
5.3.2 Berry quality

Average content of titratable acids in strawberry in this experiment was 1.1 g/100 ml fruit juice (predominant acid is citric acid). No differences existed in the concentration of TA in berry between the treatments as measured for two times (Table 5). Concentrations of TSS ranged from 8.4 °Brix to 9.5 °Brix and were not different between the treatments early in the harvesting season, but were significantly different later during harvesting, when berries in SRF3 treatment contained less soluble solids compared to ones under SRF2 treatment. Consequently, there were also differences in the ratio of TSS and TA; berries under SRF3 and TF had significantly higher TSS/TA ratio as compared to SRF2.

Average content of dry matter of strawberry was 10.4 %, average vitamin C content 77.5 g/l, and average total phenolics content 1.4 mg/g in this experiment. These three parameters in berry exhibited no differences between the treatments (Table 6).

Strawberries lost on average 3.3 % weight during one-week storage at +5 °C, but no differences were observed between different fertigation treatments (Table 7). Berries harvested from different fertigation treatments exhibited no differences in firmness. Firmness values of berries under all treatments increased during the storage.

The contents of TA and the contents of total TSS in strawberry fruit did not change during the 7-day storage; effects of treatments, storage or the interaction between treatments and storage were not significant (Table 8).
Table 5. Content of total soluble solids (TSS), titratable acids (TA), and the ratio of sugar to acid (TSS/TA) at two harvesting time points, for strawberries under traditional fertigation (TF) treatment and split root fertigation (SRF) treatments with three different EC combinations. Data are means of eight replicates. Values marked with same letters within columns are not significantly different by Tukey’s Test at P=0.05.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>TSS (°Brix)</th>
<th>TA (g/100 ml)</th>
<th>TSS/TA (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Week 11</td>
<td>Week 12</td>
<td>Week 11</td>
</tr>
<tr>
<td>TF (1.4/1.4)</td>
<td>8.8</td>
<td>8.8 ab</td>
<td>1.0</td>
</tr>
<tr>
<td>SRF1 (0.7/1.4)</td>
<td>8.6</td>
<td>9.3 ab</td>
<td>1.0</td>
</tr>
<tr>
<td>SRF2 (0.7/2.8)</td>
<td>9.0</td>
<td>8.4 b</td>
<td>1.1</td>
</tr>
<tr>
<td>SRF3 (0.7/4.2)</td>
<td>9.0</td>
<td>9.5 a</td>
<td>1.1</td>
</tr>
<tr>
<td>P-value</td>
<td>ns</td>
<td>0.03</td>
<td>ns</td>
</tr>
</tbody>
</table>

Table 6. Content of dry matter (DW/FW), vitamin C (VC), and total phenolics (TPH) in berries under traditional fertigation (TF) and split root fertigation (SRF) treatments. Data are means of eight replicates. P=0.05.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>%DW/FW</th>
<th>VC (g/l)</th>
<th>TPH (mg/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TF (1.4/1.4)</td>
<td>10.0</td>
<td>76.8</td>
<td>1.5</td>
</tr>
<tr>
<td>SRF1 (0.7/1.4)</td>
<td>10.7</td>
<td>79.7</td>
<td>1.3</td>
</tr>
<tr>
<td>SRF2 (0.7/2.8)</td>
<td>10.4</td>
<td>79.1</td>
<td>1.5</td>
</tr>
<tr>
<td>SRF3 (0.7/4.2)</td>
<td>10.4</td>
<td>74.3</td>
<td>1.5</td>
</tr>
<tr>
<td>P-value</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
</tbody>
</table>

Table 7. Berry weight loss during storage and firmness (indicated as maximum force in penetration test) before and after a 7-day-storage at 5 °C when strawberries were grown under traditional fertigation (TF) and split root fertigation (SRF) treatments with three different EC combinations. Data are means of four replicates.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Weight loss (%)</th>
<th>Firmness (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 d</td>
<td>7 d</td>
</tr>
<tr>
<td>TF (1.4/1.4)</td>
<td>3.6</td>
<td>1.68</td>
</tr>
<tr>
<td>SRF1 (0.7/1.4)</td>
<td>3.1</td>
<td>1.82</td>
</tr>
<tr>
<td>SRF2 (0.7/2.8)</td>
<td>3.5</td>
<td>1.78</td>
</tr>
<tr>
<td>SRF3 (0.7/4.2)</td>
<td>3.1</td>
<td>1.81</td>
</tr>
<tr>
<td>P-value</td>
<td>ns</td>
<td>ns</td>
</tr>
</tbody>
</table>
Table 8. Values of titratable acids (TA) and total soluble solids (TSS) before and after storage when strawberries were grown under traditional fertigation (TF) and split root fertigation (SRF) treatments with three different EC combinations. Data show means of 4 replicates.

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Change during storage</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TSS (Brix°)</td>
<td>TA (g/100ml)</td>
<td></td>
</tr>
<tr>
<td>TF (1.4/1.4)</td>
<td>8.8</td>
<td>8.1</td>
<td>1.0</td>
</tr>
<tr>
<td>SRF1 (0.7/1.4)</td>
<td>9.3</td>
<td>7.8</td>
<td>1.1</td>
</tr>
<tr>
<td>SRF2 (0.7/2.8)</td>
<td>8.4</td>
<td>8.7</td>
<td>1.1</td>
</tr>
<tr>
<td>SRF3 (0.7/4.2)</td>
<td>9.5</td>
<td>9.6</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Change during storage:

<table>
<thead>
<tr>
<th>Treatments</th>
<th>TSS (Brix°)</th>
<th>TA (g/100ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>Treatment × storage</td>
<td>ns</td>
<td>ns</td>
</tr>
</tbody>
</table>
6 DISCUSSION

6.1 Plant water use

While monitoring the EC values in both substrate and leakage, I found that when adequate or even excessive amount of irrigation water was given to pot-grown strawberries, EC values in both substrate and leakage were similar and corresponding to the EC values in irrigation water. This result was consistent with the work of Jokinen (2011) that EC in the outflow water didn’t differ from the inflow one. But this result was in contrast with the previous observation of Ondrasek et al. (2008), who found the EC values in rooting medium being over twice of the ones in the nutrition solutions when cultivating melon (*Cucumis melo* L.) in peat.

High EC values in the substrate of the high-EC sides of SRF treatments were the cause of the greater volumetric water content (θ) and larger amount of leakage in the same sides. This finding indicated that a high EC in the fertigation solution caused osmotic stress and reduced water uptake for this crop. Water was taken up preferentially from the low EC sides, which proves that our experimental system functioned. From the calculated percentages of water uptake, I can conclude that SRF treatments affected not the total water up-take, but the water uptake distribution in this experiment. This result was consistent with former studies (Sonneveld and Voogt 1990; Sonneveld and Kreij 1999; Tabatabie et al. 2003; Mavrogianopoulos et al. 2012).

There were no differences in WUE between TF and SRF treatments in our experiment about strawberry. Same results have been obtained in other experiments on cucumber and tomato (Karhula 2012, Mäkelä’s 2012, Mononen 2011). The increase of WUE in the SRF fertigation system that has been found in ventilated greenhouse cucumber cultivation (Jokinen et al., 2011) was not observed in our tests on strawberry. In the test by Jokinen et al. (2011), it was the higher yield obtained rather than a reduction of water uptake that improved the WUE in SRF treatment.

Here is a potential for more tests in the future. Based on the results of my study, the SRF system may have no benefits on strawberry production in terms of water use.
However, for applying SRF on strawberry production, more EC combinations with greater differences between different EC sides could be tested in future.

### 6.2 Growth and yield of strawberry plants

**6.2.1 Plant growth**

The general vegetative structure of strawberry plants was not affected by different fertigation treatments. The results were consistent with Mononen’s (2011) experiments on cucumber. The only difference found in the present study was the increase in the total leaf area in SRF2 treatment (EC 0.7/2.8) compared to traditional fertigation (TF). Since strawberry plants suffering from water deficiency have lower total leaf area (Liu et al. 2006), I suggest that under optimum conditions with adequate water and nutrient supply, promotion in the total leaf area can be obtained; the combination of EC in SRF2 might be optimal for strawberry leaf growth. On the contrary, Jokinen et al. (2011) observed that the whole architecture of cucumber plants in SRF was positively modified compared to the TF: the leaf number, plant fresh weight and plant height were promoted significantly in SRF treatment compared to TF. Thus, compared to cucumber plants, strawberries might not be so salt-sensitive to be affected by treatment with different EC values in fertigation water.

The SRF treatments tested here provided enough water and nutrients and avoided the decrease in the total leaf area that would affect the photosynthesis and the final yield. The decrease of leaf area caused by drought stress under deficient irrigation (DI) and PRD treatments as observed by Liu et al. (2007), was not found in our experiment, indicating that SRF system caused no drought stress symptoms.

The result on the leaf mineral contents indicated that SRF treatments caused no serious nutrient deficiency. High EC in SRF treatments (SRF2 and SRF3) had no negative effects on mineral nutrients, and even increased the leaf Mg and leaf N contents presumably because of higher contents of nutrients in irrigation water in the high EC sides. The decrease in micronutrients B and Mn in SRF1 was probably caused by fertigation water with a lower fertilizer concentration in SRF1 treatment.
An interesting finding was that the flowering process was accelerated by SRF treatments. With the increase of the EC in fertigation solution, the emergence of flowers was concentrated in a fewer days. However, the number of inflorescences was not affected by SRF treatments.

SRF treatments did not affect stolon production or their biomass. Root system in low EC sides of SRF treatments contained more lateral roots for absorbing water, which is in consistency with the result that more water was taken up from the low-EC sides.

6.2.2 Yield and yield quality

The SRF treatments did not affect the strawberry fresh yield or the number of berries. However the average berry weight was lower in SRF3 compared to other treatments. Since high EC caused by NaCl was found to reduce both fresh yield and berry size of cv. Elsanta (Lieten et al. 2006b), the lower berry weight in SRF3 might indicate that plants had suffered from certain level of osmotic stress. However, berry dry matter content was not affected by SRF treatments, indicating that plants did not suffer from drought stress or salinity stress (Awang et al. 1995) during the fruit development period. The cucumber yield has been observed to increase under SRF (Jokinen et al. 2011; Mononen 2011), and the tomato yield to decrease under SRF (Karhula 2012). However, no significant differences in cucumber fresh yield under SRF were found by Mäkelä (2012). It appears that the effect and function of SRF method vary greatly between crop species. Different SRF treatments with different EC combination might be the cause for the differences in cucumber, tomato and strawberry yield results. Since yield is regarded as the dominant parameter to evaluate a fertigation system, we recommend more combinations with wider range of EC for the future studies.

Changes in the content of TSS, TA and TSS/TA, as taste related compounds in strawberry under SRF were reported for the first time. The titratable acid contents were uninfluenced by SRF treatments. TSS contents interpreted by °Brix in the later harvest date indicated that strawberries in SRFs contained the same amount of TSS compared with berries in TF. Berries in SRF2 (EC 0.7/2.8) had less sugars than in SRF3 (EC 0.7/4.2), and consequently had lower TSS/TA than in TF or SFR3, indicating less sweetness compared to TF (Jouquand et al. 2008). To explain the
lower TSS in berries in SRF2 but not in SRF3 or SRF1, I suppose that plants in TF and SRF1 did not suffer from osmotic stress because that EC values in substrate were in a proper range. Plants under SRF2 and SRF3 took up water mainly from the low EC (0.7) side because high EC (2.8 and 4.2) in the other side depressed the water and nutrient uptake of that side. Since Lieten (2006b) found that sugar contents increased with the increasing of NaCl concentration; berry dry matters increased under salinity stress (Keutgen and Pawelzik 2008). The lower TSS in strawberries under SRF2 is difficult to be explained. Firstly, plants did not suffer from water deficiency. Secondly, plants in our experiment did not suffer from nutrient deficiency (no deficiency in leaf nutrient contents and almost no albino berries occured). Literature shows that salinity stress can cause the increase of dry matters and sugar content (Keutgen and Pawelzik 2008; Lieten 2006b), which had not been found in this SRF systems. And in my experiment, only SRF3 reduced the berry size, which might indicate it suffered from salinity stress. Further studies about the SRF system with some physiological parameters might be necessary to explain the phenomenon.

Values of ascorbic acid and total phenolics were similar between TF and SRFs. However it proved that plants did not suffer from drought stress. The increase in vitamin C and ellagic acid (Dodds et al. 2007) and the improvement in fruit firmness under high EC stress (D’Anna et al. 2003; Lieten et al. 2006b) was not found in this experiment.

SRF treatments had no influences on the strawberry fruit shelf life. On a contrary, the increase of shelf life in cucumbers under split root system has been found (Sonneveld and Kreij 1999; Tabatabie et al. 2003). Differences in TSS/TA between SRF2 and TF on TSS/TA disappeared after storage, which might be due the respiration during storage. The increases in the firmness values are common in short time storage, where the increase of CO₂ in the atmosphere has been shown to increase strawberry fruit firmness in several experiments (El-Kazzaz et al., 1983; Smith 1992; Smith and Skog 1992; Harker et al., 2000). The storage time in the test of shelf life here was proved to be too short to find out differences. For further tests, a storage time about 3 weeks is recommended.
Yield of fruits is affected by various factors. Differences in yield of cucumber under split root system with different EC combinations were found in the spring production, but could not be repeated in the experiment carried out in the autumn (Sonneveld and Kreij 1999). As Sonneveld and Kreij (1999) demonstrated that, low average EC values in the split root system might not make differences in cucumber yield. We recommend more EC combinations for larger EC range for further studies of SRF system on strawberry.
7 CONCLUSION

In this experiment, water uptake of strawberry plants was successfully modified under SRF treatments. Water was taken up preferably from the low-EC side, which means an unequal distribution of water uptake within the two root compartments. However, the total water uptake had no differences between TF and SRF treatments. Plants vegetative growth was affected in total leaf area, leaf nutrient content and flowering date. Plants SRF2 (EC 0.7 / 2.8 mS/cm) obtained the highest total leaf area at the end of the experiment. Leaf nutrients were affected. Acceleration in flowering by SRF was also observed in the experiment. For fruit quality, average berry weight reduced by SRF3 that had the highest EC values in irrigation water. TSS/TA decreased in berries under SRF2. Although changes were found in some aspects, most parameters tested here showed no differences including some important parameters like berry yield and WUE. In the future, more combinations of EC in a wider range are recommended for further research.
8 ACKNOWLEDGEMENTS

I would like to express my gratitude to all those who helped me during the writing of this thesis. My deepest gratitude goes first to my supervisor Dr. Pauliina Palonen, for her constant encouragement and guidance. She has guided me through all the stages of the conducting the experiment and writing of this thesis. Without her consistent and illuminating instruction, this thesis could not have reached its present form.

Second, I would like to express my gratitude to Professor Dr. Paula Elomaa, who gave me so many help and valuable advices during my two years of study. I am also greatly indebted to the technicians and teachers at the Department of Agriculture Sciences: Marjo Kilpinen and Matti Salovaara, who have instructed and helped me in the experiment. My thanks gives also to phD student Tero Tommila for his help for solving various problems in the experiment.

At last my thanks would go to my beloved family for their loving considerations and great confidence in me all through these years. I also owe my sincere gratitude to my friends and my fellow classmates who gave me their help and time in helping me work out my problems during the difficult course of the thesis.
REFERENCES


University of Helsinki. Finland. Only abstract available from Dr. Pauliina Paulonen.


# APPENDIX 1

Fertigation recommendation

Date: 01,2013

<table>
<thead>
<tr>
<th>Development stages</th>
<th>Turve-superex (peat) g/1000 l</th>
<th>Typpi-happo (N) ml/1000 l</th>
<th>CaN-jauhe () g/1000 l</th>
<th>N mg/l</th>
<th>K mg/l</th>
<th>N:K</th>
<th>EC in fertigation (water)</th>
<th>EC in sub:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic fertigation</td>
<td>590</td>
<td>30</td>
<td>286</td>
<td>121</td>
<td>161</td>
<td>1:1.34</td>
<td>1.2</td>
<td>2.0-3.</td>
</tr>
<tr>
<td>After establishment</td>
<td>960</td>
<td>40</td>
<td>246</td>
<td>161</td>
<td>261</td>
<td>1:1.63</td>
<td>1.6</td>
<td>2.0-3.</td>
</tr>
<tr>
<td>Early flowering stage</td>
<td>1330</td>
<td>40</td>
<td>282</td>
<td>211</td>
<td>361</td>
<td>1:1.71</td>
<td>2.0</td>
<td>2.5-3.</td>
</tr>
<tr>
<td>Late flowering stage</td>
<td>1040</td>
<td>40</td>
<td>120</td>
<td>151</td>
<td>281</td>
<td>1:1.87</td>
<td>1.6</td>
<td>3.0-4.</td>
</tr>
<tr>
<td>Harvesting stage</td>
<td>930</td>
<td>30</td>
<td>0</td>
<td>121</td>
<td>251</td>
<td>1:2.08</td>
<td>1.3</td>
<td>3.0-4.</td>
</tr>
</tbody>
</table>

P.S. pH between 5.5-6.5