



Split root fertigation enhances cucumber yield in both an open and a semi-closed greenhouse

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ABSTRACT

We investigated the hypothesis that split root fertigation (SRF) approach could provide complementary benefits over traditional fertigation (TF) in terms of water use, vegetative growth and yield formation in the high radiation season and under two atmospheric conditions in a greenhouse. Plants of cucumber (*Cucumis sativus* L. cv. Cumuli) were grown in a traditional high-wire cultivation system in a peat growing medium. In the SRF method the root system of a plant was separated into two compartments over the crop cycle. One compartment received fertigation solution with low EC (1.2 dS m^{-1}) and the other compartment solution with high EC (3.5 dS m^{-1}) value. In the TF method the EC value of fertigation solution was 2.4 dS m^{-1} . The atmospheric conditions included an open (ventilated) and a semi-closed (cooled) greenhouse. The employment of cooling resulted in an enhancement of the average CO_2 in a semi-closed (810 ppm) over an open (530 ppm) greenhouse resulting in a yield improvement (37%). SRF improved water uptake in both atmospheric conditions and water use efficiency (WUE) in an open greenhouse. The water uptake in SRF was highest in the root part with the low EC values, namely 61% in the open and 66% in the semi-closed greenhouse. In both atmospheric conditions, SRF decreased flower abortion, leading to an improved fruit set with a small effect on vegetative growth. SRF increased yield by 21% in the open and 17% in the semi-closed greenhouse compared to TF in corresponding greenhouses.

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1. Introduction

In order to achieve a significant reduction in the environmental impact of greenhouse production it is essential to develop climatic controls and cultivation methods, maximizing the use of available resources such as solar radiation, water and nutrients. It is commonly accepted that a high concentration of nutrient salts in the fertigation solution causes water stress whereas a low concentration results gradually in nutrient deficiency. Thus fertigation programs can be managed according to electrical conductivity (EC, dS m^{-1}), which is a better indication of the availability of nutrients to the plants than the fertilizer concentration in the nutrient solution (Van Iersel, 1999). The yields of most crops are significantly decreased when the EC value of irrigation water or fertigation solution is too high (Maas and Hoffman, 1977; Sonneveld, 2000; James and Van Iersel, 2001; Sonneveld et al., 2004). The crop-specific threshold value (EC value) without yield reduction, is between 0.7 and 3.8 dS m^{-1} for substrate-grown crops in the greenhouse and depends on climatic conditions (Sonneveld, 2000). The growth

reduction due to high EC is intensified at increased radiation levels and temperature (Sonneveld, 2000).

Greenhouse seedless cucumber (*Cucumis sativus* L.) has a high nutrient requirement and is very productive when supplied with sufficient nutrients, but it is also considered to be moderately salt-sensitive (Sonneveld and Voogt, 1978). An EC value of about 1.5 dS m^{-1} was shown to be sufficient for maximum cucumber production, and the salinity threshold value was about 2.5 dS m^{-1} (Sonneveld, 2000). Since the uptake of nutrients changes with the growing conditions and even from day to day, the concentration of one or more nutrients in the root environment may become insufficient. An increase of the nutrient concentration in the fertigation solution will improve the nutritional status of the plant, but beyond the salinity threshold value, the water uptake of the plant will decrease, resulting in a yield decrease of this crop (Sonneveld, 2000). Moreover, in summer and on high radiation days, the transpiration of the plant canopy in the greenhouse can be so great that the root system is unable to provide enough water to maintain water potential and yield formation (Puustjarvi, 1977), the stomata close, and CO_2 utilization is severely limited (Bunce, 2006). Thus, adjusting the optimum level of the EC value in the fertigation solution to gain maximum production, in the unpredictable greenhouse atmosphere, remains challenging.

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Split root fertigation (SRF) approach may provide complementary benefits over traditional fertigation (TF) in terms of water and nutrient uptake and ultimately yield improvement. In the SRF method variable fertilizer EC values can be applied to separate root compartments of a plant. Plant response to nutrient salts, as affected by an unequal distribution of salts in the root environment, was studied with cucumber in rockwool in the recirculated nutrients (Sonneveld and Kreij, 1999). An EC values of 2–3 dS m⁻¹, the uptake of nutrients was highest in the root parts with the highest concentration of nutrients, but at higher EC values nutrient uptake decreased rather quickly. Water was preferably absorbed from the root part with the lowest EC and at high EC values water uptake was significantly restricted.

A split root approach is also utilized in partial root-zone drying (PRD), where water is distributed unevenly to the root system and assimilates are predominantly partitioned to support fruit growth (reviewed by Shao et al., 2008). Among other studies, the PRD experiments confirm that under osmotic stress, chemical signals such as abscisic acid (ABA), pH and cytokinins are implicated in root to shoot signalling (Skriver and Mundy, 1990; Davies et al., 2000; Jiang and Hartung, 2008; Schachtman and Goodger, 2008).

In addition to precise nutrient and water management, a properly managed atmosphere can improve the marketable yield and quality. Air CO₂ concentration is a relevant climate variable to be controlled in greenhouses as it has a marked effect on plant CO₂ assimilation (Stanghellini, 2005; Särkkä et al., 2006; Luomala et al., 2008; Sánchez-Guerrero et al., 2009). In addition to the yield improvement, the CO₂ enrichment has significant effects on the water use efficiency of the greenhouse agroecosystem (Sánchez-Guerrero et al., 2009). Moreover, elevated CO₂ supply has been shown to lead to increased salt tolerance (reviewed by Sonneveld, 2000).

Theoretically, in properly managed SRF, the low EC roots provide the major part of water to shoots and prevent water deficits in atmospheric conditions that are favourable for high production and high transpiration particularly. Therefore, our main objective of this study was to assess the interaction and contribution of the split root fertigation and atmospheric conditions in a semi-closed greenhouse (mostly high CO₂ concentration) on the yield formation and water use of the peat-grown cucumber crop in Northern Europe. Our major hypothesis was that the SRF system would increase the fruit yield of cucumber over the TF systems mainly due to the enhanced water availability. We also hypothesized that cucumber productivity would further be increased in a semi-closed greenhouse with SRF as compared to an open greenhouse with TF due to the improved utilization of the available growth factors.

2. Materials and methods

2.1. Growth conditions and plant material

The experiment was carried out in two greenhouse compartments (cooled vs. ventilated) in Piikkiö (60°23'N, 22°33'E) in southwestern Finland. Two fertigation systems (traditional, TF vs. SRF, split root fertigation) were installed in each greenhouse compartment (130 m², wall height 3.2 m on the flat side).

In the cooled compartment (a semi-closed greenhouse), air temperature and humidity were controlled with the cooling system (Särkkä et al., 2006), and the roof vents were opened only when cooling capacity was insufficient (threshold 26 °C). From the beginning of July on, the opening of the vents in the cooled compartment was limited to the maximum of 28%. In the ventilated compartment (an open greenhouse), temperature was controlled by opening the vents. CO₂ enrichment (target 1000 µmol mol⁻¹) was applied when the vents were less than 30% open. High pressure fogs were used for

humidity control in both compartments. An ITU Multi Station 10 climate controller (Itumic, Jyväskylä, Finland, www.itumic.fi) in each compartment automatically controlled the microclimate. The values of greenhouse air temperature, vapour pressure deficit (VPD), CO₂ concentration, roof vent aperture, root-zone temperature, and outdoor global radiation and air temperature were automatically recorded every four minutes.

Seeds of cucumber (*Cucumis sativus* L.) cv. Cumuli were sown in rockwool blocks (10 × 10 × 7.5 cm) on May 12, 2008. Seedlings were raised on benches and flood irrigated according to standard recommendations (Tailor-Made Superex, Kekkila Finland; EC 2.5 dS m⁻¹, pH 5.5). Day and night temperatures were 22 °C and 20 °C, respectively. The HPS lamps at 200 cm above the ground supplied 150 µmol m⁻² s⁻¹ (PAR) in an empty greenhouse. Twenty-one days after sowing, and after the appearance of the fifth true leaf, transplants 40 cm tall were transferred into the experimental conditions.

In order to compare traditional fertigation (TF) and split root fertigation (SRF) with their different EC values, sets of four cucumber plants were grown in a peat board (Vegetable board, Kekkila, Finland) of 100 cm length, 20 cm width and 9 cm height, providing 4.5 L of peat for each plant. There were two drippers per plant. In the SRF method the board was completely separated by a plastic barrier to prevent solution transport between them. Each seedling was placed onto the board in such a way that it could grow roots into both. Sonneveld and Kreij (1999) describe the basic scheme of this approach. In the SRF method the boards were fertigated by separated drip systems (one dripper per plant per side), which allowed the provision of different nutrient concentrations on the two compartments. For the first two weeks, all the plants were supplied with the same fertigation solution (EC 2.4 dS m⁻¹), so plants could root equally. For the SRF treatments, different EC values in the separated peat board were established after this interval.

The experimental cucumber plants were cultivated from June 3rd to August 28th 2008 for 11 harvesting weeks. The plants were grown using the high wire method (top at the height of 3.2 m) and in single rows at a density of 2.3 plants m⁻². Artificial light was supplied for 20 h d⁻¹ when outdoor global radiation was less than 150 W m⁻². The top and interlighting HPS lamps supplied 220 µmol m⁻² s⁻¹ in an empty greenhouse at 80 cm above the ground.

2.2. Fertigation

The fertigation system, identical in both greenhouse compartments, was an open-loop system, which applied the solution through drip irrigation. The nutrients and water were added as a complete fertigation solution, as recommended for commercial cucumber growing in peat (Tailor-Made Superex, Kekkila Oy, Finland). At an EC value of 2.0, the concentrations of elements in the nutrient solution added were (mg/L): N 218, P 42, K 303, Ca 137, Mg 38, S 30, Fe 0.92, Mn 0.42, B 0.26, Zn 0.14, Cu 0.08, Mo 0.05 and Co 0.01.

To avoid water stress and for precise control of the nutrient concentrations and pH of the solution, 30–40% excess fertigation solution was applied daily over the cultivation period. The fertigation was performed five to ten times a day. The EC values and pH were monitored weekly in samples from the drip solutions in both greenhouses. In addition, the amount, pH and EC of the leaching solution were monitored daily in a collecting tray within the crop. The average inflow values of EC (± SE) over the crop cycle in the split root fertigation (SRF) were 1.2 (± 0.1) dS m⁻¹ and 3.5 (± 0.2) dS m⁻¹ in low and high EC solutions, respectively. In the traditional fertigation treatment (TF), the EC value was 2.4 ± 0.1 dS m⁻¹. The solution

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