

Sustainable Cities: Viability of a Hybrid Aeroponic/Nutrient Film Technique System for Cultivation of Tomatoes

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Abstract—Growing environmental and sustainability concerns have driven continual modernization of horticultural practices, especially for urban farming. Controlled environment and soilless production methods are increasing in popularity because of their efficient resource use and intensive cropping capabilities. However, some popular substrates used for hydroponic cultivation, particularly rock wool, represent a large environmental burden in regard to their manufacture and disposal. Substrate-less hydroponic systems are effective in producing short cropping cycle plants such as lettuce or herbs, but less information is available for the production of plants with larger root-systems and longer cropping times. Here, we investigated the viability of a hybrid aeroponic/nutrient film technique (AP/NFT) system for the cultivation of greenhouse tomatoes (*Solanum lycopersicum* ‘Panovy’). The plants grown in the AP/NFT system had a more compact phenotype, accumulated more Na⁺ and less P and S than the rock wool grown counterparts. Due to forced irrigation interruptions, we propose that the differences observed were confounded by the differing severity of water-stress for plants with and without substrate. They may also be caused by a higher root zone temperature predominant in plants exposed to AP/NFT. However, leaf area, stem diameter, and number of trusses did not differ significantly. The same was found for leaf pigments and plant photosynthetic efficiency. Overall, the AP/NFT system appears to be viable for the production of greenhouse tomato, enabling the environment to be relieved by way of lessening rock wool usage.

Keywords—Aeroponic/nutrient film technique, greenhouse, nutrient dynamic, soilless culture, urban farming, waste reduction.

I. INTRODUCTION

In recent years, there has been increased effort to modernize horticultural practices to meet the demands of a population approaching 9 billion, with 66% of the world’s population projected to be urban by 2050 [1]. The capacity for traditional horticulture to meet the food-security and sustainability needs of the growing population has been called into question. Soil based crop production faces severe limitations including:

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diminishing land area, high nutrient and water inputs, soil degradation, prevalence of pests and disease, seasonal production limitations, high labour costs, and climatic changes due to global warming [2], [3]. Soilless production systems, however, are already recognized globally for their intensive crop production and high water and nutrient use efficiency, especially when used as a closed system [4]. These benefits do not only satisfy the producer in terms of resource use efficiency, but also satisfy the sustainability and environmental concerns of the consumer. In this context, we have seen continual increase in soilless cultivation with more than 405000 ha of greenhouse vegetable production worldwide, and more of such systems are being used for urban farming [5], [6].

In soilless production systems, plant roots are grown in solid organic (bark, peat, coir etc.) or inorganic (sand, gravel, perlite, rock wool etc.) media, which are frequently irrigated with nutrient solution, or grown directly in the nutrient solution without any solid medium [7], [8]. Compared to soil based production, the volume of growing media is much smaller or absent, which presents challenges in water retention. An effective growing medium must have sufficient water retention to prevent drought stress between irrigation events, but must also drain well enough to prevent asphyxia from continued waterlogging of the roots [9], [4].

Traditionally, selection and development of growing mediums was driven by performance and economic considerations. However, changes in societal attitudes have seen an increased focus on environmentally considerate and sustainable practices. Rock wool, for example, is a popular inorganic substrate used widely for vegetable cultivation, particularly for tomatoes, cucumbers and capsicums [10]. Rock wool cultivation systems are easily handled and assembled, have good drainage properties, offer good plant support and are completely inert, excluding minor effects on pH [10], [11]. However, the production and disposal of rock wool presents serious environmental challenges [9]. An Environmental Impact Analysis of greenhouse tomato cultivation was conducted in the Netherlands, where it was found that the rock wool substrate contributed 57.0 to 81.7% of the environmental impact of all auxiliary equipment (i.e., greenhouse materials excluding structure and climate control) [12]. While there has been moderate success in reusing rock wool, its widespread use still represents a significant waste burden [13], [14].

Because substrate-less hydroponic systems use no rooting media they have considerably lower environmental impact [14], [15]. The Nutrient Film Technique (NFT), for example, is a popular hydroponic system by which a thin layer of nutrient solution passes over bare roots held within watertight channels [5]. NFT is commonly used for short harvest cycle crops such as lettuce and herbs which can be harvested before the roots block the channels and reduce oxygenation and nutrient uptake [16]. Due to the lack of a solid substrate, plants grown in NFT systems are susceptible to drought stress caused by fertigation interruptions, such as power outages. Furthermore, because of the low nutrient solution volume these systems are susceptible to temperature fluctuations due to seasonal climatic changes [17]. Another alternative to rock wool based plant production are aeroponic systems, where plant roots are suspended in a fine mist of nutrient solution supplied continuously or intermittently [18]. Plants are fixed in a closed container and nutrient solution is applied to the hanging roots via micro-jet sprayers, misters or foggers inside the unit. Exposure of the roots to atmospheric oxygen has been shown to promote root metabolism and plant growth and eliminates the risks of root asphyxia faced by other hydroponic systems [19]. As with NFT, aeroponic cultivation is susceptible to irrigation and temperature disruptions due to the lack of a solid media to buffer these changes. Numerous vegetable and herb crops have been shown to have improved yield in aeroponic systems compared to either field grown or alternate hydroponic systems [8], [20]. However, few studies have analyzed the efficacy of aeroponic systems for the cultivation of larger plants such as full sized greenhouse tomato cultivars. Due to the large root system of tomato plants it would be impractical to construct a container which would completely suspend the roots. Therefore, we have created a hybrid aeroponic/nutrient film technique (AP/NFT) system which suspends the topmost section of the roots in an aeroponic mist, while the lower segment rests in a nutrient film of the returning excess nutrient solution. In the present study, we investigated the viability of the AP/NFT system for cultivation of tomato in a closed greenhouse mainly to dispense with growing substrates. We compared the vegetative development of *Solanum lycopersicum* L. (cv. Pannovy) in the AP/NFT system and a conventional rock wool hydroponic setup run in parallel in a single greenhouse unit. Root zone temperatures, plant physical parameters, macronutrient assimilation, photosynthetic efficiency, and pigment accumulation were analyzed. Furthermore, operating costs were compared.

II. MATERIAL AND METHODS

A. Climate Control in the Greenhouse

The experiments were carried out in an experimental greenhouse at Humboldt-Universität of Berlin from 1st November 2016 until 23rd January 2017. Both the rock wool and AP/NFT experiments were carried out side by side in a single greenhouse compartment. The wall regions were constructed from double glazed (16 mm) glass and the roof

from single (4 mm) glass with energy screens that automatically closed if global radiation dropped below 3 W/m². Floor level heating was installed directly under the cultivation systems and set at 18 °C/20 °C (day/night) with roof ventilation opened above 24 °C. Supplemental overhead 400 W HPS lamps (Philips SON-T AGRO) provided 50 μmol/(m²s) at 1.5 m from table surface, i.e. plant 'ground' level 16 h daily for the duration of the experiment.

B. Plant Material

Tomato (*Solanum lycopersicum* L., cv. Pannovy) seeds were sprouted in peat and transferred into rock wool blocks (10 × 10 × 10 cm) or perlite filled pots with the same dimension, which were used for the rock wool and AP/NFT systems, respectively. After two weeks' growth in the starter units, 16 plants per treatment were moved to the main greenhouse chamber and planted into the respective cultivation systems. String suspended from an overhead wire was used to support the plants during development.

C. Cultivation Systems and Mineral Analysis in the Nutrient solution

The recirculating AP/NFT system was a box (3.15 × 1.5 × 0.35 m) constructed from an aluminium frame and twin-wall corrugated plastic sheets, topped with interlocking high-density polystyrene foam panels (Styrodur[®]; BASF, Germany) and covered with a black and white (white side external) plastic sheet to isolate light influx to the root zone (Fig. 1). Two rows of eight square shaped holes (4 × 4 cm) were placed at a distance of 60 cm apart on the top of the box for a final plant density of 3.6 plants/m². The plants were wrapped with a small piece of rock wool at their base for support prior to planting. Within the root environment agricultural misters (Coolnet-Pro Fogger, 7.5 L/h, 28 – 13 psi check valve; Netafim, USA) were placed every 60 cm, roughly below each plant. AP/NFT fertigation events were every 5 minutes (day and night) for a duration of one minute, totaling 4 hours per day. The base of the unit was constructed with a slight decline (1%) to return excess nutrient solution to the open holding tank below the unit. This hybrid system exposed the top half of the root system to the aeroponic misting, while the lower half of the roots laid along the bottom of the box, in a nutrient solution film of the excess fertigation (Fig. 1).

The rock wool system was constructed from two rock wool slabs (Cutilene[®]Exact; Tilburg, The Netherlands) arranged side by side in nutrient solution channels. Eight holes (10 × 10 cm) per row were cut 60 cm apart into which the rock wool starter blocks were planted to achieve a final plant density of 3.6 plants/m². The plastic wrapper was slit in the underside of each slab to allow return of excess nutrient solution to the holding tank. Fertigation was achieved by means of two dripper-irrigation spikes per plant. Fertigation ran for 15 minutes per hour for a total of 4 h/d. Furthermore, the fertigation was forced to interrupt for two hours once a week to simulate power outages. This was done to investigate the buffer capability of both systems and plant responses caused by these events.

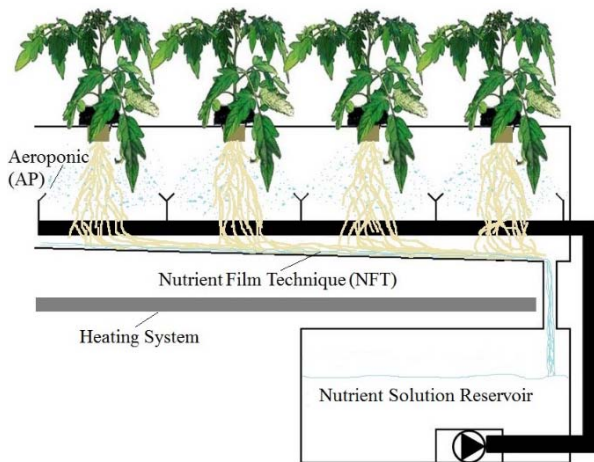


Fig. 1 Systemic Illustration

The nutrient solution used for both systems was prepared with fresh water as outlined by [21]. The 300-L holding tank was drained, and fresh nutrient solution prepared when remaining reservoir volume dropped below 20%. Samples from the outflow were taken weekly for 4 weeks starting on 22nd December 2016. These samples were analyzed for macronutrients (Ca, K, Mg, Na, P and S) via ICP-OES. The ICP Emission Spectrophotometer (iCAP 6300 Duo MFC, Thermo; Waltham, USA) was set to 1150 W RF power and 0.55 L/min nebulizer gas flow, with argon utilized for both the plasmogen and carrier gas. For each element, a standard solution (1000 mg/L) was used for preparation of analytic calibration solutions (1.4 mol/L HNO₃). The calibration curves were established as follows: blank 1.4 mol/L HNO₃; 0–100 mg/L of P; 0–300 mg/L of K; 1–300 mg/L Ca; 0–100 mg/L of Mg; 0–50 mg/L S and 0–100 mg/L Na. Each mentioned element was measured at a specific wavelength published in [9], except for Na which was measured at a wavelength of 598.9 nm. Samples were analyzed in duplicate and the final values expressed as mg/L.

D. Assessment of Phenotypic Changes

Digital sensors were used to monitor the root zone temperature (RZT) and nutrient solution reservoir temperatures of both systems. Sensors were placed in the areal part of the aeroponic system and in the main slab for the rock wool system and connected to a data analyser (Fluke, Hydra 2620A; Kassel, Germany) from which the temperature was recorded a minimum of three times daily over the period of one week.

During the first four weeks of the experiment, phenotypic data were collected for eight randomly selected plants in each system. Leaf number, internode distance, and leaf area measurements were performed only on mature (>20 cm) leaves. Leaf area was estimated as described in [22] calculated from the measured leaf width and length. The stem diameter was measured using a set of digital callipers at ground level, where the average of which was used for further analysis. Trusses were counted only upon first flower opening.

E. Optical Readings

A portable, hand-held spectrophotometer device (Pigment PA+/1101/801, CP, Control in applied Physiology GbR; Falkensee, Germany) equipped with photodiode arrays was used to measure the reflectance spectra of tomato leaves in the visible and near infrared range from 402 to 1048 nm (MMS1 NIR enh.; Carl Zeiss, Germany), providing a spectral resolution of 3.3 nm. An integrated light cup equipped with light-emitting diodes, capturing the entire wavelength range recorded, served as the light source. For calibration of this device, spectralon (20% certified, Labshere Ltd.; North Sutton, USA) was used as the white reference.

During calendar week two in 2017, 40 measurements from the 5th fully expanded leaf of different plants were collected per treatment group and their average reflectance indices used for estimation of the chlorophyll, carotenoid and the chlorophyll: carotenoid ratio (Table I). The normalized difference vegetation index (NDVI) was calculated by the pigment analyzer, and the average values were calculated.

TABLE I
LEAF REFLECTANCE SPECTRA INDICES USING THE RELATING INTENSITY (*I*)
AT A SPECIFIC WAVELENGTH

Index	Equation	Indicator for	Literature
Lichtenthaler's index	$I750/I550$	Chlorophyll (Chl)	[23]
Car-Ratio	$I550/I455$	Carotenoids (Car)	[24]
SIPI	$(I800-I445) / (I800-I680)$	Chl to Car ratio	[25]

Six weeks after planting, chlorophyll fluorescence was measured using a pulse-amplitude modulated system (IMAGING MAXI-PAM, M-series, Heinz Walz GmbH; Effeltrich, Germany) on 20-minute dark adapted leaflets. Nine randomly selected leaflets per treatment group were measured, and their readings were averaged to represent the average of plants within each system. A saturating light source was applied to dark adapted leaves to analyze the maximum quantum yield of photosystem II (F_v/F_m). The electron transport rate (ETR) was calculated as well. Both were done to detect stress responses of plants. The first mentioned parameter measures the ratio of variable fluorescence (F_v) to maximum fluorescence (F_m) (for parameter definition see [26]), whereas ETR is calculated as follows: $ETR = Y(II) \times PPFD \times 0.84 \times 0.5$.

F. Dry Matter and Chemical Analyses

For dry matter analysis, the fifth mature leaf and a 10 cm-section of stem were collected from six randomly selected plants and added to pre-weighed drying crucibles. Fresh weights were taken, and the samples dried overnight (24h) at 105 °C before being reweighed. The dry weight of six leaf and stem samples from each treatment group was averaged, and the value was expressed as a percentage of fresh weight (% DM).

For leaf mineral analysis (Ca, K, Mg, Na, P, S), three mature leaves (leaf from apex) were randomly selected three times from plants not being assessed for physical parameters. The sampling was done in parallel with the nutrient solution

sampling, i.e. four times. Leaves were harvested and stored at $-20\text{ }^{\circ}\text{C}$ and afterwards freeze-dried for 48 h (Christ Alpha 1-4, Christ; Osterode, Germany). The freeze-dried samples were ground to a fine powder and mixed so that each week-sample was comprised of three homogenized leaf-samples, which were stored in a desiccator until macronutrient analysis. To prepare the leaf samples for ICP-OES, 0.2 g of freeze-dried sample was weighed into deionized microwave-digestion tubes. 5 mL HNO_3 (65%) and 3 mL H_2O (30%) was added to each tube and the samples loaded into the microwave (MARS Xpress, CM; North Carolina, USA). The following digestion program was used: step 1, 20 min to reach $200\text{ }^{\circ}\text{C}$; step 2, 5 min at $200\text{ }^{\circ}\text{C}$; step 3, 1 min to reach $210\text{ }^{\circ}\text{C}$; step 4, 5 min at $210\text{ }^{\circ}\text{C}$; step 5, 1 min to reach $220\text{ }^{\circ}\text{C}$; step 6, 5 min at $220\text{ }^{\circ}\text{C}$; and step 7, 30 min cooling. Room temperature digestion products were transferred to a 50-mL volumetric flask, brought to volume with distilled water and filtered into plastic sample flasks. The ICP Emission Spectrophotometer was calibrated with standard solutions and run with the same operating conditions as outlined in Section C. Measurements were made in triplicate, with their average value used for further analysis.

For the measurement of carbon and nitrogen in the leaf samples, an elemental analyzer (vario MAX, Elementar Analysensysteme GmbH; Hanau, Germany) was utilized [27], [28]. 0.3 g of the sample was weighed into individual crucibles and was catalytically combusted at $900\text{ }^{\circ}\text{C}$ with pure oxygen. The combustion products and helium (carrier gas) passed through adsorption columns at $830\text{ }^{\circ}\text{C}$ to separate carbon and nitrogen. Based on the differences in thermal conductance, carbon and nitrogen concentrations in the sample were calculated using glutamic acid as a standard reference. Measurements were made in triplicate and expressed as g/kg dry weight (DW).

G. Statistical Analysis

Comparative analysis of mean values for the two systems was performed using SPSS package version 19.0. Mean variability was indicated as standard deviation. Significance of differences between the systems was calculated using the paired-two sample Student's t-test ($\mu_1 - \mu_2 = 0$, $\alpha = 0.05$). Correlations between variables were calculated via linear regression analysis, with the model-fit displayed as the coefficient of determination (R^2).

III. RESULTS AND DISCUSSION

A. Phenotypic Changes

The space limitations inherent in controlled environment cultivation mean that the phenotype, especially the height of plants, is important when assessing the viability of a cultivation system. Most of the parameters analyzed were unaffected by the two different cultivation systems over the entire assessment period, therefore only results of the last assessment day are highlighted (Table II).

Four weeks after the start of treatment, leaf number, total leaf area, and number of trusses did not differ significantly.

While average stem diameter showed no significant difference, the stem mid-section of AP/NFT plants was notably larger than those in the rock wool system, especially in the final week of assessment (data not shown). AP/NFT plants had significantly shorter internodes and total plant height; $85\pm 6\%$ and $75.6\pm 6\%$ of the rock wool-grown plants, respectively. Overall, the above ground sections of AP/NFT grown plants were more compact than their rock wool counterparts, while not differing in leaf number, area, or truss development. Generally, semi-dwarf plants are desirable for modern agriculture as they have lower resource usage (including spatial requirements) for equivalent or greater yields [29]. However, as all plants used in this study were of the same genetic line, it is likely that the observed phenotypic differences were a result of environmental conditions. The forced electrical interruptions, for example, caused a stopping of the irrigation for both systems for a duration of two hours once a week. This may have caused water stress for plants in both systems though this effect would have been more severe for the AP/NFT plants due to the lack of solid substrate to buffer this interruption. Although no wilting of leaves was visible, it is well known that water deficit promotes the development of root hairs and results in a net shift of photosynthate allocation to root development [30]. Unfortunately, because of the difficulty taking root samples from plants grown in rock wool, we were unable to assess whether this was the case in our experiment.

TABLE II
PHENOTYPIC CHANGES BY DIFFERENT SOILLESS SYSTEMS

Parameter (units)	Rock wool	AP/NFT
Plant height (cm)	105.63 ± 5.93^b	79.88 ± 4.39^a
Leaves (number/plant)	14.75 ± 0.83^a	14.63 ± 0.70^a
Leaf area (m^2)	0.845 ± 0.096^a	0.870 ± 0.051^a
Internode distance (cm)	5.69 ± 0.30^b	4.88 ± 0.26^a
Stem diameter (cm)	13.69 ± 1.56^a	15.88 ± 1.01^a
Trusses (number/plant)	1.38 ± 0.48^a	1.38 ± 0.48^a

The data represent average values ($n = 8$) per treatment group four weeks after start of treatment. Variability expressed as \pm standard deviation. Significance indicated by superscript letters ($p < 0.05$).

B. Reservoir and Root Zone Temperature

Root zone and nutrient solution-reservoir temperatures were recorded over a period of seven days to observe the fluctuations that result from nutrient solution replacement. Distinct drops in temperature can be seen on the 9th and 16th of January when the holding tanks were flushed and replaced with fresh water for mixing the solution (Fig. 2). In both instances, the temperature took approximately 24h to stabilise after a change. As expected, the AP/NFT root zone temperature closely followed that of the reservoir, while the solid-substrate in the rock wool system was able to buffer the temperature changes and remain relatively stable. Interestingly, during the period where the temperature was stable between solution changes, the AP/NFT ($\bar{\sigma} 25.9\text{ }^{\circ}\text{C}$) was approximately 4° warmer than the rock wool system ($\bar{\sigma} 21.9\text{ }^{\circ}\text{C}$) (Fig. 2). This was mainly based on the construction of the AP/NFT system, which can absorb more heat from the heat

output of the heating system than the rock wool system. Roots are more thermosensitive than shoots, and small changes to the RZT can have significant effects on plant growth and activity [31]. Previous studies have shown that root-zone heating can reduce root respiration and promote the growth of roots and shoots in hydroponically grown tomatoes [17]. 25 °C is regularly reported as the optimum RZT for soilless tomato cultivation, with severe reductions to growth below 15 °C and above 30°C [17], [32], [33]. We did observe differences in plant phenotype, which may have resulted from variations in temperature. However, in established literature, the relatively small differences in RZT seen in our study (4 °C) did not have as significant an effect (24.4 % reduction in shoot height) as we observed here [32], [33]. However, as we did not record the total root or shoot biomass we cannot determine the relative resource allocation between the two treatments.

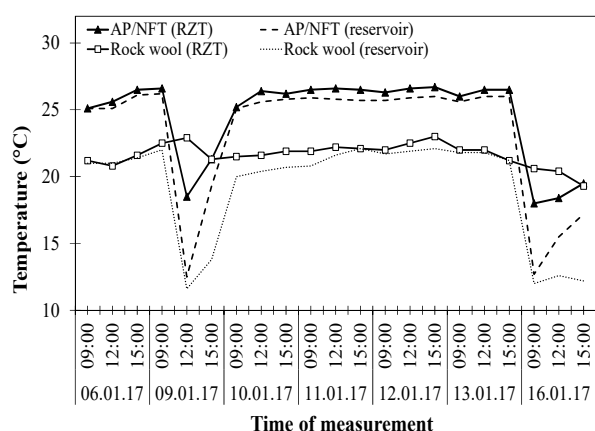


Fig. 2 Root zone temperature (RZT) and reservoir temperatures as recorded by four separate digital thermometer probes

C. Dry Matter and Nutrient Content

Dry matter did not differ significantly between treatments in either foliar or stem sections (Fig. 3). The distribution of dry matter among plant organs is a key variable in the survival and competitiveness of individual plants [34]. Many environmental variables affect the assimilation and partitioning of photoassimilates, including the availability of nutrients, moisture levels, and temperature [35]. Unfortunately, because we were unable to measure the dry weight of the roots, we could not assess whether there was different photoassimilate allocation between the two systems (i.e., differences in root/shoot DM ratio).

We monitored the nutrient solution and foliar macronutrient content weekly, for four weeks. The average phosphorus and sulphur content of leaves was found to be 13.7±8.5% and 13.6±21% higher in the rock wool treatment, respectively (Table III). Conversely, sodium accumulation in the AP/NFT plants was 42.7±19.7% higher than the plants grown in the rock wool system. All other measured macronutrients (N, C, Ca, K and Mg) did not differ significantly.

Generally, salt concentrations were uniformly higher in the AP/NFT solution, though the difference was non-significant. (Table IV). We suspect that this is a result of increasing water requirements of plants and higher evaporation due to higher reservoir and root zone temperatures causing a more rapid concentration of the solution. Especially, sodium in recirculating systems must be carefully monitored as evaporation and the water-consumption of the plants can concentrate salts over time [36]. A sodium concentration of 1148 mg/L has been shown to cause above 50% weight losses of tomato fruit and growth reduction when plants were produced using Deep Flow Technique [37]. Although the Na concentration in AP/NFT nutrient solution was high enough to cause a significant higher Na concentration in leaves, it is unlikely that the growth reduction in our AP/NFT plants was solely a result of the higher Na concentration, as the total concentration was 91.92 mg/L at highest; far below the approximated threshold for the 24.4% reduction in shoot height that we observed.

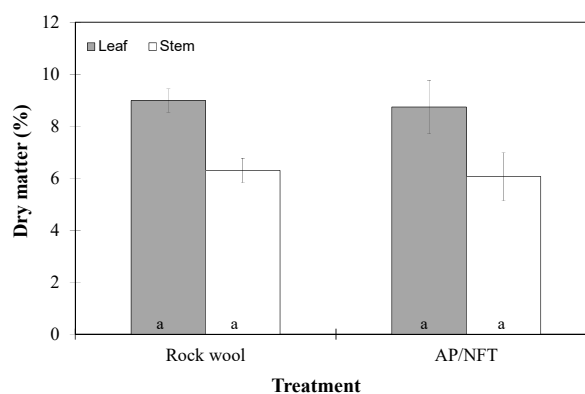


Fig. 3 Dry matter content of foliar and stem samples (n = 6 per treatment). Different small letters indicate significant differences at $p < 0.05$ and bars standard deviations

TABLE III
MINERAL CONTENT OF FOLIAR SAMPLES

Macronutrient	Rock wool (g/kg DW)	AP/NFT (g/kg DW)
N	49.60 ± 5.93 ^a	53.12 ± 4.65 ^a
C	413.36 ± 12.02 ^a	413.39 ± 10.70 ^a
Ca	21.91 ± 4.56 ^a	20.37 ± 3.25 ^a
K	61.01 ± 7.22 ^a	65.65 ± 3.85 ^a
Mg	6.55 ± 1.02 ^a	5.67 ± 0.54 ^a
Na	0.55 ± 0.19 ^a	0.96 ± 0.19 ^b
P	10.69 ± 0.92 ^b	9.24 ± 0.34 ^a
S	8.99 ± 1.90 ^b	7.76 ± 2.54 ^a

Mean values (± SD) from three tests of four replicates are presented for each treatment group. Significant differences ($p < 0.05$) are indicated by the superscript letters.

Osmotic adjustment via accumulation of ions or osmolytes is a conserved process in the plant kingdom in response to water stress [38]. Sodium is compartmentalized under both water and salinity stress to avoid cytosol toxicity but also increase the osmotic gradient [39]. Due to the forced irrigation interruptions, it is possible that the higher accumulation of Na

in AP/NFT leaves was a response to water-stress. This effect may have been compounded by the higher sodium concentration of the AP/NFT nutrient solution. Sodium ion adjustment is usually coupled with a higher Na/K ratio [40] as also shown in the present study (Tables III and IV).

TABLE IV
MINERAL CONTENT IN NUTRIENT SOLUTION OF THE EXCESS FERTIGATION

Macronutrient	Rock wool (mg/L)	AP/NFT (mg/L)
Ca	140.00 ± 30.02 ^a	162.18 ± 39.43 ^a
K	365.13 ± 85.33 ^a	365.35 ± 85.16 ^a
Mg	60.58 ± 13.70 ^a	70.35 ± 14.35 ^a
Na	88.35 ± 10.93 ^a	92.63 ± 18.04 ^a
P	49.85 ± 25.87 ^a	71.18 ± 33.78 ^a
S	128.93 ± 16.33 ^a	143.95 ± 24.31 ^a

Mean values (± SD) from four tests are presented for each treatment group. Significant differences ($p < 0.05$) are indicated by the superscript letters.

Phosphorous is an essential nutrient for proper plant functionality, with an unsubstitutable role in several key plant processes including energy transfer, photosynthesis, sugar and starch transformation, nutrient transport, and synthesis of genetic material [41]. De Groot et al. [42] showed that under high-light supply, a 2-fold increase in P-supply only increased foliar concentrations by 1%. Our results also conform to this trend; while the system concentrations of phosphorous were inconsistent, the leaf accumulation showed very little variability (Table III vs. Table IV). The plants from the two systems had differing levels of phosphorous accumulation, seemingly independent of P availability. Intermittent drought stress has previously been shown to decrease P uptake [43]. This may explain the lower P accumulation of AP/NFT plants in further support of water-stress being a causal factor in the variability observed between the two treatments.

Sulphur has a variety of important nutritional and functional roles within the plant and is considered the 'fourth major essential nutrient' after nitrogen, phosphorus, and potassium [44]. The interaction of nutrient solution and foliar concentrations of sulphur showed a strong positive correlation in both systems (data not shown). While the sulphur concentration was higher in the AP/NFT nutrient solution (Table IV), we observed a lower foliar concentration than in the rock wool plants (Table III); counter to the solution/foliar correlation that we observed. Significant reductions in sulphur uptake and accumulation is a known response of water-stressed tomato plants [45]. Again, the observed difference between the cultivation systems appears to be a result of the increased drought stress for the AP/NFT plants and higher salt concentrations in the nutrient solution.

D. Chlorophyll Fluorescence and Leaf Pigments

As an estimate of the maximum efficiency of photosystem II, we measured F_v/F_m and electron transport rate (ETR) of dark-adjusted leaflets. No significant differences were found between the treatment groups for either variable (Fig. 4). Furthermore, no clear effect on the pigment content of leaves was observed as a result of the cultivation system (Table V). The relative reflectance indices attributed to chlorophyll content (NDVI and Lichtenthaler's index) showed no

significant differences between the measurements taken from the AP/NFT and rock wool systems. Similarly, the carotenoid-related 'carotenoid ratio' index showed no significant differences. Consequently, the chlorophyll to carotenoid ratio index 'SIPI' indicated that there was no difference in pigment production between the two treatments.

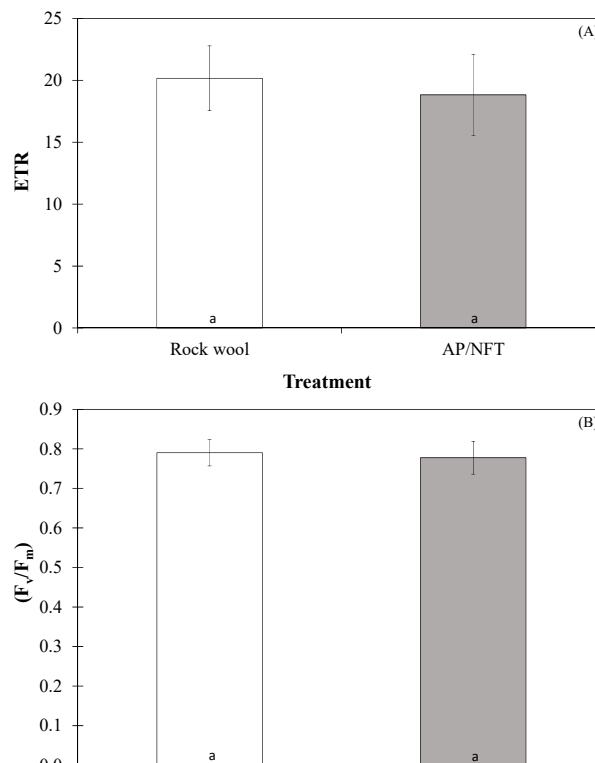


Fig. 4 Chlorophyll fluorescence kinetics of leaflets. (A) ETR – electron transport rate and (B) F_v/F_m – maximum quantum yield of photosystem II. Bars represent mean value of nine measurements per treatment. Different letters indicate significant differences ($p < 0.05$) and error bars represent standard deviation

TABLE V
SPECTRAL REFLECTANCE INDICES FOR ESTIMATES OF LEAF PIGMENTS

Index	Rock wool	AP/NFT
Lichtenthaler's index	1.47 ± 0.23 ^a	1.44 ± 0.23 ^a
NDVI	0.56 ± 0.13 ^a	0.52 ± 0.11 ^a
Car-Ratio	1.55 ± 0.45 ^a	1.39 ± 0.28 ^a
SIPI	0.77 ± 0.26 ^a	0.79 ± 0.16 ^a

Values represent the mean of 40 measurements per treatment. Statistical significance ($p < 0.05$) is indicated by the superscript letters. NDVI and Lichtenthaler's index served as estimation for chlorophyll content, whereas Car-ratio and SIPI were used for the estimation of carotenoid content and chlorophyll: carotenoid ratio, respectively.

While not significant, the AP/NFT plants had lower chlorophyll and carotenoid content in addition to lower ETR and maximum quantum yield. Ogren and Oquist [46] found a significant correlation between maximum quantum yield and water stressed plants, with a decrease in maximum quantum yield. Further, we would expect some differences in pigment production and photosynthetic efficiency if the effects on

other parameters were a result of a moderate water and salt stress. Photosynthetic pigments and processes are known to be affected negatively by both water-stress and nutrient supply [47]-[49].

IV. CONCLUSIONS

Rock wool is a popular substrate for hydroponic tomato cultivation, but its production and disposal represents a large environmental burden. We carried out this study to ascertain whether greenhouse tomatoes could be cultivated successfully in a substrate-less hydroponic system, thus reducing the net waste of production. The hybrid AP/NFT system produced plants that differed in height and internode distance, as well as accumulation of sodium, phosphorous, and sulphur. All other measured parameters did not differ significantly. Irrigation system redundancy is an essential aspect of soilless cultivation in both experimental and commercial scenarios. It appears that the differences that we observed were a result primarily of forced irrigation interruptions for the substrateless AP/NFT plants. This means that the buffering capacity of this system was lower than that of the rock wool system. To confirm this, the study should be repeated, with some alterations to the experimental design to ensure a more thorough and complete dataset. To collect data on the root systems, pre-weighing of rock wool slabs and divisions of the AP/NFT root-zone for individual plants would allow us to compare the root/shoot resource allocation. Fruit yield is an important variable for commercial producers. In future analyses, the assessment period should be extended until at least maturity of the first fruit set. Ultimately, the hybrid AP/NFT system produced comparable plants as traditional rock wool cultivation even under more severe water-stress. With the addition of irrigation redundancy, this system may prove to be a more sustainable, environmentally-friendly method for controlled-environment cultivation of tomatoes.

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