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Research article

Investigating minimal requirements for plants on textile substrates in low-cost hydroponic systems

Bennet Brockhagen[1], Fabian Schoden[1], Jan Lukas Storck[1,*], Timo Grothe[1], Christian Eßelmann[1], Robin Böttjer[1], Anke Rattenholl[2] and Frank Gudermann[2]

[1] Institute for Technical Energy Systems (ITES), Bielefeld University of Applied Sciences, Interaktion 1, 33619 Bielefeld, Germany
[2] Faculty of Engineering and Mathematics, Bielefeld University of Applied Sciences, Interaktion 1, 33619 Bielefeld, Germany

* **Correspondence:** Email: jan_lukas.storck@fh-bielefeld.de; Tel: +4952110670725.

Abstract: With a growing world population and the concentration of citizens in big cities new methods of agriculture are required. Vertical farming attracts more attention in mending these growing problems. To enable a widespread use of low-cost hydroponic systems this study investigates minimal requirements for plants (different herbs and vegetables) in such a hydroponic vertical farming system and the suitability of textiles as sustainable substrates. Therefore, this study aims to investigate plant stress levels, germination rates and water usage in a low-cost hydroponic system with no special lightning in principle comparison with indoor cultivation in soil. The results of the pulse-amplitude-modulation (PAM) measurements as measure of photosynthetic performance indicate that the plants were equally stressed in hydroponic and in soil cultivation. In this respect, the photosynthetic quantum yield in both cultivation systems is on average only slightly lower than the values expected under optimal conditions. It was observed that chive and lovage not only had a significantly higher germination rate in the hydroponic system but also accumulated significantly more fresh as well as dry biomass, while spinach, thyme and marjoram showed higher germination rates in soil cultivation. The water consumption in the setup was considerably higher for the hydroponic system compared to indoor soil cultivation.

Keywords: vertical farming; plant stress; textile fabrics; knitted fabrics; hydroponics; water efficiency; photosynthesis; pulse-amplitude-modulation

1. Introduction

The growing world population and the progressive climate change pose great challenges to mankind and require new farming methods for food and feed production. A method that promises higher yields while needing less space is vertical farming [1]. Usually, vertical farming is used in indoor farms [2] in aeroponic, aquatic or hydroponic systems, which are vertically stacked [3]. In addition to higher yields, food production could be realized in cities, where the majority of humans will live in the near future [4]. This would not only simplify long-distance transportation and costly logistics but would also allow the urban population to get engaged in growing their own food. Besides cities, light industrial buildings in rural areas, for example in Canada, could be retrofitted as hydroponic farms for local food supplies [5]. Majid et al. found in their research that hydroponic systems in temperate regions produce higher yields in less time and have a lower water consumption compared to soil-based systems [6].

Plants need substrate and mechanical support for proper growth. Thus, it is important to look at suitable and sustainable substrates to grow plants on. Materials like sand, peat, perlite [7] or textile fabrics [8] can replace soil in conventional farming systems. For several substrates (rock wool, perlite, vermiculite, peat, coconut fiber, bark, sand), life-cycle assessment (LCA) analyses and carbon footprints were compared, with the result, that sand is most suitable for hydroponic systems when costs and sustainability are taken into account [9]. However, textile substrates were not included in the study. Using textile fabrics for cultivating plants in hydroponic systems provides several advantages like stress resistance or the possibility to influence several parameters resulting in individually optimized substrates for each plant species [8]. The mechanical stability and persistence make the material more sustainable, because unlike other substrates, the textile fabric can be reused and is not degraded by roots growing through the knitted or woven fabric [10]. Nonetheless, few scientific studies investigated the application of textile fabrics in hydroponic systems [11]. That is why knitted fabrics from new yarn were chosen as substrates for the low-cost hydroponic system. To improve the long-term sustainability, recycled textiles could be used as substrates.

The downside of vertical farming, however, is its high energy consumption due to artificial illumination to enable photosynthesis, water circulation to stabilize plant water relations, and ventilation, heating as well as cooling to establish suitable growth conditions [12]. Therefore, vertical farming regimes should comply with sustainable development goals and the required energy should be provided from renewable sources. Al-Chalabi modeled how much energy would be necessary for a farmscraper as well as the carbon footprint of vertically grown food and interviewed stakeholders to evaluate what barriers and opportunities exist. He concluded that the building could generate enough energy with renewables to power the vertical farm, however, the carbon footprint for vertically grown lettuce is in summer five times higher compared to open field grown lettuce [3]. Additionally, in closed controlled environments the consumption of electrical energy should be shifted to times of low energy cost and high energy availability, for example at times when wind or solar power provide energy to the power grid. By this way vertical farming can become a moveable load and make the power supply more resilient [13]. The opportunity of vertical farming is the controlled environment, which allows crops to be grown over the entire year with higher biomass production, leading ultimately to increased energy efficiency [14].

Since large farms are more profitable, big companies rather than small farmers own and operate modern farmscrapers. Thus, the food supply depends on few large companies, which can jeopardize the food supply in the event of bankruptcy, plant diseases, malfunctions or natural disasters [8]. Low-cost, small-scale approaches could enable viable vertical farming applications and could alleviate the disadvantages of the large farmscraper issue. Not only for cities but also for farmers low-cost hydroponic systems could help to overcome fodder scarcities [15]. Mold is often responsible for seed loss. A possible solution for low-cost hydroponic systems is using sterile or aseptic conditions [16]. Standardization and procedures for a secure and pathogen free production is not yet established and the risk of human pathogen internalization in leafy vegetables exists [17]. To further improve low-cost hydroponic systems, it is important to investigate the main parameters, like water temperature or light quality, which could improve plant growth.

Here, the performances and stress levels of plants as well as the water consumption in a textile-based low-cost hydroponic system were studied to evaluate the suitability of textile substrates and the minimal plant requirements. Thus, the hypothesis that textile substrates are suitable for germination and cultivation in a low-cost and simple hydroponic vertical farming system and do not result in increased stress levels compared to indoor cultivation in soil was investigated. To this end, a pulse-amplitude-modulation (PAM) device was used to assess the photosynthetic performance of the plants as indicator for the stress level. Also, the germination rates and the accumulated biomasses were examined. Many studies compare low-cost hydroponic systems with outdoor soil cultivation [18–21] but not with indoor soil cultivation. That is why the water consumption of the presented low-cost hydroponic system with textile substrates was also investigated in comparison with indoor soil cultivation. This is of particular interest to potentially enable water-efficient forms of agriculture through vertical farming in the context of regions with water scarcity [22].

2. Materials and method

To investigate the minimal requirements of plants in low-cost hydroponic systems, the experimental setup depicted in Figure 1 was used. The dimensions of the boxes used for cultivation, which can be seen in Figure 1, are presented in Table 1.

Figure 1. Experimental setup of plant cultivation.

Table 1. Dimensions of boxes.

Parameter	Length in cm	Width in cm	Depth in cm
Small box	36.5	26.5	12
Large box	56.5	36.5	12
Water reservoir	56.5	36.5	32

The boxes were filled with a bottom layer of expanded clay (Floragard Vertriebs-GmbH, Oldenburg, Germany) and a top layer of cultivation soil (COMPO GmbH & Co. KG, Münster, Germany). The detailed information about both layers is displayed in Table 2.

Table 2. Soil parameters.

Type	Salt content in g/L	pH value	P_2O_5 in mg/L	K_2O in mg/L
Cultivation soil	1.8	5.0–6.5	80–300	100–350
Expanded clay	1.5	6.0–8.0	10–100	10–100

The plants in the soil were irrigated as needed. The large boxes formed the low-cost hydroponic system. As can be seen in Figure 1, chicken wire was used to hold the textile fabrics on a constant water level. The lower box served as a water reservoir. To enable a slow water circulation, a Heissner smartline HSP600-00 pump (Heissner, Lauterbach, Germany) was used. The water used was common tap water with a hardness level of 16 °d, i.e., 16 degrees of hardness – "hard" water. No nutrients were added to the tap water at the beginning of the experiment. Since the germination process and the early growth phase were investigated, the endogenous nutrient contents of the seeds were expected to be sufficient.

Since the experiment continued beyond the early growth phase and ran for 47 days in total, the water was exchanged every 14 days with supplemented hydroponic fertilizer (NPK-Fertilizer 6 + 4.5 + 5, Mairol GmbH, Gussenstadt, Germany) in a concentration of 1 mL fertilizer per 1 L water. Two Osram LED-tubes (TubeKIT LED 1.5 m 21.5W/830, Osram, Munich, Germany) with 150 cm length, color temperature of 3000 K, 21.5 W power input, 150° angle of irradiation, color rendering index CRI = 80 and luminous flux of 1890 lm were mounted on a self-made wooden construction in order to provide photosynthetic radiation to the plants. A timer controlled the LED-tubes and the light phase lasted from 6 a.m. to 10 p.m. to supply the plants with 16 h light and 8 h darkness per day. Since the laboratory was not darkened, daylight could enter and possibly provide the plants with a certain amount of light. This additional illumination was measured about 1 W/m^2 and therefore considered insignificant relative to the artificial light.

For the measurement of the photometric data of the lamps, the lamp measurement system "illumia" (Labsphere Inc., North Sutton, USA) was used. The measurement system contained an integrating sphere with a diameter of 1.95 m (LMS-195, Labsphere Inc., North Sutton, USA), a spectrometer (CDS-600, Labsphere Inc., North Sutton, USA) and the application software "lightMtrX" (Labsphere Inc., North Sutton, USA). To ensure the supply voltage of 230 V, a variable transformer (STT 2000 B-4,5, Elektro-Automatik GmbH & Co. KG, Viersen, Germany) was used. The electrical power input of the lamps was measured with a multimeter (METRAHIT Energy TRMS System Multimeter M249A, Gossen Metrawatt, Nürnberg, Germany). To ensure stable conditions, the photometric measurements were conducted in a thermally steady state (warmed-up lamp with no changes in luminous flux).

The used fabrics consisted of polyacrylonitrile yarn (fineness 22/2, i.e., two threads with a linear weight of 1 g per 22 m each). Single-jersey samples of 5 cm × 5 cm were knitted on a hand flat knitting machine Silver Reed SK 280 (Knittax, Darmstadt, Germany) with needle gauge E5.6 (needle distance of 4.5 mm). The machine-specific stitch dimension of 5 (on a scale from 1–10) was used, resulting in the fabric parameters shown in Table 3.

Table 3. Parameters of knitted fabrics.

Parameter	Value
Stitch length	12.0 mm
Thickness	1.82 mm
Areal weight	196 g/m ^{2}
Course density	4.4 cm^{-1}
Wale density	4.4 cm^{-1}

These fabrics were chosen because they proved their suitability in previous experiments [8,10]. The dimensions of the fabrics were knittable, without yarn break. Areal weight was determined with an analytical balance SE-202 (VWR International GmbH, Darmstadt, Germany). To evaluate the thickness, a digital gauge J-40-T (Wolf-Messtechnik GmbH, Freiberg, Germany) was used. With a digital microscope VHX-600K (Keyence, Neu-Isenburg, Germany) the course and wale densities were examined. All fabric samples were coated with a hydrogel consisting of Konjac gum powder (Special Ingredients, Chesterfield, UK) dissolved in water at a concentration of 20.8 g/L using a doctor blade. Konjac glucomannan is a polysaccharide strongly gelatinizing and binding water, extracted from *Amorphophallus konjac* [23] and often used in the food industry [24].

On each coated fabric 9 seeds were placed in a 3 × 3 matrix. After the seeds were placed, the coated fabrics were dried for 2 h at room temperature. The plant species used in this experiment are listed in Table 4. The individual seed masses of thyme and marjoram were so small that values from external sources were used.

Table 4. Characterization of the seeds used in this study, including average seed masses (N = 25). All seeds were purchased from Kiepenkerl, Bruno Nebelung GmbH, Everswinkel, Germany.

Species	Individual seed mass in mg	Group	Requirement of light for germination
Spinach (*Spinacia oleracea*)	20.8 ± 3.1	Dicots	No [25]
Thyme (*Thymus vulgaris*)	0.2–0.4 [26,27]	Dicots	Yes [28]
Chive (*Allium schoenoprasum*)	1.4 ± 0.3	Monocots	No [25]
Marjoram (*Origanum majorana*)	0.15–0.3 [29,30]	Dicots	Yes [31]
Lovage (*Levisticum officinale*)	2.8 ± 0.6	Dicots	Yes [32]

The basins for the hydroponic system have four columns of seed spots and five rows. The number behind the abbreviated plant species indicates the row in which they were placed. So for instance, there exists no Ch 4 because no chives were planted in the fourth row. Since each soil box was turned by 90 degrees, the columns and rows are swapped in the soil boxes. The fabrics and the seeds were arranged in the experiment setup as depicted in Figure 2.

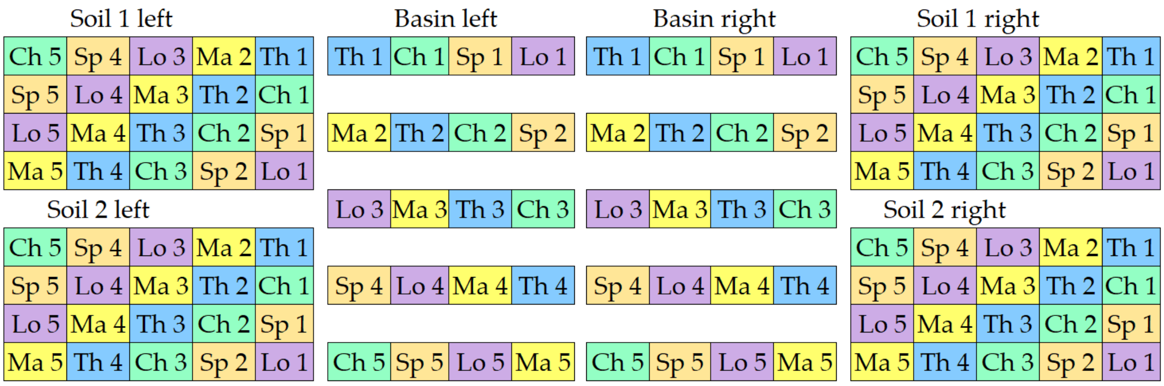

Figure 2. This figure shows how the seeds were placed on the test setup. Thyme: Th, Chive: Ch, Spinach: Sp, Marjoram: Ma, Lovage: Lo.

The radiant intensity was (6.9 ± 2.3) W/m^2 as measured with a KIMO SL-200 (Kimo Instruments, Chevry-Cossigny, France). In Figure 3 the radiant intensity at each position is given in W/m^2. These intensities are similar to the light compensation point of many crop plant species, like radish (7 W/m^2) for example and thus, only a small increase in dry biomass can be expected [33]. To investigate minimal requirements for plants, these low-level radiant intensities are well suited. This way no special lighting system is required and the material and energy costs for lighting are low.

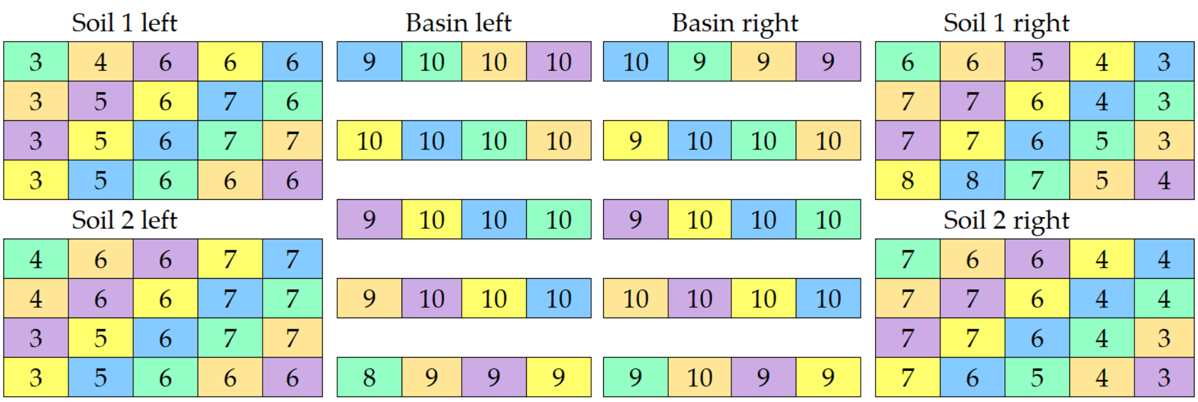

Figure 3. In this figure the radiant intensity on each area of the test setup is given in W/m^2. The colors indicate the positions of the plant samples from Figure 2 where the intensities were also measured.

The main objective was to investigate the suitability of textile substrates for germination and cultivation of various herbs and spinach in a low-cost hydroponic system and to identify the minimal plant requirements. Therefore, it was investigated how many plants germinated and how much dry as well as wet biomass grew, respectively. In particular, the plant stress level was studied to evaluate the cultivation success and suitability of the textile substrates compared to soil as conventional substrate. In this regard, PAM measurements (MINI-PAM-II, Heinz Walz GmbH, Effeltrich, Germany), which essentially determines the quantum yield of photosystem II based on chlorophyll a-fluorescence, were performed. Chlorophyll a-fluorescence analysis offers an easy and non-invasive access to photosynthetic performance of plants. The PAM device employed a 1.6 kHz light pulse of very low intensity (0.05 W/m^2) to determine the relative emission of chlorophyll fluorescence from photosystem II. The variable fluorescence yield (FV) was determined by applying a saturating light pulse of >4000 µmol photons/(m^2 s) of 1 s (FM'), subtracting the steady state fluorescence (FS) (FV = FM' − FS) and dividing this value by FM'. This gives the relative quantum yield of photosystem II (ΦPSII = FV/FM'). ΦPSII has a value of about 0.8 under optimal conditions and this value drops if the photosynthetic quantum yield is impaired [34]. Additionally, the pH value and the temperature in the basins were observed, using a pH meter (Thermo Scientific™ Orion Star™ A329, Thermo Fisher Scientific Inc., Waltham, Massachusetts, USA).

The experiment ran for 47 days. Afterwards the wet biomass of each seedling was measured, dried and quantified with an analytical balance again [35]. The drying process was executed with a universal heating cabinet UN 75 (Memmert, Schwabach, Germany) at 60 ℃ for 48 h. The percentage of germination as well as fresh and dry masses were compared.

The data was analyzed using Excel (Microsoft Corporation, Redmond, USA) and Origin (OriginLab, Northampton, USA). Statistical analysis was performed using the Welch test due to the unequal numbers of samples in the hydroponic/soil part. p-values < 0.05 are regarded as statistically significant.

Furthermore, a separate experiment was conducted to investigate the water requirement of the low-cost hydroponic system compared to conventional soil cultivation as well as the biomass output. Here, a similar test setup as before was used. As can be seen in Figure 4, this time no small textile fabrics but larger ones with the same parameters but dimensions of 46 cm × 31.5 cm were used. The fabrics were not coated with Konjac gum powder. The soil boxes were watered as necessary, each box with a different amount: 100 mL, 200 mL, 300 mL or 400 mL of tap water. This was to investigate the optimal irrigation intensity. The medium of the hydroponic system consisted of 1 L tap water and 1 mL of hydroponic fertilizer, providing an excess of available water at any time. This system of irrigation was chosen because of its proximity on final customer conditions, in which irrigation would also happen when it is needed.

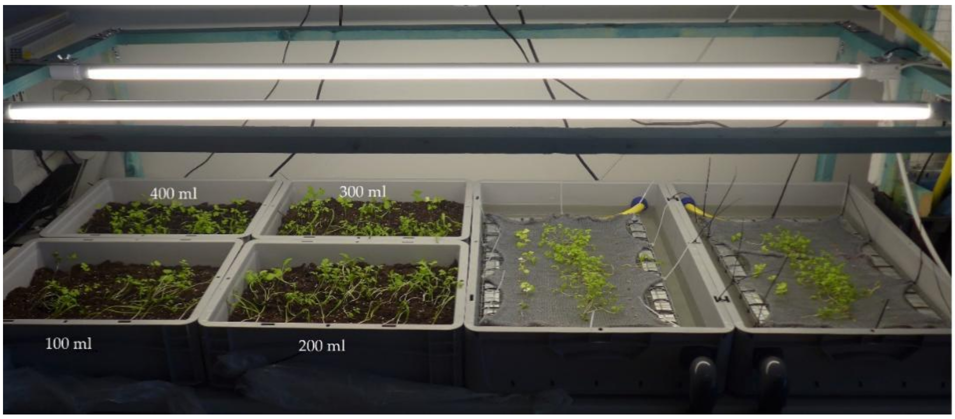

Figure 4. Test setup for comparing water use.

To test a wider variety of plants on the low-cost hydroponic test setup, the following species were chosen [10]:

1. Chinese cabbage (Michihilli brassica pekinensis, Kiepenkerl)
2. Garden cress (Lepidium sativum, Kiepenkerl)
3. Spinach (Spinacia oleracea, Kiepenkerl)

The room temperature, atmospheric pressure and humidity were measured with a sensor (BME280 Digital Sensor Modul, YXPCARS Store, Shen Zhen Shi, China) connected and read out with a Raspberry Pi (Raspberry Pi 3B, Raspberry Pi Foundation, Caldecote, UK). The experiment ran for 16 days. In the end the residual water was measured as well as the water in the biomass, soil and in the fabrics. The same instruments were used as for the previous experiment.

Table 5 shows the amount of water, which was consumed and the time of irrigation. In 16 days, the "100 mL box" was irrigated 10 times with 100 mL, indicated by "y" for each day the box was irrigated. The "200 mL box" was irrigated six times (0.6 times as much as the "100 mL box") during this period, and 200 mL were added each time. The other boxes were irrigated four times (0.4 times as much as the "100 mL box") during the experiment, and according to the name of the box, 300 mL and 400 mL were added at each irrigation, respectively. From these irrigations with the respective quantities matching the name of the box, the sums shown at the end of the table result in the total volume of water added over the entire cultivation period per box.

Table 5. Watering protocol; y (yes was watered), n (no was not watered).

Box \ Days	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Sum
Soil 100 mL	y	y	y	y	y	n	n	y	y	n	y	y	n	n	y	n	1.0 L
Soil 200 mL	y	y	n	y	y	n	n	y	n	n	n	y	n	n	n	n	1.2 L
Soil 300 mL	y	y	n	n	y	n	n	n	n	n	n	y	n	n	n	n	1.2 L
Soil 400 mL	y	y	n	n	y	n	n	n	n	n	n	y	n	n	n	n	1.6 L

3. Results and discussion

3.1. pH value and temperature of the water

The pH value and the water temperature were monitored during the experiment and revealed acidification upon addition of nutrients, which can be seen in Figure 5. The average air temperature during the experiment was 26 ℃, the relative air humidity 55% and the average atmospheric pressure was 1005 hPa.

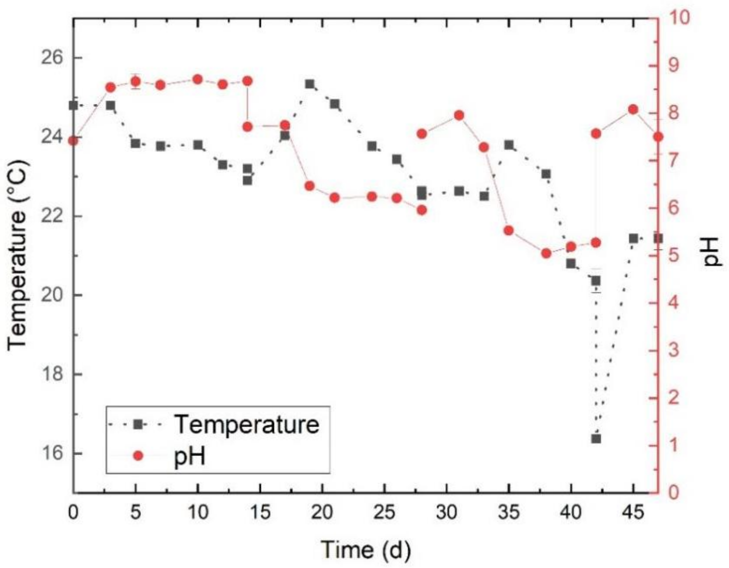

Figure 5. pH value and water temperature.

Every two weeks the water was exchanged because of algae and bacterial growth. The pH value returned to around 7.5 after the water exchange. At days 14, 28 and 42 the solution was exchanged and hydroponic fertilizer was added. The fertilizer had a pH value of 7.89 and influenced the pH value of the system. Five days after the medium change the pH value dropped to 6.5, which is the recommended value for hydroponic systems [36]. A suitable pH value for hydroponics is in a range between 5.5 and 6.5 [36]. The pH value remained in this range until the next medium change occurred at day 28. Again, the pH value returned to the recommended value 5–6 days after the medium change. A similar behavior can be observed after the last medium change on day 42.

One possible reason for the fluctuation of the pH value could be that it depends on the temperature [37]. The uptake of nutrients from the plants as well as bacteria and algae growth influence the pH value additionally [36]. This effect dominated the pH of the medium, since the pH stayed constant as long as no nutrients were added between days 0 and 14. Afterwards, nutrient uptake commenced and was driven by the proton motive force at the plasma membrane. The plasma membrane H^+-ATPase pumps H^+- into the medium at the expense of hydrolysis of ATP in the cytosol. Many nutrients like nitrate are taken up by cotransport with H^+. Another reason for the decreasing pH value might be the presence of CO_2, which is soluble in water [38]. At day 43 the water temperature dropped by 4 ℃ because the water temperature was measured directly after the fresh water was filled in the system.

3.2. Illumination

The laboratory in which the experiments took place was not artificially darkened. That is why diffuse daylight with very low intensities could reach the plants. In Figure 6 the light spectrum of the artificial lighting system can be seen. The absorption spectra of chlorophyll a and b display two peaks, one in the range between 425–480 nm (blue) and the other between 600–700 nm (red) [39]. This indicates that the light spectrum was not optimized for supporting photosynthesis.

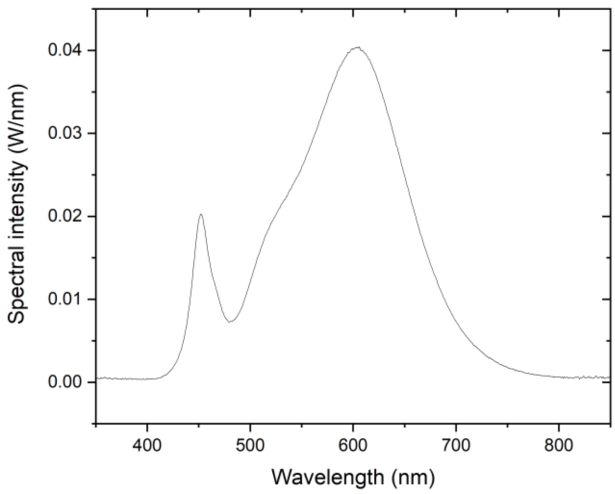

Figure 6. Light spectrum of the lighting system.

Zhang et al. investigated the optimal illumination for commercial growing lettuce with artificial lighting. To save energy, they recommended to go down to a radiant intensity of 250 µmol/(m^2 s), which corresponds to about 60 W/m^2 [40]. This is a 7 times higher intensity than the chosen setup provides. Even in winter the intensity at day is around 145 µmol/(m^2 s) in greenhouses and the low intensity affects the nitrate concentration in plants, e. g. spinach [41].

3.3. Germination success and grown biomass

The average percentage of germination per textile fabric for each plant species is presented in Table 6. For all plant species, the proportions of germinated plants differ significantly according to the Welch test, although the standard deviations are mostly overlapping. Spinach, thyme and marjoram have higher germination rates in soil while chive and lovage germinate better in hydroponics.

Table 6. Average percentage of germination for each plant species in soil and hydroponic cultivation. Data are means ± standard deviation (SD).

Germination in %			p	Significance
Species	hydroponic	soil		
Spinach	3 ± 5	72 ± 20	< 0.001	Significant
Thyme	36 ± 25	62 ± 27	< 0.001	Significant
Chive	43 ± 20	28 ± 18	< 0.001	Significant
Marjoram	31 ± 22	58 ± 21	< 0.001	Significant
Lovage	76 ± 18	65 ± 26	< 0.005	Significant

The average fresh and dry mass of the shoots as well as the number of grown plants can be seen in Table 7. Shoots were cut from the root just above the soil/textile fabric. Thus, only the stem and leaf masses are depicted in Table 7. The roots were intertwined with the textile fabric and could not be separated without damaging them. Similarly, the roots could not be pulled out as a whole from the soil.

Table 7. The average biomass and dry mass grown as well as the number of plants grown. Data are means ± SD.

Species/culture	Average fresh plant mass in g	p/significance	Average dry plant mass in g	p/significance
Spinach/hydro	0.300 ± 0.326	0.705/not significant	0.048 ± 0.006	0.069/not significant
Spinach/soil	0.185 ± 0.079		0.010 ± 0.004	
Thyme/hydro	0.019 ± 0.011	1/not significant	0.004 ± 0.002	< 0.001/significant
Thyme/soil	0.019 ± 0.029		0.002 ± 0.001	
Chive/hydro	0.035 ± 0.023	< 0.001/significant	0.003 ± 0.002	0.008/significant
Chive/soil	0.014 ± 0.015		0.001 ± 0.002	
Lovage/hydro	0.090 ± 0.042	< 0.001/significant	0.012 ± 0.020	0.002/significant
Lovage/soil	0.051 ± 0.041		0.003 ± 0.002	
Marjoram/hydro	0.026 ± 0.014	0.629/not significant	0.003 ± 0.001	1/not significant
Marjoram/soil	0.024 ± 0.026		0.003 ± 0.004	

Chive and lovage revealed a significantly higher germination rate in the hydroponic system and also accumulated more fresh as well as dry biomass. Regarding thyme, only the dry mass differs significantly with more grown biomass in the hydroponic system. Spinach developed a higher shoot mass in the hydroponic culture, but the difference is not significant. The biomass increase of marjoram is also not significantly different between hydroponic culture and soil.

Thus, it can be concluded that the cultivation systems result in significant differences in terms of germination and biomass obtained for the different plant species (cf. Tables 6 and 7). However, no trend can be observed which system is generally more suitable for the cultivation of plants. In terms of plant species, it appears that the hydroponic system with textile substrates is more suitable for chive and lovage, whereas soil is the more promising substrate for spinach, thyme and marjoram. It should be noted that the comparison between the hydroponic system and soil is not without limitations because the plants in the hydroponic system were illuminated at significantly higher intensities than the plants in soil (cf. Figures 1 and 3). This limits the validity of the results of the compared cultivation systems.

The problem of root rot in hydroponic spinach cultivation is well known and can be treated by ultraviolet irradiation of the medium [42] or cooling it [43]. At medium temperatures from 16 ℃ to 18 ℃ plants remained symptomless [43]. During the presented experiment the medium temperature was above 20 ℃ during almost the entire cultivation period, as can be seen in Figure 5. That is why most of the spinach seeds suffering from mold were lost in the hydroponic test setup.

3.4. PAM measurements of photosynthesis

The PAM device was used to investigate the stress levels of the plants. Figure 7 depicts the results of PAM measurements regarding hydroponic and soil cultivation. On days 12 and 26, PAM values are significantly higher for cultivation in soil compared to the hydroponic system. Regarding the other three measurement points, no significant differences were found according to the Welch test. Because the majority of the measurements do not yield significant differences and the standard deviations all overlap greatly except for day 12, the differences in the PAM measurements and thus the stress levels of the plants are considered to be not significantly different overall between cultivation in the hydroponic system and in soil during the cultivation. Again, due to the uneven illumination, the validity of the comparison of the cultivation systems is limited.

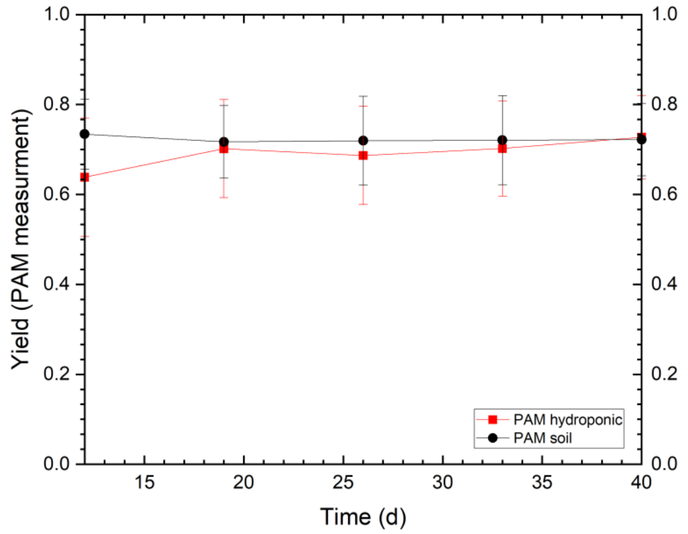

Figure 7. Quantum yield of photosystem II (ΦPSII) of plants grown in hydroponic or soil culture. Data are means ± SD.

Figure 8 summarizes the mean ΦPSII values of each plant species in the soil system. For chive, the soil setup seems to be less suitable if compared to the performance of the other species. On day 12 no values for chive could be measured because the plants were too small. All species, except chive, displayed a similar value of around 0.7. The difference for chive, however, was not significant.

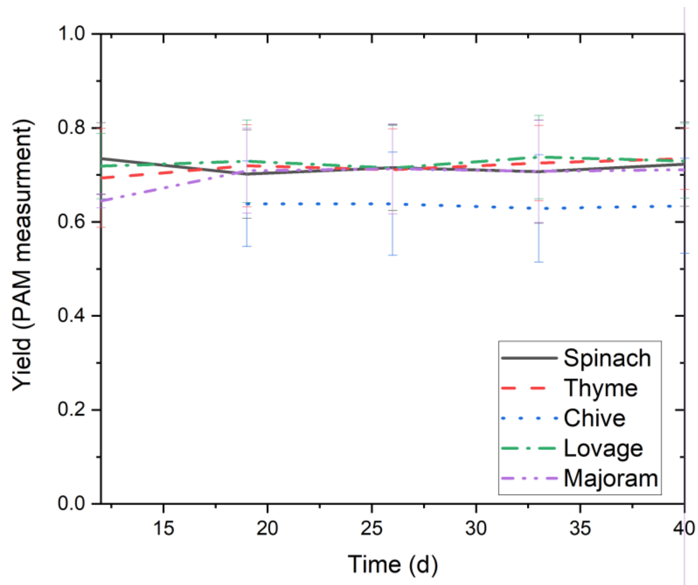

Figure 8. Quantum yield of photosystem II (ΦPSII) of each species grown in soil culture. Data are means ± SD.

Figure 9 depicts the ΦPSII of plants grown in hydroponic culture. Like before, chive plantlets were too small to get reliable PAM values until day 19. The results for spinach were not reliable since only (3 ± 5)% of the plants germinated. All species displayed similar quantum yields of photosystem II.

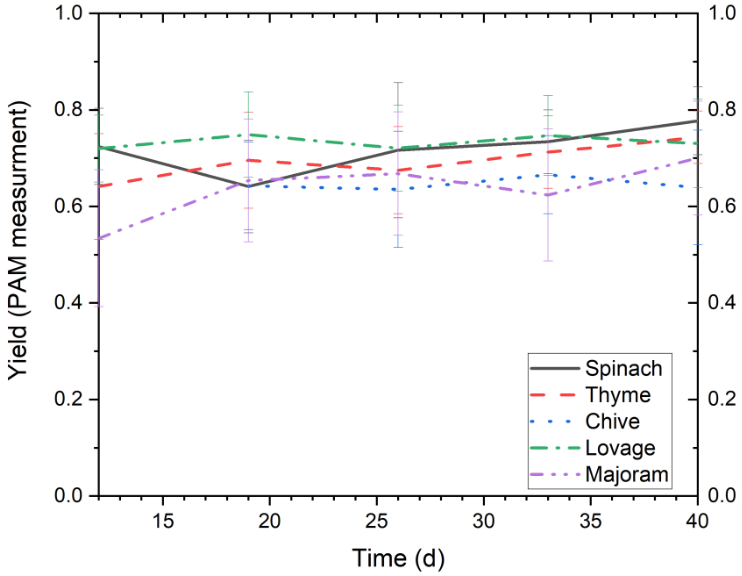

Figure 9. Quantum yield of photosystem II (ΦPSII) of each species grown in hydroponics culture. Data are means ± SD.

As described above, a PAM value of 0.8 indicates optimal conditions [34]. In soil as well as in the hydroponic system, an average value slightly below 0.8 (about 0.7) was reached, which could indicate potentially higher stress levels of the plants due to non-optimal cultivation conditions. Due to the low illumination intensity, limited quantum yields of the plants were expected. However, it is noteworthy that the value on average is not substantially lower than 0.8 in both soil and hydroponic system. The presented cultivation setup with the low illumination intensity of (6.9 ± 2.3) W/m^2 apparently meets the minimal requirements of the plants regarding lighting. Thus, the simple and inexpensive cultivation system is generally sufficient to ensure plant growth with relatively low stress symptoms. This confirms the hypothesis that textile fabrics are suitable substrates for germination and cultivation of plants in a low-cost hydroponic vertical farming system. Also, the limited comparison (due to the uneven lighting) with indoor soil cultivation suggests that the textile substrates or the simple hydroponic system probably do not result in higher stress levels.

3.5. Water consumption

The experimental setup for this investigation is depicted in Figure 4. The average room temperature over 16 days was 24.5 ℃ with a maximum of 26.0 ℃ and a minimum of 22.9 ℃. The average air humidity was 60% with a maximum of 72% and a minimum of 43%. The average atmospheric pressure was 1003 hPa with a maximum of 1010 hPa and a minimum of 996 hPa.

The cultivation area was again 967.25 cm^2 regarding the soil box and 1449 cm^2 with regard to the hydroponic system. Table 8 shows the fresh mass grown during this experiment. For cabbage more irrigation improved the yield while garden cress grew best in “Soil 200 mL” and spinach in “Soil 300 mL”. For the hydroponic system, it is noticeable that spinach did not germinate and grew well while garden cress and cabbage grew successfully.

Table 8. Fresh mass grown on the test setup by plant and irrigation method.

Grown in	Fresh mass in g		
	Chinese cabbage	Garden cress	Spinach
Soil 100 mL	0.337	1.952	1.162
Soil 200 mL	1.024	3.868	1.338
Soil 300 mL	1.046	2.470	1.805
Soil 400 mL	1.229	3.059	1.531
Hydroponic right	0.588	3.793	0.167
Hydroponic left	0.616	3.981	0.342

In Table 9 the dry biomass is depicted. The observations correlate with the data obtained for fresh mass. For Chinese cabbage and garden cress, most dry mass grew in “Soil 200 mL”. For spinach, most dry mass grew in “Soil 300 mL”.

Table 9. Dry mass grown on the test setup by plant and irrigation method.

Grown in	Dry mass in g		
	Chinese cabbage	Garden cress	Spinach
Soil 100 mL	0.024	0.139	0.091
Soil 200 mL	0.085	0.264	0.105
Soil 300 mL	0.057	0.163	0.154
Soil 400 mL	0.080	0.161	0.082
Hydroponic right	0.036	0.278	0.008
Hydroponic left	0.043	0.233	0.020

To evaluate the total water use for the hydroponic system, the residual water at the end of the experiment was measured with 41.8 L. The starting amount of water was 50.1 L, which means 8.3 L evaporated, was incorporated in the plants or in the textile fabric. The water associated with the plants can be measured by subtracting the values in Table 9 from those in Table 8. The amount of water in the fabric was measured by weighing the dried and wrung out moisturized fabric, resulting in a volume of 0.1 L water bound to all fabrics. Similarly, the amount of water used in the soil cultivation was determined. Thus, the soil was weighted before and after a drying process. The water remaining in the soil as well as in the textile fabric could theoretically still have been usable for cultivation. Therefore, the loss of water without water in the soil, fabric or plants was measured and is shown in Table 10.

Table 10. Water usage without water in the soil, fabric or plants.

Grown in	Irrigation in L	Water in soil/fabric in L	Water in plants in L	Water usage in L
Soil 100 mL	1.0	0.532	0.003	0.465
Soil 200 mL	1.2	0.560	0.006	0.634
Soil 300 mL	1.2	0.577	0.005	0.618
Soil 400 mL	1.6	0.702	0.005	0.893
Hydroponic, left & right	8.2	0.123	0.009	8.068

Finally, the evaporation loss of water in the hydroponic system was 8 L. To make the water usage comparable, this value per cultivated area is given in Table 11.

Table 11. Water usage and grown dry biomass per cultivated area.

Grown in	Water per cultivated area in mL/cm ^{2}
Soil 100 mL	0.484
Soil 200 mL	0.661
Soil 300 mL	0.644
Soil 400 mL	0.928
Hydroponic, left & right	2.803

Table 11 illustrates that the presented hydroponic system uses much more water than indoor soil cultivation. In the first experiment the water was exchanged three times, which makes the water consumption even higher. In the future, the water efficiency needs to be improved. Changing the water every two weeks could possibly be avoided by using chemicals or ultraviolet irradiation that prevent algae and bacterial growth. However, such treatment would not comply with the expectation of many consumers for bioorganic growth conditions. Otherwise, filtering the water in a close cycle and avoiding illuminating the medium by complete covering of the boxes could improve the water efficiency of the growth system.

Barbosa et al. compared the water and energy requirements between a hydroponic system and soil cultivation. They found that in hydroponic greenhouses the water consumption is considerably lower with the cost of higher energy demand [18]. However, the calculations were only for a hypothetical enclosed hydroponic greenhouse. They calculated the water usage by evapotranspiration of each plant. They increased the final value by 10% to make the guess more conservative [18]. Another study used no flowing water but manually irrigated the hydroponic cultures and used only natural sunlight. This way they reached higher water efficiency for their hydroponic system compared to plant growth in the open field [19]. Other studies found that only 10–20% [20] or even 3–5% [21] of water was needed to yield the same amount of biomass.

In contrast, the here investigated soil cultivation was placed in the same room with the hydroponic system and thus had the same conditions. There was also no seepage of water in the closed soil boxes, as there would be in an open field, so water consumption was correspondingly low. This indicates that hydroponic systems are only more water efficient when compared to conventional open-air agriculture. However, it must be considered that this thesis is based on a very simple hydroponic system that is not optimized for water consumption.

4. Conclusion

The results from this study show that spinach, thyme, chive, marjoram and lovage have similar photosynthetic performances as well as stress levels in indoor soil and on textile substrates in low-cost hydroponic cultures. Despite the low illumination intensity and non-optimal cultivation conditions, the mean quantum yield of the plants was only slightly lower than the value expected under optimal conditions. This confirms the working hypothesis and demonstrates the possibility of successfully cultivating various plants even with a low-cost hydroponic vertical farming system. Accordingly, the used textile fabrics are considered to be suitable substrates with easy handling and high potential in terms of sustainability.

Due to the simple hydroponic setup without cooling or disinfection of the medium, the germination rates, especially regarding spinach, were lower than in the comparative cultivation in soil, due to mold. Thus, measures should be considered, at least for spinach cultivation, to improve the test setup to enhance the germination rate. However, chive and lovage displayed significantly higher germination rates and significantly accumulated more biomass in the hydroponic system. Despite the limitations of the comparison, this suggests that, for some plant species, low-cost hydroponic systems are sufficient or even better suited than conventional soil cultivation during the germination phase. Therefore, it would be possible in the future to germinate plants in a hydroponic system on biobased textiles. These could then be placed on soil for further cultivation, where the textiles would biodegrade.

A disadvantage of the investigated setup was the high water consumption. The second experiment has shown that this hydroponic system needs around four times the amount of water compared to soil cultivation with the same environmental conditions. In addition to mold prevention the low-cost setup could be improved regarding water efficiency. Finally, the low-cost illumination system of the test setup had a very low intensity but was sufficient for the studied first 46 days of cultivation. In the future, lighting should be optimized as one of the most important parameters in cultivation to obtain a higher biomass increase [40].

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Conflict of interest

The authors declare no conflict of interest.

Author contributions

Bennet Brockhagen: conceptualization, methodology, formal analysis, investigation, visualization; Fabian Schoden: conceptualization, methodology, formal analysis, investigation, visualization, writing–first draft; Jan Lukas Storck: conceptualization, methodology, formal analysis, investigation, visualization; Timo Grothe: conceptualization, investigation, visualization; Christian Eßelmann: investigation, validation; Robin Böttjer: methodology; Anke Rattenholl: validation; Frank Gudermann: validation. All authors read and substantially modified the manuscript.

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