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Marielle Trenkner

marielle.trenkner@uni-hohenheim.de

University of Hohenheim

Iris Lewandowski

University of Hohenheim

Filippo Cappezone

University of Hohenheim

Andrea Bauerle

University of Hohenheim

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Growth of two different *Ocimum basilicum* L. varieties on digestate-based peat alternatives in a hydroponic setup

Marielle Trenkner[1*], Iris Lewandowski[1], Filippo Capezzone[2], Andrea Bauerle[1]

[1*]Institute of Crop Science, Department of Biobased Resources in the Bioeconomy, University of Hohenheim, Fruwirthstraße 23, Stuttgart, 70599, Baden-Württemberg, Germany.
[2]Institute of Crop Science, Biostatistics Unit ,University of Hohenheim, Fruwirthstraße 23, Stuttgart, 70599, Baden-Württemberg, Germany.

*Corresponding author(s). E-mail(s): marielle.trenkner@uni-hohenheim.de;
Contributing authors: iris_lewandowski@uni-hohenheim.de; filippo.capezzone@uni-hohenheim.de; a.bauerle@uni-hohenheim.de;

Abstract

Peat is the dominant growing substrate in horticulture, yet extraction of peat accounts for tremendous ecological damage, through greenhouse gas emissions and the exploitation of peatlands. Finding sustainable, functional alternatives for peat as a growing substrate is therefore an environmental necessity. This study evaluated two peat-replacement strategies in a nutrient film technique (NFT) hydroponic setup, mineral (rockwool) and organic (nutrient-depleted anaerobic digestate) against a peat-based commercial substrate, using two *Ocimum basilicum* L. varieties ('Genovese' and 'Thai Siam Queen') as test plants. Fresh mass, dry mass, plant height, canopy width, and dry matter content were determined across four substrates in a row-column design with four replications. peat plugs produced the highest yields across all measured parameters. Both digestates and rockwool performed similarly for Genovese. For Thai Siam Queen, the manure-rich digestate (DIG2) performed better than the maize-dominant digestate (DIG1) and rockwool, indicating variety-specific substrate response. As digestates and rockwool did not differ significantly across all parameters, the choice between these peat alternatives is an ecological one. In which the digestate, as a compostable byproduct of an existing agricultural waste stream,

which requires no additional production energy, holds a clear advantage over the non-biodegradable rockwool.

Keywords: peat substitutes, waste valorization, circular economy, digestates

1 Introduction

Soil is the foundation of global food security, with approximately 98.8% of the food consumed by humans originating from it [Greco et al., 2021]. Soil is also responsible for providing invaluable ecological functions, such as carbon sequestration and greenhouse gas regulation. However, it is a limited resource. With the world population expected to exceed 10 billion by 2080 and the simultaneous need for increased food production, the pressure on soil is set to to increase further [United Nations, 2024, Kopittke et al., 2019].

One strategy to mitigate this pressure is soil-less cultivation [Laudicina et al., 2016]. Soil-less cultivation in hydroponic systems can ensure the year-round cultivation of fresh produce, without disadvantages such as soil-borne diseases, soil salinity and poor fertility [Tzortzakis et al., 2020]. Additionally, it enables densely populated areas to be supplied with locally grown fresh produce [Velazquez-Gonzalez et al., 2022].

Cultivation substrates affect the development of plants as well as the quality and yield of the produce [Fascella et al., 2006]. When choosing a cultivation substrate, factors such as low bulk density, high water-holding capacity, and high total porosity need to be considered [Chamindu Deepagoda et al., 2013].

Due to its exceptional physical properties (e.g. high porosity and water-holding capacity), peat is considered the dominant horticultural growing medium [Kitir et al., 2018]. Approximately 14 million metric tons of peat are used in horticulture each year worldwide [He and Roulet, 2023] . However, peat is a non-renewable resource and its extraction has immense ecological drawbacks, including the emission of approximately 1.9 gigatonnes of greenhouses gases per year [Barrett et al., 2016, IUCN, 2023].

Over the past decade, national and international strategies have been established for the reduction and phasing out of the use of peat [BMEL, 2022, Gruda et al., 2024]. To achieve the European Commission's climate targets for 2025, it is necessary to implement strategies that reduce emissions from peatland exploitation. This creates a need to find sustainable peat alternatives for use as a growing medium in hydroponics and horticulture in general.

Replacing peat in horticulture is challenging since its properties are unmatched, and the quality of peat-free growing media is generally considered to be inferior [Hirschler and Osterburg, 2025]. Several materials have been explored as sustainable alternatives to peat, such as biochar and paper sludge [Fascella et al., 2018, Chong and Hamersma, 1996].

In recent years, the focus has shifted more towards the utilization of biogas digestates as potential peat replacements [Nesse et al., 2019, Calisti et al., 2022, Asp et al., 2022, Ehmann et al., 2019]. Digestates are a by-product of the biogas production process

and their use as a horticultural growing medium could provide a sustainable, carbon-neutral alternative to peat. However, in hydroponic systems, where peat is also one of the most commonly used substrates [Raviv and Lieth, 2008, Barrett et al., 2016], using digestates as a sustainable peat alternative remains largely unexplored.
Several studies have found basil, which belongs to the *Lamiaceae* family, to be a suitable crop for hydroponic cultivation [Walters and Currey, 2015, Saha et al., 2016, Roosta, 2014]. As the globally most popular fresh herb, demand for basil is increasing [Walters and Currey, 2015]. In addition to being used as a herb, it is also commonly applied in cosmetics, medicine and oil production [Indira et al., 2024, Maurer et al., 2023, Wogiatzi et al., 2011]. Basil requires warm temperatures to thrive and, while it is usually grown outdoors, year-round production in colder climates can only be achieved in a controlled environment [Walters and Currey, 2015].
This study explores two broad strategies for replacing peat in a nutrient film technique (NFT) hydroponic system: mineral substrates, in this case rockwool (an established growing medium), and organic substrates, in this case waste-derived anaerobic digestates from a Geltz-process anaerobic digestion system [Geltz and Geltz, 2023].
The study evaluates these strategies using a peat substrate as a conventional reference and two varieties of *Ocimum basilicum* L. ('Genovese' and 'Thai Siam Queen') as test crops. We hypothesize that both replacement strategies will achieve comparable results to the peat-based reference. Additionally, we propose that, of the two replacement strategies, the digestate substrate has several ecological advantages over the mineral substrate, as it is a compostable, renewable by-product of an existing agricultural waste stream, making it the more sustainable alternative.

2 Materials and Methods

2.1 Experimental setup: Nutrient Film Technique

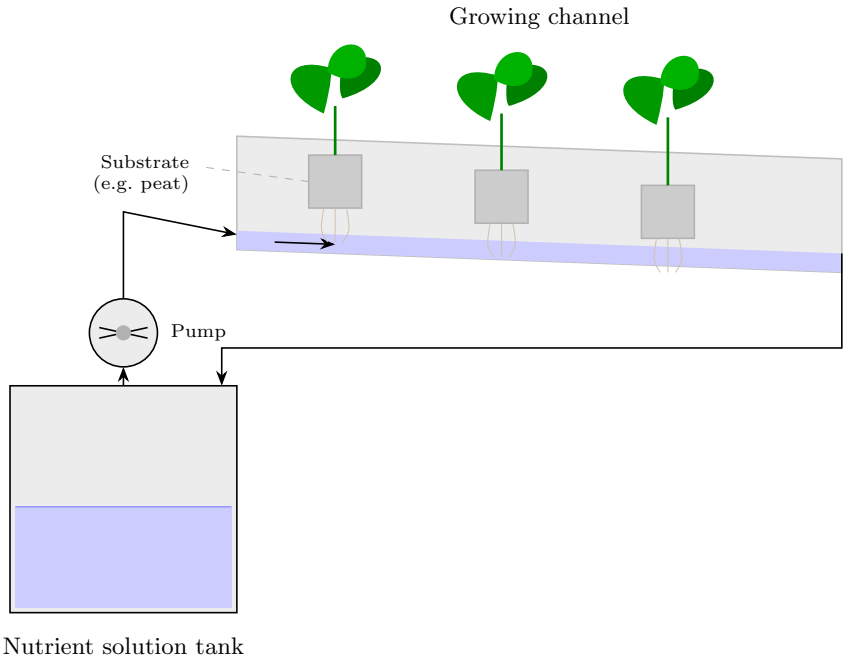


Fig. 1 Principle of an NFT hydroponic setup, showing the growing channel with the plants inserted and the roots hanging in the nutrient solution. The channel is sloped to ensure a constant flow of the solution back into the nutrient tank, from where a pump circulates it back to the channels.

The trial was conducted in a nutrient film technique (NFT) hydroponic setup consisting of four channels, each with 15 planting positions. Each channel had a slope of approximately 2% and shared a nutrient tank holding 60 litres of nutrient solution. Each channel was equipped with a submersible water pump (Awroutdoor, 10 W, maximum flow rate 600 L/h). Figure 1 shows an example of such a hydroponic setup. The nutrient solution was monitored throughout the entire growing period and adjusted twice a week. Before adjustment, the pH values of the nutrient solution ranged between 6.4 and 7.4, likely due to alkalization through nutrient uptake. The pH in the nutrient solution was maintained at values between 5.5 and 6.2 to ensure optimal plant growth and nutrient uptake. This was achieved by adding Terra Aquatica pH- Down Regulator. The electrical conductivity (EC) was increased continuously to match the plants' growing needs for nutrients over time. Starting values of 300 µS/cm (tap water) were steadily increased by adding Terra Aquatica TriPart hydroponic fertilizer, ending with values of about 1500 µS/cm.

2.2 Greenhouse conditions

The experiment took place in a greenhouse at the University of Hohenheim from 3 July 2025 to 18 August 2025, during which time the plants experienced a natural photoperiod of 16-17 h of daylight. The greenhouse air temperature and relative humidity (RH) were recorded at 15-minute intervals using a data logger (Elitech RC-4HC). During the growing period (11 July to 18 August), average temperatures of 27.2 °C were reached, with maximum temperatures of 43.3 °C and minimum temperatures of 12.7°C (see Figure 2). On sunny days, temperature peaks above 35 °C occurred regularly. The humidity ranged between 13.6% and 94.6%, averaging 52.5%.

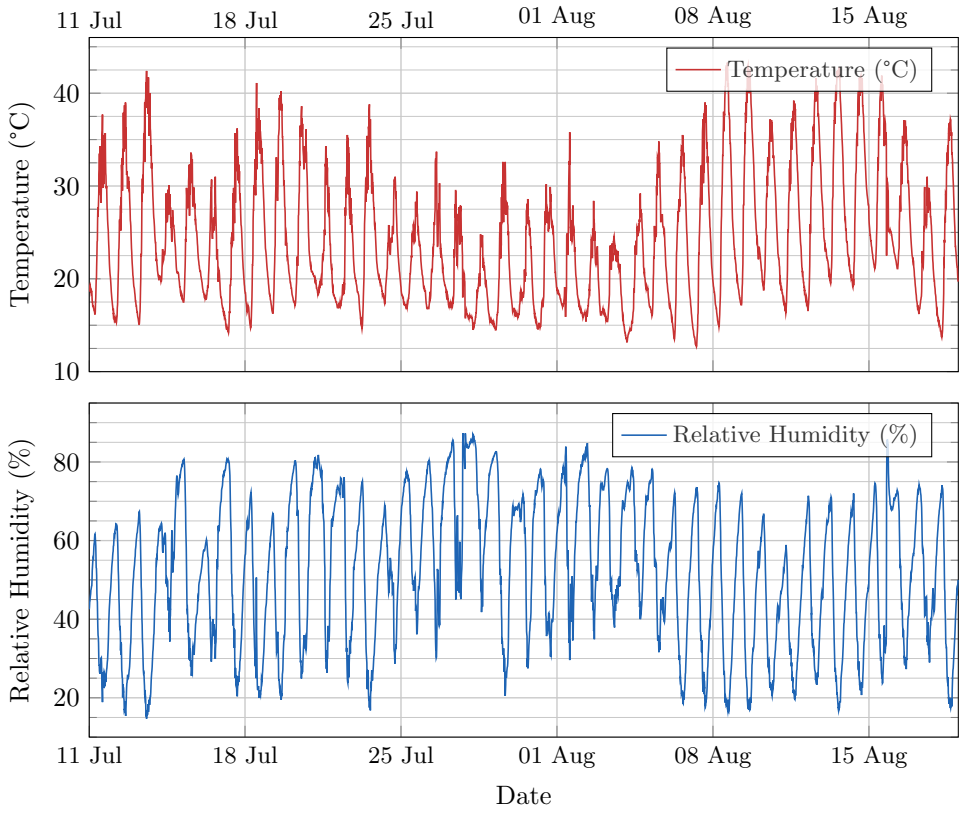


Fig. 2 Temperature and relative humidity in the hydroponic greenhouse (11 July – 18 August 2025). Measurements taken every 15 minutes.

2.3 Substrate treatments



Fig. 3 Four different growing substrates in the hydroponic net pots. From left to right: DIG1, DIG2, Rockwool and peat plugs, authors' own image

The trial tested four different substrate treatments: one peat-based substrate and three peat-free substrates consisting of a commercially available rockwool plug and two different biogas digestate-based peat alternatives. Both digestates were derived from a Geltz-process, in which the solid and liquid fractions of digestates are separated. The liquid fraction is used to produce liquid recycled fertilizer, generating a nutrient-depleted solid digestate as a by-product. This solid digestate was used in the trial. Treatment A used a digestate from the Geltz-process, referred to here as 'DIG1'. The loose substrate was filled into hydroponic net pots measuring 4.7 x 4.7 x 5 cm. 10 grams of substrate were filled into each net pot. Treatment B used a different digestate from a Geltz-process, referred to here as 'DIG2'. Again, 10 grams of substrate were filled into net pots. Both digestate substrates were soaked in water before the seeds were sown. The two digestate substrates differed in terms of input materials in the biogas process. Feedstock materials and compositions are shown in Table 1. DIG1 has a mixed organic composition with high carbon inputs from energy crops such as maize silage (28.8%) and corn-cob-mix (CCM), as well as cup plant and other crops. In addition, it contains a large fraction of cattle slurry and manure. By contrast, DIG2 contains no maize silage or other energy crops but consists mostly of nutrient-rich solid manure fractions and grass silage. Treatment C consisted of rockwool plugs with a side length of 36 mm, commercially available from Grodan, Roermond, the Netherlands. They were soaked in water prior to sowing. Treatment D consisted of organic growing plugs made from a mixture of peat, coco peat, and added nutrients. These plugs (Eazy Plugs CT104C), produced by Eazy Plug®, a registered trademark of HGA Garden

Table 1 Feedstock composition of the biogas processes resulting in the two different digestate-based peat substitutes

Feedstock	DIG1 (t/a)	DIG1 (%)	DIG2 (t/a)	DIG2 (%)
Maize silage	16,540	28.6%	—	—
Grass silage	848	1.5%	7,017	23.3%
Cattle slurry (raw)	14,640	25.3%	4,970	16.5%
Cattle manure (solid)	14,077	24.3%	9,511	31.6%
Separated cattle slurry (solid)	—	—	8,474	28.1%
Corn-cob-mix (CCM)	4,127	7.1%	—	—
Cup plant	3,666	6.3%	—	—
Whole crop silage (GPS)	1,183	2.0%	—	—
Lieschkolben silage (LKS)	1,613	2.8%	—	—
Sugar beet pulp	—	—	80	0.3%
Sheep/goat manure	—	—	93.5	0.3%
Cereals	380	0.7%	1	<0.1%
Grape marc	505	0.9%	—	—
Straw	288	0.5%	—	—
Total	**57,867**	**100%**	**30,147**	**100%**

Table 2 Characterization of substrate treatments A-D

Parameter	DIG1	DIG2	Rockwool	peat plugs
Dry matter (TS)	28.57%	42%	unknown	unknown
Bulk density	261 g/l	156.85 g/l	-	128 kg/l [Eden, 2015]
Dry density	74.7 g/l	66.33 g/l	46- 67.5 g/l [Bougoul et al., 2005]	92% pore volume [Eden, 2015]
Water-holding capacity	409 ml/l	861 ml/l	60-80 % [Istenič et al., 2024]	unknown
pH	3.14	4.0	7.5 [Bougoul et al., 2005]	5.9 [Eden, 2015]
Salt (KCl)	∼0.1 g/l	0.15 g/l	50 - 100 mS/cm [Bougoul et al., 2005]	1.0 [Eden, 2015]
Nmin (CAT)	40 mg/l	<90 mg/l	-	1.6 mmol/l [Eden, 2015]
S (CAT)	62 mg/l	—	-	unknown
P (CAT)	3.7 mg/kg	6.6 mg/kg	-	0.85 mmol/l [Eden, 2015]
K (CAT)	22.5 mg/kg	57 mg/kg	-	1.6 mmol/l [Eden, 2015]
Mg (CAT)	6.8 mg/kg	60 mg/kg	-	unknown
P (aqua regia)	6.43 mg/l	327 mg/l	-	unknown
K (aqua regia)	128 mg/l	1430 mg/l	-	unknown
Mg (aqua regia)	44.33 mg/l	963 mg/l	-	unknown
Air-to-water ratio	-	-		20:80 [Eden, 2015]
Organic matter			0% (inert)	96% [Eden, 2015]
Compostable	Yes	Yes	No	Yes
Ash content	4.24%	4.01%	-	unknown

B.V, had a diameter of 35 mm diameter and a height of 55 mm. They were soaked in water before sowing. This substrate is referred to as 'peat plugs' in this manuscript. All four substrates filled into the net pots are shown in Figure 3.

As can be seen in Table 2, the two digestates differ in their chemical and physical properties. These characteristics were determined in a laboratory using methods described in the VDLUFA Method Book, Volumes I and II [VDLUFA, 1991, 1995]. DIG1 had a higher bulk density (261 g/L) than DIG2 (156.85 g/l), while DIG2 had a

notably higher water-holding capacity (861 ml/L, compared to 409 ml/L for DIG1). Both digestates were strongly acidic, with pH values of 3.14 for DIG1 and 4.0 for DIG2. DIG2 exhibited substantially higher nutrient concentrations in the aqua regia extraction for all measured elements, most likely reflecting its manure-dominated feedstock composition. Both digestates and peat plugs are compostable, in contrast to rockwool, which is non-biodegradable.

2.4 Plant material and propagation

In this trial, two varieties of *Ocimum basilicum* were used: Plant variety 1 consisted of *Ocimum basilicum* L. var. 'Thai Siam Queen', referred to in this manuscript as 'Thai Siam Queen'. The seeds were obtained from Agri-Saaten GmbH. Plant variety 2 consisted of *Ocimum basilicum* L. var. 'Genovese', obtained from Bobby-Seeds, and referred to as 'Genovese'. Both varieties were sown on 3 July 2025. During germination, 100 % humidity was ensured by allowing the seeds to germinate in closed boxes in the greenhouse. Four repetitions of the trial were carried out within the same time period with 15 replicates per treatment in each repetition. The plants underwent an eight-day propagation period before being transferred to the NFT system on 11 July 2025.

2.5 Measured parameters

The following parameters were measured repeatedly over the trial period and recorded for each plant: plant height (cm), canopy width (cm), BBCH growth stage [Meier, 2018], node count, and number of side shoots. At harvest, the fresh mass (FM, in g) and dry mass (DM, in g) were determined for each plant. To obtain DM values, the plants were dried in a drying oven at 60°C for two days. Dry matter content (%) was calculated as dry mass / fresh mass × 100.

2.6 Statistical analysis

The trial was conducted using a row-column design with four complete replications (NFT units). PROC OPTEX in SAS (version 9.4, SAS Institute Inc., Cary, NC, USA) was used for randomization, with channels (rows) and plant positions within the NFT units (columns) as blocking factors. All response variables (fresh mass, plant height, canopy width, dry mass, and dry matter content) were analyzed using a linear mixed model with PROC GLIMMIX, with varieties, substrate and substrate-variety interaction included as fixed effects. Response variables were square-root transformed prior to analysis to stabilize residual variance. The NFT unit (table), channel inserted within NFT unit (channel (table)), and position inserted within NFT unit (position (table)) were included as random effects, accounting for the row-column blocking structure. Degrees of freedom were adjusted using the Kenward-Roger method. Least squares means were compared using Tukey-Kramer adjusted pairwise tests ($\alpha = 0.05$) with slice analyses conducted for substrates within each variety and varieties within each substrate. Letter groupings were generated using the LINES option.

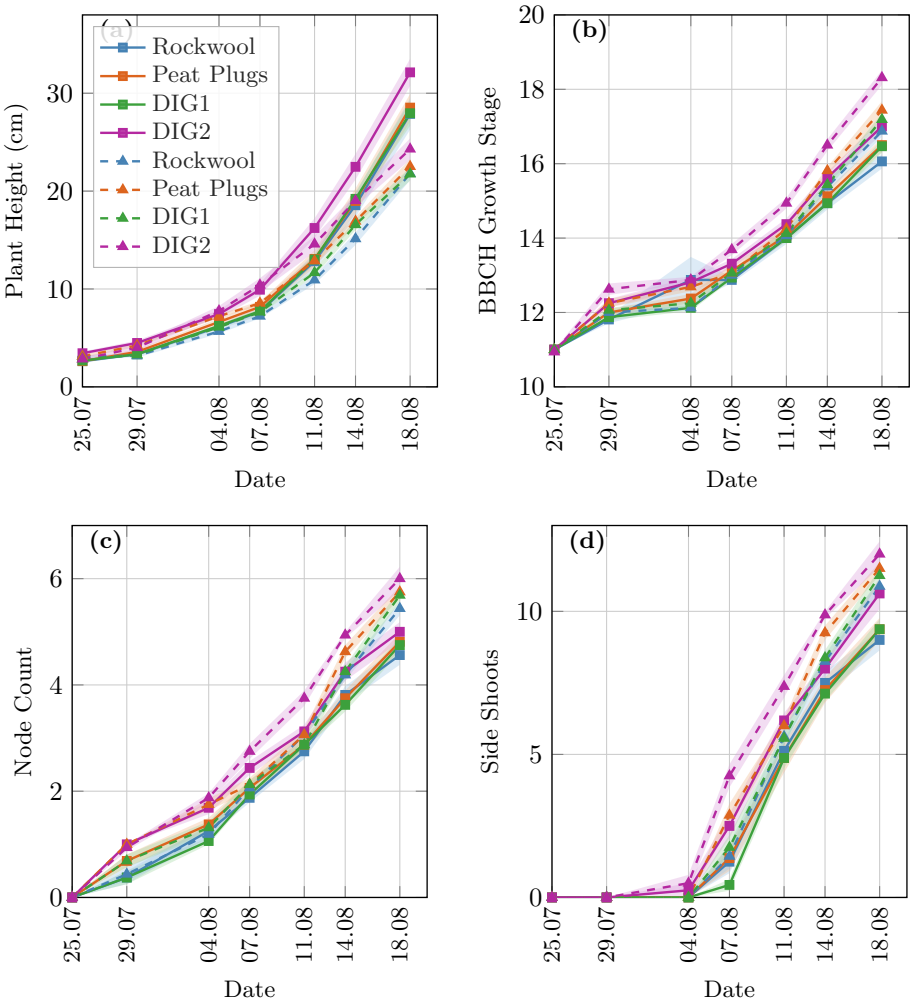
2.7 AI assistance declaration

In the preparation of this manuscript, the authors used Claude Sonnet 4.6 (Anthropic, claude.ai, accessed 2026) to assist with cross-checking statistical reporting against SAS and for cross-checking and generating LaTeX code for figures and graphical elements. All AI-generated content was carefully checked and reviewed by the authors. The authors take full responsibility for the accuracy of the original manuscript.

3 Results

Growth dynamics and nutrient parameters over the trial period are presented here together with the results of the harvest parameters (fresh mass, dry mass, plant height, and canopy width).

3.1 Growth dynamics



Solid lines (□) = *O. basilicum* 'Genovese'; Dashed lines (△) = *O. basilicum* 'Thai Siam Queen'. Colours indicate substrate.

Fig. 4 Growth dynamics of two basil varieties in four hydroponic substrates (NFT system, $n = 4$ replications). Shaded areas represent ±SE of arithmetic treatment means across replications (descriptive, not model-derived) (a) Plant height; (b) BBCH growth stage; (c) Node count; (d) Side shoots.

Figure 4 shows the growth dynamics over the five-week trial period from 25 July 2025 to 18 August 2025. Plant height increased continuously over the growing period in all treatment variations, with peat plugs producing the tallest plants from 7 August 2025 onwards. The BBCH progression was similar, though peat plugs reached higher

BBCH stages earlier than the other substrates, especially with Thai Siam Queen. Node count and side shoot development increased continuously, with peat plugs also showing slightly faster development compared to the other substrates.

3.2 Growth parameters

3.2.1 Fresh mass, dry mass and dry matter content

Fresh mass (FM) was significantly affected by substrate ($F = 68.83$, $p < 0.0001$), variety ($F = 11.78$, $p < 0.0007$), and substrate-variety interaction ($F = 5.40$, $p = 0.0014$). The highest FM was obtained for Thai Siam Queen grown on peat plugs, with an average yield of 28.29 g per plant (Figure 5a). The lowest FM results were found for Genovese grown on DIG1 digestate, with an average of 13.36 g per plant. Overall, peat plugs produced the best results for both varieties (Table 2). Conversely, the two digestate substrates (DIG1 and DIG2) did not differ significantly from rockwool, indicating comparable performance to the commercial standard. An overall comparison of all substrate × variety combinations confirmed that the highest FM was achieved by Thai Siam Queen on peat plugs, followed by Genovese on peat plugs (b) and Thai Siam Queen on DIG2. No significant differences were found between the remaining cominations (Figure 5a).

For dry mass (DM), the effects of substrate ($F = 67.93$, $p < 0.0001$) and substrate-variety interaction ($F = 5.43$, $p = 0.0013$) were significant (Figure 5b). As with FM, peat plugs achieved the highest DM for both varieties, with averages per pot of 4.92 g on Thai Siam Queen and 4.27 g on Genovese. There were no significant differences between rockwool and the two digestate substrates for the cultivation of Genovese. For Thai Siam Queen, the DIG2 digestate (3.23 g) achieved significantly higher DM than DIG1 (2.17 g) and rockwool (2.46 g). There was no significant difference between DIG1 and rockwool. An overall comparison showed that there were no significant differences between the two varieties on peat plugs. Thai Siam Queen on DIG2 ranked second best for DM, while rockwool showed intermediate results for both varieties. DIG1 ranked lowest for both varieties (Figure 5b).

Dry matter content (%DM) was significantly affected by both plant variety ($F = 32.02$, $p < 0.0001$) and substrate ($F = 3.66$, $p = 0.0134$), but not by substrate-variety interactions ($F = 1.44$, $p = 0.2335$). Consistently higher values were obtained for Genovese on all substrates. Within this variety, no significant differences between substrates were found. For Thai Siam Queen, the lowest DM percentages were found on DIG1 (8.55%), which were significantly lower than all Genovese substrates.

3.2.2 Plant height and canopy width

Plant height was significantly affected by variety ($F = 64.79$, $p < 0.0001$) and substrate ($F = 3.38$, $p = 0.0192$); however their interaction did not have a significant effect ($F = 2.38$, $p = 0.701$) (Figure 5c). Though the substrate × variety interaction was not significant for plant height, slice analyses were conducted for consistency. For 'Genovese', statistical slice analyses in SAS found no significant differences in height across all substrates ($p > 0.05$ for all analyses). For Thai Siam Queen, a significant difference was found between the substrates, with peat plugs producing significantly

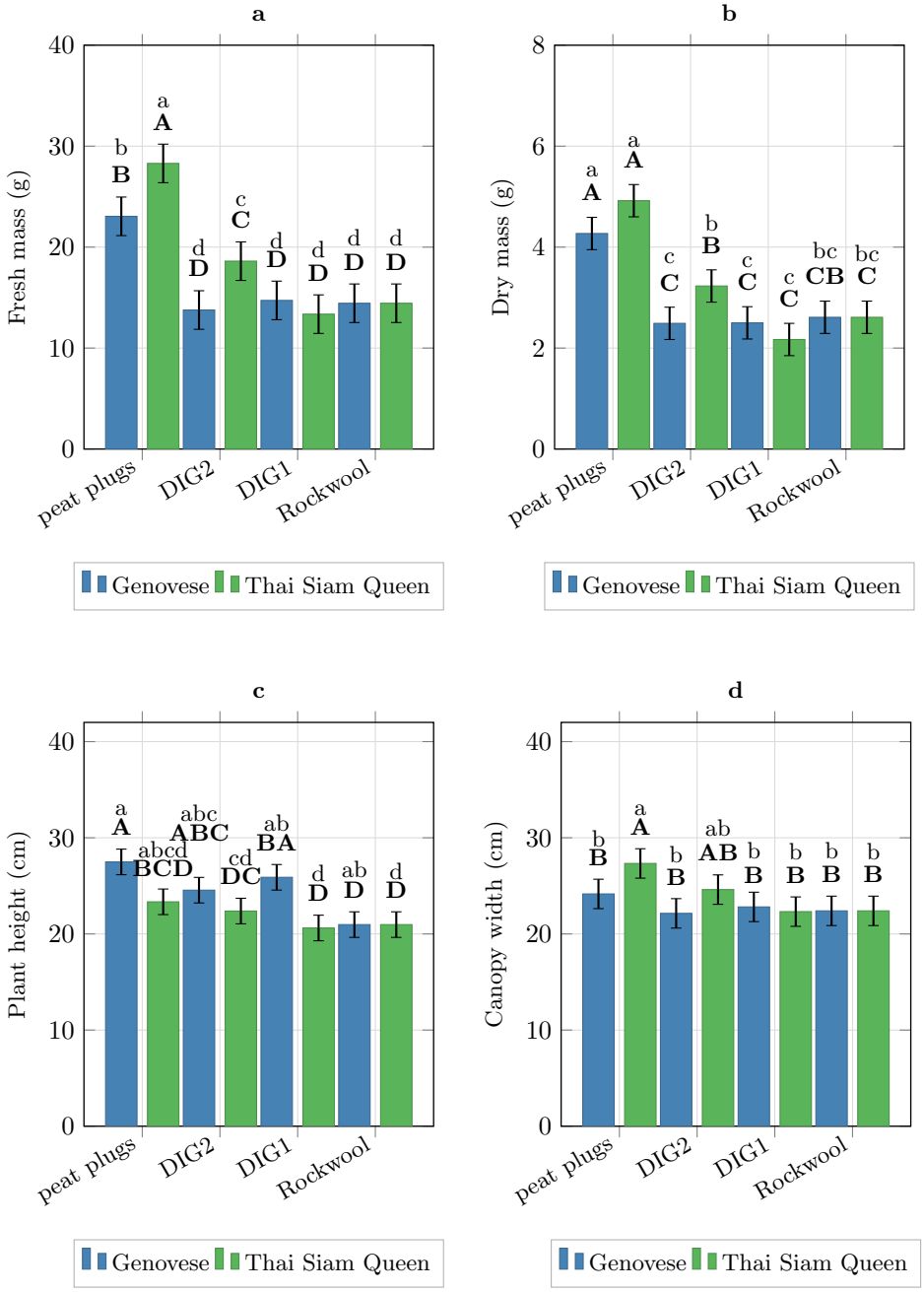


Fig. 5 Yield parameters of two basil varieties in four hydroponic substrates (NFT system, $n = 4$). Error bars = SE of least square means from the linear mixed model (PROC mixed). Uppercase letters indicate significant differences between substrates within each species; lowercase letters indicate significant differences between species within each substrate × substrate combinations (Tukey-Kramer, $p < 0.05$). (a) Fresh mass; (b) Dry mass; (c) Shoot length; (d) Canopy width.

taller plants than DIG1 ($p = 0.0165$) and rockwool ($p = 0.0068$). 'Genovese' consistently produced taller plants than Thai Siam Queen, whereas the Thai variety tended to have bushier growth, rather than producing taller plants. The tallest plants were produced on peat plugs, with an average of 27.49 cm for Genovese and 23.34 cm for Thai Siam Queen. Overall comparisons of the combinations resulted in overlaps between groups, with Genovese on peat plugs producing the largest plants. Most other combinations showed no significant differences. This reflects a large in-treatment variation in plant height. (Figure 5c). Canopy width was significantly affected by substrate ($F = 10.98$, $p < 0.0001$), variety ($F = 7.90$, $p = 0.0054$), and variety-substrate interactions ($F = 4.85$, $p = 0.0027$). The greatest width was observed in Thai Siam Queen on peat plugs (27.33 cm), while Genovese on DIG2 digestate produced the narrowest width (22.14 cm). Overall comparisons show that Thai Siam Queen on peat plugs ranked significantly higher than all other treatments. Thai Siam Queen on DIG2 produced intermediate results, while there were no significant differences between the other combinations (Figure 5d).

3.3 Visual Results

Visually, there was no difference between the plants grown on the different substrates. No signs of nutrient deficiency or disease were detected. Additionally, the substrates did not show any mould formation at any point during growth. Although DIG1 and DIG2 were loosely filled into the net pots without being pressed into plugs beforehand, no wash-out or dissolving of the substrates was detected, thus no clogging of the pumps or channels occurred. Representative harvest samples of all combinations are shown in Figure 6.

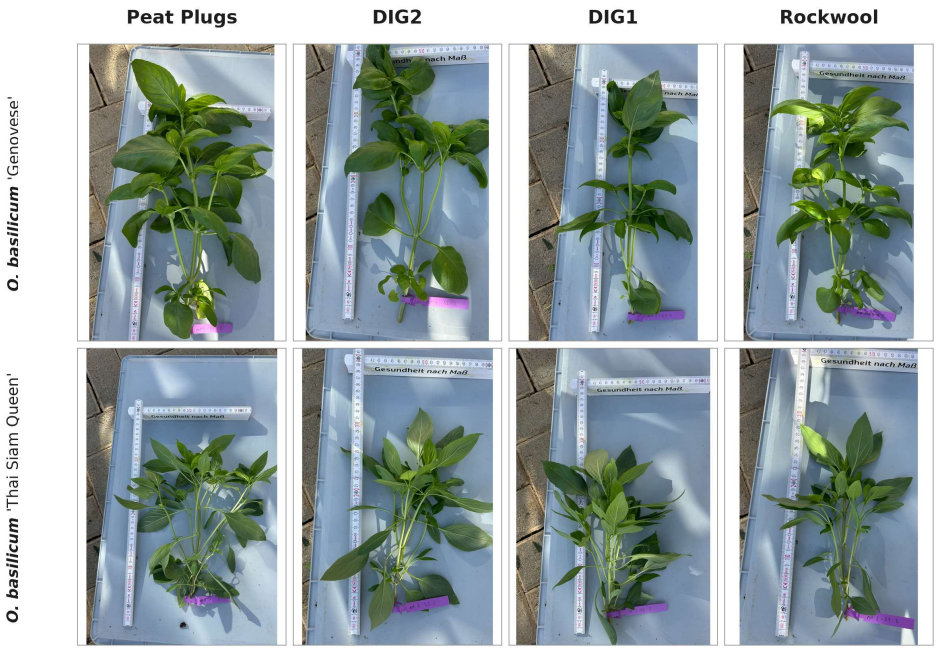


Fig. 6 Representative harvest samples of Genovese (top row) and Thai Siam Queen (bottom row) grown in four hydroponic substrates (peat plugs, DIG2, DIG1, Rockwool) in an NFT system. Plants are displayed at a consistent scale across all panels. Ruler increments are centimetres.

4 Discussion

4.1 Peat as the superior growing medium

Of all the tested growing media, peat plugs produced the highest yields. FM values reached 23.05 g per plant for Genovese and 28.29 g per plant for Thai Siam Queen. A study comparing different basil varieties in an NFT system reported yields of 34.3 g per plant for Genovese [Walters and Currey, 2015], exceeding the findings from our study. This difference is further discussed in section 4.3. Both varieties performed consistently better in all measured parameters. This can be explained by the pre-fertilization and the optimal properties found in the peat-based growing medium, such as a near-neutral pH, optimal pore volume, and efficient air-to-water ratio, which are favourable for root development and plant growth [Kitir et al., 2018]. While this finding does not contradict the main conclusions of the study, it emphasizes the benchmark that peat substitutes need to achieve to successfully replace peat as the superior growing medium. In this study, peat plugs achieved over 50 % more FM than the mineral and organic replacement materials. Acceptance of this gap in practice depends on multiple factors, including cost, ecological footprint, and the availability of alternative substrates.

4.2 Evaluation of peat replacements

For Genovese, there were no significant differences between the two digestates (DIG1 and DIG2) and rockwool in terms of FM (14.72, 13.77, and 13.79 LS means), DM, plant height and canopy width. This demonstrates that these mineral and organic peat replacements do not differ in agronomic value. Therefore, the choice of peat replacement to be used in an agricultural (or horticultural) context is based on ecological and practical considerations, in which case digestate offers clear advantages over rockwool. The production of rockwool involves melting basaltic rock at temperatures exceeding 1500 °C [Mugahed Amran et al., 2020]. Studies have found that the production of rockwool accounts for carbon emissions of 1471 CO_2eq/t [Huang and Zhang, 2020]. Digestates are usually recycled to agricultural fields and can therefore be considered a by-product of a waste stream. Consequently, the digestate substrate can be considered carbon neutral. Even after use in a hydroponic system, they can be returned to agricultural fields or composted, thus adding a more valuable cascade through this usage. Rockwool is non-compostable, and while its recycling appears feasible, studies investigating its addition to cultivation substrates have shown only limited habitat functions for earthworms, which are bio-indicators of soil quality [Istenič et al., 2024]. However, it should be noted that rockwool can be partially recycled to produce bricks, supporting the building sector [Rockwool Group, 2020]. By contrast, the digestates used in this study were derived from a cascading process involving agricultural wastes and renewable resources. Using the Geltz-process, raw digestate is treated to convert the nutrients into a liquid form. This is followed by solid-liquid separation. The liquid fraction, which contains the nutrients, is used to produce recycled fertilizers, leaving the nutrient-depleted solid fraction as a waste product. By reusing this by-product as a substrate, it is given a valuable end-of-life purpose. Additionally, the digestate substrate can be composted after use. Viewed in a bioeconomic context, not only is energy created using renewable resources, but the cascading use of digestates helps close nutrient cycles by returning waste to the soil to support agricultural food production [Zapata-Morales and Moreno-Andrade, 2025, Asp et al., 2022]. However, challenges in the use of digestates, such as the presence of pathogens and heavy metals, as well as batch variability, need to be managed through frequent quality control measures [Zapata-Morales and Moreno-Andrade, 2025].

4.3 Contextualization of the yield gap and potential of pre-treatment

The yield gap found here is most likely due to two key differences between the replacement substrates and peat plugs: the pre-fertilization of the peat plugs and the strongly acidic pH of the digestates, compared to the near neutral pH of the peat plugs (see table 2). In this study, yields of plants grown on digestates did not differ significantly from those grown on rockwool, even though the pH value of the digestates was strongly acidic (pH 3.14 to 4.0), well below the optimal range for basil. Nutrient uptake has been reported to be negatively affected in this pH range [Gillespie et al., 2020]. Although these values would probably result in decreased yield in a pot or growing bag setup, it can be assumed that the circulation of the nutrient solution in

the NFT system buffered this effect. Although efficient plant growth and yield were observed, the low pH most likely put stress on the seedlings during the initial growth phase. Slower development in the phase before NFT insertion is a possible explanation for the yield gap between the digestate and the peat plugs. Adding a pre-treatment step to optimize the pH level of the digestates (e.g. by adding lime) could possibly increase the yield on the digestates and help to close the yield gap with peat [Enesi et al., 2023, Sopha et al., 2021]. Since peat naturally has a lower pH of around 3.0 - 4.0 [Lee et al., 2021], liming is also a common practice prior to its use as a growing substrate [Kanang et al., 2025]. Additionally, the peat plugs used as a reference substrate were pre-fertilized. Due to the Geltz-process used to separate the solid and liquid fractions of the digestate to produce fertilizer, the solid digestates used here are nutrient-depleted. This could potentially explain the yield gap compared to the pre-fertilized peat plugs. Adding nutrients to the digestate before sowing could lead to larger seedlings. These findings are supported by Figure 4, which shows a slightly faster development on the peat plugs for all growth dynamic parameters. Before making decisions regarding pre-treatment, various economic factors need to be considered. In this study, the digestates were loosely filled into the net pots, without the costly addition of fertilizer or lime. Considering the visual results of the plants, no deficiencies or diseases were detected on plants grown on these substrates. This results in the hypothesis that the environment was only unfavourable in the early stages of plant development, slowing down growth. This leads to the assumption that, with a couple more days in the NFT system, the plants grown on digestates would have reached the same heights and widths, and achieved the same FM and DM. The choice between investing in costlier growing media or extending production timelines requires careful economic evaluation. Other factors explaining the yield gap include the climate conditions in the greenhouse where the trial was conducted. In our study, temperature peaks above 35 °C occurred regularly, as can be seen in Figure 2. Temperatures above 35 °C induce heat stress, which is reported to reduce the plant height and yield of Genovese basil [Ryu et al., 2024, Deveikytė et al., 2025, Walters and Currey, 2019]. For Thai Siam Queen on peat plugs, yields of 28.29 g per plant were found in this study, which aligns with findings of a comparable study, showing FM yields of 26.9 g [Walters and Currey, 2015]. This is most likely due to the Thai varieties of *O. basilicum* having a higher heat tolerance on account of their origin.

4.4 Comparison of the two digestates

As can be seen in Table 2, the two digestates tested in this study differ in their physical and chemical characteristics. Genovese performed equally well on both digestates, butdeviating responses were found for Thai Siam Queen . DIG2 achieved significantly higher FM (18.61 g) and DM per plant (3.31 g) compared to DIG1 (13.63 g, 2.26 g) and rockwool (14.30 g, 2.48 g). This suggests that Thai Siam Queen has a higher sensitivity to substrate characteristics. Studies have shown this this variety is more sensitive to production system types and environmental conditions than other basil varieties, including Genovese [Feldzensztajn et al., 2022, Doty et al., 2020]. The difference in yield may also be due to the higher water holding capacity of DIG2 (861 ml/l, compared to 409 ml/l for DIG1). Given the frequent temperature peaks, which lead to

accelerated drying of the substrate, a high water-holding capacity seems favourable in reducing water stress. DIG2 shows a considerably higher nutrient content in the aqua regia extraction for all elements, most likely due to the high manure input. It has been reported that the interaction between the chemical properties and physical characteristics of growing substrates determines the overall development of plant roots [Blok and Wever, 2008]. The additional nutrients in the immediate vicinity of the roots could explain the higher yields on DIG2. The chemical properties also include pH [Blok and Wever, 2008], in which DIG1 and DIG2 differ: DIG1 has a substantially lower pH (3.14) than DIG2 (4.0). Although both values are lower than the reported optimum of 5.5 - 6.0 [Gillespie et al., 2020], DIG2 has values that are still tolerated by basil [Gillespie et al., 2020]. In the early growing stages in particular, when the roots were in direct contact with the substrate without the buffering effects of the nutrient solutions, development could have been impaired by root stress due to the low pH. In the literature, substrate properties during the propagation phase have been reported to influence plant yield, since the root system develops at an early stage and determines the plants' capacity for nutrient uptake [Yafuso et al., 2019]. Future research should evaluate the effects of digestate substrates' properties on early plant development, including nutrient release, moisture dynamics, pH-induced stress and root-sensitivity, to explain the observed responses in DIG1.

5 Conclusions and Outlook

This study evaluated two peat-replacement strategies in the form of mineral (rockwool) and organic (digestate-based) substrates compared to a peat-based reference in an NFT hydroponic system, using two *Ocimum basilicum* L. varieties as test plants. Peat-based plugs performed significantly better in all measured parameters for both basil varieties. This emphasizes the higher suitability of peat as an optimal growing environment for plants. However, the yield gap observed in the replacement substrates must be weighed up against the detrimental ecological impacts of continued peat extraction and exploitation of peatlands. The main finding of this study is that the two peat substitution strategies performed comparably. No significant differences were found for Genovese in all measured parameters on both rockwool and the two digestates. For Thai Siam Queen, DIG2 showed a better agronomic performance compared to rockwool and DIG1. This suggests variety-specific substrate sensitivity, which should be explored further in future trials. When choosing a peat alternative for hydroponic purposes, ecological factors need to be considered. Both digestates are compostable, carbon-neutral by-products of an existing agricultural waste stream. Therefore, using digestates as peat replacements has a clear ecological advantage over non-biodegradable rockwool, which accounts for global annual emissions of approximately 1,417 CO_2eq/t. Further trials are planned to explore closing the yield gap between the digestates and peat plugs. Differences in yield are possibly due to the acidic pH value of the two digestates (pH 3.14-4.0), as well as their nutrient-depleted state after processing in a Geltz-process. Increasing the pH using lime, for example, and adding nutrients to the substrate before sowing seeds, could be promising strategies for closing the yield gap. However, the economic feasibility of these additional

working steps needs to be considered in such trials. It is also intended to explore batch-to-batch variability in digestate quality and the performance of digestate substrates over multiple growing cycles. This study evaluated the agronomic performance of two *Ocimum basilicum* varieties. In order to evaluate growing substrates with the aim of finding a universal solution, other plant species, such as leafy vegetables, should be tested. Additionally, different hydroponic systems and setups, such as deep water culture and ebb-and-flow, need to be tested to determine whether the results can be transferred to different cultivation systems. In a bioeconomic framework, scaling up by using digestates as a horticultural growing medium adds a higher value to a by-product and also a valuable cascade to an existing agricultural waste stream. This supports the transition to more sustainable and circular agricultural production.

6 Declarations

6.1 Funding

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6.2 Competing Interest

The authors declare no competing interests, according to the Springer guidelines.

6.3 Data availability

The datasets generated during this study are available from the corresponding author upon reasonable request.

7 Author contribution statement

M.T. wrote the main manuscript text and prepared the figures and tables. I.L. and A.B. provided conceptual guidance and critically revised the manuscript. F.C. developed the statistical analysis code in SAS and critically revised the statistical analyses. All authors reviewed and approved the final manuscript.

References

Md. Asaduzzaman, Md. Saifullah, A.K.M. Salim Reza Mollick, Md. Mokter Hossain, G.M.A. Halim, and Toshiki Asao. Influence of Soilless Culture Substrate on Improvement of Yield and Produce Quality of Horticultural Crops. In Md. Asaduzzaman, editor, *Soilless Culture - Use of Substrates for the Production of Quality Horticultural Crops*. InTech, February 2015. ISBN 978-953-51-1739-1. doi: 10.5772/59708.

Håkan Asp, Karl-Johan Bergstrand, Siri Caspersen, and Malin Hultberg. Anaerobic digestate as peat substitute and fertiliser in pot production of basil. *Biological Agriculture & Horticulture*, 38(4):247–257, October 2022. ISSN 0144-8765, 2165-0616. doi: 10.1080/01448765.2022.2064232.

G.E. Barrett, P.D. Alexander, J.S. Robinson, and N.C. Bragg. Achieving environmentally sustainable growing media for soilless plant cultivation systems – A review. *Scientia Horticulturae*, 212:220–234, November 2016. ISSN 03044238. doi: 10.1016/j.scienta.2016.09.030.

C. Blok and G. Wever. EXPERIENCE WITH SELECTED PHYSICAL METHODS TO CHARACTERIZE THE SUITABILITY OF GROWING MEDIA FOR PLANT GROWTH. *Acta Horticulturae*, (779):239–250, January 2008. ISSN 0567-7572, 2406-6168. doi: 10.17660/ActaHortic.2008.779.29.

BMEL. Going peat-free, protecting the climate: The Peat Use Reduction Strategy of the Federal Ministry of Food and Agriculture. Technical report, Federal Ministry of Food and Agriculture (BMEL), Berlin, July 2022.

S. Bougoul, S. Ruy, F. De Groot, and T. Boulard. Hydraulic and physical properties of stonewool substrates in horticulture. *Scientia Horticulturae*, 104(4):391–405, May 2005. ISSN 03044238. doi: 10.1016/j.scienta.2005.01.018.

Roberto Calisti, Luca Regni, Daniela Pezzolla, Mirko Cucina, Giovanni Gigliotti, and Primo Proietti. Evaluating Compost from Digestate as a Peat Substitute in Nursery for Olive and Hazelnut Trees. *Sustainability*, 15(1):282, December 2022. ISSN 2071-1050. doi: 10.3390/su15010282.

T.K.K. Chamindu Deepagoda, Jose Choc Chen Lopez, Per Møldrup, Lis Wollesen De Jonge, and Markus Tuller. Integral parameters for characterizing water, energy, and aeration properties of soilless plant growth media. *Journal of Hydrology*, 502: 120–127, October 2013. ISSN 00221694. doi: 10.1016/j.jhydrol.2013.08.031.

Calvin Chong and Bob Hamersma. Raw Paper Mill Sludge in A Rooting Medium for Deciduous Woody Cuttings. *HortScience*, 31(5):869–871, September 1996. ISSN 0018-5345, 2327-9834. doi: 10.21273/HORTSCI.31.5.869.

Justina Deveikytė, Aušra Blinstrubienė, Natalija Burbulis, and Aldona Baltušnikienė. Foliar Application of Amino Acids Increases Sweet Basil (Ocimum basilicum L.) Resistance to High-Temperature Stress. *Plants*, 14(5):739, February 2025. ISSN 2223-7747. doi: 10.3390/plants14050739.

Samuel Doty, Ryan W. Dickson, and Michael Evans. Evaluation of a Novel Shallow Aggregate Ebb-and-flood Culture System and Transplant Size Effects on Hydroponic Basil Yield. *HortTechnology*, 30(5):585–592, October 2020. ISSN 1063-0198, 1943-7714. doi: 10.21273/HORTTECH04635-20.

Daniel Eden. Technical specs Eazy Plug. https://www.eazy-plug.com/eazy-plug-tech-specs/, 2015.

Andrea Ehmann, Inga-Mareike Bach, Jennifer Bilbao, Iris Lewandowski, and Torsten Müller. Phosphates recycled from semi-liquid manure and digestate are suitable alternative fertilizers for ornamentals. *Scientia Horticulturae*, 243:440–450, January 2019. ISSN 03044238. doi: 10.1016/j.scienta.2018.08.052.

Rebecca Oiza Enesi, Miles Dyck, Scott Chang, Malinda S. Thilakarathna, Xiaoli Fan, Stephen Strelkov, and Linda Yuya Gorim. Liming remediates soil acidity and improves crop yield and profitability - a meta-analysis. *Frontiers in Agronomy*, 5: 1194896, June 2023. ISSN 2673-3218. doi: 10.3389/fagro.2023.1194896.

G. Fascella, G.V. Zizzo, and S. Agnello. SOILLESS CULTIVATION OF MOTHER PLANTS OF EUPHORBIA X LOMI HYBRIDS ON DIFFERENT SUBSTRATES.

Acta Horticulturae, (718):507–514, October 2006. ISSN 0567-7572, 2406-6168. doi: 10.17660/ActaHortic.2006.718.59.

G. Fascella, M. Mammano, F. D'Angiolillo, and Y. Rouphael. Effects of conifer wood biochar as a substrate component on ornamental performance, photosynthetic activity, and mineral composition of potted *Rosa rugosa*. *The Journal of Horticultural Science and Biotechnology*, 93(5):519–528, September 2018. ISSN 1462-0316, 2380-4084. doi: 10.1080/14620316.2017.1407679.

Mateusz Feldzensztajn, Dariusz Kulus, Adam Mazikowski, and Anita Woźny. Optical, Biochemical, and Biometrical Properties of Thai Basil (Ocimum Basilicum VAR. Thyrsiflora L.) and Red Rubin Basil (Ocimum Basilicum VAR. Rubrum L.) Grown in Different Lighting Conditions. *SSRN Electronic Journal*, 2022. ISSN 1556-5068. doi: 10.2139/ssrn.4221597.

Filippo Ferlito, Biagio Torrisi, Maria Allegra, Fiorella Stagno, Paola Caruso, and Giancarlo Fascella. Evaluation of Conifer Wood Biochar as Growing Media Component for Citrus Nursery. *Applied Sciences*, 10(5):1618, February 2020. ISSN 2076-3417. doi: 10.3390/app10051618.

F. Geltz and U. Geltz. VERFAHREN UND ANORDNUNG ZUR HERSTELLUNG EINES TORFERSATZSTOFFES AUS EINER FASERSTOFFSUSPENSION, January 2023.

D. Gillespie, C. Kubota, and S. Miller. Effects of Low pH of Hydroponic Nutrient Solution on Plant Growth, Nutrient Uptake, and Root Rot Disease Incidence of Basil (Ocimum basilicum L.). *HortScience*, 55(8):1251–1258, August 2020. ISSN 0018-5345, 2327-9834. doi: 10.21273/HORTSCI14986-20.

Carlo Greco, Antonio Comparetti, Giancarlo Fascella, Pierluigi Febo, Giulia La Placa, Filippo Saiano, Michele Massimo Mammano, Santo Orlando, and Vito Armando Laudicina. Effects of Vermicompost, Compost and Digestate as Commercial Alternative Peat-Based Substrates on Qualitative Parameters of Salvia officinalis. *Agronomy*, 11(1):98, January 2021. ISSN 2073-4395. doi: 10.3390/agronomy11010098.

N. Gruda. SUSTAINABLE PEAT ALTERNATIVE GROWING MEDIA. *Acta Horticulturae*, (927):973–979, February 2012. ISSN 0567-7572, 2406-6168. doi: 10.17660/ActaHortic.2012.927.120.

Nazim Gruda. Increasing Sustainability of Growing Media Constituents and Stand-Alone Substrates in Soilless Culture Systems. *Agronomy*, 9(6):298, June 2019. ISSN 2073-4395. doi: 10.3390/agronomy9060298.

N.S. Gruda, O. Hirschler, and J. Stuart. Peat reduction in horticulture – an overview of Europe. *Acta Horticulturae*, (1391):545–560, March 2024. ISSN 0567-7572, 2406-6168. doi: 10.17660/ActaHortic.2024.1391.75.

Hongxing He and Nigel T. Roulet. Improved estimates of carbon dioxide emissions from drained peatlands support a reduction in emission factor. *Communications Earth & Environment*, 4(1):436, November 2023. ISSN 2662-4435. doi: 10.1038/s43247-023-01091-y.

O. Hirschler and B. Osterburg. Achieving peat-free hobby gardening for climate mitigation in Germany: Insights into prices of growing media constituents, potting soils and policy options. *Resources, Conservation and Recycling*, 220:108330, June 2025.

ISSN 09213449. doi: 10.1016/j.resconrec.2025.108330.

Meng Chi Huang and Yan Jiao Zhang. Carbon Emissions Analysis of Rock Wool Board Products. *Materials Science Forum*, 993:1545–1551, May 2020. ISSN 1662-9752. doi: 10.4028/www.scientific.net/MSF.993.1545.

D. Indira, A. Sabitha Rani, and Department of Botany, University College of Science, Osmania University, Hyderabad, Telangana, 500 007 India. Comparative Analysis of Growth Parameters in Hydroponic and Soil-Grown Systems of Ocimum basilicum L. (Basil). *Plant Science Archives*, 9(2):26–32, May 2024. doi: 10.51470/PSA.2024.9.2.26.

Darja Istenič, Franja Prosenc, Neva Zupanc, Matejka Turel, Andrej Holobar, Radmila Milačič, Stefan Marković, and Rok Mihelič. Composting of recovered rock wool from hydroponics for the production of soil amendment. *Environmental Science and Pollution Research*, 31(20):29280–29293, April 2024. ISSN 1614-7499. doi: 10.1007/s11356-024-33041-2.

IUCN. IUCN 2022 annual report. Technical report, IUCN, Gland, Switzerland, 2023.

Kevin D. Kanang, Hasmah Mohidin, Auldry C. Petrus, Michaela C. W. Liuan, Goh K. Joo, and Lulie Melling. Effects of liming on the chemical properties of tropical peat soils: An incubation-based analysis. *Archives of Agronomy and Soil Science*, 71 (1):1–17, December 2025. ISSN 0365-0340, 1476-3567. doi: 10.1080/03650340.2025.2527094.

Nurgul Kitir, Ertan Yildirim, Üstün Şahin, Metin Turan, Melek Ekinci, Selda Ors, Raziye Kul, Hüsnü Ünlü, and Halime Ünlü. Peat Use in Horticulture. In Bülent Topcuoğlu and Metin Turan, editors, *Peat*. InTech, September 2018. ISBN 978-1-78923-746-7 978-1-78923-747-4. doi: 10.5772/intechopen.79171.

Peter M. Kopittke, Neal W. Menzies, Peng Wang, Brigid A. McKenna, and Enzo Lombi. Soil and the intensification of agriculture for global food security. *Environment International*, 132:105078, November 2019. ISSN 01604120. doi: 10.1016/j.envint.2019.105078.

Vito Armando Laudicina, Eristanna Palazzolo, Anna Piotrowska-Długosz, and Luigi Badalucco. Soil profile dismantlement by land levelling and deep tillage damages soil functioning but not quality. *Applied Soil Ecology*, 107:298–306, November 2016. ISSN 09291393. doi: 10.1016/j.apsoil.2016.07.002.

So-Young Lee, Eun-Gyeong Kim, Jae-Ryoung Park, Young-Hyun Ryu, Won Moon, Gyu-Hwan Park, Mohammad Ubaidillah, Su-Noh Ryu, and Kyung-Min Kim. Effect on Chemical and Physical Properties of Soil Each Peat Moss, Elemental Sulfur, and Sulfur-Oxidizing Bacteria. *Plants*, 10(9):1901, September 2021. ISSN 2223-7747. doi: 10.3390/plants10091901.

N. K. G. K. R. Manawasinghe, S. H. Weerasekara, C. S. L. M. Karunaratne, W. A. P. Weerakkody, and B. Kulapala. Influence of Substrate and Supplementary LED lighting on Vertical Farming of Basil (Ocimum basilicum L.) and Pak Choi (Brassica rapa var. chinensis). *Asian Journal of Agricultural and Horticultural Research*, pages 42–52, February 2021. ISSN 2581-4478. doi: 10.9734/ajahr/2020/v7i430103.

Dalia Maurer, Alona Sadeh, Daniel Chalupowicz, Shimon Barel, Jakob A Shimshoni, and David Kenigsbuch. Hydroponic *versus* soil-based cultivation of sweet basil: Impact on plants' susceptibility to downy mildew and heat stress, storability and

total antioxidant capacity. *Journal of the Science of Food and Agriculture*, 103(15): 7809–7815, December 2023. ISSN 0022-5142, 1097-0010. doi: 10.1002/jsfa.12860.

Uwe Meier. Growth stages of mono- and dicotyledonous plants: BBCH Monograph. 2018. doi: 10.5073/20180906-074619.

Mădălin Vasile Chiuoaru, Gabriela Butnariu, Daniel Nagy, Maria Adochiței, and Ligia Ion. Research on the growing particularities of some basil genotypes (Occimum basilicum) from southern Romania. *World Journal of Advanced Research and Reviews*, 27(2):1094–1101, August 2025. ISSN 25819615. doi: 10.30574/wjarr.2025.27.2.2935.

Y.H. Mugahed Amran, Mohamed El-Zeadani, Yeong Huei Lee, Yee Yong Lee, G. Murali, and Roman Feduik. Design innovation, efficiency and applications of structural insulated panels: A review. *Structures*, 27:1358–1379, October 2020. ISSN 23520124. doi: 10.1016/j.istruc.2020.07.044.

Astrid Solvåg Nesse, Trine Sogn, Trond Børresen, and Bente Foereid. Peat replacement in horticultural growth media: The adequacy of coir, paper sludge and biogas digestate as growth medium constituents for tomato (*Solanum lycopersicum L.*) and lettuce (*Lactuca sativa L.*). *Acta Agriculturae Scandinavica, Section B — Soil & Plant Science*, 69(4):287–294, May 2019. ISSN 0906-4710, 1651-1913. doi: 10.1080/09064710.2018.1556728.

Adeoluwa Abraham Olasehinde. Biodegradable Growth Media Alternatives for Sustainable Hydroponic Farming. *Current Journal of Applied Science and Technology*, 44(3):147–152, February 2025. ISSN 2457-1024. doi: 10.9734/cjast/2025/v44i34506.

Michael Raviv and J.H. Lieth. *Soilless Culture*. Elsevier, 2008. ISBN 978-0-444-52975-6. doi: 10.1016/B978-0-444-52975-6.X5001-1.

Rockwool Group. Regenerative by nature: Sustainability report 2020. Technical report, Rockwool Group, Hedehusene, Denmark, 2020.

Hamid R. Roosta. Comparison of the Vegetative Growth, Eco-Physiological Characteristics and Mineral Nutrient Content of Basil Plants in Different Irrigation Ratios of Hydroponic:Aquaponic Solutions. *Journal of Plant Nutrition*, 37(11):1782–1803, September 2014. ISSN 0190-4167, 1532-4087. doi: 10.1080/01904167.2014.890220.

Da Hye Ryu, Jwa Yeong Cho, Muhammad Hamayun, Dong Gyu Lee, and Ho-Youn Kim. Metabolic modulation of Basil (Ocimum basilicum L.): An insight into growth, metabolomics and antioxidant activity under varying temperature and light conditions. *Chemical and Biological Technologies in Agriculture*, 11(1):10, January 2024. ISSN 2196-5641. doi: 10.1186/s40538-023-00532-2.

Subhrajit Saha, Amber Monroe, and Martin R. Day. Growth, yield, plant quality and nutrition of basil (Ocimum basilicum L.) under soilless agricultural systems. *Annals of Agricultural Sciences*, 61(2):181–186, December 2016. ISSN 05701783. doi: 10.1016/j.aoas.2016.10.001.

G A Sopha, A M Effendi, F Aprianto, and A Firmansyah. The incorporation of lime and NPK fertilizer on shallot production in peat soil. *IOP Conference Series: Earth and Environmental Science*, 653(1):012057, February 2021. ISSN 1755-1307, 1755-1315. doi: 10.1088/1755-1315/653/1/012057.

Nikolaos Tzortzakis, Silvana Nicola, Dimitrios Savvas, and Wim Voogt. Editorial: Soilless Cultivation Through an Intensive Crop Production Scheme. Management

Strategies, Challenges and Future Directions. *Frontiers in Plant Science*, 11:363, April 2020. ISSN 1664-462X. doi: 10.3389/fpls.2020.00363.

United Nations. World Population Prospects 2024: Summary of Results. Technical Report UN DESA/POP/2024/TR/NO. 9, United Nations, New York, USA, 2024.

VDLUFA. Methodenbuch Band I: Die Untersuchung von Böden, 1991.

VDLUFA. Methodenbuch Band II: Die Untersuchung von Wirtschaftsdüngern, Sekundärrohstoffdüngern, Substraten und Hilfsstoffen., 1995.

Roberto S. Velazquez-Gonzalez, Adrian L. Garcia-Garcia, Elsa Ventura-Zapata, Jose Dolores Oscar Barceinas-Sanchez, and Julio C. Sosa-Savedra. A Review on Hydroponics and the Technologies Associated for Medium- and Small-Scale Operations. *Agriculture*, 12(5):646, April 2022. ISSN 2077-0472. doi: 10.3390/agriculture12050646.

Kellie J. Walters and Christopher J. Currey. Hydroponic Greenhouse Basil Production: Comparing Systems and Cultivars. *HortTechnology*, 25(5):645–650, October 2015. ISSN 1063-0198, 1943-7714. doi: 10.21273/HORTTECH.25.5.645.

Kellie J. Walters and Christopher J. Currey. Growth and Development of Basil Species in Response to Temperature. *HortScience*, 54(11):1915–1920, November 2019. ISSN 0018-5345, 2327-9834. doi: 10.21273/HORTSCI12976-18.

Eleni Wogiatzi, Alexandras Papachatzis, Helen Kalorizou, Adamantia Chouliara, and Nikolaos Chouliaras. Evaluation of Essential Oil Yield and Chemical Components of Selected Basil Cultivars. *Biotechnology & Biotechnological Equipment*, 25(3): 2525–2527, January 2011. ISSN 1310-2818, 1314-3530. doi: 10.5504/BBEQ.2011.0067.

Katarzyna Wystalska, Krystyna Malińska, Jolanta Sobik-Szołtysek, Danuta Dróżdż, and Erik Meers. Properties of Poultry-Manure-Derived Biochar for Peat Substitution in Growing Media. *Materials*, 16(19):6392, September 2023. ISSN 1996-1944. doi: 10.3390/ma16196392.

Erin J. Yafuso, Paul R. Fisher, Ana C. Bohórquez, and James E. Altland. Water and Air Relations in Propagation Substrates. *HortScience*, 54(11):2024–2030, November 2019. ISSN 0018-5345, 2327-9834. doi: 10.21273/HORTSCI14145-19.

Ana Laura Zapata-Morales and Ivan Moreno-Andrade. Valorization of digestates from organic solid waste as fertilizers, soil improvers, and agricultural prebiotics: Panorama and perspectives. *3 Biotech*, 15(10):333, October 2025. ISSN 2190-572X, 2190-5738. doi: 10.1007/s13205-025-04507-y.

8 Appendix

Table 3 shows the least square means (±SE) of growth and yield parameters for two basil varieties cultivated on four substrates in an NFT hydroponic system.

Table 3 Least square means (±SE) of growth and yield parameters for two basil varieties cultivated on four substrates in an NFT hydroponic system.

Species	**Substrate**	**Fresh mass [g]**		**Height [g]**		**Width [cm]**		**Dry mass [g]**		**%DM**	
		Mean	Sig.	Mean	Sig.	Mean	Sig.	Mean	Sig.	Mean	Sig.
O. basilicum 'Genovese'	peat plugs	23.05	**B**	27.49	**A**	24.16	**B**	4.27	**A**	9.21	**A**
O. basilicum 'Genovese'	DIG2	13.77	**D**	24.55	**BAC**	22.14	**B**	2.49	**C**	9.44	**A**
O. basilicum 'Genovese'	DIG1	13.79	**D**	25.89	**BA**	22.81	**B**	2.50	**C**	9.36	**BA**
O. basilicum 'Genovese'	Rockwool	14.72	**D**	26.06	**BA**	22.75	**B**	2.7	**CB**	9.19	**BA**
O. basilicum 'Thai Siam Queen'	peat plugs	28.29	**A**	23.34	**BDC**	27.33	**A**	4.92	**A**	9.09	**BA**
O. basilicum 'Thai Siam Queen'	DIG2	18.61	**C**	22.38	**DC**	24.61	**BA**	3.23	**B**	8.93	**BAC**
O. basilicum 'Thai Siam Queen'	DIG1	13.36	**D**	20.62	**D**	22.32	**B**	2.17	**C**	8.33	**C**
O. basilicum 'Thai Siam Queen'	Rockwool	14.44	**D**	20.97	**D**	22.4	**B**	2.61	**C**	9.17	**BC**
	SE	±1.91		±1.33		±1.53		±0.32		±0.39	
	Species	0.0007		<0.0001		0.0054		0.1008		<0.0001	
	Substrate	<.0001		0.0192		<.0001		<.0001		0.0134	
	Sp×Sub	0.0014		0.0701		0.0027		0.0013		0.2335	

Means within a column sharing the same letter are not significantly different (Tukey-Kramer, α=0.05). Green p-values indicate significance (p<0.05). SE = pooled standard error of the least square means. Sp × Sub = Species × Substrate interaction. FM = fresh mass per pot (average of 2 plants). DM = dry mass corrected for bag weight (bag tare = 10.76 g). %DM = dry matter content = $DM/FM_{bag} \times 100$. For all varieties that were square-root transformed and %DM, which was log-transformed prior to analysis, back-transformed least square means are presented.