Growth Performance and Water-Use Efficiency of Red Rubin and Genovese Basil Varieties in Aeroponic Cultivation

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ABSTRACT

Our study investigated the growth of two basil varieties – Red Rubin (*Ocimum basilicum* var. *purpurascens*) and Genovese (*Ocimum basilicum* var. *Genovese*) – under aeroponic conditions at the Institute of Water and Environmental Management, University of Debrecen. Growth dynamics were monitored using morphological parameters (plant height and leaf number), manual LiDAR measurements, and yield analysis. The aim was to evaluate the performance of these varieties in terms of growth characteristics and productivity under controlled light, climate, and nutrient conditions, with particular emphasis on water-use efficiency. The results revealed differences in growth patterns between the two varieties, as well as in their responses to nutrient availability and environmental factors. This research offers valuable insights for optimizing aeroponic basil cultivation and supports sustainable, resource-efficient agricultural practices, especially in urban and vertical farming systems. The research presented in the article was carried out within the framework of the Széchenyi Terv Plusz programme, with support from the RRF-2.3.1-21-2022-00008 project.
Keywords: aeroponics, basil, soilless cultivation, water use efficiency

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1. INTRODUCTION

The agricultural sector currently faces numerous global challenges. Climate change, which has already caused adverse effects for several decades, is expected to intensify and lead to even more profound disruptions in the coming years. At the same time, the reduction of arable land due to urbanisation and industrial expansion – combined with soil degradation through salinisation, nutrient depletion, erosion, and contamination with pesticides or heavy metals – poses an increasing threat to global food production. Plants have inherent limitations in rapidly adapting to rapidly changing conditions, resulting in reduced yields, lower crop quality, and greater vulnerability to pests and diseases. Together, these factors create significant risks to food security and economic stability.

At the same time, market demand for fresh, high-quality herbs – particularly basil – is steadily increasing due to the growth of the food industry and gastronomy, as well as the rising popularity of functional foods rich in bioactive compounds. However, basil is highly sensitive to environmental fluctuations, and traditional field cultivation often fails to deliver stable yields and uniform quality. This has made controlled environment agriculture (CEA) increasingly important for producing consistent, contamination-free plant material with predictable growth characteristics (Gomez et al., 2019).

Soilless cultivation technologies offer promising solutions to these challenges. Among them, aeroponics stands out as one of the most innovative and efficient plant production systems (Kumar, 2024). By suspending plant roots in air and delivering a nutrient-rich mist directly to the rhizosphere, aeroponics provides optimal root-zone oxygenation, precise nutrient delivery, and significantly reduced water consumption. Its closed-loop design minimises water losses from evaporation or leaching, making it particularly suitable for regions facing water scarcity. In addition, aeroponics eliminates exposure to soil-borne pathogens and enables pesticide-free production, thereby supporting sustainable horticultural practices.

Recent developments in digital phenotyping, including LiDAR-based morphological monitoring, further enhance the potential of aeroponics (Gano et al., 2024). These technologies enable high-resolution, non-destructive tracking of plant development, offering valuable insights into genotype-specific growth responses and supporting data-driven optimisation of cultivation protocols.

Given these technological advancements and the increasing need for sustainable, water-efficient crop production, evaluating the performance of different basil varieties under aeroponic conditions is both timely and relevant. Understanding how varietal traits interact with controlled environmental parameters can help refine production strategies and improve the overall efficiency of urban and vertical farming systems.

2. LITERATURE REVIEW

Aeroponics has emerged as an innovative and highly efficient plant production method, attracting growing attention for its ability to reduce water use and enhance growth rates (Garzón et al., 2023; Lakhiar, 2018). In this system, roots are suspended in air and supplied with water and nutrients as a fine mist (Blok et al., 2017), promoting optimal plant development while minimising resource consumption. As a closed production technology, aeroponics enables precise environmental control and reduces pathogen pressure, thereby eliminating soil-borne diseases and supporting pesticide-free cultivation (Scortichini, 2022). The beneficial effects of aeroponic cultivation have been successfully demonstrated in tomatoes (Tafesse et al., 2021), cucumbers (Jamshidi et al., 2020), leafy

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greens (Chandra et al., 2014; Lim, 1996), potatoes (Farran & Mingo-Castel, 2006; Tunio et al., 2020), and herbs and medicinal plants (Hayden, 2006). Positive results have also been observed with lettuce (Kovács et al., 2025a) and seed potatoes (Kovács et al., 2025b).

Basil (*Ocimum basilicum*) is a widely used culinary and economically important herb, valued for both fresh consumption and its essential oils, which have applications in the food, pharmaceutical, and cosmetic sectors. Its short production cycle, high market demand, and sensitivity to environmental fluctuations make it particularly suited to controlled environment agriculture. Aeroponic production is especially advantageous for basil, which requires a tightly regulated nutrient and water supply (Khater et al., 2021; Salachas et al., 2015). Environmental factors such as light, nutrients, and water availability strongly influence its growth and essential-oil profile (Stagnari et al., 2018), while the species responds well to precise nutrient delivery and a highly oxygenated root zone.

Studies consistently show that basil grown aeroponically develops faster and produces greater biomass and more refined root systems than when grown under hydroponic or soil-based conditions (Mourantian et al., 2023; Pasch et al., 2021; Salachas et al., 2015). Improved oxygenation enhances enzyme activity, nutrient transport, and stress tolerance, while water-use efficiency (WUE) – shaped by transpiration, leaf area expansion, and biomass-to-water ratios – also tends to increase. Aeroponics' pulsed water delivery creates alternating wet-dry cycles that can stimulate water uptake and nutrient efficiency, thereby increasing chlorophyll content, accelerating canopy development, and enhancing essential-oil synthesis. Overall, the resource-efficient, year-round production enabled by closed systems positions aeroponics as a key technology for meeting the growing global demand for high-quality basil.

This study aimed to evaluate the performance of these basil varieties in terms of growth characteristics and productivity under controlled light, climate, and nutrient conditions, with particular emphasis on water-use efficiency.

3. MATERIALS AND METHODS

We conducted the experiments in the Aeroponics Laboratory of the Institute of Water and Environmental Management, Faculty of Agricultural and Food Sciences and Environmental Management, University of Debrecen. The closed climate chamber enabled controlled conditions for up to 80 plants by regulating temperature, relative humidity, and light cycles.

3.1 The two basil varieties used in the experiment

"Red Rubin" (*Ocimum basilicum* var. *purpurascens*) is a red-leaved basil variety characterised by medium plant height, a strong clove-like aroma, vigorous stems, and dense foliage. Under optimal conditions, plants typically reach 40-60 cm in height.

The traditional sweet basil variety "Genovese" (*Ocimum basilicum* var. *Genovese*) is widely cultivated for fresh consumption and pesto production. It features large, bright-green leaves, a strong aroma, and high yield potential, making it well-suited to hydroponic and aeroponic cultivation systems (Biksa, 2022). It is considered the standard cultivar for Italian-style basil production (Gardenia, 2025).

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3.2 Description of the experiment

Basil seeds were germinated on 3.6 × 3.6 cm rockwool cubes (*Figure 1*). Seedling cultivation took place in a Mammoth Lite 80+ indoor growing tent equipped with a SANLIGHT Q5W GEN2 grow lamp capable of emitting light in the 400-780 nm wavelength range.

Figure 1: The seedling nursery tent (left) and the pre-grown seedlings (right) in the cotton cubes

Source: The authors

At sowing, four basil seeds were placed in each rockwool cube, and a thin layer of perlite was added. Two-week-old pre-grown seedlings were then transplanted into the Aeroponics Laboratory. In each of the four growing units (each with a surface area of 1 m²), ten seedlings per variety were planted. The climate chamber contained four aeroponic growing units, each connected to its own nutrient storage tank via a pipe system. Plants were placed in basket-shaped growing pots filled with clay pellets as the inert growth medium.

The aeroponic nozzles were adjusted to deliver a fine nutrient mist evenly onto the suspended plant roots. Pumps were equipped with timers, and nutrient delivery was set to 10 min every hour throughout the experiment.

Data-collecting sensors were installed in the climate chamber, connected to a central computer, and continuously recorded temperature and humidity. *Figure 2* shows the variation in temperature and relative humidity over the 111-day experimental period in the aeroponic system. During the first 60 days, the temperature fluctuated between 15 °C and 25 °C with noticeable variation before stabilising at approximately 20 °C to meet the plants' developmental requirements. Relative humidity initially ranged widely between 60 % and 90 %, then stabilised at around 70 % from day 40 onward.

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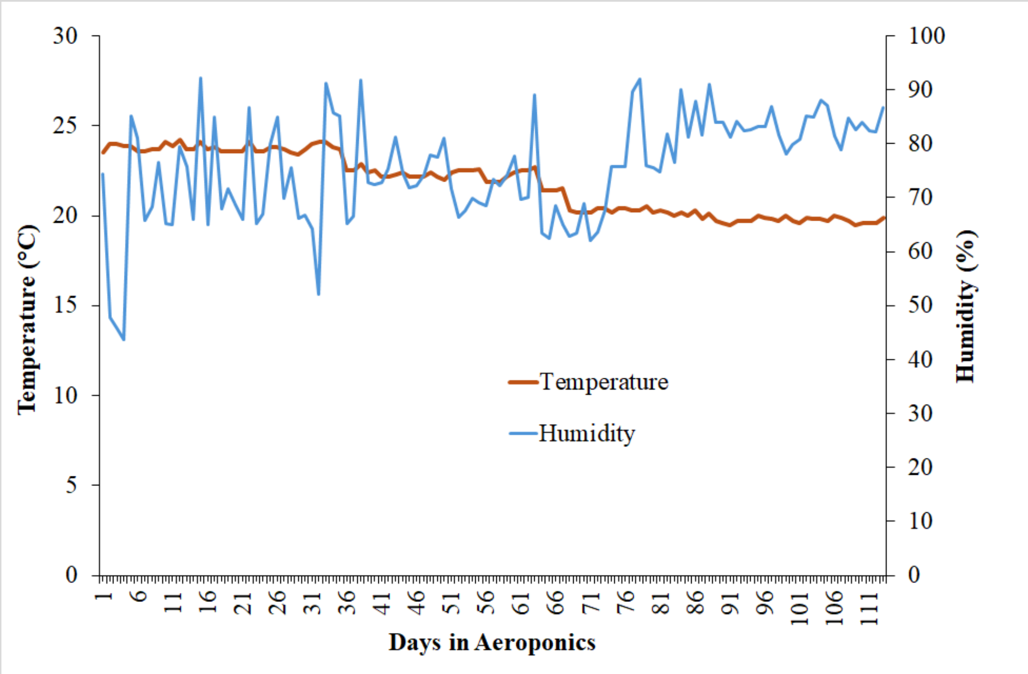

Figure 2: The temperature and humidity changes during the experiment in the Aeroponics

Source: The authors' data

The plants were illuminated using Research Top Light full-spectrum, high-intensity, four-channel horticultural LED grow lamps controlled by the Hungarian "Power Grow" software developed by Tungsram. The lighting system operated fully automatically throughout the experiment.

During the early seedling stage, basil does not require far-red light; therefore, far-red wavelengths were omitted from the spectrum. After the vegetative expansion stage, far-red light becomes necessary. Incorporating far-red light into the spectrum provides significant benefits for biomass production and resource-use efficiency. Far-red (FR) light treatments are associated with increased carbohydrate reserves, more efficient stachyose production, and potentially improved phloem loading in intermediary cells through enhanced sucrose homeostasis. The combination of higher biomass yield, increased resource-use efficiency, and elevated leaf carbohydrate concentrations in response to FR light supplementation offers promising opportunities for commercial crop production in controlled environment agriculture (Driesen et al., 2023). *Figure 3* shows the light intensity and spectrum applied before and after the addition of far-red light.

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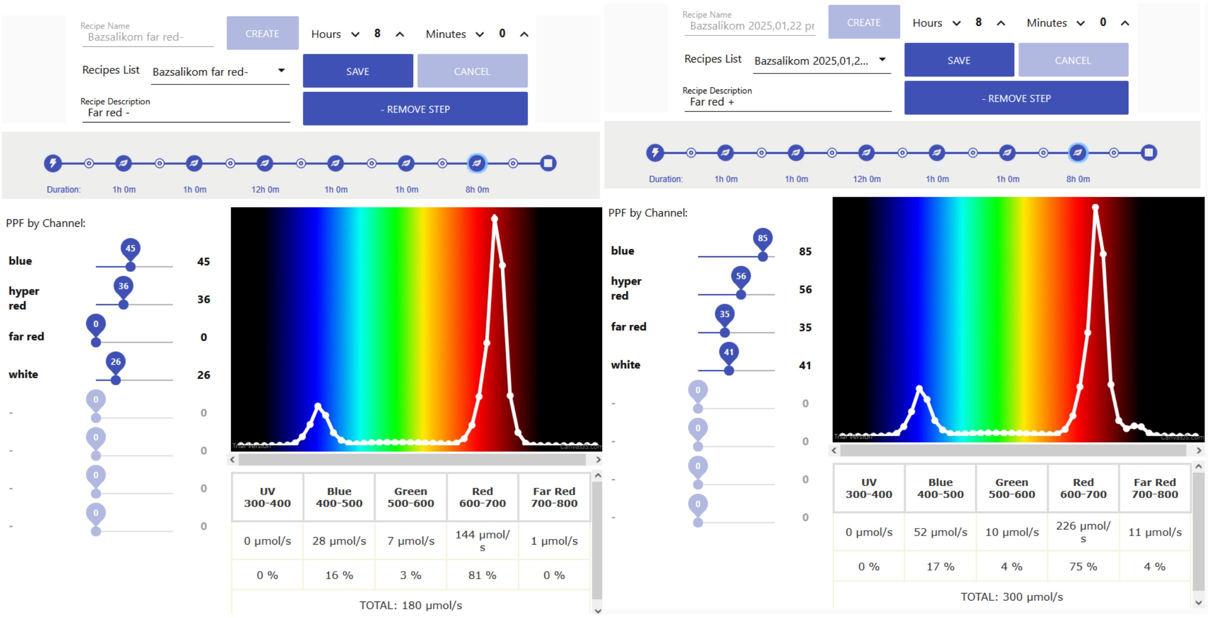

Figure 3: The applied light protocol before and after the use of far-red light

Source: The authors

During the experiment, four growing units were available in the laboratory, each capable of accommodating 20 plants. Each unit was supplied by its own nutrient solution tank, allowing independent adjustment of nutrient replenishment according to specific requirements. The nutrient solution was prepared in accordance with the manufacturer's recommendations using GHE–Terra Aquatica TriPart Grow and Micro concentrates. *Table 1* summarises the nutrients supplied to each unit over the entire experiment, along with the total amount of water replenished.

Table 1: Nutrient solution and water replenished throughout the experiment

***Ocimum basilicum* var. *purpurascens* (1)**			***Ocimum basilicum* var. *Genovese* (2)**			***Ocimum basilicum* var. *purpurascens* (3)**			***Ocimum basilicum* var. *Genovese* (4)**		
Grow (ml)	**Micro (ml)**	**Water (L)**	**Grow (ml)**	**Micro (ml)**	**Water (L)**	**Grow (ml)**	**Micro (ml)**	**Water (L)**	**Grow (ml)**	**Micro (ml)**	**Water (L)**
164	57	90	180	65	100	136	68	85	144	72	90

Source: The authors' data

The slight differences in the amount of nutrient solution supplied to each unit were mainly due to operational adjustments during the cultivation period. Since the primary experimental objective was to assess varietal performance rather than nutrient treatment effects, the results were evaluated on a variety basis by averaging the data from the two corresponding units.

During the experiment, plant height (*Figure 4*) and leaf number were measured weekly. On day 42, regular pruning of the basil plants began, with larger leaves removed. For each unit, the fresh weight of all harvested leaves was recorded. The leaves were then dried to determine their dry weight. At final harvest, the total fresh mass of the plants (including shoots and roots) was measured, followed by drying to determine dry matter content. At the end of the experiment, the total volume of water used during cultivation was quantified to calculate the water-use efficiency (WUE) index.

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Water-use efficiency (WUE) is a measure of how efficiently plants utilise water. It was calculated as the ratio of produced biomass (g) to total water consumption (L). A high WUE indicates that plants produced more biomass per unit of water, whereas a low WUE suggests that water consumption did not result in proportionally greater growth.

Figure 4: The two basil varieties in the growing units

Source: The authors

In this experiment, basil plants (*Ocimum basilicum* L.) were grown in an aeroponic system inside a closed climate chamber. Throughout cultivation and measurement procedures, the temperature was maintained at 25 °C, and the relative humidity was kept near 70 %. The developmental stages of the plants were recorded across the entire vegetation period at all major phenophases.

To survey the plant stand, we employed an X120GO handheld 3D LiDAR scanner, which operates on an active remote-sensing principle and produces high-density 3D point clouds. The device has a maximum range of 120 m, a minimum measurement distance of 0.5 m, and a relative accuracy of 6 mm under controlled conditions. It features 16 vertical channels, operates at a sampling frequency of 320,000 points per second, and has a 360° × 270° field of view with a class 1 laser source. The integrated camera system consists of three RGB cameras, each with a resolution of 5 megapixels (total 15 megapixels), providing a 200° × 100° field of view for capturing hemispherical colourised point clouds. Measurement data were stored in the scanner's 32 GB expandable memory. At the same time, real-time visualisation was performed on an Android-based device, and post-processing was carried out using the manufacturer's GOpost software.

During data acquisition, the operator slowly walked through the climate chamber between rows of plants while holding the scanner. Three-dimensional point clouds were generated from raw LiDAR data and subsequently cleaned using noise filtering and erroneous-point removal procedures. From the denoised point clouds, we derived plant height, canopy volume, and other geometric characteristics. Based on the resulting 3D canopy structure information, established modelling approaches can be applied to estimate leaf area and biomass, providing a basis for further water and energy balance analyses. Our objective was to extract quantitative plant parameters from the point clouds – including plant height, leaf area, leaf count, and leaf orientation – and to monitor their temporal dynamics.

The data were organised, analysed, and plotted using Microsoft Excel spreadsheets. One-way analysis of variance (ANOVA) was used to identify significant differences between groups.

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4. RESULTS

Averaged data for the two basil varieties (*Figure 5*) show that growth was gradual in both, but Genovese (green) grew significantly faster and reached a higher height by day 70. In contrast, Purpurascens (purple) exhibited slower growth, with final plant height reaching only about half to two-thirds that of Genovese. Error bars (representing standard deviations or standard errors) indicate measurement variability, which increased over time – particularly for the Genovese variety. After day 42, when weekly pruning began, Genovese growth slowed and the height curve levelled off.

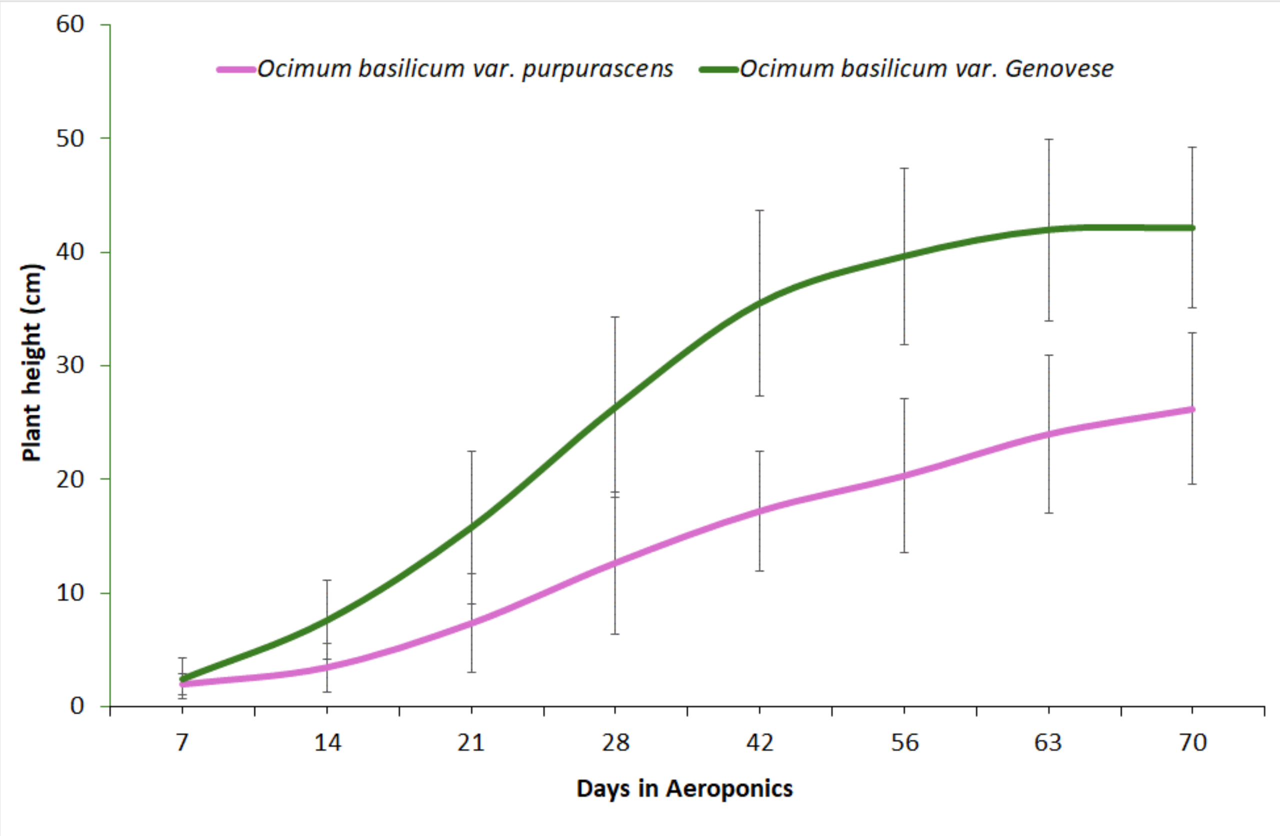

Figure 5: The development of plant height of the two basil varieties during the experiment

Source: The authors' data

Although the height development of the two basil varieties differed markedly, one-way ANOVA indicated that this difference was not statistically significant at the 5 % probability level ($P = 0.08$). The high variance reduced statistical confidence in the result. Nevertheless, the observed differences in plant height development suggest distinct growth strategies between the two varieties under controlled aeroponic conditions. Genovese exhibited more intensive vertical growth, likely associated with its genetic characteristics and the strong vegetative vigour commonly reported in commercial sweet basil cultivars. In contrast, Purpurascens showed slower height growth, a trait typical of red-leaved basil types that often allocate more resources to leaf pigmentation and structural tissues. The increasing variance in later stages suggests that individual plant responses became more heterogeneous as plant size increased and regular pruning influenced canopy architecture.

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Leaf number development was also examined in each unit throughout the experiment. *Figure 6* shows the average leaf number for the two varieties over time. After regular pruning began on day 42, leaf numbers changed rapidly, and no significant difference was observed between the varieties for this parameter. Leaf counts were recorded at regular intervals (days 7, 14, 21, 28, 42, 56, 63, and 70). Both varieties showed a steady increase in leaf number during the early cultivation period. From day 28 onward, Purpurascens generally had a slightly higher leaf count than Genovese, with the difference becoming more pronounced in the later stages (days 63-70). Error bars represent standard deviations, reflecting variability among individual plants. These data suggest that, while both varieties perform well under aeroponic conditions, Purpurascens may achieve a higher leaf number in the later growth stages.

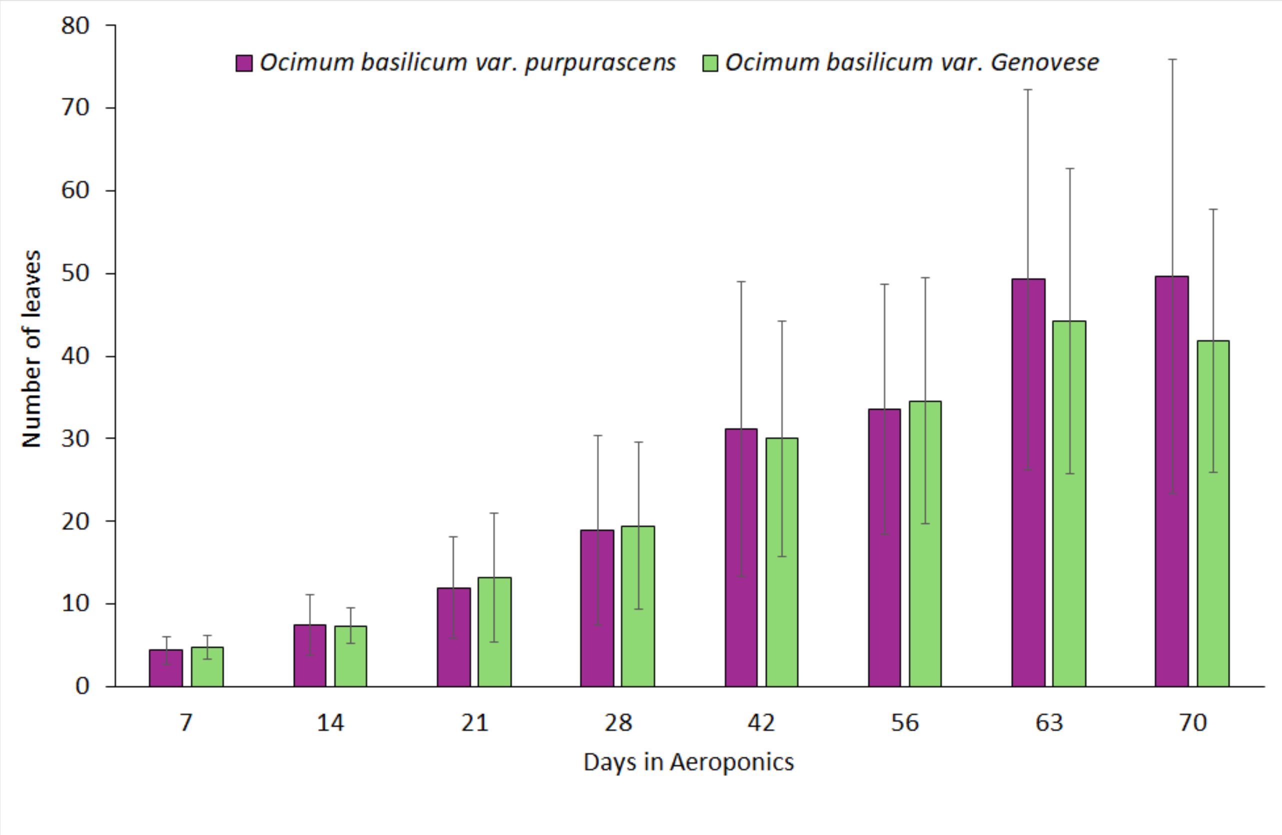

Figure 6: The development of leaf number of the two basil varieties during the experiment

Source: The authors' data

The dynamics of leaf number development provide additional insight into the morphological differences between the two varieties. Although Genovese showed more pronounced vertical growth, Purpurascens tended to maintain a slightly higher leaf number in the later stages of cultivation. This suggests that the varieties may differ in canopy architecture and biomass allocation patterns. The pruning practices introduced during the experiment likely influenced lateral shoot development and leaf production, which may account for the rapid fluctuations in leaf number after day 42. Such responses are typical in basil cultivation, where regular harvesting or pruning stimulates new leaf formation and branching.

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Basil plants grown in the aeroponic system were continuously monitored using LiDAR to track real-time growth dynamics and morphological changes across all phenological phases (*Figure 7*). The aim was to quantitatively extract plant parameters, including height, leaf area, leaf count, and leaf angle. However, the controlled conditions in the climate chamber – particularly the high relative humidity of 70 % maintained alongside a stable temperature of 25 °C – significantly affected the quality of the LiDAR scans. Due to the elevated humidity, the raw point clouds were extremely noisy. Although effective de-noising algorithms were applied, this processing inevitably reduced point density and, consequently, the level of detail captured in the point clouds. *Figure 7* presents RGB-coloured, denoised point clouds from three different phenological phases to visually illustrate the growth pattern of basil plants.

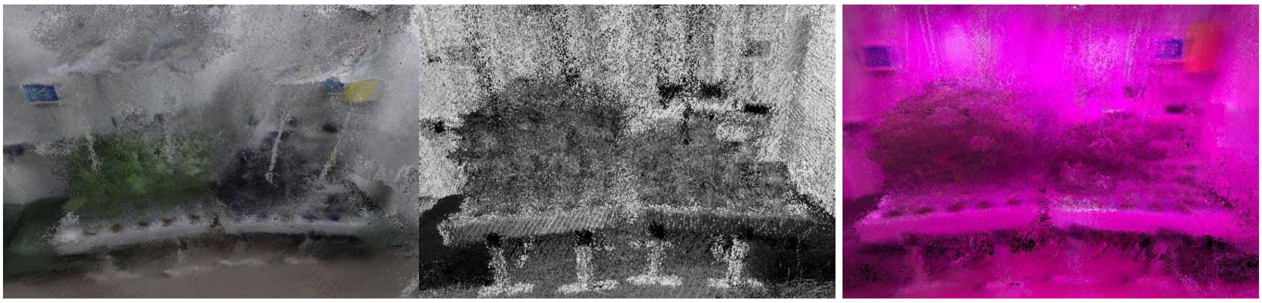

Figure 7: Monitoring morphological parameters with a LiDAR camera

Source: The authors

The application of LiDAR-based monitoring demonstrated the potential of three-dimensional plant phenotyping methods in controlled-environment agriculture. Although the high humidity in the climate chamber reduced the quality of the raw point clouds, the processed data still provided valuable visual information on canopy structure and plant development. Such non-destructive monitoring techniques can support detailed analysis of plant growth dynamics and may contribute to the optimisation of cultivation strategies in future studies.

Water-use efficiency (*Figure 8*) was much higher for the Genovese variety than for Purpurascens (9.39 g L^{-1} vs. 4.83 g L^{-1}), representing nearly a twofold difference. The relatively small standard deviations indicate low measurement variation and confirm the reliability of the results. Genovese not only grew faster but also demonstrated greater water-use efficiency under aeroponic cultivation compared with Purpurascens.

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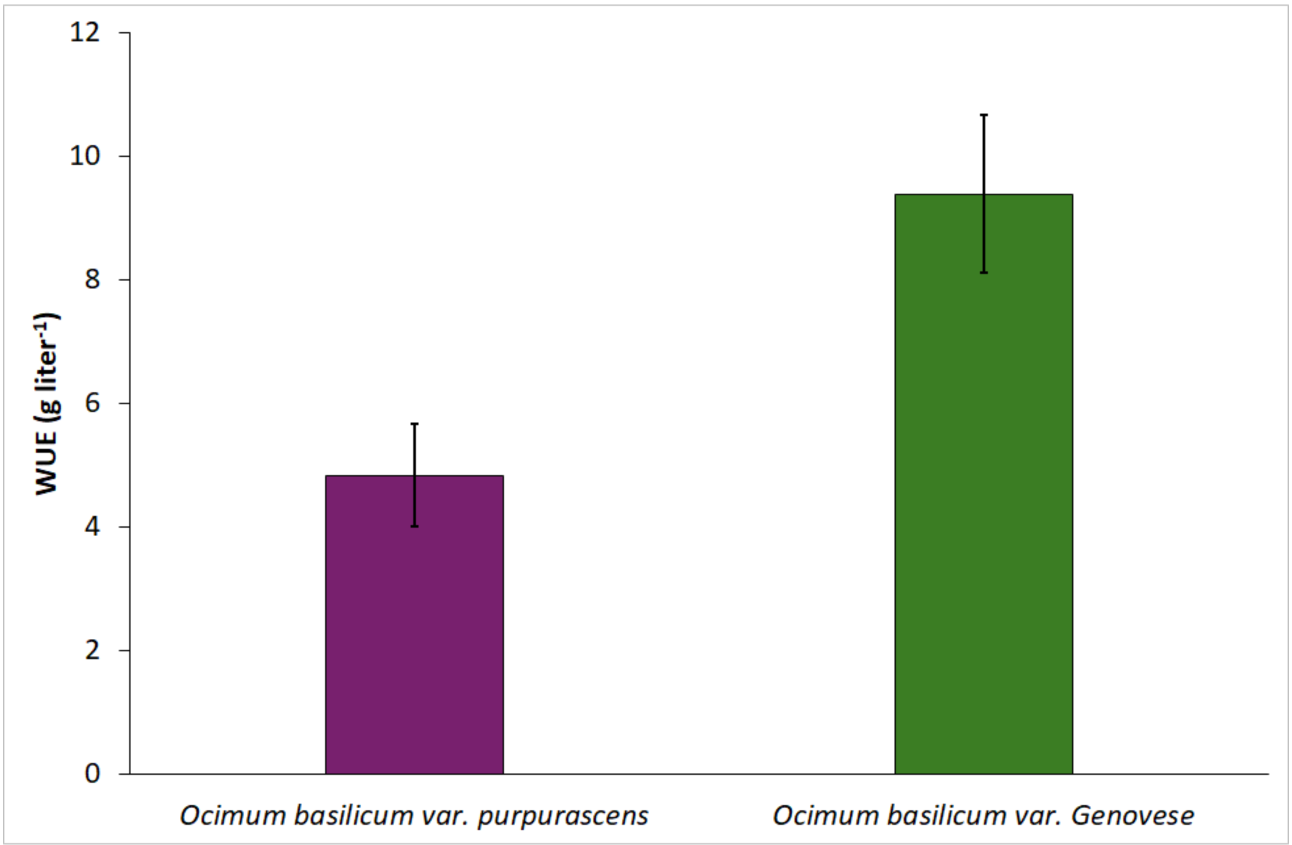

Figure 8: The development of water use efficiency of the two basil varieties during the experiment

Source: The authors' data

The observed differences in water-use efficiency underscore the importance of varietal traits in determining plant performance under controlled cultivation systems. The higher WUE values recorded for Genovese indicate that this cultivar converted supplied water into biomass more efficiently than Purpurascens under the experimental conditions. This difference may be linked to Genovese's faster growth rate and larger canopy development, which enhance photosynthetic activity and biomass accumulation. Similar varietal differences in water-use efficiency have been reported in controlled-environment basil cultivation, where genotype-specific responses to water and nutrient availability influence overall productivity.

5. CONCLUSION

The results demonstrate that the aeroponic system provided a favourable cultivation environment for both tested basil varieties, although each responded differently to environmental factors and modifications in the light programme. The inclusion of far-red light proved particularly significant, accelerating vegetative growth, increasing canopy biomass, and improving photosynthetic efficiency.

The varietal differences highlight the importance of defining clear cultivation objectives. Genovese is ideal when the goal is high yield and efficient water use. In contrast, Purpurascens is advantageous when the aim is to produce plants with a distinctive appearance, unique pigmentation, and strong aromatic qualities.

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The findings also indicate that minor adjustments to environmental parameters – such as light intensity, spectral composition, or nutrient concentration – affect plant development to varying degrees. Future studies should explore further fine-tuning of the light spectrum and test different microclimate scenarios. In addition, clarifying the role of genetic factors – particularly in biomass accumulation and water-use efficiency (WUE) – would justify broader comparative trials. Overall, the present experiment confirmed that the aeroponic system is a controllable cultivation method enabling efficient plant development and water use under controlled environmental conditions.

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Bazsalikomfajták növekedésének vizsgálata biztonságos és víz-hatékony aeroponikus körülmények között

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ÖSSZEFOGLALÁS

Kutatásunk két bazsalikomfajta – Red Rubin (*Ocimum basilicum* var. *purpurascens*) és Genovese (*Ocimum basilicum* var. *Genovese*) – növekedését vizsgálta aeroponikus körülmények között a Debreceni Egyetem MÉK Víz- és Környezetgazdálkodási Intézetében. A két fajta növekedési dinamikáját különböző morfológiai paraméterek (növény magassága, levelek száma), manuális LiDAR-mérések és hozamelemzés segítségével követtük nyomon. A cél az volt, hogy értékeljük ezen bazsalikomfajták teljesítményét növekedési jellemzőik és termékenységük alapján, kontrollált fény-, éghajlat- és tápanyagkörülmények mellett, a vízhatékonyság figyelembevételével. Az eredmények különbségeket mutattak a két fajta növekedési mintázatai között, valamint azok válaszát a tápanyagellátottságra és a környezeti tényezőkre. A kutatás értékes információkat nyújt a bazsalikom aeroponikus termesztésének optimalizálásához, különösen a fenntartható, erőforráshatékony mezőgazdasági gyakorlatokhoz, amelyek a városi és vertikális gazdálkodási rendszerekben is alkalmazhatók. A dolgozatban bemutatott kutatás a Széchenyi Terv Plusz program keretében valósult meg az RRF-2.3.1-21-2022-00008 számú projekt támogatásával.
Kulcsszavak: aeropónia, bazsalikom, talaj nélküli termesztés, vízfelhasználás

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