THE EFFECT OF SUPPLEMENTAL OXYGENATION AND LED LIGHTING ON ROOT DEVELOPMENT AND CARBOHYDRATE CONTENT IN LETTUCE GROWN IN THE NFT SYSTEM (NUTRIENT FILM TECHNIQUE)

EFECTUL OXIGENĂRII SUPLIMENTARE ȘI AL ILUMINĂRII CU LED ASUPRA DEZVOLTĂRII RĂDĂCINILOR ȘI CONȚINUTULUI DE CARBOHIDRAȚI LA SALATA CRESCUTĂ ÎN SISTEMUL NFT (NUTRIENT FILM TECHNIQUE).

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Abstract.

The NFT system is a type of hydroponics where a thin layer of nutrient solution constantly circulates over the plant roots. This ensures continuous access to water, nutrients, and oxygen, which promotes rapid and healthy plant growth. Controlling the conditions in this system, such as oxygen levels and lighting, plays a crucial role in the efficiency of photosynthesis and, implicitly, in carbohydrate content.

Oxygen is essential for plant growth, especially for the roots, as it aids in root respiration. In hydroponic systems like NFT, water and nutrients are recirculated, and the oxygen level in the nutrient solution can affect plant metabolism, including carbohydrate synthesis. Supplemental oxygenation of the nutrient solution can improve nutrient uptake and photosynthesis, which could increase carbohydrate levels in lettuce.

LED lights are frequently used in plant cultivation because they are energy-efficient and can be adjusted to provide the light spectrum necessary for photosynthesis.

Key words: Oxygen, roots, nutrients, respiration, carbohydrates

Rezumat.

Sistemul NFT este un tip de hidroponie în care un strat subțire de soluție nutritivă circulă constant peste rădăcinile plantelor. Acest lucru asigură accesul continuu la apă, nutrienți și oxigen, ceea ce promovează o creștere rapidă și sănătoasă a plantelor. Controlul condițiilor din acest sistem, cum ar fi nivelurile de oxigen și iluminarea, joacă un rol crucial în eficiența fotosintezei și, implicit, în conținutul de carbohidrați.

Oxigenul este esențial pentru creșterea plantelor, în special pentru rădăcini, deoarece ajută la respirația acestora. În sistemele hidroponice precum NFT, apa și nutrienții sunt recirculați, iar nivelul de oxigen din

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soluția nutritivă poate afecta metabolismul plantelor, inclusiv sinteza carbohidraților. Oxigenarea suplimentară a soluției nutritive poate îmbunătăți absorbția nutrienților și fotosinteza, ceea ce ar putea crește nivelul de carbohidrați din salată.

Lămpile LED sunt frecvent utilizate în cultivarea plantelor deoarece sunt eficiente din punct de vedere energetic și pot fi ajustate pentru a furniza spectrul de lumină necesar pentru fotosinteză.

Cuvinte cheie: Oxigen, rădăcini, nutrienți, respirație, carbohidrați.

INTRODUCTION

Lettuce, scientifically known as *Lactuca sativa* L., is a vegetable plant belonging to the Asteraceae (Compositae) family. This family includes numerous genera and species spread across the globe. Other plants in the same family include chicory (*Cichorium intybus* L.), sunflower (*Helianthus annuus*), and dandelion (*Taraxacum officinale*). According to opinions expressed by Ciofu et al. (2004) and Stan et al. (2003), the varieties of lettuce that belong to the Compositae family include the following types: head lettuce (which forms heads at maturity - *Lactuca sativa convar. capitata*), leaf lettuce (which does not form heads at maturity - *Lactuca sativa convar. secalina*), and romaine lettuce (which is distinguished by forming elongated heads - *Lactuca sativa convar. longifolia*). Depending on the variety, lettuce requires 8 to 10 hours of direct sunlight daily, especially during the vegetative growth phase. Optimal yields are achieved when light intensity is between 12-17 mol/m², combined with adequate ventilation. Too much light intensity can negatively affect plant development. Some varieties require higher light intensity, and when grown under insufficient light conditions, they struggle to grow. Therefore, the choice of varieties should be made according to the season and the intended use—whether for greenhouse, tunnel, or open field cultivation. During winter, the additional use of light for periods of 16 to 24 hours, at an intensity of 100-200 μmol/m²/s (17 mol/m²/day), promotes plant biomass growth and shortens the crop cycle by approximately 25%. At the same time, extending light exposure reduces the nitrate content in lettuce by 10-26% (Gaudreau et al., 1994). LED lighting allows for adjusting the light spectrum according to the plants' needs. Red (R) and blue (B) lights play an important role in stimulating photosynthesis. Research has highlighted the influence of R and B spectral components on the physiology, biochemistry, and resource use efficiency of lettuce plants (Drăghici et al., 2012) The research conducted by Pennisi et al. (2019) compared the effects of red and blue (RB) spectrum provided by LED lamps with the light from fluorescent control lamps (RB = 1) in six experimental variants under controlled conditions (PPFD = 215 μmol m−2 s−1), with a day length of 16 hours. The results showed that using LEDs increased bioyield by 1.6 times and improved energy efficiency by 2.8 times compared to fluorescent lamps. Experiments conducted by researchers such as Meng & Runkle (2019) on different *Lactuca sativa* L. varieties, under controlled conditions in a climate chamber, revealed that partially or fully replacing blue light (B) with green light (G) led to an increase in the average plant mass. Conversely, replacing green light (G) with blue light (B) resulted in poor leaf pigmentation, especially in "Rouxai" type red-leaf lettuce varieties, such as oak leaf lettuce. Although the study demonstrated clear advantages of green light (G) in crop growth, it is uncertain whether these results are due to the increase in green light (G), the reduction of blue light (B), or a combination of both.

MATERIAL AND METHOD

The research was conducted at the University of Agronomic Sciences and Veterinary Medicine of Bucharest, in the greenhouse block of the Research Center for the Study of the Quality of Agri-Food Products. The varieties of lettuce, Lugano and Carmesi, were cultivated in the experiment, using certified seeds for the quality of the biological material. Cultivation was carried out in an NFT (Nutrient Film Technology) system between March 21 and May 8, 2024. Additional oxygenation of the nutrient solution was provided by a SERA AIR 550 R PLUS pump, which ensures low energy consumption of 8W, an air flow rate of 9.2 l/min, and 55 l/h.

The LED lighting system used in the experiment was configured for specific wavelengths and photoperiod, with a power of 100W, a water resistance rating of IP67, a frequency of 50 Hz/60 Hz, and an input voltage of AC 220V, featuring a full spectrum of wavelengths ranging from 380 to 840 nm. The experiment was a 2 x 2 factorial design with three repetitions. Factor A represented the two lettuce varieties, Lugano and Carmesi, while Factor B represented the cultivation technology with the following levels: b1 - natural oxygenation, b2 - additional oxygenation, b3 - additional oxygenation plus LED lighting. No external oxygen sources were used in the experiment. Planting in the NFT system took place on March 21, 2024. Throughout the entire growth cycle, climatic factors such as light, atmospheric humidity, and air temperature, as well as the temperature of the nutrient solution, were monitored. After 48 days from planting, the plants were harvested, and for the tested variants, the root length and volume were measured using an EPSON Flatbed Expression 11000X scanner. The carbohydrate content was determined at harvest using a refractometer for measuring carbohydrates.

RESULTS AND DISCUSSIONS

The roots were scanned using an EPSON Flatbed Expression 11000X scanner. For the Lugano lettuce variety (a1), the average root length was 31.70 cm, while for the Carmesi variety, it was 32.83 cm.

Fig. 1 Root measurements of Lugano and Carmesi

The difference in root length between the two varieties is 1.13 cm, not being statistically significant (Table 1).

Table 1

Table 1. Morphometric analysis of root length in lugano and carmesi lettuce varieties)

Factor A	Average Root Length (cm))	Difference from Mt	Significance
a_1Lugano	31.70	Mt	
a_2Carmesi	32.83	1.13	-

DL 5 % DL 1 % DL 0.1 %
4.0 5.6 7.9

Morphometric analysis of the average root length indicates a significant influence of additional oxygenation and led lighting on lettuce root development. Compared to the control (b1 - natural oxygenation), the application of additional oxygenation (b2) increased the average root length by 5.05 cm, suggesting that extra oxygen promotes better water and nutrient absorption, leading to more robust root development.

Additionally, the addition of led lighting (b3) further increased the average root length by 11.50 cm over the control, indicating that improved photosynthesis and growth stimulation provided by artificial light, combined with additional oxygenation, optimize conditions for plant growth. Thus, the combination of these two technologies represents an advanced system for enhancing yield (Table 2).

Table 2

Table 2. Morphometric analysis of average root length in lettuce under different cultivation technologies

Factor B	Average Root Length (cm)	Difference from Ct	Significance
b_1 natural oxygenation	26.75	Ct	
b_2 additional oxygenation	31.80	5.05	**
b_3 additional oxygenation plus LED Light	38.25	11.50	***

DL 5 % DL 1 % DL 0.1 %
3.3 4.6 6.5

Analyzing the impact of cultivation technologies on the average root length for lettuce varieties, it is observed that for the Lugano variety, under natural oxygenation conditions (b1), the average root length is 28.67 cm.

Additional oxygenation (b2) had a negative effect on root length, reducing it to 24.83 cm, a difference of -3.83 cm compared to the control (Ct). This indicates that additional oxygenation may not be ideal for this variety under certain conditions.

Under additional oxygenation plus LED lighting (b3), the root length was nearly similar to the control, at 28.27 cm, suggesting that the extra LED lighting may compensate for the decrease in root length caused by additional oxygenation.

For the Carmesi variety, under natural oxygenation (b1), the root length was greater at 35.33 cm, showing a significant increase compared to Lugano.

Additional oxygenation (b2) increased the length to 38.17 cm, indicating a positive reaction of the Carmesi variety to this technology.

Adding LED lighting to additional oxygenation (b3) resulted in a root length of 38.33 cm, the highest among all tested technologies, demonstrating that this variety responds well to the combination of additional oxygenation and LED lighting (Table 3).

Table 3

Table 3. Impact of cultivation technologies on the average root length in Lugano and Carmesi lettuce varieties

Factor B	Factor A	Average Root Length (cm)	Difference from Ct	Significance
b_1 natural oxygenation	a_1 Lugano	28.67	Ct	
b_2 additional oxygenation	a_1 Lugano	24.83	-3.83	-
b_3 additional oxygenation plus LED Light	a_1 Lugano	28.27	-0.40	-
b_1 natural oxygenation	a_2 Carmesi	35.33	6.67	***
b_2 additional oxygenation	a_2 Carmesi	38.17	9.50	***
b_3 additional oxygenation plus LED Light	a_2 Carmesi	38.33	9.97	***

DL 5 % DL 1 % DL 0.1 %
3.36 4.61 6.31

The average root volume of the two lettuce varieties was also determined by scanning, with the following results: for the Lugano lettuce variety, the average root volume was 11.29 cm³, considered the control (Ct) in this experiment.

The Carmesi variety had an average root volume of 10.62 cm³, which is a decrease of 0.66 cm³ compared to Lugano; however, this difference was not statistically significant.

The root volume for Carmesi was smaller than that for Lugano, but the difference is not large enough to be considered significant. This suggests that, under the applied cultivation conditions, both varieties exhibit similar behavior regarding root volume (Table 4).

Table 4

Table 4. Analysis of the average root volume in Lugano and Carmesi lettuce

Factor A	Average Root Volume (cm^3)	Difference from Ct	Significance
a_1Lugano	11.29	Ct	
a_2Carmesi	10.62	- 0.66	-

DL 5 % DL 1 % DL 0.1 %
1.9 2.7 3.8

Analyzing the average root volume for the two lettuce varieties shows that natural oxygenation (b1) serves as the control (Ct), with an average root volume of 9.92 cm³. Supplemental oxygenation (b2) led to an increase in root volume to 11.10 cm³, a positive difference of 1.18 cm³ compared to the control, indicating a beneficial impact of supplemental oxygenation on root development. With supplemental oxygenation combined with LED lighting (b3), the average root volume increases to 11.85 cm³, with a difference of 1.93 cm³ compared to the control. The combined effect of supplemental oxygenation and LED lighting shows an even more pronounced increase in root volume, suggesting synergy between additional lighting and increased oxygen availability. LED lighting stimulates photosynthesis and, therefore, the overall metabolism of the plant, including root growth, which is essential for absorbing the resources necessary for development. LEDs, being an efficient light source, enhance photosynthesis, leading to greater production of sugars and other carbohydrates, which are transported to the roots, thus supporting their growth (Table 5).

Table 5

Table 5. Analysis of the average root volume in Lugano and Carmesi lettuce under different cultivation technologies

Factorul B	Average Root Volume (cm^3)	Difference from Ct	Significance
b_1 natural oxygenation	9.92	Ct	
b_2 additional oxygenation	11.10	1.18	
b_3 additional oxygenation plus LED Light	11.85	1.93	***

DL 5 % DL 1 % DL 0.1 %
1.6 2.2 3.1

Analyzing the impact of cultivation technologies on the average root volume in lettuce varieties shows that for the Lugano variety, natural oxygenation (b1) served as the control, with an average root volume of 10.17 cm³. In the case of supplemental oxygenation (b2), there was a slight decrease in root volume to 9.67

cm³, with a negative difference of -0.49 cm³ compared to the control. This suggests that supplemental oxygenation does not have a significantly positive effect for this variety in the absence of other factors.

The technology combining supplemental oxygenation with LED lighting (b3) had a significantly positive effect, leading to an increase in root volume to 12.03 cm³, with a difference of 1.87 cm³ compared to the control. This increase suggests that LED lighting, along with supplemental oxygenation, improves growing conditions for this variety.

For the Carmesi lettuce variety, natural oxygenation (b1) resulted in the same root volume as for Lugano, 10.17 cm³, with no difference from the control. Supplemental oxygenation (b2) led to an increase in root volume to 11.67 cm³, with a positive difference of 1.50 cm³, statistically significant. This result indicates that the Carmesi variety responded better to supplemental oxygenation than the Lugano variety.

The technology with supplemental oxygenation and LED lighting (b3) resulted in a root volume of 11.03 cm³, with an increase of 1.87 cm³ compared to the control, which is significant. As with Lugano, the combination of supplemental oxygenation and LED lighting is the most effective (Table 6).

Table 6

Table 6. The impact of cultivation technologies on root volume in Lugano and Carmesi lettuce varieties

Factor B	Factor A	Average Root Volume (cm^3)	Difference from Ct	Significance
b_1 natural oxygenation	a_1 Lugano	10.17	Ct	
b_2 additional oxygenation	a_1 Lugano	9.67	-0.49	
b_3 additional oxygenation plus LED Light	a_1 Lugano	12.03	1.87	***
b_1 natural oxygenation	a_2 Carmesi	10.17	0.00	
b_2 additional oxygenation	a_2 Carmesi	11.67	1.50	***
b_3 additional oxygenation plus LED Light	a_2 Carmesi	11.03	1.87	***

DL 5 %	DL 1 %	DL 0.1 %
0.69	0.94	1.29

For the Lugano variety, under natural oxygenation conditions (b1), the average carbohydrate content was 4.05 g/100g, considered the control (Ct). Supplemental oxygenation (b2) slightly increased this content to 4.38 g/100g, indicating an improvement in carbohydrate synthesis, although this difference is not statistically significant. In contrast, the combination of supplemental oxygenation and LED lighting (b3) had a significant effect on carbohydrate content, increasing it to 4.87 g/100g (a difference of +0.82 g/100g), marking a statistically significant improvement. This increase can be explained by the stimulation of photosynthesis under the influence of LEDs, which enhances the efficiency of carbohydrate production in the Lugano plant.

In the case of the Carmesi variety, the carbohydrate content under natural oxygenation conditions (b1) was 4.34 g/100g, with a positive difference of +0.29 g/100g compared to the Lugano control, which is statistically significant. This higher value suggests superior metabolic efficiency of the Carmesi variety under baseline conditions. However, with the application of supplemental oxygenation (b2), the carbohydrate content decreased to 3.86 g/100g, suggesting possible metabolic stress caused by excessive oxygenation, which negatively affects carbohydrate synthesis in this variety. Nevertheless, with the technology combining supplemental oxygenation and LED lighting (b3), the carbohydrate content increased again to 4.48 g/100g, with a difference of +0.42 g/100g compared to the control. This increase signifies an improvement in carbohydrate metabolism under the influence of LED lighting, which stimulates photosynthesis and helps the plant recover the metabolic efficiency previously affected by supplemental oxygenation (Table 7).

Table 7

Table 7. The impact of cultivation technologies on the carbohydrate content in Lugano and Carmesi lettuce varieties.

Factor B	Factor A	Average carbohydrate g/100g	Difference from Ct	Significance
b_1 natural oxygenation	a_1 Lugano	4.05	Ct	
b_2 additional oxygenation	a_1 Lugano	4.38	0.33	
b_3 additional oxygenation plus LED Light	a_1 Lugano	4.87	0.82	***
b_1 natural oxygenation	a_2 Carmesi	4.34	0.29	***
b_2 additional oxygenation	a_2 Carmesi	3.86	-0.19	
b_3 additional oxygenation plus LED Light	a_2 Carmesi	4.48	0.42	

DL 5 %	DL 1 %	DL 0.1 %
0.36	0.50	0.68

CONCLUSIONS

Supplemental oxygenation combined with LED lighting is the most effective technology for both varieties, significantly stimulating root volume growth. The Carmesi variety responds better to supplemental oxygenation compared to the Lugano variety. Lugano benefits significantly from the addition of LED lighting, overcoming the negative effect of simple supplemental oxygenation. LED lighting, in combination with supplemental oxygenation, has proven to be the most effective technology for increasing carbohydrate content in both lettuce varieties, demonstrating a synergy between enhanced photosynthesis and carbohydrate metabolism.The Lugano variety responded favorably to this combination, showing a significant increase in carbohydrate content. Although the Carmesi variety is sensitive to supplemental oxygenation alone, it also benefited from the additional stimulation provided by LEDs, which allowed for optimized carbohydrate synthesis.

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