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# CARBON FOOTPRINT OF LETTUCE GROWED WITH MINERAL AND BIOLOGICAL FERTILIZATION IN GREENHOUSES

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***Abstract***

*The amounts of carbon emissions during the cultivation of lettuce in greenhouse conditions during the autumn-winter period were measured in a polyethylene greenhouse. Fertilised and unfertilised soils, with and without plants, were placed in hermetically sealed chambers for 24 hours under identical conditions, after which the quantitative content of $CO_2$ in each chamber was determined. The impact of mineral and biological fertilizers on greenhouse gas emissions was studied. To assess the contribution of soil microflora to carbon emissions in the gas chambers, a comparison was made between the $CO_2$ levels measured in the unfertilised and fertilized soil variants, as well as between soils with and without plants. Model calculations were performed for the absorbed $CO_2$ gas over a relatively equal period in each of the three research years for NPK-fertilized, biologically fertilized, and unfertilized lettuce cultivation variants. It was found that mineral fertilization when cultivating salads in greenhouse production conditions, in norms N12.5P4.17K15.83 and has lower emissions - as a share in greenhouse gases (in the amount of 90.74 g/m$^3$) compared to unfertilized and fertilized with organic plants.*

**Key words**: *greenhouses gases, lettuce, carbon emission, mineral and biological fertilization.*

## INTRODUCTION

The greenhouse effect, driven by the accumulation of greenhouse gases (GHGs) in the atmosphere, represents one of the most pressing environmental issues of the 21st century. The most significant impact on the greenhouse effect is exerted by methane and carbon dioxide emissions (Borisova at al., 2023). Lettuce cultivation plays a significant role in global horticultural production, necessitating sustainable management practices to minimize environmental impact while ensuring high yields. Among the key factors influencing both productivity and ecological footprint are fertilization strategies and greenhouse management techniques. The selection of organic versus mineral fertilization has been shown to affect soil microbiota, root exudation patterns, and plant defense mechanisms, ultimately shaping the overall health of lettuce crops (Windisch et al., 2021). Understanding these interactions is crucial for optimizing agricultural practices that balance sustainability and crop performance.

Furthermore, soil carbon emissions represent a critical aspect of agricultural sustainability, as greenhouse gas emissions from lettuce fields contribute to climate change concerns. Recent studies indicate that different irrigation and fertilization strategies significantly influence soil gaseous emissions, emphasizing the need for tailored approaches to mitigate environmental impact (Zhang et al., 2024). Addressing the combined effects of fertilization type and irrigation methods on lettuce cultivation is essential for developing climate-smart agricultural practices.

Previous studies have highlighted that the type of fertilization strategy used can influence these environmental impacts significantly. Fertilizer application, particularly nitrogen-based fertilizers, is a key driver of greenhouse gas emissions from agricultural systems, contributing to both direct emissions of nitrous oxide ($N_2O$) and indirect emissions from the production and transportation of fertilizers (Thapa, Chatterjee, & Awale, 2016). This research seeks to quantify the carbon footprint associated with two different fertilization approaches, mineral and biological, and analyze their impacts on GHG emissions during lettuce cultivation in greenhouses.

A number of authors have studied the influence of different organic fertilizers on different crops in terms of their growth and development (Kostadinova at al., 2018; Dermendzhieva et al., 2021; Borisova et al., 2022).

Several studies have explored the impact of different fertilization techniques on the carbon footprint of greenhouse vegetable production.

The effects of reduced mineral fertilization and straw return on vegetable cultivation have been examined, concluding that integrating organic practices such as straw return can help balance greenhouse gas emissions while maintaining vegetable yield (Huang et al., 2020).

This aligns with the study of the carbon emissions of cucumber, tomato, and lettuce production in greenhouses which demonstrated that optimizing fertilizer use could significantly reduce the carbon footprint of greenhouse agriculture, particularly in systems using biological fertilizers (Pereira et al., 2021).

Mineral fertilizers, while effective in enhancing crop yield, have been associated with significant environmental costs. Conventional fertilization practices in lettuce production have an environmental burden, particularly in terms of the increased emissions of $N_2O$ (Rahman, Alam, and Hossain, 2018). In contrast, biological fertilization, which incorporates natural soil amendments such as biofertilizers, has been suggested as a viable alternative to mitigate environmental impacts. It has been reviewed the potential of biofertilizers to reduce greenhouse gas emissions by enhancing soil microbial activity, thus promoting more sustainable crop growth (Schmalenberger and Fox, 2017).

The carbon footprint of lettuce production in greenhouses is also influenced by various operational practices, such as irrigation methods and temperature regulation. It has been explored the role of irrigation methods in influencing soil gaseous emissions in lettuce fields, emphasizing that efficient irrigation can reduce both water and nitrogen losses, thereby minimizing the overall carbon footprint of the system (Wang et al., 2024). Furthermore, has been provided a comprehensive analysis of environmental factors impacting the quality and sustainability of greenhouse-grown vegetables, suggesting that integrated management practices, including optimized fertilization, are crucial for reducing the environmental footprint (Gruda, 2005). Continuous organic and mineral fertilization and their impact on the soil microbiome and $CO_2$ emissions have been studied (Kuncheva et al., 2024).

The growing body of literature has shown that integrating biological fertilization methods, such as the use of biochar and other organic amendments, can mitigate the carbon footprint of greenhouse crop production (Pereira et al., 2015; Zhang et al., 2023). Biofertilizers, which harness the power of beneficial soil microbes, have been identified as a key tool in promoting sustainable agriculture by reducing reliance on mineral fertilizers (Schmalenberger & Fox, 2017). Biochar, in particular, has been shown to alter nitrogen transformations in soil, thereby reducing nitrous oxide emissions and enhancing soil carbon sequestration (Qi et al., 2020).

In terms of life cycle analysis (LCA), several studies have quantified the total environmental impact of lettuce production systems. They provide an LCA of nitrogen fertilizers, highlighting the substantial contribution of nitrogen application to global warming potential (Lättemäe, Särekanno, and Järvenpää, 2020). Similarly, LCA has been employed to evaluate the carbon emissions of fresh produce supply chains in Western Australia, including lettuce, and found that fertilizer use and transportation significantly contributed to the carbon footprint (Gunady et al., 2012).

Overall, the literature indicates that both fertilization type and greenhouse management practices play pivotal roles in determining the carbon footprint of lettuce cultivation. Reducing emissions while maintaining yield requires careful consideration of both fertilizer type and operational strategies, a balance that this research aims to explore in depth. This research focuses on evaluating the carbon footprint of lettuce grown under two contrasting fertilization strate-/gies-mineral and biological-within greenhouse systems. This study aims to evaluate the carbon footprint of lettuce grown under contrasting fertilization strategies-mineral and biological-within controlled greenhouse environments.

By integrating insights from microbiological interactions and soil gas emissions, the research seeks to provide a comprehensive understanding of sustainable lettuce production.

The findings will contribute to the broader discussion on optimizing resource use in horticulture while minimizing adverse environmental consequences.

## MATERIALS AND METHODS

The experiment was conducted during the period 2021-2024 in an unheated polyethylene greenhouse at the Agricultural University of Plovdiv. The study examined the amount of greenhouse gases emitted during lettuce cultivation. It investigated the impact of mineral and organic fertilization on gas exchange within the soil-plant-atmosphere system. Two fertilization treatments were tested: mineral fertilization (NPK) and Vitaorganic, with an unfertilized control. The study was carried out with lettuce of the Maritima variety (Batavia type). The experiment was set up with four replications, each consisting of 28 plants per plot. Fertilization was applied during the final soil preparation. The organic fertilizer Vitaorganic was applied at a rate of 1500 kg/ha, while mineral fertilization was conducted using potassium sulfate, triple superphosphate, and ammonium nitrate (N – 125 kg/ha, $P_2O_5$ – 41.7 kg/ha, $K_2O$ – 158.3 kg/ha). The lettuce was planted at the 4-5 leaf stage in early November, following a spacing scheme of 70 + 30 + 30 + 30/30 cm. During the vegetation period, all planned agronomic practices were carried out, and irrigation was performed using a drip system.

1. ***Influence of the type of fertilizer used on the CO2 emissions released by soil microflora***

The influence of the fertilizer used on the emission of carbon dioxide from fertilized and unfertilized soils was studied. The difference in the amounts of gas between the chambers of the variants of unfertilized, organic and mineral fertilization without plants was calculated. The data are plotted in graphs 1-3.

The values X0 shown in the graphs were calculated using the formulas:

$$X0_{soil\ NPK} = C_{\%CO_2}^{contr.soil} - C_{\%CO_2}^{NPK\ fert.soil.}$$

$$X0_{soil\ BIO} = C_{\%CO_2}^{contr.soil} - C_{\%CO_2}^{BIO\ fert.soil}$$

where:

- $X0_{soil\ NPK}$ represents the NPK-fertilized value in the graphs, and $X0_{soil\ BIO}$ represents the BIO-fertilized value.
- $C_{\%CO_2}^{contr.soil}$ is the percentage concentration of $CO_2$ in the control soil chamber.
- $C_{\%CO_2}^{NPK\ fert.soil}$ and $C_{\%CO_2}^{BIO\ fert.soil}$ are the percentage $CO_2$ concentrations in the chambers with mineral (NPK) and organic fertilization, respectively.

2. ***Influence of grown plants on $CO_2$ emissions***

The difference in the amounts of gas between variants with and without plants in chambers without fertilization, organic and mineral fertilization was calculated.

The values for gas exchange in the NPK variant, plotted in graphs, were calculated according to the formulas:

$$X1_{NPK\ fert.} = C_{\%CO_2}^{NPK\ fert.soil.} - C_{\%CO_2}^{NPK\ fert.soil+plant}$$

where:

-$X1_{NPK\ fert.}$ is the NPK-fertilized value in the graphs.

- $C_{\%CO_2}^{NPK\ fert.soil+plant}$ is the percentage concentration of $CO_2$ in the chamber with NPK-fertilized soil containing plants.

The calculations for the other variants were made similarly.

3. ***Influence of fertilization and plants on $CO_2$ emissions***

The difference in gas quantities between the unfertilized variant without plants and the chambers without fertilization, organic and mineral fertilization with plants was calculated.

The gas exchange values for the NPK variant, plotted in graphs, were calculated according to the formulas:

$$X3_{NPK} = (C_{\%CO_2}^{contr.soil} - C_{\%CO_2}^{NPK\ fert.+plant}) \times 10 \times 44{,}01/22{,}4,\ g/m^3$$

where:

- $X3_{NPK}$ is the NPK-fertilized value in the graphs, calculated in g/m³.
-$C_{\%CO_2}^{contr.soil}$ и $C_{\%CO_2}^{NPK\ fert.+plant}$ are the percentage concentrations in the respective chambers.
- $M_{CO_2}$= 44.01 g/mol is the molecular mass of $CO_2$.
- $V_{CO_2}$= 22.4 L is the molar volume of gas.

The calculations for the other treatments followed the same methodology.

Further calculations in the tables include:

$$X_{average}^{NPK} = \left[\sum_{09.02.to\ 06.04} X3_{NPK}\right]/9$$

$$X_{CO_2}^{NPK\ sum} = X_{average}^{NPK} \times 57\ days$$

where:
- $X_{average}^{NPK}$ is the average value of $X3_{NPK}$ across the measured dates.
- $X_{CO_2}^{NPK\ sum}$ is the modeled $CO_2$ absorption for the NPK treatment over 57 days.

The calculations for the other options are made analogously to those for the NPC.

Gas Composition Monitoring and Measurement

The gas composition was monitored dynamically by measuring $CO_2$ exchange. Gas composition analysis was performed using chambers measuring 0.5 × 0.5 × 0.5 m³, placed weekly over the experimental plots for 24 hours, covering four plants per chamber. The chambers were embedded 10 cm into the soil to ensure airtight conditions and prevent gas leakage.

After 24 hours, air samples were collected from each chamber. $CO_2$ concentration was measured every seven days over a 68-day experimental period, until the end of the harvest. The quantitative determination of $CO_2$ was performed using a gas chromatograph INTERSMAT IGC 112M with Porapak "Q" columns and a catharometer detector.

Microclimatic factors such as solar radiation, humidity, and air and soil temperature were monitored using a Meteobot weather station. The gas analysis results were presented in both graphical and tabular form, showing the relationship between $CO_2$ exchange and the interaction between lettuce plants and environmental factors.

Calculations were based on gas sample collection from chambers with different combinations of fertilization and plant presence:

1. Control: $CO_2$ percentage in an unfertilized, plant-free soil chamber.
2. NPK Fertilization: $CO_2$ percentage in an NPK-fertilized, plant-free soil chamber.
3. Organic Fertilization: $CO_2$ percentage in an organically fertilized, plant-free soil chamber.
4. NPK with Plants: $CO_2$ percentage in an NPK-fertilized soil chamber with plants.
5. Organic Fertilization with Plants: $CO_2$ percentage in an organically fertilized soil chamber with plants.

To estimate $CO_2$ emissions (g/m³) for fertilized and unfertilized treatments over 50–60 days during the final growth phase of lettuce, a mathematical model was applied. The model used values derived from the difference between the accumulated $CO_2$ in the control chamber (unfertilized, plant-free) and those in chambers with plants (unfertilized, NPK, and Vitaorganic treatments).

The model assumed that daily $CO_2$ exchange remained constant, averaging all measurements taken during the observation period. The sum of emission and absorption values was divided by the number of measurements to estimate total $CO_2$ exchange during the vegetation period. The average daily values were multiplied by the duration of the experiment (57 days in 2022, 57 and 56 days in 2023 and 2024, respectively).

## RESULTS AND DISCUSSIONS

The results of the three-year study confirm that the dynamics of $CO_2$ in the soil is a complex process influenced by multiple interconnected factors, including soil temperature, moisture, solar radiation, plant cover, and type of fertilization. The values in the graphs below represent the difference in $CO_2$ quantity between the experimental chambers under different comparisons. Positive values indicate that the plants (or soil) in the respective variant absorb $CO_2$, while negative values indicate emission.

### 1. ***Influence of Fertilizer Type on $CO_2$ Emissions from Soil Microflora***

The analysis of the recorded $CO_2$ concentration values allows for determining the impact of key agro-climatic factors on the $CO_2$ balance.

#### 1.1. *Influence of Soil Temperature on $CO_2$ Dynamics*

The data from the study are presented in Figures 1-3. During the measurement period, the soil temperature ranged between 11ºC and 19ºC, with no significant changes in depth (Figure 1). For both fertilization variants, a general trend was observed - a decrease in $CO_2$ emissions with increasing soil temperature. This confirms the importance of soil temperature in relation to microbiological activity and the decomposition of organic matter, which leads to either $CO_2$ release or absorption. On April 4th, significant $CO_2$ absorption was recorded for both fertilization types compared to other measurements, at soil temperatures ranging from 17ºC to 19ºC. Since the analyzed variant was without plants, it can be assumed that the absorption was due to increased microbiological activity.

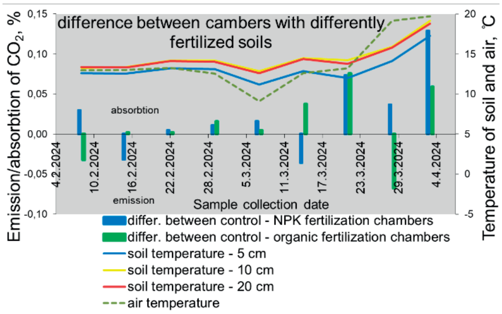


Figure 1. Influence of soil and air temperature on $CO_2$ emission/absorption in chambers without plants

A comparative analysis between the NPK and organic fertilization variants revealed a significant difference. $CO_2$ absorption at higher temperatures in the NPK chamber was twice as high as in the BIO chamber. This is likely due to the higher solubility and availability of mineral fertilizer, which increases the rate of uptake by microorganisms and plants.

On February 8th and March 28th, $CO_2$ absorption was observed in the NPK variant, while the BIO variant exhibited emissions. On these dates, soil temperatures were approximately the same, with a difference of about 2°C. At the same time, under similar temperature conditions, the opposite effect was observed-$CO_2$ emissions from NPK and absorption in the BIO-fertilized variant (February 15th, March 14th). This suggests that soil temperature alone is not the determining factor in $CO_2$ emissions or absorption.

Within a temperature range of 10-20°C, an inverse relationship was observed between temperature and $CO_2$ emissions-higher temperatures were associated with lower emissions. Despite this trend, opposing effects were recorded at similar temperatures during certain periods, highlighting the influence of additional factors.

### 1.2. *Influence of Soil Water Content on $CO_2$ Dynamics*

The water content in the upper soil layers varied significantly throughout the experiment, ranging from 3 to 32 l/m² depending on the sampling date and soil depth (Figure 2). As expected, soil moisture was higher in the middle and deeper layers (5, 10, and 20 cm).

On colder days (February 8th and March 7th), low moisture levels in the upper layer increased $CO_2$ emissions only in the organic fertilization variant. As moisture levels increased, soil permeability decreased, leading to lower $CO_2$ emissions. A similar trend was observed on March 28th-when the moisture level in the upper soil layer dropped below 21 l/m², $CO_2$ emissions increased in the organic fertilization variant.

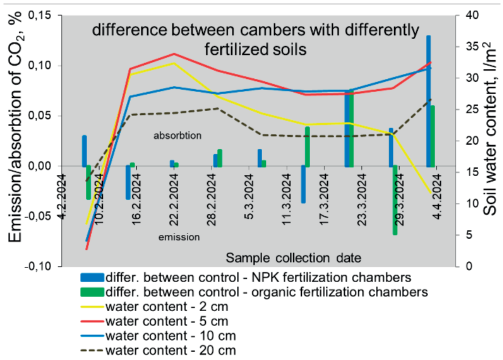


Figure 2. Influence of soil water content on $CO_2$ emission/absorption in chambers without plants

The data from April 3rd show a reverse trend - further decreases in soil moisture were associated with significant $CO_2$ absorption. Once again, this confirms that $CO_2$ balance is influenced by multiple overlapping variables rather than a single factor.

A comprehensive assessment of $CO_2$ dynamics indicates that soil moisture affects metabolic processes, with higher moisture levels enhancing microbial activity and leading to increased $CO_2$ emissions. The surface soil layer plays a crucial role as a barrier that regulates $CO_2$ release from deeper layers.

From a chemical perspective, alkaline soils tend to absorb more $CO_2$ compared to neutral and acidic soils. In alkaline conditions, $CO_2$ can form carbonates, bicarbonates, and mixed hydroxycarbonates, allowing it to remain in crystalline form.

High soil moisture (>25%) correlates with intense microbial activity and increased emissions, whereas low moisture levels (<15%) result in enhanced $CO_2$ absorption, particularly in the organic fertilization variant. This confirms that $CO_2$ balance is determined by the interaction of multiple factors rather than individual influences.

1.3. *Influence of Solar Energy on $CO_2$ Dynamics*
Solar energy varied between 0.023 and 0.151 kWh/m² during the measurement period (Figure 3). The data indicate that on days with higher soil temperatures and intense solar activity, $CO_2$ absorption increased significantly.

Notably, on days with higher solar radiation, such as March 21st and April 3rd, a substantial increase in $CO_2$ absorption was observed. The figures demonstrate that soil temperature rises in proportion to increasing solar activity. Since the illuminated surface is relatively small compared to the total volume of soil in the experiment, the leading factor influencing $CO_2$ absorption appears to be soil temperature.

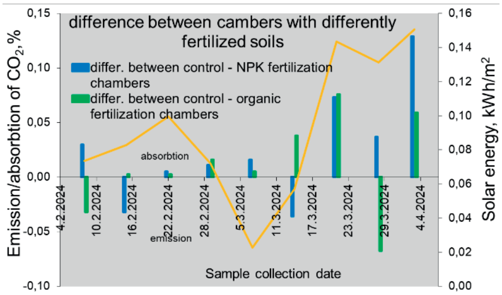


Figure 3. Influence of solar energy on $CO_2$ emission/absorption in chambers without plants

2. ***Influence of Cultivated Plants on $CO_2$ Emissions Under Organic and Mineral Fertilization, With and Without Plants*** (Figures 4, 5, 6)

For most of the experiment, the variants with plants (especially in chambers with mineral and organic fertilizers) showed a tendency to absorb $CO_2$, particularly on days with higher temperatures (Figure 4).

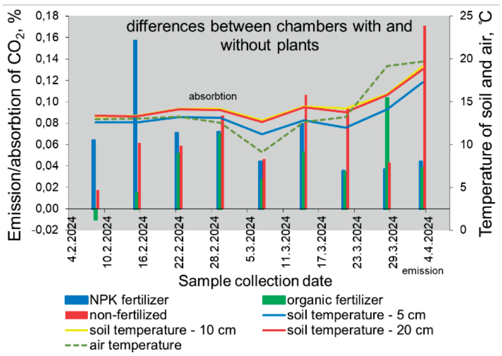


Figure 4. Influence of soil and air temperature on $CO_2$ emission/absorption in chambers with plants

A natural course of absorption is also observed with an increase in the leaf mass of the plants. Negative values in the data indicate that there is an additional amount of $CO_2$ in the chambers compared to the unfertilized soil.

On some dates, especially during the winter months and at lower temperatures, the (NPK) variant shows a significant release of $CO_2$, probably due to intense microbial activity associated with the decomposition of the fertilizer in the soil (Figure 5).

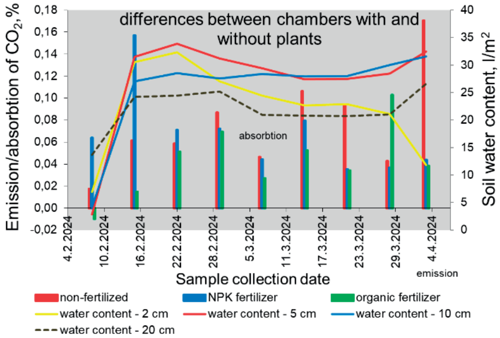


Figure 5. Influence of soil water content on $CO_2$ emission/absorption in chambers with and without plants

The results show that organic and mineral fertilization have different effects on the $CO_2$ balance. NPK fertilization leads to greater dynamics in the $CO_2$ values and is more dependent on meteorological conditions and the phenophase of the plants (Figure 6).

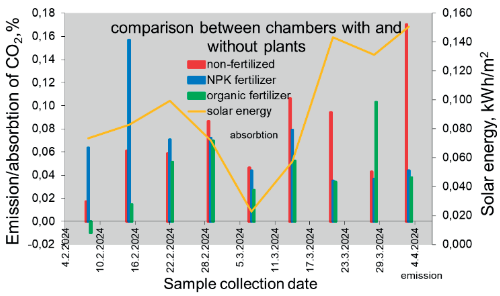


Figure 6. Influence of solar energy on $CO_2$ emission/absorption in chambers with and without plants

On some days (16.02.), significant $CO_2$ absorption is observed, which can be associated with the activity of microorganisms decomposing the fertilizer in the soil. The better availability of mineral fertilizers to soil microorganisms. The high water solubility of mineral fertilizer, its uptake and metabolism by microorganisms is significantly accelerated compared to biofertilizer. In later dates, especially after March, there is a trend towards greater $CO_2$ absorption.

3. ***Influence of fertilization and plants on $CO_2$ emissions***

The experimental results are shown in Figures 7-9. Stoichiometric calculations are based on the air volume in the chambers, the molar mass and molar volume of the gas. The $CO_2$ values are calculated in g/m$^3$. The data indicate that the more intensive growth of plants with increasing daily temperatures accelerates photosynthesis and compensates for the release of gases from the soil (Figure 7). The biofertilizer variant shows constant and stable $CO_2$ absorption values compared to mineral fertilizer. This can be associated with more balanced microbial activity in the soil, as well as better and more consistent decomposition of organic matter in the biofertilizer over time. As vegetation progresses, the biofertilizer variant tends to reduce $CO_2$ (Figure 8). This suggests a better long-term ecological effect of organic fertilizer compared to mineral fertilization. At the beginning of vegetation, the mineral fertilization (NPK) variant shows higher $CO_2$ absorption values. This can be explained by intense microbial activity and the initially small leaf mass of the lettuce. As vegetation progresses and photosynthesis intensifies, increased $CO_2$ absorption is observed. Of all the factors studied, soil temperature and solar activity have the greatest influence on emissions (Figures 7 and 9).

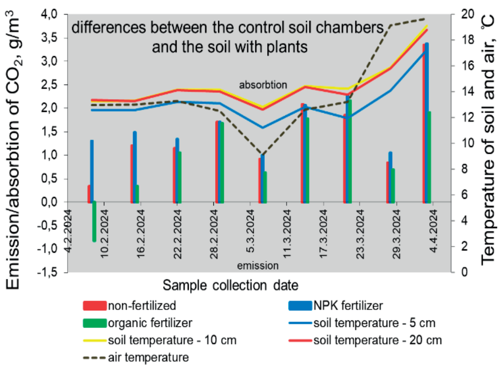


Figure 7. Influence of soil and air temperature on $CO_2$ emission/absorption in chambers with and without plants

It is observed that $CO_2$ absorption increases proportionally with increasing temperature and solar energy. The recorded results of carbon dioxide emissions show that even after planting, plants begin to absorb this gas in the variants without fertilization and those fertilized with biofertilizer. Plants from these variants manage to compensate for the $CO_2$ release from microorganisms in the soil. Low solar activity and temperature slow down plant photosynthesis. The increase in $CO_2$ emissions from the soil is facilitated by low moisture in the topsoil layer and more active microbiological metabolism (Figures 7 and 9).

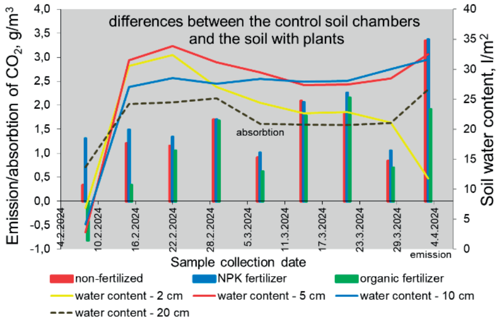


Figure 8. Influence of soil water content on $CO_2$ emission/absorption in chambers with and without plants

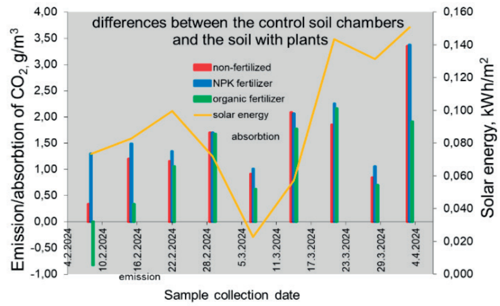


Figure 9. Influence of solar energy on $CO_2$ emission/absorption in chambers with and without plants

Tables 1-3 show the calculation results for the absorbed carbon dioxide from the plant chambers over a relatively equal period of time for the three research years. As sampling was performed once a week, as mentioned above, a mathematical model of averaging and estimation was used.

The values highlight that mineral fertilization (NPK) generally leads to the highest total $CO_2$ uptake, with values reaching 96.97 g/m³ in 2024.

Organic fertilization shows more stable uptake trends but is weaker than NPK at high temperatures. Interestingly, the unfertilized chambers in 2023 demonstrate the highest sequestration efficiency (94.72 g/m³), possibly due to the optimal balance of microbial and plant activity under the prevailing climatic conditions.

The analysis of the data shows that in the experimental year 2022, the largest absorbed amount of $CO_2$, within 86.43 g/m³, was recorded with mineral fertilization (Table 1) and the least in the unfertilized variant. Trends of increased absorption with mineral fertilization were also calculated for 2024.

Table 1. Total amount of $CO_2$ absorbed during the cultivation period, g/m³, 2022

| 2022/57 days sample collection date | Non-fertilized | NPK fertilizer | Organic fertilizer |
|---|---|---|---|
| 9.2.2022 | 0.21 | 0.11 | 0.37 |
| 15.2.2022 | 0.64 | 0.66 | 0.49 |
| 23.2.2022 | 1.88 | 1.69 | 1.69 |
| 2.3.2022 | 0.02 | 0.40 | 0.33 |
| 9.3.2022 | 0.15 | 0.34 | 0.53 |
| 16.3.2022 | 0.75 | 0.65 | 0.41 |
| 23.3.2022 | 2.02 | 2.09 | 1.99 |
| 30.3.2022 | 3.56 | 3.85 | 3.90 |
| 6.4.2022 | 3.88 | 3.86 | 3.81 |
| average value | 1.46 | 1.52 | 1.50 |
| Total amount of CO2 absorbed during the cultivation period | 82.94 | 86.43 | 85.67 |

This fact can be explained not by the ongoing microbiological activity in the soil, but by the increased growth resulting from mineral fertilization.

Table 2. Total amount of $CO_2$ absorbed during the cultivation period, g/m³, 2023

| 2023/57 days sample collection date | Non-fertilized | NPK fertilizer | Organic fertilizer |
|---|---|---|---|
| 18.1.2023 | 1.90 | 1.63 | 1.71 |
| 25.1.2023 | 1.41 | 1.20 | 0.98 |
| 1.2.2023 | 1.90 | 1.47 | 1.61 |
| 8.2.2023 | 1.95 | 1.85 | 1.75 |
| 15.2.2023 | 2.16 | 2.02 | 2.02 |
| 22.2.2023 | 1.30 | 1.56 | 1.54 |
| 1.3.2023 | 0.48 | 0.26 | 0.84 |
| 8.3.2023 | 2.69 | 2.62 | 2.21 |
| 15.3.2023 | 1.17 | 1.17 | 0.84 |
| average value | 1.66 | 1.53 | 1.50 |
| Total amount of $CO_2$ absorbed during the cultivation period | 94.72 | 87.29 | 85.49 |

Table 3. Total amount of $CO_2$ absorbed during the cultivation period, g/m³, 2024

| 2024/56 days sample collection date | Non-fertilized | NPK fertilizer | Organic fertilizer |
|---|---|---|---|
| 8.2.2024 | 0.34 | 1.30 | -0.82 |
| 15.2.2024 | 1.20 | 1.49 | 0.34 |
| 22.2.2024 | 1.15 | 1.34 | 1.06 |
| 29.2.2024 | 1.70 | 1.70 | 1.68 |
| 7.3.2024 | 0.91 | 1.01 | 0.62 |
| 14.3.2024 | 2.09 | 2.06 | 1.77 |
| 21.3.2024 | 1.85 | 2.25 | 2.16 |
| 28.3.2024 | 0.84 | 1.06 | 0.70 |
| 3.4.2024 | 3.35 | 3.37 | 1.91 |
| average value | 1.49 | 1.73 | 1.05 |
| Total amount of $CO_2$ absorbed during the cultivation period | 83.54 | 96.97 | 58.56 |

The averaged values of carbon dioxide absorption in the chambers of the different experimental variants for the three experimental years repeat the trends observed in the individual years (Table 4). The averaged values somewhat eliminate the climatic factors influencing emissions. Mineral fertilizers increase absorption by 3.63% compared to unfertilized soil and by 17.92% compared to organic fertilization. Although NPK increases absorption, its production has a high carbon footprint, especially from nitrogen fertilizers-in synthesis through the Haber-Bosch process (Smith, 2020).

Table 4. Average absorption values of the three years (2022-2024), g/m³

| Average absorption values of the three years, g/m³ | | |
|---|---|---|
| non-fertilized | NPK fertilizer | organic fertilizer |
| 87.07 | 90.23 | 76.57 |

Biological fertilization leads to reduced absorption (by 12.08% compared to unfertilized soil), which is due to the slower decomposition of organic matter. However, organic fertilizers have a lower carbon footprint because they come from natural sources and do not require energy-intensive production processes. Optimizing greenhouse conditions (humidity, temperature, aeration) can improve absorption and reduce the need for intensive fertilization. Mineral fertilization (NPK) increases absorption but has a high carbon footprint. Biological fertilization has lower absorption but better environmental sustainability. A combined approach (mixing mineral and organic fertilizers) may be optimal for reducing the carbon footprint while maintaining good productivity.

## CONCLUSIONS

From the experiment conducted to determine the influence of fertilization methods (biological and conventional) on greenhouse lettuce production during the autumn-winter period, and specifically the studied fertilizers, the following conclusions can be made:

The highest $CO_2$ emissions are observed in the unfertilized variant.

When growing lettuce with mineral fertilization in greenhouse conditions during the autumn-winter period, less $CO_2$ is released.

Soil moisture modulates the respiration of microorganisms, affecting both emissions and absorption.

The cultivated crop plays a key role in stabilizing $CO_2$ dynamics, mitigating extreme fluctuations.

NPK fertilization improves $CO_2$ capture but can lead to increased emissions under specific soil moisture conditions.

Temperature and solar activity stand out as dominant factors for $CO_2$ dynamics in the soil.

At low temperatures (< 10°C) and weak radiation (< 0.025 kWh/m²), increased emissions are recorded, while under favorable conditions (T > 10°C, high solar activity), plants and soil processes support $CO_2$ absorption.

Biological fertilization shows a longer-lasting positive effect on the carbon balance, while mineral fertilization has a short-term but more dynamic effect.

The results provide an empirical basis for optimizing soil conditions to improve the carbon balance in agroecosystems.


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