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

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***Abstract***

*To determine the amount of greenhouse gases during the period 2021-2024, an experiment was set up with spinach under greenhouse conditions. The following options were tested: 1. spinach chamber without fertilization - control; 2. spinach chamber with mineral fertilization - NPK; 3. spinach chamber with organic fertilization - Vitaorganic; 4. Chamber without lettuce and without fertilization. At each reading, the CO2 concentration was additionally measured outdoors and in the polyethylene greenhouse. Readings were carried out weekly from planting to harvesting - from January to April. Under adverse weather conditions, young plants fertilized with organic fertilizer consume less CO2, compared to that released from the soil and available in the atmosphere. As temperatures rise, they begin to consume increasingly larger amounts, with the maximum at the end of February, after which consumption decreases to on March 28. The mineral fertilization option has a higher degree of CO2 fixation compared to organic fertilization. When entering economic maturity, the CO2 fixation values are highest for mineral fertilization, while with organic fertilization the fixation is less.*

***Key words****: greenhouse gases, spinach, carbon emission, mineral and biological fertilization.*

## INTRODUCTION

The need for sustainable agricultural practices is increasingly urgent, particularly in addressing the environmental impact of food production. Agriculture significantly contributes to greenhouse gas (GHG) emissions, with nitrogen-based fertilizers being a major source of nitrous oxide ($N_2O$), a potent greenhouse gas. Agricultural production is also accompanied by the release of greenhouse gases $CH_4$ and $CO_2$ during the decomposition of plant residues. Their determination and the development of technology for their reduction have also been the subject of research (Borisova et al., 2023).

Spinach, a widely cultivated leafy green, requires intensive fertilization to achieve high yields. The carbon footprint of spinach production, particularly under different fertilization strategies, has become a key focus for researchers seeking to reduce environmental impacts while maintaining agricultural productivity (Pereira et al., 2022).

Fertilization is a double-edged sword in agriculture. While it enhances crop yields, it also contributes to significant nitrogenous gas emissions (Pan et al., 2022).

The impact of different formulations of organic and biological fertilisers on greenhouse emissions is the subject of several modern studies (Kostadinova et al., 2018; Dermendzhieva et al., 2021; Borisova et al., 2022).

The emissions from synthetic nitrogen fertilizers, particularly ammonia ($NH_3$) and nitrous oxide ($N_2O$), have been extensively documented (Xu et al., 2019; Ma et al., 2021). These gases play a critical role in global warming, air quality degradation, and ecosystem disruption. The adoption of biological fertilizers-derived from organic and microbial sources-offers a promising alternative, as they can enhance soil health and reduce GHG emissions (Yang et al., 2020).

The role of nitrogen in agriculture and its environmental implications have been the subject of extensive research. It has been highlighted the necessity of addressing nitrogenous gas emissions from croplands to transition toward low-emission agriculture (Pan et al., 2022). The authors emphasized that nitrogen management is integral to reducing the carbon footprint of agricultural systems.

Similarly, have been examined 50-year trends in nitrogen use efficiency, revealing a critical balance between crop yield enhancement and nitrogen input optimization (Lassaletta et al., 2014). Their findings underscore the need for sustainable fertilization practices to mitigate environmental impacts.

Sustainable agricultural practices, including the use of organic and mineral fertilizers in optimal rates, are a way to reduce greenhouse gas emissions (Kuncheva et al., 2024).

Synthetic fertilisers, while effective in boosting productivity, are a primary source of ammonia volatilization (Pan et al., 2016). It is provided empirical estimates of global ammonia emissions from synthetic nitrogen fertilisers, underscoring their significant contribution to atmospheric pollution (Xu et al., 2019). Complementing these findings, refined emission factors for soil-derived ammonia, it is offered a more nuanced understanding of regional and crop-specific impacts (Ma et al., 2021).

Biological fertilizers present an eco-friendly alternative to synthetic fertilizers. It is demonstrated the efficacy of combining Azolla, a nitrogen-fixing aquatic fern, with urease inhibitors to reduce ammonia volatilization in rice cultivation, Yang et al. (2020). This strategy not only mitigates emissions but also improves nitrogen use efficiency and crop yields. It is explored the role of biochar in reducing nitrogen leaching in paddy soils, noting its potential to enhance nutrient cycling while managing GHG emissions Wang et al. (2017).

Ammonia emissions are not just a local concern but have global implications for air quality and climate. Providing insights into compliance with air quality regulations, has been analyzed the costs and benefits of ammonia emission abatement in Europe (Giannakis et al., 2019). Similarly, has been discussed how controlling ammonia emissions in China could mitigate haze pollution and nitrogen deposition, though it may exacerbate acid rain issues (Liu et al., 2019).

Nitrogen emissions are intrinsically linked to soil processes. It has been explored the relationship between redox potential, soil organic matter turnover, and nutrient cycling in submerged soils, providing a comprehensive view of nitrogen dynamics (Marschner, 2021). It is highlighted that pathways such as leaching, volatilization, and denitrification nitrogen losses from the soil-plant system have been reviewed (Cameron et al., 2013).

The interplay between carbon and nitrogen cycles is critical in understanding the environmental impacts of fertilization. The dual emissions of reactive nitrogen gases and carbon dioxide from fertilization have been examined, emphasizing the need for integrated management strategies to address these intertwined cycles (Pan et al., 2023). It has been provided a global inventory of nitric oxide emissions from soils, further elucidating the environmental footprint of agricultural practices (Davidson and Kingerlee, 1997).

The literature underscores the complexity of balancing productivity with environmental sustainability in agriculture. This study builds on these findings to compare the carbon footprint of spinach production under mineral and biological fertilization in greenhouses. By quantifying emissions and assessing mitigation strategies, the research aims to contribute to the broader goal of sustainable agriculture.

The study investigates the carbon footprint of spinach grown in greenhouses using mineral and biological fertilization, with an emphasis on understanding emissions associated with different fertilization methods.

## MATERIALS AND METHODS

The experiment was conducted between 2021 and 2024 in an unheated polyethylene greenhouse at the Agricultural University of Plovdiv. The study focused on measuring greenhouse gas emissions during the autumn-winter cultivation of spinach (variety ‘Matador’). The influence of organic and mineral fertilization on the $CO_2$ balance in the soil-plant-air system was evaluated.

Two fertilization treatments were applied: a biological fertilizer (Vitaorganic) and mineral fertilization at an active substance rate per ton of production- $N_{3.75}P_{1.25}K_{4.75}$. A control variant with no fertilization was also included.

$CO_2$ Emission Measurement Variants

$CO_2$ emissions were calculated based on the following measurement variants:

1. Control – $CO_2$ percentage in a chamber without fertilization and plants.

2. NPK fertilization – $CO_2$ percentage in a chamber fertilized with NPK but without plants.
3. Biological fertilization- $CO_2$ percentage in a chamber fertilized with bio-fertilizer but without plants.
4. NPK fertilization with plants – $CO_2$ percentage in a chamber fertilized with NPK, with plants.
5. Biological fertilization with plants – $CO_2$ percentage in a chamber fertilized with bio-fertilizer, with plants.

The experiment was set up with four replications. The experimental plot size was 3.36 m², while the measuring plots for determining $CO_2$ emissions were 0.25 m². Fertilization was applied during the final soil preparation. The organic fertilizer Vitaorganic was applied at a rate of 1500 kg/ha. Mineral fertilization was carried out using potassium sulfate, triple superphosphate, and ammonium nitrate, based on active substance rates: N – 312 kg/ha, $P_2O_5$ – 128 kg/ha, $K_2O$ – 224.8 kg/ha.

Spinach was sown in early November in rows according to the scheme 70 + 6 X 15 cm, with a seeding rate of 15 kg/ha. The crop was cultivated following an established production technology for polyethylene greenhouse cultivation during the autumn-winter period (Aleksiev, 2007). Climate characteristics were recorded using a Meteobot weather station installed in the greenhouse.

To determine and visualize $CO_2$ emission values, three calculation models were developed:

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

The study examined the influence of different fertilizers on $CO_2$ emissions from fertilized and unfertilized soils. The difference in gas emissions between the control and the fertilized variants (organic and mineral) without plants was calculated. The results are presented in Figures 1-3.

The values **X1**, displayed in the graphs, were calculated using the following formulas:

$$X1_{soil\ NPK} = C_{\%CO_2}^{contr.soil} - C_{\%CO_2}^{NPK\ fert.soil.}$$
$$X1_{soil\ BIO} = C_{\%CO_2}^{contr.soil} - C_{\%CO_2}^{BIO\ fert.soil}$$

- $X1_{soil\ NPK}$ is the displayed value of emission/absorption in camber with NPK fertilization soil in the graphs, and $X1_{soil\ BIO}$ is the value for the BIO-fertilized variant;
- $C_{\%CO_2}^{contr.soil}$ is the percentage concentration of carbon dioxide in the chamber with control soil;
-$C_{\%CO_2}^{NPK\ fert.soil}$ and $C_{\%CO_2}^{BIO\ fert.soil}$ are the percentage concentrations of carbon dioxide in the chambers with mineral (NPK) and organic fertilization, respectively.

2. **Effect of Organic and Mineral Fertilizers on $CO_2$ Emissions**

The data presented in Figures 4-6 were obtained by comparing chambers with plants grown in differently fertilized soils. In this case, the measured $CO_2$ amounts in the chamber with unfertilized soil were subtracted from the $CO_2$ amounts in the chambers with NPK and BIO fertilization. Positive values indicate higher $CO_2$ absorption compared to the chamber with unfertilized plants.

The gas exchange values for the NPK variant, as shown in the graphs, were calculated using the following formula:

$$X2_{NPK\ fert.} = C_{\%CO_2}^{non-fert.soil+plant} - C_{\%CO_2}^{NPK\ fert.soil+plant}$$

where:
- $X2_{NPK\ fert.}$ is the displayed value of NPK-fertilized in the graphs
- $C_{\%CO_2}^{non-fert.soil+plant}$ is the percentage concentration of carbon dioxide in the chamber with unfertilized soil and plants planted in it.
- $C_{\%CO_2}^{NPK\ fert.soil+plant}$ is the percentage concentration of carbon dioxide in the chamber with NPK fertilized soil and plants planted in it.

The calculations for the remaining variants were performed similarly.

3. **Influence of the fertilizers used (organic and mineral) on the emission of $CO_2$**

The data presented in Figures 4-6 were obtained by comparing the chambers with plants, with differently fertilized soils. In this case, the amounts of gas in the chambers from the NPK fertilization and BIO fertilization variants were subtracted from the measured amounts of carbon dioxide in the chamber with unfertilized soil. Here too, positive values mean higher absorption of $CO_2$ in relation to the chamber with unfertilized plants.

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

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

where:

- $X3_{NPK\ fert.}$ is the displayed value of NPK-fertilized in the graphs
- $C^{NPK\ fert.+plant}_{\%CO_2}$ is the percentage concentration of carbon dioxide in the chamber with NPK fertilized soil and plants planted in it.

The calculations for the other variants were made similarly.

Further calculations in the tables include (Table 1):

$$X^{NPK}_{average} = \left[ \sum_{09.02.to\ 05.04} X3_{NPK\ fert.} \right] /9$$

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

where:

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

The calculations for the other variants are made similarly.

## RESULTS AND DISCUSSIONS

The three-year study confirms that $CO_2$ dynamics in the soil is a complex process influenced by multiple interconnected factors, such as soil temperature, moisture, solar radiation, vegetation cover, and type of fertilization.

The graphs below present the difference in $CO_2$ concentration between the various experimental chambers. Positive values indicate that the soil (or plants) in the respective variant absorb $CO_2$, while negative values indicate emissions.

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

The data presented in Figures 1-3 show that the soil temperature during the study period varied between 11°C and 19°C, with changes in depth remaining insignificant (Figure 1).

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

The data presented in Figures 1-3 show that the soil temperature during the study period varied between 11°C and 19°C, with changes in depth remaining insignificant (Figure 1).

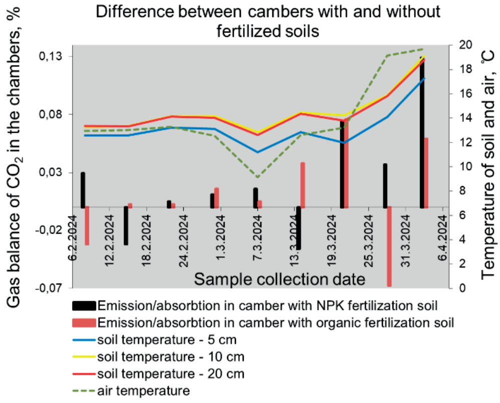


Figure 1. The temperature dependence of $CO_2$ dynamics in abiotic experimental chambers

The analysis of the measured $CO_2$ concentrations allows for an assessment of the impact of key agro-climatic factors on the soil $CO_2$ balance. For both fertilization methods, there is a tendency for $CO_2$ emissions to decrease as soil temperature rises. This highlights the importance of temperature for microbiological activity and the decomposition processes of organic matter, leading to either $CO_2$ emission or absorption. A particularly pronounced absorption was recorded on April 4th, when the temperature ranged between 17-19°C. Since this variant does not include plants, the increased $CO_2$ uptake is likely due to enhanced microbiological activity.

A comparative analysis between mineral (NPK) and biological fertilization reveals significant differences. At higher temperatures, $CO_2$ absorption in the NPK chamber is twice as high as in the bio-fertilized chamber. This is likely due to the high solubility and availability of mineral fertilizers, which accelerate nutrient uptake by soil microflora.

On February 8th and March 28th, $CO_2$ absorption was observed in the NPK variant, while biological fertilization resulted in emissions, despite minimal temperature differences (around 2°C). At the same time, on February 15th and March 14th, under similar temperature conditions, the effect was reversed-NPK led to emissions, whereas biological fertilization resulted in $CO_2$

absorption. This suggests that soil temperature alone is not the sole determining factor in $CO_2$ dynamics.

Within the temperature range of 10°C to 20°C, an inverse relationship between temperature and $CO_2$ emissions was established - higher temperatures lead to reduced emissions. However, during certain periods with similar temperatures, different effects were recorded, emphasizing the importance of additional factors in regulating the soil carbon balance.

## 1.2. Influence of Soil Moisture on $CO_2$ Dynamics

Soil moisture in the upper layers varied significantly throughout the experiment, ranging between 3 and 32 l/m², depending on the sampling date and soil layer depth (Figure 2). As expected, the middle and deeper soil layers (5, 10, and 20 cm) retained higher moisture levels.

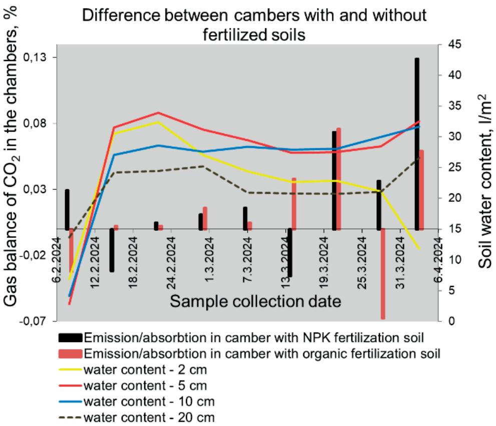


Figure 2. The effect of soil moisture on $CO_2$ dynamics in abiotic experimental chambers

On colder days (February 8th and March 7th), low moisture content in the upper soil layer led to increased $CO_2$ emissions, but only in the biologically fertilized variant. As moisture levels increased, soil permeability decreased, limiting $CO_2$ release. A similar trend was observed on March 28th, when moisture levels in the upper layer dropped below 21 l/m², triggering an increase in $CO_2$ emissions in the biologically fertilized soil.

On April 3rd, an opposite trend was observed - further reduction in soil moisture led to significant $CO_2$ absorption. This confirms that the $CO_2$ balance depends not only on individual factors but on a combination of multiple variables.

## 1.3. Influence of Solar Energy on $CO_2$ Dynamics

During the measurement period, solar energy ranged from 0.023 to 0.151 kWh/m² (Figure 3). The data indicate that at higher soil temperatures and more intense solar radiation, $CO_2$ absorption increases. On days with greater solar activity, such as March 21st and April 3rd, $CO_2$ uptake was significantly higher.

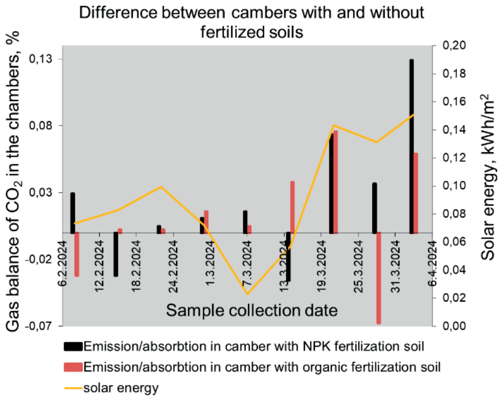


Figure 3. The radiative forcing of solar energy on $CO_2$ dynamics in plant-free experimental chambers

The figure illustrates that the increase in soil temperature is directly linked to the rise in solar radiation. Although the illuminated surface is small compared to the volume of the studied soil, the primary factor influencing $CO_2$ absorption appears to be soil temperature.

## 2. Influence of the applied fertilizers (organic and mineral) on $CO_2$ emissions

The analysis of the impact of the applied fertilizer on $CO_2$ levels reveals a distinct difference (Figures 4, 5, and 6). Most measurements indicate that higher amounts of $CO_2$ are released in chambers with mineral and organic fertilization.

This indicates that the application of mineral and organic fertilizers at the specified rates leads to increased $CO_2$ emissions. This effect is most pronounced during the first two measurements on February 8 and February 15, when the plants were still in their early growth stages. Soil moisture (Figure 5) does not appear to have a significant influence, as the difference in gas emissions between mineral and organic fertilization remains consistent regardless of low or high moisture levels.

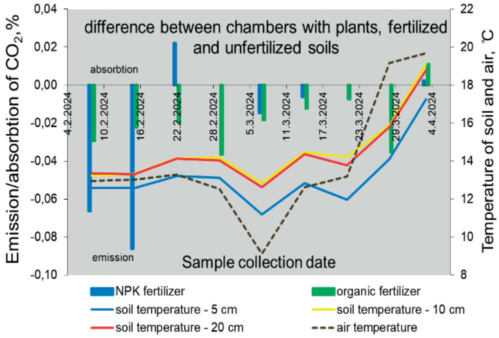


Figure 4. Influence of soil temperature on $CO_2$ emissions under different fertilization types

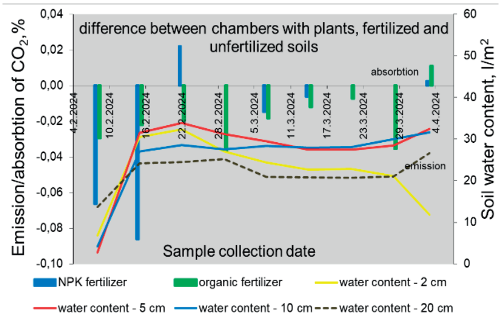


Figure 5. Influence of soil moisture on $CO_2$ emissions under different fertilization types

The graphs also highlight a higher $CO_2$ uptake in the mineral fertilization variant on February 22 and April 3. On these dates, soil moisture remained relatively stable, while temperatures varied. Among all the external factors examined, increased $CO_2$ absorption correlates most strongly with higher solar activity (Figure 6).

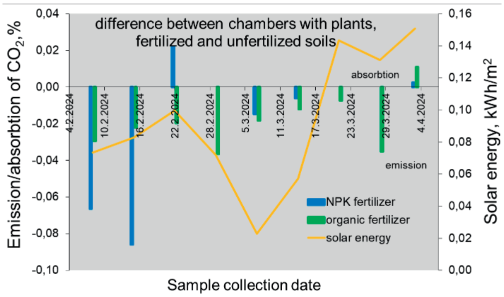


Figure 6. Influence of solar activity on $CO_2$ emissions under different fertilization types

The analysis suggests that at relatively lower air and soil temperatures, mineral fertilization promotes more intensive photosynthesis compared to organic fertilization. Lower temperatures slow down the mineralization of organic fertilizers, which in turn affects photosynthetic efficiency and results in less vegetative biomass formation.

Organic fertilization leads to more stable and long-term $CO_2$ absorption, with average values of 2.03 g/m³ and 1.89 g/m³ recorded in 2022 and 2023, respectively. However, in 2024, a decline to 1.13 g/m³ was observed, likely due to climatic anomalies.

Mineral fertilization (NPK) exhibits greater fluctuations in $CO_2$ absorption. While the average values were relatively high in 2022 and 2023 (1.59 g/m³ and 1.92 g/m³), they dropped to 1.18 g/m³ in 2024, suggesting a shorter-lasting effect.

Control samples (without fertilization) showed moderate and stable $CO_2$ absorption, though with lower overall values compared to fertilized treatments.

3. **Influence of spinach on $CO_2$ emissions (difference between control soil and plant variants)**

The graphs clearly illustrate that, regardless of the type of fertilizer used, $CO_2$ emissions are consistently lower in plant-containing variants compared to the control (unfertilized soil) in almost all measurements.

Higher air and soil temperatures, combined with increased solar activity, tend to equalize the differences between fertilized and unfertilized variants. On March 14, March 21, and April 3, the difference in $CO_2$ absorption was negligible.

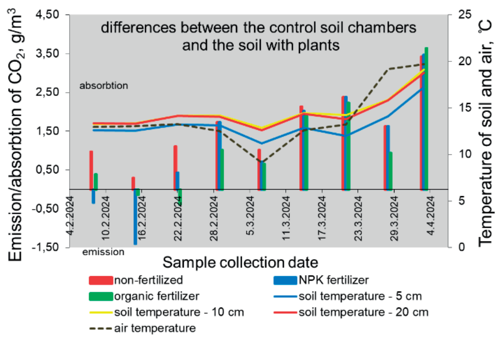


Figure 7. Influence of air and soil temperature on $CO_2$ emissions during plant cultivation

A temperature drop and increased cloud cover on March 7 affected photosynthesis, leading to lower carbon absorption. The decrease in air temperature was around 3°C, indicating that the primary factor behind the reduced absorption was lower solar radiation. A similar effect was observed on March 28, where despite higher temperatures, reduced solar activity resulted in lower $CO_2$ absorption.

An increase in soil moisture, combined with mineral fertilization during the early growth phase, led to higher carbon emissions (Figure 8).

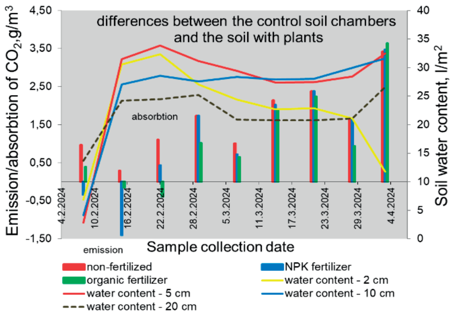


Figure 8. Influence of soil water content on $CO_2$ emissions during plant cultivation

This confirms the earlier observation that mineral fertilizers, when applied in the specified amounts and under conditions of relatively higher soil moisture, stimulate soil microbiota activity, potentially increasing greenhouse gas emissions.

The data show that high soil moisture correlates with increased $CO_2$ emissions, especially under organic fertilization. This can be attributed to the accelerated microbial decomposition of organic matter. Under optimal moisture conditions, the best balance between emissions and absorption is observed.

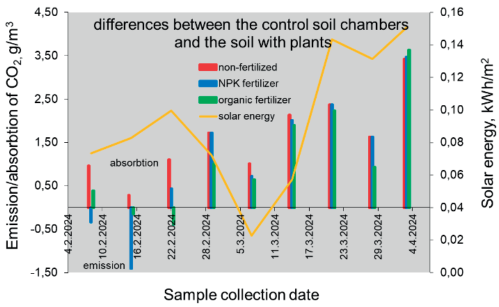


Figure 9. Influence of solar activity on $CO_2$ emissions during plant cultivation

## 4. Evaluation and Comparison of Carbon Emissions Under Different Fertilization Regimes in Winter Spinach Cultivation

Tables 1-3 compare $CO_2$ absorption results for similar cultivation periods of spinach over the three-year experiment. The values in the tables are calculated by subtracting the $CO_2$ amounts measured in the chambers with plants (for the unfertilized, NPK, and BIO variants) from those in the control soil chamber. The differences were recorded by the chromatograph in percentage terms and converted to g/m³.

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

| 2022/57 days sample collection date | Soil temperature - 10 cm | Non-ferti-lized | NPK fertilizer | Organic fertilizer |
|---|---|---|---|---|
| 9.2.2022 | 5.9 | -0.18 | 0.61 | 0.73 |
| 14.2.2022 | 5.8 | 0.21 | 0.04 | 0.33 |
| 23.2.2022 | 9.9 | 1.66 | 1.71 | 2.02 |
| 2.3.2022 | 8.2 | 0.94 | 0.99 | 1.30 |
| 9.3.2022 | 7.8 | 0.87 | 0.92 | 1.23 |
| 16.3.2022 | 8.8 | 1.18 | 1.23 | 1.54 |
| 23.3.2022 | 11.8 | 3.25 | 3.30 | 3.61 |
| 30.3.2022 | 16.8 | 2.68 | 2.15 | 3.33 |
| 5.4.2022 | 15.9 | 3.72 | 3.33 | 4.15 |
| average value | | 1.59 | 1.59 | 2.03 |
| Total amount of CO2 absorbed during the cultivation period | | 90.77 | 90.41 | 115.46 |

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

| 2023/56 days sample collection date | Soil temperature - 10 cm, °C | Non-fertilized | NPK fertilizer | Organic fertilizer |
|---|---|---|---|---|
| 12.1.2023 | 8.4 | 1.64 | 1.64 | 1,64 |
| 18.1.2023 | 8.0 | 2.12 | 2.12 | 2,12 |
| 25.1.2023 | 6.7 | 1.54 | 1.54 | 1,54 |
| 1.2.2023 | 6.7 | 1.94 | 1.94 | 1,94 |
| 8.2.2023 | 5.1 | 2.09 | 2.09 | 2,16 |
| 15.2.2023 | 8.3 | 2.11 | 2.14 | 2,28 |
| 22.2.2023 | 12.3 | 1.30 | 1.63 | 1,25 |
| 1.3.2023 | 10.3 | 1.39 | 1.53 | 1,25 |
| 8.3.2023 | 10.6 | 2.52 | 2.67 | 2,81 |
| average value | | 1.85 | 1.92 | 1.89 |
| Total amount of CO2 absorbed during the cultivation period | | 103.63 | 107.65 | 105.71 |

To approximate the absorption difference between the variants, an assumption was made that plants absorb the average value of all measurements taken on the respective dates over 24 hours. This average value was then multiplied by the number of days in the study period, yielding the total amount of gas absorbed during the cultivation cycle. The study period was 57 days in 2022 and 56 days in both 2023 and 2024.

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

| 2024/56 days sample collection date | Soil temperature - 10 cm, °C | Non-fertilized | NPK fertilizer | Organic fertilizer |
|---|---|---|---|---|
| 8.2.2024 | 13.3 | 0.96 | -0.34 | 0,39 |
| 15.2.2024 | 13.3 | 0.29 | -1.40 | -0,14 |
| 22.2.2024 | 14.2 | 1.10 | 0.43 | -0,39 |
| 29.2.2024 | 14.2 | 1.73 | 1.73 | 1,01 |
| 7.3.2024 | 12.9 | 1.01 | 0.72 | 0,65 |
| 14.3.2024 | 14.5 | 2.13 | 2.01 | 1,89 |
| 21.3.2024 | 14.2 | 2.37 | 2.37 | 2,23 |
| 28.3.2024 | 15.9 | 1.63 | 1.63 | 0,94 |
| 3.4.2024 | 19.1 | 3.42 | 3.47 | 3,64 |
| average value | | 1.63 | 1.18 | 1.13 |
| total amount of CO2 absorbed during the cultivation period | | 91.13 | 66.10 | 63.53 |

Organic fertilization resulted in more stable and long-term $CO_2$ absorption, with average values of 2.03 g/m$^3$ in 2022 and 1.89 g/m$^3$ in 2023. However, a decline was observed in 2024 (1.13 g/m$^3$), likely due to climatic anomalies.

Mineral fertilization (NPK) exhibited greater fluctuations in absorption. While the average values were relatively high in 2022 and 2023 (1.59 g/m$^3$ and 1.92 g/m$^3$, respectively), they dropped to 1.18 g/m$^3$ in 2024, suggesting a shorter-term effect. Control samples (without fertilization) demonstrated moderate and stable $CO_2$ absorption but with lower final values compared to the fertilized variants.

Throughout all the experimental years, a positive correlation was observed between soil temperature and $CO_2$ absorption levels (Table 1). The highest absorption values were recorded at temperatures above 14°C (e.g., April 3, 2024 - 19.1°C, with a maximum absorption of 3.64 g/m$^3$ under organic fertilization). At lower temperatures (<8°C), a reduced $CO_2$ exchange activity was observed, likely due to slowed microbial activity.

In 2022, the lowest emissions were observed in the variant fertilized with biological fertilizer (Table 1). This is explained by the relatively lower air and soil temperatures at the beginning of the vegetation period compared to the end of the vegetation period.

For 2023, the lowest emissions were observed in the NPK-fertilized variant, and in 2024, in the unfertilized spinach variant.

Table 4. Average absorption values of the three years (2022-2024), g/m$^3$

| Average absorption values of the three years, g/m$^3$ | | |
|---|---|---|
| non-fertilized | NPK fertilizer | organic fertilizer |
| 95.17 | 88.05 | 94.90 |

Soil temperature is a key factor for the dynamics of $CO_2$ exchange – the highest absorption is observed at temperatures above 14°C. Soil moisture affects the intensity of $CO_2$ emissions, with excessive moisture potentially leading to increased $CO_2$ release. Solar radiation has a positive effect on $CO_2$ absorption, particularly in the presence of plants. Organic fertilization provides a more sustainable carbon balance in the soil in the long term, while mineral fertilization has a stronger but short-lived effect. Annual variations show that climatic conditions have a significant impact on $CO_2$ absorption, highlighting the need for adaptive agricultural practices.

These results contribute to the understanding of the mechanisms regulating carbon balance in agroecosystems and can be used to optimize microclimate management and root nutrition to reduce $CO_2$ emissions and increase carbon storage in the soil.

## ACKNOWLEDGEMENTS

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