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Research Article

CO_2 Emissions per Unit of Yield and Water Use for Lettuce Grown in Soil Fertilized with Manure and Irrigated at Different Intervals

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Abstract: Organic fertilization plays a crucial role in enhancing crop yields and water efficiency in agriculture. Nevertheless, it is equally vital to consider how irrigation practices can impact the potential for CO_2 emissions during short-term crop production. A field study was conducted on curly lettuce, comparing two doses of cattle manure (M1 and M2, with approximately 3% and 4.5% soil organic matter content, respectively) with mineral fertilization (F). Irrigation intervals were set at every two (IR1) and four days (IR2). The M2IR1 treatment had the highest seasonal average CO2 emission of 0.909 g CO_2 m^{-2}, which was 90.2% higher than in the FIR1 treatment. The emission quantities exhibited a strong linear correlation with soil organic matter and moisture contents. The M2 treatment had the highest marketable yield at 7.84 kg m^{-2}, which was 5.7% and 12.7% higher than in the M1 and F treatments, respectively. The M2IR2 treatment had the highest emission per kg yield at 143.5 g CO_2, which was 83.7% higher than the FIR1 treatment. The M2 treatment provided lower evapotranspiration values. CO_2 emission per m^3 of water use in the M2IR2 treatment was the highest at 8.50 kg CO_2, which was 217.2% greater than in the FIR1 treatment. The study concluded that reducing water usage and increasing yields under manure-fertilized conditions may not lower CO_2 emissions per unit of yield and water use for lettuce in the short-term period.

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Footnote: The study includes a part of the Master thesis study.

1. Introduction

Fertilization and irrigation are primary agricultural inputs that greatly influence high-yielding vegetable production among various agricultural inputs. To ensure optimum plant growth, it is essential to supply adequate amounts of macro and micro-nutrients consistently. Producers' excessive use of chemical fertilizers for high yields, without considering soil and ecosystem health, not only pollutes soil and water resources but also disrupts the natural balance between soil, plants, and microbial populations (Rather et al., 2018). Organic fertilization is essential to reduce the environmental impact of conventional chemical fertilizers (Khan et al., 2024). Organic fertilizer is crucial for plant growth as it supplies macro and micronutrients in a readily available form. Mineralization also improves the physical and chemical characteristics of the soil, leading to enhanced soil health. Soil microbial biomass is vital for soil stability and nutrient cycling. Incorporating organic amendments into the soil stimulates microbial activity, diversity, and proliferation, thereby increasing plant nutrient availability (Khan et al., 2024). Organic vegetable production relies heavily on macronutrients, particularly nitrogen, to boost yields, especially for leafy greens like lettuce (Toonsiri et al., 2016). Growing lettuce organically is preferred for salad crops, and manuring is a beneficial practice that improves quality without leaving harmful residues (Rather et al., 2018).

However, manure application contributes to soil carbon storage, which can be degraded into CO_2 over time (Liu et al., 2024). CO_2 release from the soil involves microbial and plant root respirations (Ray et al., 2020). CO_2 emissions are linked to soil organic matter and its decomposition by microbial activities (Yerli et al., 2023a). Organic carbon, oxidized by microbes, leaves the soil as CO_2 (Yerli, 2023). Soil organic carbon serves as an energy source for microorganisms (Tang et al., 2022). Nitrogen deficiency weakens organic matter mineralization by soil microorganisms (Navarro-Pedreño et al., 2021). High nitrogen content from organic fertilization enhances soil biological capacity and organic matter mineralization, increasing soil respiration (Tang et al., 2018). While high organic matter can release more CO_2 from the soil, favorable environmental conditions for microbial activity in the organic matter decomposition processes are crucial. Soil temperature and moisture directly affect microorganism activity, leading to higher CO_2 emissions from the soil due to organic matter mineralization (Yerli et al., 2022a; Yerli et al., 2023a).

Understanding the environmental impact of manure requires quantifying its contribution to CO_2 emissions across various agricultural production and management practices. Limited information is available on the impacts of chemical fertilizer and alternative cattle manure on CO_2 emissions from soil, especially in the context of lettuce cultivation. The study aims to explore the possibility of reducing CO_2 emissions per unit yield and water use by lowering water consumption and increasing lettuce yield within a short-term period. Adjusting the irrigation interval can be a practical way to reduce greenhouse gas emissions per unit yield in manured lettuce soils. Fewer emissions are expected, which aligns with the European Green Deal's objective of decreasing CO_2 emissions.

2. Materials and Methods

2.1. Study area, climate, and soil properties

The field experiment was conducted in the application area of Atatürk University Plant Production Application and Research Center in Erzurum province in 2024 at 39.933º N latitude, 41.235º E longitude, and 1780 m altitude from July 8 to August 28. The region has a semiarid climate with an average annual precipitation of 395.7 mm, and a total of 80 mm of precipitation was observed in the 2024 vegetation period of curly lettuce. The average air temperature during the vegetation period was 19.6 °C.

The texture was clay loam in the 0–20 cm surface soil layer of the experimental field, and it was loam in the 20–40 cm soil layer. The pH, EC, OM, and $CaCO_3$ contents in the surface soil layer of 0-20 cm were 7.61, 0.228 dS m^{-1}, 1.86%, and 0.42%, respectively. In the 20-40 cm soil layer, the values were 8.02, 0.251 dS m^{-1}, 1.13%, and 1.19%, respectively. The available moisture content of the experimental field soil was 55.5 mm with an effective rooting depth of 40 cm. The analyses were conducted using the methods mentioned in Klute (1986) and Page et al. (1982).

2.2. Experimental procedures

The experiment was carried out in a 3x2 factorial design with 3 replications, totaling 18 plots, following a random blocks trial plan. Three fertilizer applications, mineral (F) and two doses of mature cattle manure (M1 and M2), were tested with two irrigation intervals (IR1: 2 days and IR2: 4 days). The fertilizer treatments were assigned to the main plots, and the subplots were established with irrigation intervals.

Experimental soil was tilled with a plough and amended with a disc harrow 21 days before planting seedlings. Mature cattle manure with a moisture content of 29.7% was applied in doses that would increase the organic matter content in the 20 cm surface soil layer to medium-high (approximately 3%) in the M1 treatment and to high (approximately 4.5%) in the M2 treatment. The cattle manure was spread homogeneously on the surface of the plots and mixed into the 15 cm top-soil layer with a hoe machine. The pH, electrical conductivity, and organic matter content of the cattle manure used were 7.86, 2.78 dS m^{-1}, and 57.3%, respectively.

The nitrogen was applied at a dose of 120 kg ha^{-1} of urea (45-46% N), based on the soil analysis results, to the mineral fertilizer plots. Half of the required amount was applied manually to the plant rows during seedling planting, and the other half was applied 3 weeks after planting. Phosphorus fertilizer was applied to the plant rows during seedling planting at a rate of 100 kg ha^{-1} triple super phosphate (43-46% P_2O_5) (Samancıoğlu 2016). Mineral fertilizer was not applied to the cattle manure plots. Hoeing was applied to destroy weeds when necessary.

Seedlings of the Davidole variety of curly lettuce were planted in the plots with a 30 cm distance between rows and plants. Each plot consisted of 8 rows measuring 2.4 m × 4.2 m, with a space of 1.5 m left between the plots and 2 m between the blocks.

Irrigation was done using a surface drip irrigation system with groundwater that has no salinity problems for crops or sodium risks for the soil (pH= 7.46; EC = 0.290 dS m^{-1}, SAR = 0.49). Driplines with 33 cm dripper spacing providing 4 L/h dripper flow at 0.01 MPa operating pressure were installed between two rows of lettuce.

During the initial growing period (July 8 – August 3), when the sum of (estimated crop evapotranspiration (ETc) – precipitation) reached 11.1 mm, which equals 20% of the available soil moisture, irrigations were planned. However, since precipitation during this period met the calculated ETc, irrigation was not needed. The total ETc was calculated to be 91.1 mm, and the total precipitation measured was 80 mm. Therefore, the first irrigation was carried out on August 3 for IR1 and on August 5 for IR2 treatment, marking the beginning of the scheduled irrigation period.

In ETc calculations, the equation “ETc = ETo x kc” was used, and reference evapotranspiration (ETo) values were determined with the FAO56_Penman-Monteith model in the CROPWAT (Ver. 8.0) program. Lettuce crop coefficients (kc) for Erzurum province were taken from the “Plant Water Consumption Guide for Irrigated Plants in Turkey” (GDARP, 2017). Climate data were provided daily from the Erzurum Airport Meteorological Station near the experimental area; precipitation was measured with a pluviometer installed in the trial area. Considering the moisture measurements in the soil layer of 40-60 cm, below the effective rooting depth, 72.5% of the total 80 mm precipitation falling during the vegetation period was stored in the root region and consumed by the plant.

After the initial growing period, irrigations were scheduled every 2 or 4 days, carried out in amounts required to bring the available soil moisture at 40 cm effective root depth in the middle block plots of each fertilizer treatment to field capacity, with a wetting ratio of 0.85. Moisture measurements at 0-20 cm were taken using a soil moisture meter (TDR, Trime-Pico, IPH/T3, IMKO) calibrated to the experimental field, while moisture measurements at 20-40 cm and 40-60 cm were done gravimetrically. Control measurements at 0-20 cm were also taken using the gravimetric method.

The depth and volume of irrigation water applied to the plots were calculated using the following equations (Cakmakci and Sahin, 2021).

$$I = (FC - CM) \times \gamma t \times D \times WR / 10 \quad (1)$$

$$V = I \times A \quad (2)$$

Where I is the irrigation quantity, in mm; V is the irrigation volume in L; FC is the moisture amount retained at field capacity as a percentage of weight; CM is the current soil moisture content as a percentage of weight; γt is the soil bulk density in g cm^{-3}; D is the effective rooting depth in 40 cm; WP is the wetting ratio (0.85), and A is the plot area in m^2.

Seasonally, 12 and 6 irrigations were applied in IR1 and IR2 treatments, respectively. Seasonal irrigation quantities in FIR1, FIR2, M1IR1, M1IR2, M2IR1, and M2IR2 treatments were 148.8 mm, 130 mm, 114.4 mm, 80.4 mm, 77.9 mm, and 54.9 mm, respectively.

Actual evapotranspiration was calculated using the following equation (Cakmakci and Sahin, 2021).

$$ET_a = I + P + Cr - Dw - Rf \pm \Delta S \quad (3)$$

Where Et is the actual crop evapotranspiration in mm; I is the seasonal irrigation quantity in mm, Dw is the deep seepage below the effective rooting depth in mm, and ΔS is the change in moisture content in the effective rooting depth in mm. Capillary rise (Cr) was not considered due to the deep water table, and surface runoff (Rf) did not occur due to controlled irrigation. Soil moisture measurements were taken before each irrigation, at the beginning of the season (during seedling planting), and at the end of the season (during harvest). Moisture content measurements were conducted 10-15 cm away from the dripper, between two plants in the middle of the plot. The ETa values in FIR1, FIR2, M1IR1, M1IR2, M2IR1, and M2IR2 treatments were 218.2 mm, 205.5 mm, 181 mm, 148.5 mm, 141.5 mm, and 120.8 mm, respectively.

2.3. Measurement and calculations

The trial was conducted between July 8 and August 28. To determine the marketable yield of curly lettuce at harvest maturity, ten crops were collected from the middle of the plot to avoid edge effects. Damaged outer leaves were removed and weighed, and the yield per unit area was calculated (g m^{-2}). Soil samples were collected at 0-20 cm and 20-40 cm depths during harvest and analyzed for organic matter content using the Smith–Weldon method (Nelson and Sommers, 1982).

Soil CO_2 emissions were measured using an EGM-5 infrared gas analyzer (CFX-2, Systems, Stotfold, UK) on the day of planting, on the 1st, 2nd, and 3rd days after planting, 1 day before and 1 day after irrigation, and also during harvest. Measurements were made at a point located in the central region of each plot, between two plant rows and 10-15 cm from the drippers, repeated 3 times in 3 different random points. In this process, the measurement circle was placed in the soil at a depth of 1-2 cm, and data were recorded for 1 min (Yerli et al., 2022a). While measuring CO_2 emissions, soil temperature, and moisture were also measured at depths of 5 cm, 10 cm, and 20 cm. Soil moisture was measured with a TDR probe (Trime-Pico, IPH/T3, IMKO), and soil temperature was measured with a probe connected to a CO_2 measuring device. In addition, H_2O emission and air temperatures were monitored with an EGM-5 infrared gas analyzer during each measurement.

Seasonal cumulative CO_2 emissions were calculated by multiplying individual measurement values (g CO_2 m^{-2} h^{-1}) from sowing to harvest by the time of the measuring period. To determine CO_2 emissions per unit yield and water use, the seasonal cumulative emissions were divided by the marketable yield and ETa, respectively (Yerli et al., 2022a).

2.4. Statistical analysis

Experimental data from the fertilization and irrigation treatments were analyzed using SPSS (ver. 22). Significant means for fertilization treatments were analyzed with the General Linear Model, and the Independent Samples t Test was used for irrigation treatments. Interaction effects were evaluated with a One-Way ANOVA test. Significant means were classified at a 5% significance level using the Duncan multiple comparison test.

3. Results and Discussion

3.1. CO_2 emissions in different manure doses and irrigation intervals

CO_2 emissions from the soil of curly lettuce during the vegetation period showed that the values were higher in the tillage-planting period but remained relatively consistent with similar variations throughout the entire vegetation period (Figure 1). A higher dose of manure resulted in higher CO_2 emissions, while the emissions were lower under mineral fertilization. The seasonal cumulative CO_2 emission (1113.2 g m^{-2}) in the M2 treatment in IR1 was higher by 11.9% and 90.2% than the M1 and F treatments, respectively (Figure 2). The M2 treatment (1026.9 g m^{-2}) in IR2 also resulted in 14.2% and 97.2% higher cumulative emission, respectively.

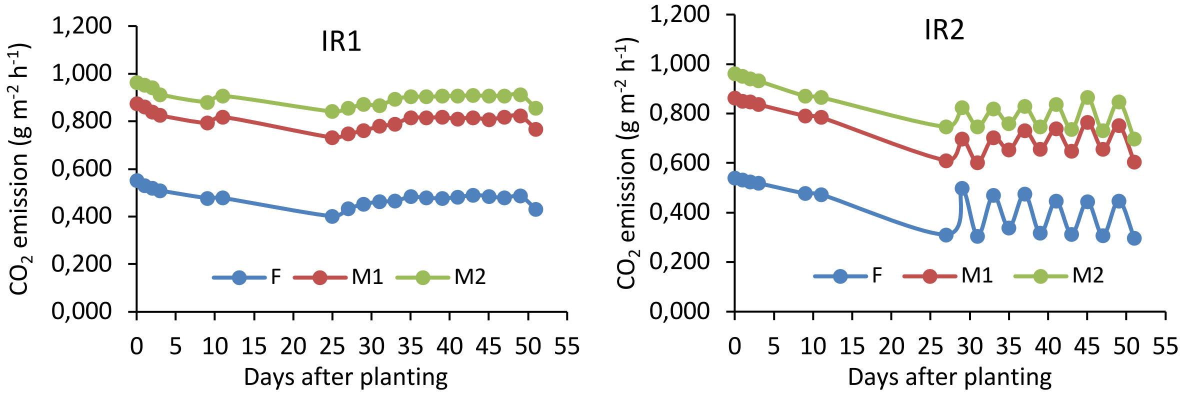

Figure 1. Comparison of seasonal CO_2 emissions during the vegetation period with two irrigation intervals (IR1 every 2 days, IR2 every 4 days) under mineral (F) and cattle manure (M1, M2) fertilization. M1 and M2 correspond to initial soil organic matter contents of approximately 3% and 4.5%, respectively.

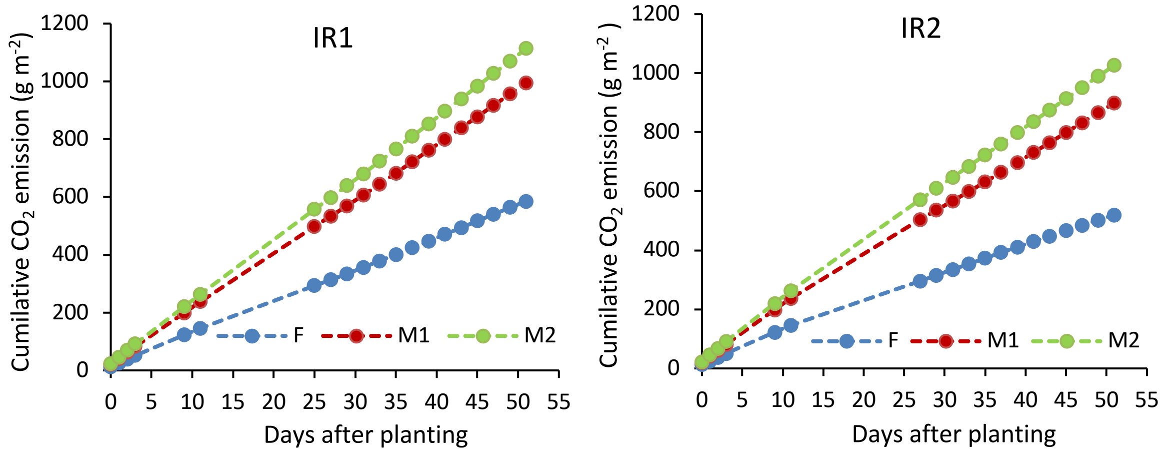

Figure 2. Cumulative CO_2 emissions during the vegetation period in two irrigation intervals (IR1 every 2 days, IR2 every 4 days) under fertilization with mineral (F) and cattle manure (M1, M2). M1 and M2 correspond to initial soil organic matter contents of approximately 3% and 4.5%, respectively.

The seasonal mean CO_2 emission in the M2 treatment was 12.9% and 93.4% higher than in the M1 and F treatments, respectively (Figure 3, Table 1). The IR1 treatment also increased mean CO_2 emissions by 10.1% compared to IR2. Therefore, the seasonal mean CO_2 emission was maximum in the M2IR1 treatment with a value of 0.909 g m^{-2}, which was higher by 90.2% compared to the FIR1 treatment.

Many studies have reported that increasing the carbon rate in the soil, as a favorable energy source for microorganism improvements, may increase CO_2 emissions by contributing more to the mineralization rate with improved soil biological activity (Tang et al., 2018 and 2022; Yerli, 2023; Yerli et al., 2023a). Therefore, the basic factor that increased CO_2 emissions with the increased dose of manure applications in this study was the high organic matter content in the soil. The soil organic matter contents in the FIR1, M1IR1, M2IR1, FIR2, M1IR2, and M2IR2 treatments at harvest were 1.28%, 2.19%, 3.26%, 1.41%, 2.43%, and 3.47%, respectively. A positive correlation was found between the organic matter content in the 0-20 cm soil layer at harvest and the seasonal mean CO_2 emissions (Figure 4). Similarly, Yerli et al. (2023a and 2003b) reported the linear relationships between CO_2 emissions and soil organic matter content.

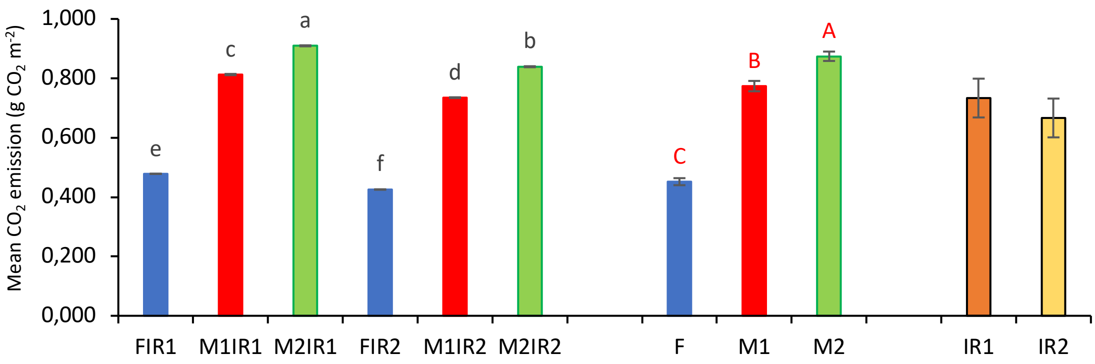

Figure 3. Seasonal mean CO_2 emissions during the vegetation period in two irrigation intervals (IR1 every 2 days, IR2 every 4 days) under fertilization with mineral (F) and cattle manure (M1, M2). M1 and M2 correspond to initial soil organic matter contents of approximately 3% and 4.5%, respectively. Means with different lowercase letters are significantly different at the 0.05 level.

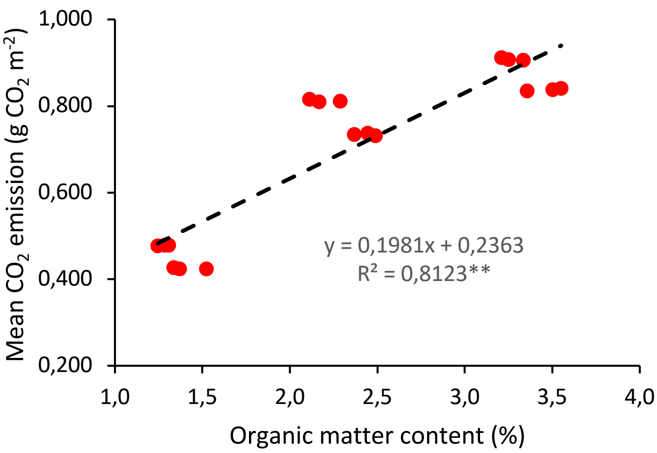

Figure 4. The linear relationship between organic matter content in the soil layer of 0-20 cm at harvest and seasonal mean CO_2 emissions.

Soil moisture greatly affects the oxidation of organic carbon (Shi and Marschner, 2014). Wetting the soil increases microbial activity, which inevitably leads to changes in soil CO_2 emissions (Hou et al., 2020). The results of this study indicated that CO_2 emissions during the vegetation period were linearly correlated with soil moisture measured at three different soil depths (5 cm, 10 cm, and 20 cm) (Figure 5). The CO_2 emissions increased with an increase in soil moisture, and there is a relationship between them. CO_2 and H_2O emissions were also significantly positively linear. Similarly, Yerli et al. (2022a) and Yerli (2023) reported linear correlations between H_2O and CO_2 emission increases under different irrigation levels. Yerli et al. (2022b) also indicated that the CO_2 emission from soil containing different organic manures had a positive linear relationship with soil moisture. The results of this study also showed that the soil surface layer temperature is directly related to the air temperature. However, it was not found to be significant that CO_2 emissions change with both air and soil temperatures (Figure 5). The mean soil temperature during the vegetation period was approximately 21-22 °C. Peregrina (2016) reported that the effect of increased temperatures on soil CO_2 emissions decreases and determined that a soil temperature of approximately 20 °C does not have a significant effect on CO_2 emissions. However, high temperatures can stimulate microbial activity, accelerating the decomposition of organic matter and increasing soil respiration, which can lead to higher CO_2 emissions from the soil (Navarro-Pedreño et al., 2021).

Table 1. Statistical analysis results

General Linear Model					
Variance Sources	**df**	**Parameter**	**Mean Square**	**F**	**P**
Fertilizer	2	Seasonal mean CO_2 emission	.292	44163.328	.000
Irrigation	1		.020	3086.017	.000
Fertilizer × Irrigation	2		.000	36.403	.000
Error	12		6.611E-006		
Fertilizer	2	Marketable yield	1163263.385	109.057	.000
Irrigation	1		6821340.480	639.508	.000
Fertilizer × Irrigation	2		29211.542	2.739	.105
Error	12		10666.546		
Fertilizer	2	CO_2 emission per unit marketable yield	5732.436	2492.965	.000
Irrigation	1		305.045	132.660	.000
Fertilizer × Irrigation	2		35.647	15.502	.000
Error	12		2.299		
Fertilizer	2	CO_2 emission per unit water use	46.921	104825.685	.000
Irrigation	1		.547	1222.173	.000
Fertilizer × Irrigation	2		.281	627.743	.000
Error	12		.000		

Independent-Samples T Test (Irrigation)				
Parameter	**df**	**t**	**F**	**P**
Seasonal mean CO_2 emission	16	.747	.068	.466
Marketable yield	16	6.590	1.044	.000
CO_2 emission per unit marketable yield	16	-.650	.564	.525
CO_2 emission per unit water use	16	-.304	.306	.765

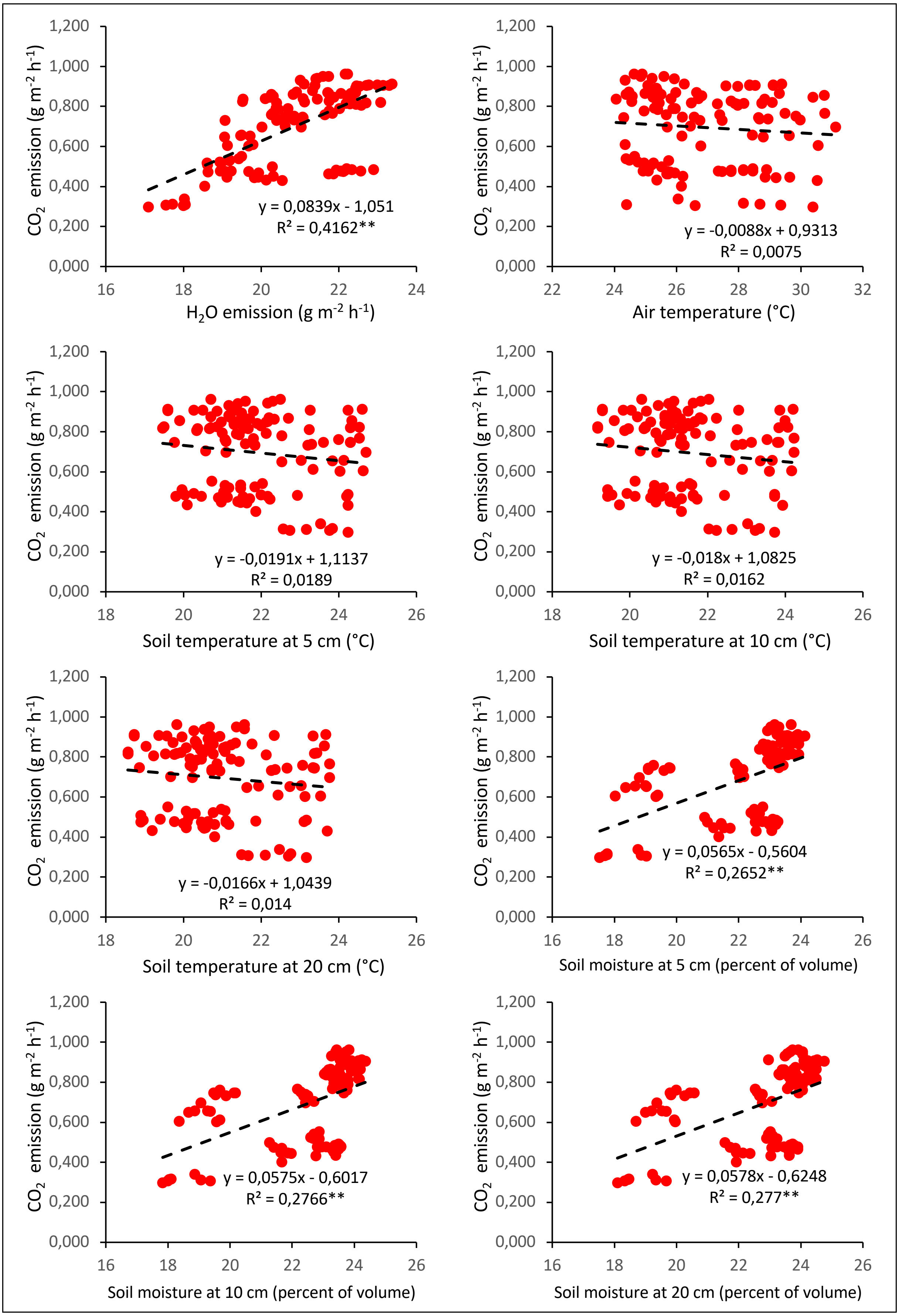

Figure 5. Linear relationships between CO_2 emissions and air temperatures, H_2O emissions, as well as moisture and temperatures at different soil depths. **: significant at the 0.01 level.

3.2. CO_2 emissions per unit yield and water use (ETa)

Manure treatment significantly increased the marketable yield in curly lettuce (Figure 6, Table 1). The M2 treatment resulted in the highest yield at 7.84 kg m^{-2}, indicating a 5.7% and 12.7% increase compared to the M1 and F treatments, respectively. Similarly, CO_2 emissions per unit marketable yield were significantly affected by the fertilization treatments (Figure 7, Table 1). The M2 treatment increased CO_2 emissions per yield by 7% and 72% compared to the M1 and F treatments, respectively. While the higher yield produced reduces the carbon footprint per unit of yield (Pereira et al., 2021), it did not reduce it in this study. The lower yield in the IR2 treatment than the IR1 treatment resulted in higher CO_2 emissions per yield. Therefore, the CO_2 emission per unit yield was the highest in the M2IR2 treatment at 143.5 g CO_2 kg $yield^{-1}$, which had a partially lower yield. Emissions can vary based on factors like cultivation method, environmental conditions, and agricultural practices. Pereira et al. (2021) reported a carbon footprint of 145 and 254 g CO_2 eq kg $yield^{-1}$ for the first and second lettuce production, respectively, which were higher than our findings. Similarly, for lettuce grown under greenhouse conditions, Plawecki et al. (2014) and Bartzas et al. (2015) reported a carbon footprint of 198 g CO_2 eq kg $yield^{-1}$ and 209-225 g CO_2 eq kg $yield^{-1}$, respectively. Martin-Gorriz et al. (2020) also reported a wide range of carbon footprint values for lettuce, ranging from 192 to 500 g CO_2 eq kg $yield^{-1}$.

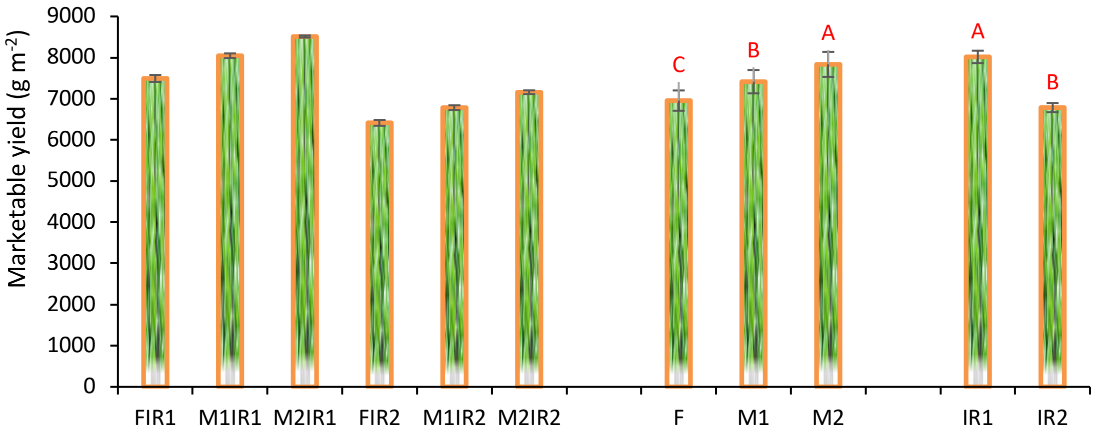

Figure 6. Marketable yield in two irrigation intervals (IR1 every 2 days, IR2 every 4 days) under fertilization with mineral (F) and cattle manure (M1, M2). M1 and M2 correspond to initial soil organic matter contents of approximately 3% and 4.5%, respectively. Means with different lowercase letters are significantly different at the 0.05 level.

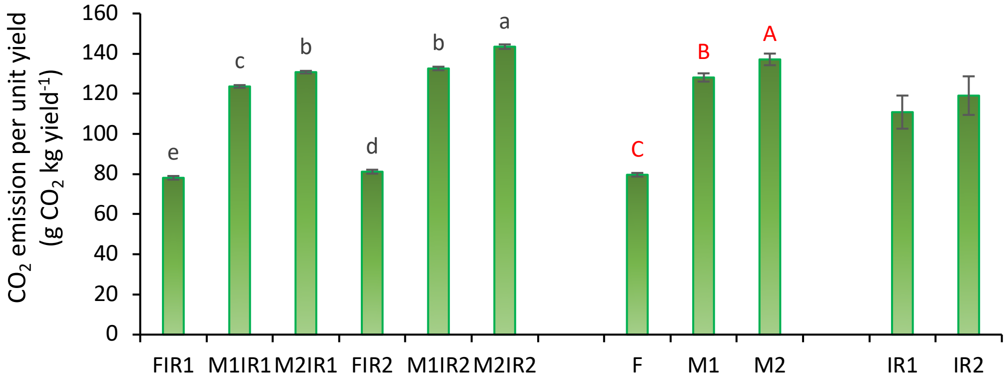

Figure 7. CO_2 emissions per unit marketable yield in two irrigation intervals (IR1 every 2 days, IR2 every 4 days) under fertilization with mineral (F) and cattle manure (M1, M2). M1 and M2 correspond to initial soil organic matter contents of approximately 3% and 4.5%, respectively. Means with different lowercase letters are significantly different at the 0.05 level.

In the M1 and M2 treatments, crop water use (ETa), which is the sum of irrigation, effective precipitation, and water from soil moisture storage during the vegetation period, was lower by 22.2% and 38.1%, respectively, compared to mineral fertilization. Furthermore, the significantly higher CO_2 emissions in these treatments resulted in a 121.5% and 213.4% increase in CO_2 emissions per m^{-3} of water use, respectively, according to the F treatment (Figure 8, Table 1). The M2IR2 treatment had the highest value at 8.5 kg CO_2 m^{-3}, indicating a 217.2% increase compared to FIR1. Similarly, the M2IR1 treatment, with the second-highest value, showed a 193.7% higher emission than the FIR1 treatment. Figure 3 shows that the seasonal mean CO_2 emissions in the M2IR2 and M2IR1 treatments were 75.5% and 90.2% higher, respectively, compared to the FIR1 treatment. Despite the water savings, the 141.7% and 103.5% higher CO_2 emissions per unit of water compared to mean CO_2 emissions suggest that soil organic matter content in the soil is the primary factor contributing to emissions, rather than reduced water use. Higher soil moisture levels under reduced water use conditions and the positive relationship between soil moisture and CO_2 levels may explain why CO_2 emissions do not decrease despite lower evapotranspiration rates (Yerli et al., 2022a and 2022b; Yerli, 2023).

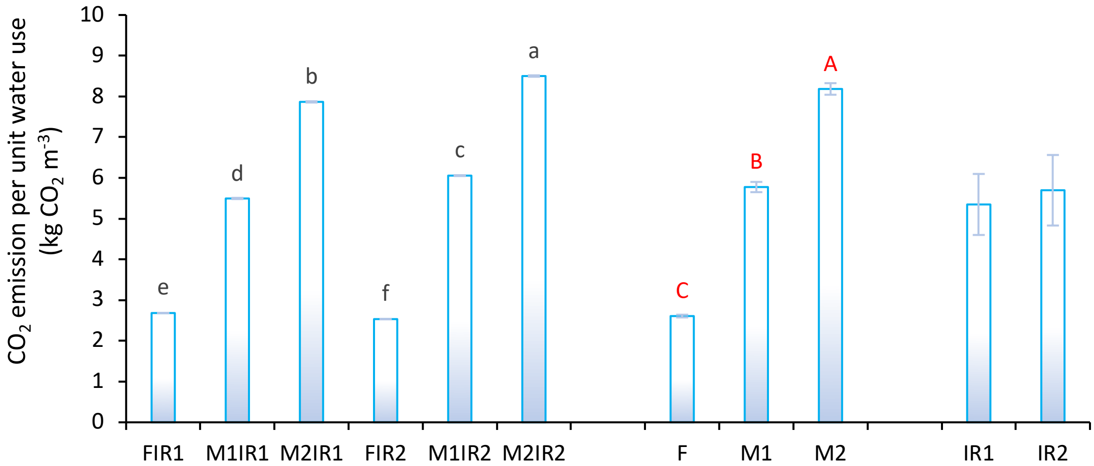

Figure 8. CO_2 emissions per m^3 of crop water use (ETa) in two irrigation intervals (IR1 every 2 days, IR2 every 4 days) under fertilization with mineral (F) and cattle manure (M1, M2). M1 and M2 correspond to initial soil organic matter contents of approximately 3% and 4.5%, respectively. Means with different lowercase letters are significantly different at the 0.05 level.

Conclusions

The study results indicate that organic fertilization can enhance crop yields and decrease water usage, but it does not have a significant impact on reducing CO_2 emissions per unit yield and water use. The main factor influencing CO_2 emissions appears to be the higher carbon mineralization in soils with higher organic matter content. Therefore, even if water usage is reduced and yields are increased, the CO_2 emissions per unit yield and per unit of water use for lettuce with short-term production cycles may not decrease.

Healthier soil has the capacity to absorb and retain carbon, which can help in reducing carbon emissions. Enhancing soil carbon levels can promote improved plant establishment and growth. Since carbon recombines with oxygen to form the greenhouse gas CO_2, if we can trap or store carbon in the soil, then it will not be released to bond with oxygen in the atmosphere to form CO_2. Less tillage and greater cover crop biomass will provide the greatest returns to soil carbon.

Ethical Statement

Ethical approval is not required.

Conflict of Interest

The authors declare that there are no conflicts of interest.

Funding Statement

No financing statement.

Author Contributions

Galad Barre Yusuf: Conducting field studies and laboratory analyses. Ustun Sahin: Methodology, visualization, supervisor, statistical analysis, writing and editing.

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