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CO_2 emission from soil irrigated with recycled wastewater at different levels and the relationships of emission with soil properties

Farklı seviyelerde geri dönüştürülmüş atık suyla sulanan topraktan CO_2 emisyonu ve emisyonun toprak özellikleriyle ilişkileri

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Abstract
The use of recycled wastewater in agricultural irrigation contributes to ecosystem by reducing the discharge of wastewater to the environment, as well as increasing soil quality with fertilizing effect. However, since the high nutrient of wastewater can make the soil a source of CO_2 emission, it is necessary to know the relationships between CO_2 emission and soil properties to the management of emissions. This study aimed to determine the relationships between CO_2 emission and soil properties by examining the changes in the properties of soil irrigated with recycled wastewater and freshwater at different levels. The results showed that the recycled wastewater caused 58.1% more CO_2 emissions than freshwater in full irrigation treatments, while the emissions decreased in the range of 8.8% to 44.5% with increased deficit irrigation. In addition, the significant relationships of CO_2 emission with EC, pH, $CaCO_3$, organic matter, total N, P_2O_5, K_2O, cation exchange capacity, porosity, aggregate stability properties of the soil and H_2O emission from the soil, soil moisture and temperature at different depths were determined, demonstrated the effectiveness of these parameters in the management of CO_2 emissions in soil irrigated with recycled wastewater. Considering the obtained findings, it was determined that deficit irrigation is very effective in reducing CO_2 emission and considering the effectiveness of soil temperature and soil properties on the emissions, CO_2 emission can be reduced by soil temperature and soil properties management, and more comprehensive studies on this subject could suggest.

Özet
Geri dönüştürülmüş atık suların tarımsal sulamada kullanımı gübreleme etkisiyle toprak kalitesini artırmanın yanı sıra atık suların çevreye deşarjını da azalttarak ekosisteme katkı sağlamaktadır. Ancak atık suyun yüksek besin içeriği toprağı CO_2 emisyonu sağlayan kaynak haline getirebileceği için emisyonların yönetimi için CO_2 emisyonu ile toprak özellikleri arasındaki ilişkilerin iyi bir şekilde bilinmesi gereklidir. Bu çalışma farklı seviyelerde geri dönüştürülmüş atık suyla ve temiz suyla sulanan toprağın özelliklerindeki değişimler inceleyerek CO_2 emisyonu ile toprak özellikleri arasındaki ilişkileri belirlemeyi amaçlamıştır. Sonuçlar, tam sulama uygulamalarında geri dönüştürülmüş atık suyun temiz sudan %58.1 daha fazla CO_2 emisyonuna neden olduğunu ancak artan kısıntılı sulama ile emisyonların %8.8 ile %44.5 aralığında azaldığını göstermiştir. Ayrıca CO_2 emisyonunun toprağın EC, pH, $CaCO_3$, organik madde, toplam N, P_2O_5, K_2O, katyon değişim kapasitesi, porozite, agregat stabilitesi özellikleri ile topraktan H_2O emisyonu ve farklı derinliklerde toprak nemi ve sıcaklığıyla önemli ilişkilerinin belirlenmiş olması geri dönüştürülmüş atık suyla sulanan toprakta CO_2 emisyonu yönetiminde bu parametrelerin etkinliğini ortaya koymuştur. Elde edilen bulgular dikkate alındığında, CO_2 emisyonu azaltımında kısıntılı sulamanın oldukça etkili olduğu ve toprak sıcaklığı ile toprak özelliklerinin emisyon üzerindeki etkisi dikkate alındığında CO_2 emisyonunun toprak sıcaklığı ve toprak özellikleri yönetimiyle azaltılabileceği ve bu konuda daha kapsamlı çalışmaların yapılması önerilebilir olarak bulunmuştur.

INTRODUCTION

More agricultural land and irrigation water are needed to meet the food needs of the increasing population. However, while the significant increase in urbanization reduces the amount of existing agricultural lands (Singh 2019), various anthropogenic effects and population growth also cause pollution of freshwater resources and increase the pressure on them (Song et al. 2018). Thus, this situation reveals the necessity of increasing the efficiency from the unit area and introducing a more economical production model while protecting freshwater resources.

The protection and sustainability of freshwater resources with the use of recycled wastewater in irrigation have been adopted as a good management method (Zhang and Shen 2019). Environmental sustainability management can also be achieved by reducing wastewater discharge into the natural environment by evaluating recycled wastewater for agricultural land (Chowdhury and Al-Zahrani 2014). With the use of recycled wastewater, which is separated from freshwater with its high organic matter and nutrient content, in irrigation, its fertilizing effect in every irrigation, reduces the cost of fertilizer and creates a more economical production system. This system acts as a soil conditioner, improving soil properties as well as increasing plant yield (Singh et al. 2012). In addition, recycled wastewater, unlike freshwater, is always ready for agricultural irrigation regardless of seasonality, climate, and other factors, which ensures the continuity of plant cultivation, especially for arid and semi-arid conditions (Zhang and Shen 2019).

All these positive repercussions are desirable for both agricultural and environmental systems. However, high salinity and heavy metals, pathogens and some harmful chemicals in wastewater may cause problems in living healthy and soil quality criteria (Singh 2021). In addition, these risks may result in toxic effects on the plant directly or indirectly in yield reductions (Li et al. 2008). In addition to all these, the very high nutrient contribution of recycled wastewater to the soil can make the soil an important source of CO_2 emissions (Fér et al. 2022).

The risk of global warming caused by the emission of CO_2, which is known as the most important greenhouse gas with the greatest impact on global warming (Thangarajan et al. 2012), from the soil is substantial (Lovelock et al. 2017). Basically, providing more organic matter to the soil in irrigation with recycled wastewater causes more CO_2 emissions with more oxidation (Fér et al. 2022). Under suitable conditions, organic carbon (C), which is a derivative of organic matter, is broken down by microorganisms and combined with oxygen (O_2), its emissions as CO_2 from the soil.

The CO_2 emission mechanism from the soil is highly affected by interconnected soil properties and possible external factors. Although soil borne CO_2 emission is governed by moisture-temperature, physical-chemical-biological properties of soil (Haddaway et al. 2017), these governing factors are not yet fully understood and clear. Therefore, in this study, the changes in the properties of the soil irrigated with recycled wastewater at different levels are examined and the effect of these changing properties on CO_2 emissions from the soil is investigated by comparing them with the soil irrigated with freshwater at different levels, it was aimed to obtain the relations of CO_2 emission with H_2O emission, and soil moisture and temperature, and soil properties.

MATERIAL AND METHODS

The experiment was carried out with plastic containers (31.5 cm × 32.0 cm) in laboratory conditions by simulating field conditions. The mean daily temperature and humidity of laboratory were 22±4°C and < 42% during the study. Triple replications randomized factorial design study was carried out with 2 irrigation water qualities (recycled wastewater: RWW, freshwater: FW) at 4 different irrigation water levels (100%, 75%, 50% and, 25%) in a total of 24 plastic containers for 10 irrigation periods, representing a mean irrigation period. While 100% represent full irrigation treatment, 75%, 50%, and 25% represent deficit irrigation treatments at 25%, 50% and 75% levels of full irrigation, respectively.

The soil, which has sandy clay loam texture (sand: 45%, clay: 31%, silt: 24%) in the particle size distribution according to USDA classification determined by the Bouyoucos hydrometer method (Gee and Bauder 1986), was collected from the upper soil layer (0-30 cm) from the experimental area of Van Yuzuncu Yil University, Faculty of Agriculture. The properties of the soil, which has non-salinity, medium-alkaline, low-organic matter, and middleclass-lime content, used in the study are given in Table.

Table 1. The properties of soil used in the study

Parameter	Soil	Parameter	Soil
Particle density	2.71	$CaCO_3$ (%)	10.74
Bulk density (Mg m^{-3})	1.30	Organic matter (%)	1.29
Porosity (%)	51.29	Total N (%)	0.079
Aggregate stability (%)	44.12	P_2O_5 (kg ha^{-1})	87.8
EC (dS m^{-1})	0.368	K_2O (kg ha^{-1})	875
pH	8.21	CEC (cmol kg^{-1})	20.91

While the freshwater used in the study was tap water, the recycled wastewater was provided from the Van-Iskele treatment plant and transported to the laboratory condition via plastic tanks before each irrigation. To determine the basic quality properties of freshwater and recycled wastewater, the analyses were made in the middle of the study period. pH and electrical conductivity (EC) were determined by direct reading with pH-meter and conductivity-meter, and Inductively Coupled Plasma-Optical Emission Spectrometer was used to determine concentrations of Ca, Mg, Na and K (Anonymous 2007). While Cl was determined by titration with silver nitrate using the potassium chromate indicator (Tuzuner 1990), the SulfaVer 4 kit-HACH 8051 was used in the Hach Lange Dr 5000 UV/VIS Spectrophotometer for the determination of SO_4 (HACH 2010). HCO_3 and CO_3 were determined by titration with sulfuric acid using phenolphthalein and bromocrocel green indicators (Tuzuner 1990). Total N was determined by the Kjeldahl method (APHA-AWWA-WEF 1989), while total P was obtained using the HACH 8048 method (Powder Pillow) in the Hach Lange Dr 5000 UV/VIS Spectrophotometer (HACH 2010). Chemical oxygen demand (COD) was determined in the HACH LCI 400 COD cuvette test with the help of ready-made test kits, Hach Lange Dr 5000 UV/VIS Spectrophotometer and HACH LT 200 thermoreactor (HACH 2005), and biological oxygen demand (BOD_5) was determined by the HACH simplified BOD_5 method in the Hach Lange Dr 5000 UV/VIS according to the estimated BOD_5 value after the COD analysis (HACH 2010). Sodium percentage, sodium adsorption ratio and residual sodium carbonate were calculated using ion concentrations according to Kanber and Unlu (2010). According to the quality analysis of waters (Table 2), it was determined that there is no-harm in the recycled wastewater for irrigation according to national and international criteria.

Table 2. The properties of irrigation waters used in the study

Parameter	Freshwater	Recycled wastewater
EC (dS m^{-1})	0.595	0.978
pH	8.01	7.59
Ca (me l^{-1})	1.78	1.89
Mg (me l^{-1})	3.44	3.15
Na (me l^{-1})	0.41	3.59
K (me l^{-1})	0.25	0.91
Cl (me l^{-1})	1.25	2.25
SO_4 (me l^{-1})	1.91	1.77
HCO_3 (me l^{-1})	2.61	5.09
CO_3 (me l^{-1})	-	-
Total N (mg l^{-1})	-	11.71
Total P (mg l^{-1})	-	1.09
COD (mg l^{-1})	-	35.08
BOD_5 (mg l^{-1})	-	21.91
Na%	6.97	37.63
SAR	0.25	2.26
RSC (me l^{-1})	-2.31	0.05

-: Not detected, COD: Chemical oxygen demand, BOD_5: Biological oxygen demand, Na%: Sodium percentage, SAR: Sodium adsorption ratio, RSC: Residual sodium carbonate

Sand gravel materials were laid in the bottom 2 cm layer of containers to improve drainage, and then, the sieved air-dry soil separated from the coarse materials placed in plastic containers. To determine the field capacity (pot capacity), plastic containers were placed in containers filled with freshwater until they were completely wet with capillarity, and then, after the excess water above the field capacity was drained, the mean pot capacity was determined as 0.225 cm^3 cm^{-3} by taking repeated measurements with the TDR (Trime Pico, IPH T3, IMKO, Germany) equipped with a data reader (HD2, IMKO, Germany). In the first irrigation, after the current moisture determined by TDR in all containers was completed to the pot capacity with freshwater, in all subsequent stages, during the study period, considering that approximately 40% of the available water of control treatment (full irrigation with freshwater) was consumed in seven days in the preliminary measurements in the soil moisture follow-up period, the irrigation was carried out at different irrigation water levels (100%, 75%, 50% and 25%) with freshwater and recycled wastewater at seven-day intervals according to the current moisture determined in the control treatment. While all the current moisture in full irrigation water level was completed to the field capacity, at 75%, 50% and 25% irrigation water levels, 25%, 50% and 75% reduced amount of irrigation water applied compared to full irrigation was applied to the soil, respectively. Thus, an equal amount of irrigation water was applied at the same irrigation water levels of freshwater and recycled wastewater, and 184 mm, 138 mm, 92 mm, and 46 mm irrigation was applied at 100%, 75%, 50% and 25% irrigation water levels, respectively, during the study period.

The particle density, bulk density, porosity, wet aggregate stability, electrical conductivity (EC), pH, $CaCO_3$, organic matter, total N, P_2O_5, K_2O and cation exchange capacity (CEC) were determined by taking soil samples from treatment. While the particle density was determined by the pycnometer method (Blake and Hartge 1986a), the approach of dividing the kiln dry weight of the soil sample taken with a soil cylinder by the cylinder volume (100 cm^3) was used to determine the bulk density (Blake and Hartge 1986b). Porosity was calculated using the particle and bulk density values according to Danielson and Sutherland (1986), and wet aggregate stability was obtained with wet-sieving method according to (Kemper and Rosenau 1986). EC and pH were obtained by reading the saturation extract at a ratio of 1:2.5 with pH-meter and conductivity-meter, and Scheibler calcimeter was used to determine $CaCO_3$ (Nelson 1982). Organic matter and total N were determined according to Walkley-Black (Nelson and Sommers 1982) and Kjeldahl (Bremner and Mulvaney 1982) methods. While Atomic Absorption Spectrophotometer was used for the determination of P_2O_5 (Olsen et al. 1982), the flame photometer was used for K_2O by Knudsen et al. (1982)'s approach was considered. CEC was determined according to the ammonium acetate method (Kacar 2009).

Measurements of CO_2 and H_2O emission from the soil and soil moisture and temperature were carried out at the same time each day to reduce the daily variation by taking three measurements from each treatment 2, 4 and 6 days after each irrigation. While an infrared gas analyser device (EGM 5, PPSystem, Stotfold, UK) with a dynamic closed room system (SRC 1, PPSystem, Stotfold, UK) was used for CO_2 and H_2O emission measurements, soil temperature measurements were made using the temperature probe of the same device (STP 1, PPSystem, Stotfold, UK) and soil moisture measurements were obtained with the TDR (Trime Pico, IPH T3, IMKO, Germany) equipped with a data reader (HD2, IMKO, Germany) used in irrigation applications. To ensure complete isolation from the external condition in the CO_2 and H_2O emission measurements, the dynamic closed room system (volume; 1334 cm^3, area; 78.5 cm^2) of the gas analyser device was placed 1-2 cm deep in the soil. The moisture and temperature of the soil were monitored at 5 and 10 cm soil depths.

The SPSS program (Ver. 23) was used in the statistical analysis of the data. The data were evaluated with the General Linear Model, and the significant means were classified with the Duncan multiple comparison test, and Pearson correlation analysis was also performed to define the relationship among the data.

RESULTS AND DISCUSSION

The changes in the chemical and physical properties of the soil in different irrigation water qualities and irrigation water levels are given in Tables 3-5. While the effect of irrigation water quality on all soil properties except particle density was statistically significant ($p<0.01$), the effect of different irrigation water levels on electrical conductivity (EC), $CaCO_3$, organic matter, total N, P_2O_5, K_2O, cation exchange capacity (CEC) and wet aggregate stability properties of the soil was statistically significant ($p < 0.01$ and $p < 0.05$). In addition, the effect of the interaction of irrigation water quality × different irrigation water levels on $CaCO_3$, organic matter, total N, P_2O_5, K_2O, bulk density and wet stability properties of the soil was also statistically significant ($p < 0.01$ and $p < 0.05$).

Table 3. The electrical conductivity (EC), pH, $CaCO_3$ and organic matter values at different irrigation water levels with freshwater and recycled wastewater

Treatments		EC (dS m^{-1})	pH	$CaCO_3$ (%)	Organic matter (%)
FW	100%	0.569±0.017	8.15±0.02	10.55±0.04 b	1.03±0.03 g
	75%	0.513±0.007	8.17±0.02	10.60±0.02 ab	1.10±0.01 fg
	50%	0.456±0.022	8.19±0.03	10.66±0.03 ab	1.15±0.02 ef
	25%	0.401±0.007	8.20±0.01	10.70±0.01 a**	1.21±0.02 e
	Mean	**0.485±0.020 B**	**8.18±0.01 A****	**10.63±0.01 A****	**1.13±0.02 B**
RWW	100%	0.859±0.024	7.95±0.04	9.38±0.02 f	1.67±0.03 a**
	75%	0.787±0.014	7.99±0.01	9.66±0.04 e	1.56±0.04 b
	50%	0.719±0.037	8.01±0.07	10.01±0.04 d	1.42±0.03 c
	25%	0.578±0.040	8.04±0.01	10.32±0.07 c	1.31±0.01 d
	Mean	**0.736±0.034 A****	**8.00±0.02 B**	**9.84±0.05 B**	**1.49±0.04 A****
Mean	100%	0.714±0.066 A**	8.05±0.05	9.96±0.04 D	1.35±0.15 A*
	75%	0.650±0.062 B	8.08±0.04	10.13±0.05 C	1.33±0.13 AB
	50%	0.587±0.062 C	8.10±0.05	10.34±0.04 B	1.29±0.09 BC
	25%	0.489±0.044 D	8.12±0.04	10.51±0.04 A**	1.26±0.02 C

FW: Freshwater, RWW: Recycled wastewater, 100%, 75%, 50%, 25%: Irrigation water levels, ±: Standard error, **: $p < 0.01$, *: $p < 0.05$

Table 4. The total N, P_2O_5, K_2O and cation exchange capacity (CEC) values at different irrigation water levels with freshwater and recycled wastewater

Treatments		Total N (%)	P_2O_5 (kg ha^{-1})	K_2O (kg ha^{-1})	CEC (cmol kg^{-1})
FW	100%	0.063±0.001 f	82.9±0.8 h	866±4 g	21.96±0.33
	75%	0.067±0.003 ef	84.4±0.3 gh	868±1 fg	21.75±0.96
	50%	0.070±0.001 de	85.8±0.6 ef	872±4 ef	21.32±0.27
	25%	0.074±0.002 d	87.2±0.7 e	874±12 e	21.00±0.25
	Mean	**0.069±0.001 B**	**85.1±0.6 B**	**870±3 B**	**21.51±0.26 B**
RWW	100%	0.131±0.004 a**	120.4±0.8 a**	985±5 a**	24.00±0.19
	75%	0.122±0.005 ab	117.3±1.1 b	969±3 b	23.50±0.28
	50%	0.111±0.001 b	115.6±0.5 c	957±7 c	23.23±0.40
	25%	0.098±0.008 c	110.4±0.4 d	937±12 d	22.17±0.71
	Mean	**0.116±0.004 A****	**115.9±1.0 A****	**962±6 A****	**23.23±0.28 A****
Mean	100%	0.097±0.015 A**	101.7±8.4 A**	926±27 A**	22.98±0.49 A*
	75%	0.094±0.013 B	100.8±7.4 B	919±23 B	22.63±0.59 AB
	50%	0.091±0.009 C	100.7±6.7 B	914±29 B	22.28±0.48 AB
	25%	0.086±0.007 D	98.8±5.2 C	906±21 C	21.59±0.43 B

FW: Freshwater, RWW: Recycled wastewater, 100%, 75%, 50%, 25%: Irrigation water levels, ±: Standard error, **: $p < 0.01$, *: $p < 0.05$

Table 5. The particle density, bulk density, porosity, and wet aggregate stability values at different irrigation water levels with freshwater and recycled wastewater

Treatments		Particle density	Bulk density (Mg m^{-3})	Porosity (%)	Wet aggregate stability (%)
FW	100%	2.71±0.003	1.33±0.007 a*	51.11±0.28	48.32±0.43 cd
	75%	2.71±0.003	1.33±0.007 a	50.74±0.28	47.58±0.37 de
	50%	2.70±0.006	1.31±0.009 ab	51.60±0.37	46.70±0.28 d
	25%	2.70±0.007	1.30±0.012 ab	51.79±0.53	44.99±0.08 e
	Mean	**2.70±0.003**	**1.32±0.006 A****	**51.31±0.21 B**	**46.90±0.40 B**
RWW	100%	2.70±0.003	1.27±0.015 b	52.78±0.49	53.56±0.34 a**
	75%	2.71±0.003	1.28±0.009 b	52.83±0.37	51.47±0.73 b
	50%	2.70±0.006	1.29±0.012 b	52.34±0.53	49.11±0.36 c
	25%	2.70±0.006	1.30±0.012 ab	51.85±0.32	46.95±0.62 de
	Mean	**2.70±0.002**	**1.28±0.006 B**	**52.45±0.22 A****	**50.28±0.78 A****
Mean	100%	2.71±0.004	1.30±0.014	51.94±0.45	50.94±1.20 A**
	75%	2.71±0.002	1.31±0.014	51.79±0.51	49.53±0.94 B
	50%	2.70±0.004	1.30±0.008	51.97±0.34	47.91±0.58 C
	25%	2.70±0.004	1.30±0.007	51.82±0.28	45.97±0.52 D

FW: Freshwater, RWW: Recycled wastewater, 100%, 75%, 50%, 25%: Irrigation water levels, ±: Standard error, **: $p < 0.01$, *: $p < 0.05$

The higher salt of recycled wastewater (Table 2) resulted higher EC than freshwater. Increasing deficit irrigation caused a lower EC by limiting the ingress of water into the soil and therefore salt ingress. The lower pH in irrigation with recycled wastewater compared to before study (Table 1) and irrigation with freshwater can be considered depending on the production of organic acids by decomposition of organic matter (Abegunrin et al. 2013) and the release of H^+ as a result of nitrification, occurs with nitrogen supply to the soil in irrigation with recycled wastewater (Silva et al. 2016). The significant ($p < 0.01$) negative correlation relationship of pH with total N also supports this situation (Table 6). Considering the increase in the solubility of $CaCO_3$ with the decrease in soil pH (Taalab et al. 2019), in irrigation with recycled wastewater, decrease in $CaCO_3$ with decreasing soil pH is an expected situation. The significant ($p < 0.01$) positive correlation relationship of $CaCO_3$ with pH also supports this situation (Table 6). The increase in soil organic matter in irrigation with recycled wastewater can be explained by the COD and BOD_5 of recycled wastewater (Table 2) providing organic matter to the soil (Bedbabis et al. 2015). With the decrease in the irrigation water level, less water entry into the soil limited the accumulation of organic matter in the soil. Similarly, decreased irrigation water level in irrigation with recycled wastewater reduced N, P and K ingress into the soil. Due to the fertilizing effect of wastewater in irrigation with recycled wastewater, more total N, P_2O_5 and K_2O accumulation occurred in the soil compared to freshwater. In irrigation with recycled wastewater, enrichment of the soil with macro-nutrients is expected (Bedbabis et al. 2015). Due to the Ca, Mg, Na and K content of the recycled wastewater (Table 2) and the organic matter contribution it provided to the soil, the CEC was higher in irrigation with recycled wastewater according to irrigation with freshwater. Organic matter improves CEC by reducing cation loss from soil and providing cation exchange to soil in a larger area (Lu et al. 2015). The significant ($p<0.01$) positive correlation relationship of CEC with organic matter also supports this situation (Table 6). In irrigation with recycled wastewater, the decrease in bulk density compared to freshwater can be explained by the organic matter contribution of wastewater to the soil. Organic matter reduces the bulk density by causing the soil to encounter more dense mineral fractions (Guo et al. 2016). The significant ($p < 0.01$) negative correlation relationship of bulk density with organic matter also supports this situation (Table 6). The decrease in bulk density in irrigation with recycled wastewater increased the pores in the soil, so a higher porosity was obtained in irrigation with wastewater compared to freshwater. The fact that the particle density did not change significantly depending on the treatments made the change of porosity dependent on the bulk density. The significant ($p<0.01$) negative correlation relationship of porosity with bulk density also supports this situation (Table 6). Irrigation with recycled wastewater provided higher wet aggregate stability, whereas it decreased with increasing deficit irrigation. This situation can be evaluated depending on the organic matter. Organic matter connects with multivalent cations, combines small aggregates, and forms micro-aggregates, providing the development of soil aggregation (Zhu et al. 2016). The significant ($p < 0.01$) positive correlation relationship of wet aggregate stability with organic matter also supports this situation (Table 6).

Table 6. The correlation relationships among parameters

	pH	$CaCO_3$	OM	TN	P_2O_5	K_2O	CEC	γt	POR	AS	CO_2	H_2O	M5	M10	T5	T10
EC	-0.809	-0.946	0.843	0.882	0.849	0.874	0.766	-0.558	0.568	0.922	0.880	0.510	0.555	0.523	-0.331	-0.431
pH		0.865	-0.767	-0.821	-0.871	-0.884	-0.754	0.526	-0.497	-0.689	-0.681	-0.339	-0.350	-0.270	0.142	0.188
$CACO_3$			-0.917	-0.926	-0.895	-0.924	-0.811	0.628	-0.621	-0.905	-0.825	-0.460	-0.497	-0.443	0.228	0.316
OM				0.958	0.921	0.933	0.696	-0.749	0.710	0.772	0.719	0.199	0.252	0.192	0.095	-0.135
TN					0.963	0.941	0.708	-0.704	0.666	0.790	0.738	0.192	0.262	0.229	-0.049	-0.128
P_2O_5						0.971	0.732	-0.706	0.679	0.705	0.699	0.110	0.167	0.127	-0.001	-0.041
K_2O							0.778	-0.654	0.629	0.741	0.715	0.205	0.257	0.168	-0.058	-0.112
CEC								-0.339	0.353	0.740	0.755	0.432	0.558	0.410	-0.040	-0.290
γt									-0.986	-0.452	-0.301	0.046	0.062	-0.038	0.072	-0.129
POR										0.463	0.306	0.004	-0.023	0.081	-0.110	0.077
AS											0.905	0.656	0.736	0.678	-0.450	-0.571
CO_2												0.581	0.669	0.570	-0.423	-0.519
H_2O													0.916	0.749	-0.653	-0.756
M5														0.837	-0.625	-0.785
M10															-0.700	-0.798
T5																0.740

OM: Organic matter, TN: Total N, CEC: Cation exchange capacity, γt: Bulk density, POR: Porosity, AS: Wet aggregate stability, M5: Soil moisture at 5 cm soil depth, M10: Soil moisture at 10 cm soil depth, T5: Soil temperature at 5 cm soil depth, T10: Soil temperature at 10 cm soil depth, ▓ : $p < 0.01$, ░: $p < 0.05$, : No significant

The changes in the CO_2 and H_2O emission from the soil and soil moisture and temperature at 5 and 10 cm soil depths in different irrigation water qualities and irrigation water levels are given in Table 7. While the effect of irrigation water quality on only CO_2 emission from the soil was statistically significant ($p<0.01$), the effect of different irrigation water levels on CO_2 and H_2O emission from the soil and soil moisture and temperature at 5 and 10 cm soil depths was statistically significant ($p < 0.01$).

Table 7. The CO_2 and H_2O emission from the soil and soil moisture and temperature at 5 and 10 cm soil depths values at different irrigation water levels with freshwater and recycled wastewater

Treatments		H_2O emission from soil ($g\ m^{-2}\ h^{-1}$)	Soil moisture at 5 cm soil depth ($cm^3\ cm^{-3}$)	Soil moisture at 10 cm soil depth ($cm^3\ cm^{-3}$)	Soil temperature at 5 cm soil depth (°C)	Soil temperature at 10 cm soil depth (°C)	CO_2 emission from soil ($g\ m^{-2}\ h^{-1}$)
FW	100%	11.6±0.5	0.182±0.004	0.185±0.001	18.6±0.4	18.5±0.3	0.2683±0.0099
	75%	10.7±0.1	0.176±0.001	0.178±0.001	18.9±0.7	18.7±0.1	0.2414±0.0289
	50%	9.9±0.3	0.166±0.002	0.169±0.006	19.3±0.4	19.1±0.2	0.2015±0.0253
	25%	8.0±0.5	0.153±0.001	0.156±0.001	20.5±0.1	20.2±0.1	0.1289±0.0105
	Mean	**10.1±0.4**	**0.169±0.003**	**0.172±0.004**	**19.3±0.3**	**19.1±0.2**	**0.2100±0.0181B**
RWW	100%	11.8±0.4	0.184±0.003	0.186±0.003	18.7±0.5	18.5±0.1	0.4050±0.0298
	75%	10.9±0.1	0.178±0.003	0.180±0.001	19.0±0.1	18.9±0.6	0.3727±0.0482
	50%	10.1±0.7	0.169±0.005	0.170±0.001	19.6±0.1	19.4±0.1	0.3056±0.0297
	25%	8.2±0.7	0.156±0.003	0.157±0.004	20.1±0.2	19.9±0.1	0.2450±0.0158
	Mean	**10.2±0.5**	**0.172±0.004**	**0.173±0.003**	**19.4±0.2**	**19.2±0.2**	**0.3321±0.0233A****
Mean	100%	11.7±0.3A**	0.183±0.002A**	0.186±0.002A**	18.7±0.3C	18.5±0.1C	0.3367±0.0336A**
	75%	10.8±0.1B	0.177±0.002B	0.179±0.001B	18.9±0.3BC	18.8±0.1BC	0.3070±0.0387B
	50%	10.0±0.3C	0.168±0.002C	0.170±0.003C	19.5±0.2B	19.3±0.1B	0.2535±0.0291C
	25%	8.1±0.4D	0.155±0.002D	0.157±0.002D	20.3±0.1A**	20.0±0.1A**	0.1870±0.0273D

FW: Freshwater, RWW: Recycled wastewater, 100%, 75%, 50%, 25%: Irrigation water levels, ±: Standard error, **: $p < 0.01$

As an expected situation, soil moisture at 5 and 10 cm soil depths increased with the increase in irrigation water levels and accordingly H_2O emission from the soil increased also. The lower moisture content in the soil with increasing deficit irrigation resulted in an increase in soil temperature at 5 and 10 cm soil depths. In other words, higher soil moisture created a cooling effect in the soil. The significant ($p<0.01$) positive correlation relationships of H_2O emission with soil moisture and the significant ($p<0.01$) negative correlation relationships of soil moisture with soil temperature also support this situation (Table 6).

While irrigation with recycled wastewater resulted in 58.1% more CO_2 emissions from the soil than irrigation with freshwater, compared to full irrigation (100%), the emissions were 8.8%, 24.7% and 44.5% less at 75%, 50% and 25% irrigation water levels, respectively. The higher CO_2 emissions from the soil irrigated with recycled wastewater can be explained by the contribution of organic matter and nitrogen to the soil (Table 3 and 4), depending on the nutrient content of the wastewater (Table 2). The significant ($p < 0.01$) positive correlation relationships of CO_2 emission from the soil with organic matter and total N also supports this situation (Table 6). Increasing organic matter in the soil is oxidized by soil microorganisms and is separated from the soil as CO_2. Since organic matter is an energy source for microorganisms, it increases soil microbial growth in increasing organic matter conditions (Tang et al. 2022). The increase in microbial growth causes more organic matter requirement by microorganisms and therefore more CO_2 emission with more mineralization (Dubinsky et al. 2010). A sufficient level of nitrogen in the soil increases the activity of microorganisms and provides oxidation of organic matter, while insufficient nitrogen conditions reduce mineralization and weaken soil respiration (Tang et al. 2018). However, the effect of nitrogen increasing soil biological activity is limited. In fact, the main source of this is the ratio of carbon, which is a derivative of organic matter, to nitrogen (C:N). Since the C:N ratio is an indicator of mineralization, it also explains the effect on CO_2 emissions (Sainju et al. 2002). An appropriate C:N ratio (below 20) improves the balance in soil microbial activity, resulting in more CO_2 emissions but a high C:N ratio limits the use of nitrogen for microorganisms and reduces the emissions by reducing the oxidation of organic matter (Figueiredo et al. 2019). The lower CO_2 emissions from the soil in deficit irrigations can be explained by the decrease in organic matter and nitrogen input the soil (Tables 3 and 4) due to less water input into the soil. In addition, the lower soil moisture in deficit irrigations may have limited the movement of microbial activities. The significant ($p < 0.01$) positive correlation relationships of CO_2 emission from the soil with soil moisture at 5 and 10 cm soil depths also supports this situation (Table 6). The reduced amount of irrigation water reduces the activity of microorganisms and thus reduces CO_2 emissions with less oxidation (Sinaie et al. 2019). As the soil moisture increases, the emission reaches the highest level as the soil pores are filled with water (Hou et al. 2016). Thus, the water supplied to the soil may pass through the pores, allowing the CO_2 trapped in the pores to be removed from the soil. Soil moisture and soil temperature are among the most effective factors governing mineralization processes in soil (Kim et al. 2012). CO_2 emission increases with increasing soil moisture and soil temperature, and the significant positive correlation relationships of CO_2 emission with soil moisture and soil temperature is mentioned (Hou et al. 2020, Zhao et al. 2020). However, in this study, the significant ($p < 0.01$) negative correlation relationships of CO_2 emission from the soil with soil temperature at 5 and 10 cm soil depths were determined (Table 6). In conditions where the independent effect of soil temperature on CO_2 emission is evaluated, the relationship between the emission and temperature can be mentioned. Therefore, it can be said that soil moisture is more dominant than soil temperature on CO_2 emission from soil. In addition, in this study, the significant ($p < 0.01$) positive correlation relationship of CO_2 emission from soil with H_2O emission from soil can be explained by the increase in H_2O based on soil moisture as an indirect effect (Table 6 and 7).

In this study, the significant ($p < 0.01$) positive correlation relationships of CO_2 emission from soil with P_2O_5, K_2O and CEC were also found (Table 6). The addition of macro and micronutrients to the soil increases the microbial community structure-diversity in the soil, resulting in more mineralization (Liu et al. 2021). The microorganisms are exposed to stress under insufficient phosphorus and potassium conditions and turn to the production of various inorganic substances (Allison et al. 2011). Increasing phosphorus and potassium in the soil rhizosphere with fertilizers increases microbial activity and thus increases emissions by causing more mineralization with biochemical transformations (Aziz et al. 2010). The relationship between CO_2 emission from soil and CEC can be explained by increasing organic matter in the soil, increasing CEC (Table 3 and 4). Organic matter provides a satisfactory microorganism activity in soil by forming simple covalent bonds and chelates with its high CEC property (Masciandaro et al. 2013). Thus, a better CEC can increase microbial activity, resulting in more oxidation (Liu et al. 2021) and increased CO_2 emissions from soil.

The EC and pH of the soil are very effective in soil microorganism management. Improper EC and pH conditions weaken microbial population growth. With the weakening of the microorganism activity, the exchange and decomposition of organic matter decreases and thus CO_2 emissions from soil are also reduced (Setia et al. 2011). The increasing Na in the soil with increasing EC can cause cell damage by damaging microorganisms in a toxic way and entering the cell via plasmolysis (Yan et al. 2015). Thus, the limited microbial population reduces CO_2 emissions from the soil with less oxidation (Sakin and Yanardag 2019). However, in this study, the significant ($p < 0.01$) positive correlation relationship of CO_2 emission from the soil with EC was found (Table 6). As stated by Setia et al. (2011), this situation can be explained by the microbial community's adaptation to low salinity due to the gradual increase in soil salinity with each irrigation. In addition, considering that Ca increases microbial metabolic activities, it is likely to increase CO_2 emission from soil with an increase in EC up to a certain point (Setia et al. 2010). In addition to all these, the dominance of organic matter over EC because of the increase in organic matter along with the increase in EC in the soil irrigated with recycled wastewater (Table 3) can explain in positive correlation of CO_2 emission from soil with EC. Similarly, Singh (2016) also stated that the prerequisite for the mineralization of organic matter in saline soils is the amount of soil organic matter. The significant ($p < 0.01$) negative correlation relationship of CO_2 emission from soil with pH can be expressed as a decrease in soil pH and an increase in emission by oxidation, resulting in a better environment for microorganisms. While soil biology develops better in neutral and near-neutral soils, very high or low pH levels can drag soil microbial activities to a point where they can completely stop (Pietri and Brookes 2008). In this study, the decrease in pH according to the before the study and approaching neutral may explain the negative relationship between CO_2 emission from soil and soil pH. Similarly, Sheng et al. (2016) also stated that CO_2 emission increased in neutral soils, but the emission decreased with decreasing mineralization in acidic soils. This situation is related to the direct or indirect effects of microorganisms that manage the physicochemical processes of the soil, depending on the soil pH (Sheng and Zhu 2018). In addition, the effect of soil physical and chemical properties depending on soil pH change also affects CO_2 emissions from soil as an indirect effect, since it changes mineralization processes. Thus, the significant ($p < 0.01$) negative correlation relationship of CO_2 emission from soil with $CaCO_3$ can also be explained (Table 6). The increase in $CaCO_3$ solubility with decreasing pH (Table 3 and 6) may explain the negative relationship between CO_2 emission and $CaCO_3$. Similarly, Pietri and Brookes (2008) also explained the relationship between CO_2 emission and $CaCO_3$ with the relationship of $CaCO_3$ with pH and stated that an important CO_2 emission value can be mentioned in conditions where the pH is above 7.

Porosity, which decreases with soil compaction, weakens the diffusion rate of oxygen by increasing the water filled pore spaces (Ball et al. 2008). The limited oxygen in more compacted soil structure reduces microbial activity, thus reducing mineralization and CO_2 emissions from soil. The CO_2 gas released from the compacted soil is kept in the soil and not released into the atmosphere, thus limiting the emission (Gungor and Akbolat 2021). Akbolat (2009) reported that CO_2 emission from soil tended to decrease due to increasing soil compaction with increasing scrapper weight, and there was a significant negative correlation relationship of CO_2 emission from soil with bulk density. However, in this study, it is thought that the predominance of organic matter over bulk density prevents the relationship of CO_2 emission from the soil with bulk density (Table 3 and 5).

Since the high rate of porosity, which expresses the voids in the soil, indicates more soil aeration, it increases the soil respiration by encouraging the mobility of microorganisms (Bozkurt and Akpolat 2016). In other words, more porosity ensures the mineralization of organic carbon by microorganisms with more oxygen entry into the soil. Microorganisms, which are the main users of oxygen, can oxidize ten times more under oxygen sufficient conditions compared to anaerobic conditions (Dubinsky et al. 2010). The organic carbon (C) combined with oxygen (O_2) results in CO_2 emission from the soil. In addition, considering that CO_2 gas is released after storage in soil pores (Lehmann et al. 2021), more porosity may mean more CO_2. Thus, the significant ($p < 0.01$) positive correlation relationship of CO_2 emission from soil with porosity found in this study can be explained (Table 6).

The increased aggregate stability of the soil creates a better environment for the presence of microbial popularity (Cosentino et al. 2006). Thus, CO_2 emission from the soil increases with the oxidation of microorganisms that show better development. The significant ($p < 0.01$) positive correlation relationship of CO_2 emission from soil with aggregate stability also supports this situation (Table 6). In addition, microorganisms located in the developing aggregates provide better access to organic matter (Marin Spiotta et al. 2014) and creating a more suitable environment for oxidation. Thus, increased aggregate stability may result in more CO_2 emission from soil.

CONCLUSION

In this study, the effect of the changes in the properties of the soil irrigated with recycled wastewater at different levels on the CO_2 emission from the soil was investigated by comparing it with the soil irrigated with different levels of freshwater, irrigation with recycled wastewater increased the EC, organic matter, total N, P_2O_5, K_2O, cation exchange capacity, porosity and wet aggregate stability of the soil, while it decreased the pH, $CaCO_3$ and bulk density, and also the increase in the EC, organic matter, total N, P_2O5, K_2O, cation exchange capacity and wet aggregate stability of the soil was limited in the deficit irrigation treatments. While irrigation with recycled wastewater resulted in significant CO_2 emissions according to freshwater, emissions were also reduced by reducing the irrigation water level. In addition, the negative correlation relationships of CO_2 emissions with pH, $CaCO_3$ and soil temperature at different depths, and positive correlation relationships with EC, organic matter, total N, P_2O_5, K_2O, cation exchange capacity, porosity, wet aggregate stability and soil moisture at different depths and H_2O emission from soil showed that CO_2 emissions can be reduced by the management of soil properties in irrigation with recycled wastewater. Thus, the results showed that soil moisture is an effective factor in reducing CO_2 emission, and it was found that it would be recommendable to conduct more comprehensive studies examining the relationship of emission with soil properties to reduce CO_2 emissions, which increase the risk of global warming.

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