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ORIGINAL RESEARCH ARTICLE

# Subsurface water retention technology does not increase greenhouse gas emissions from sandy soils under semi-arid conditions

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## ABSTRACT

Subsurface water retention technology (SWRT), a polyethylene membrane-based technology, is known to enhance water retention and potentially reduce nutrient leaching beyond the root zone, thus improving crop yields, but its effect on greenhouse gas (GHG) emissions remains unclear. This study therefore evaluated the impact of SWRT on soil carbon dioxide ($CO_2$), nitrous oxide ($N_2O$) and methane ($CH_4$) fluxes over two growing seasons (November 2021 to March 2022 and April to August 2022) using maize (*Zea mays*) as a test crop under rain-fed conditions. This study used six replicate farms in Makueni County, Kenya. In each farm, SWRT were manually installed in two plots, and the control was represented by a plot with no SWRT, with each plot measuring 20 by 10 m. Static chambers were installed, and GHG samples were collected bi-weekly to determine $CH_4$, $CO_2$, and $N_2O$ fluxes. SWRT plots emitted lower GHG during both growing seasons than the control plots. The mean daily emissions from SWRT plots ranged between -3.54 to -0.009 g $CH_4$-C $ha^{-1}$ $day^{-1}$, 1790 to 5790 g $CO_2$-C $ha^{-1}$ $day^{-1}$ and -0.07 to 2.69 g $N_2O$-N $ha^{-1}$ $day^{-1}$ for $CH_4$, $CO_2$ and $N_2O$, respectively. For the control plots $CH_4$, $CO_2$ and $N_2O$ emissions ranged between -4.02 to -1.44 g $CH_4$-C $ha^{-1}$ $day^{-1}$, 1980 to 5880 g $CO_2$-C $ha^{-1}$ $day^{-1}$ and -0.49 to 40.47 g $N_2O$-N $ha^{-1}$ $day^{-1}$, respectively. Significantly higher plant height, leaf area index (LAI) and aboveground biomass were recorded in SWRT than the control. In both seasons, the differences in $N_2O$, $CH_4$ and $CO_2$ between SWRT and control were however non-significant. As SWRT improved maize growth parameters, it can be regarded as a climate-friendly option as it improves crop growth on sandy soils without increasing GHG emissions.

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**Keywords**: Arenosols, carbon dioxide, crop yield, emission reduction, methane, nitrous oxide, water retention.

## 1.0 Introduction

Agriculture significantly contributes to global warming by emitting greenhouse gases (GHGs) such as Carbon dioxide ($CO_2$), Methane ($CH_4$) and nitrous oxide ($N_2O$), which result in climate change and variability. Globally, the emission of GHGs is increasing, with agriculture accounting for 14-17% of the total GHG emitted from human activities (Ciais *et al.*, 2011). The atmospheric concentration of GHGs is expected to increase by 50% from 25.5 billion metric tons ($GtCO_2$) in 2000 to 51 billion metric tons ($GtCO_2$) in 2030, with more climate impacts, including increased drought occurrences and erratic rainfall resulting in reduced crop yields, thus increasing food insecurity (Agovino *et al.*, 2019). Despite $N_2O$ and $CH_4$ being emitted in low quantities compared to $CO_2$, they substantially contribute to global warming (Smith et al., 2021) since they have higher global warming potentials than $CO_2$. Over a 100-year time horizon, $CO_2$ have 28 and 265 times lower global warming potential (GWP) than $CH_4$ and $N_2O$ respectively (IPCC, 2014). Croplands influence atmospheric concentration of GHG by acting as either a source or sink (Eregae et al., 2017). Therefore, soil remediation practices aimed at enhancing soil health and crop productivity can influence GHG emission levels by affecting soil drivers of GHG emissions.

In agricultural soils, anaerobic conditions mainly drive methane emission and is influenced by the soil temperature, bulk density, and carbon content (Hachem and Kang, 2023). Nitrification-denitrification processes are the main drivers of $N_2O$ production in soil (Chelangat et al., 2024). While soil rewetting enhances denitrification, transitioning from wet to dry conditions boosts nitrification (García-Gutiérrez *et al.*, 2023). Other factors regulating $N_2O$ emission include soil pH, water, temperature and the availability of substrate and soil aeration (Zhang *et al.*, 2023). Soil water alters the amount of available air spaces thereby affecting diffusion of oxygen and affecting the release of $N_2O$. According to Prakash and Shimrah (2023) about 10% of global atmospheric $CO_2$ diffuses through upland soils every year in addition to the large amount of carbon stored in soil. Furthermore, soil can emit $CO_2$ through various process such as soil organic matter mineralization and respiration by both roots and mycorrhiza (Chataut *et al.*, 2023). The soil water management practices as well as fertilizer use among smallholder farmers can affect soil characteristics with potential to influence GHG emission on Sandy soils.

Sandy soils are among the highly drained soils considered unsuitable for crop farming due to their poor nutrient and water retention capacity. The high permeability constrains rain-fed crop farming on sandy soils (Khanh *et al.*, 2024). Despite efforts to enhance sandy soil`s productivity through fertilizer application and irrigation, the water and nutrients are still leached beyond crop rootzone due to the high permeability. To overcome these challenges with sandy soil, various technologies have been developed and demonstrated to enhance soil health and crop productivity on sandy soils. Some of these technologies include the application of biochar, mulching, mixing of clay with the topsoil, use of asphalt barriers, underground installation of leaky pots, and installation of


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polythene (Ismail and Ozawa, 2007; Kavdir *et al.*, 2014; Kalu *et al.*, 2021). Subsurface water retention technology (SWRT) has recently been introduced and tested in different countries across the globe including the USA, China, India, and Egypt, and it has shown potential to improve crop productivity in sandy soils (Al-rawi et al., 2017; Mushab and Almasaf, 2019; Salim and Almasraf, 2019; Abdullah and Almasraf, 2020; Aoda *et al.*, 2021). SWRT reduces irrigation water needs by retaining at least 50% of soil moisture within the crop rhizosphere (Miller and Smucker, 2015). Demirel and Kavdır (2013) reported that SWRT retained 52% of irrigation water and improved turf grass yield and quality, and when combined with precision irrigation, SWRT increased crop yield by 89% (Aoda, Ati and AL-Rawi, 2018). SWRT offers a good climate adaptation strategy by conserving rainwater. However, besides the climate adaptation function, the increase in soil moisture and nutrient retention in the crop root-zone might affect microbial activity leading to changes in GHG emissions. Thus the need to evaluate the effect of SWRT on the emission of GHGs on sandy soil.

This study investigated the effect of SWRT on GHG emissions on maize fields in semi-arid land. We hypothesize that the increased soil moisture retention due to SWRT will increase GHG emissions. This hypothesis is based on the premise that enhanced soil moisture can create conditions conducive to microbial activity, potentially leading to higher emissions of $CH_4$, $N_2O$ and $CO_2$. Specifically, the study assessed $CH_4$, $CO_2$, and $N_2O$ emission levels on sandy soils in semi-arid and under rain-fed maize production in Makueni county, Kenya. We also measured maize growth and yield indicators such as plant height, leaf area index and grain yields.

## 2.0 Materials and methods

### 2.1 The study area

This study was conducted in six purposively selected farms in Kibwezi East Constituency, Makueni County, Kenya (Fig. 1). The county has an arid and semi-arid climate, which is characterized by severe water scarcity, high food insecurity and low adaptive and resilience potential to the changes and variability in climatic patterns (Muema *et al.*, 2018). The lowlands, where experiments were done, receive 150-650 mm of rainfall per annum, with the long and short rains occurring from March to April and November to December, respectively (Recha *et al.*, 2016). Two sites were selected in the lowlands to evaluate the effect of SWRT on GHG flux. The study area experiences frequent droughts, which constrain crop farming, a livelihood source depended upon by communities in the region.



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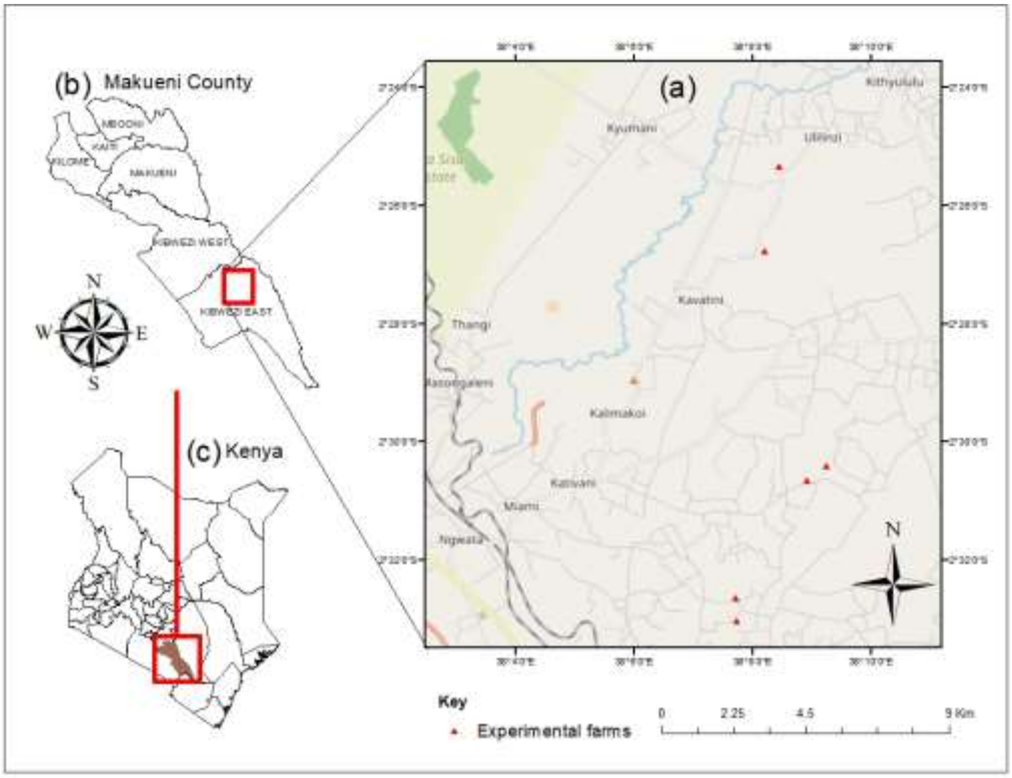


*Fig. 1: The study sites on selected farms in Kibwezi East Constituency, Makueni County, Kenya.*

## 2.2 Site selection, field management and soil characterization

Six replicate farms were selected to examine the impact of SWRT on GHG emissions and crop parameters. The selection included only those with sandy soil to at least 1-meter depth. This was determined by sampling at 15 cm intervals up to a depth of 120 cm and testing soil texture by quick field test method (Jaja, 2016) in each plot. The samples were analyzed for soil organic carbon (SOC), total nitrogen (TN), and texture at the CropNuts laboratory in Limuru, Kenya.
In each farm, SWRT were installed in two plots, and one was used as a control (without SWRT), with each plot measuring 20 by 10 m. The SWRT is made of polyethylene membrane and ware manually installed at alternating depths of 40 and 60 cm subsurface.

Plots were ploughed using hand held-hoe, one week before planting, at the beginning of each season. Maize was then planted at within and between rows spacing of 30 cm and 90 cm respectively. Three weeks after planting the maize were top dressed using Calcium Ammonium Nitrate (CAN) at 70Kg N/ha. Weeding was done twice, the first and the second done at three and six weeks after planting respectively. Field management practices were similar in both growing seasons.

To monitor the physical changes in the soil brought by SWRT, the soil moisture and soil temperature were also recorded using the TERROS 11 moisture sensors during both growing


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seasons. The measurements were automatically detected, recorded, and stored in the data logger every 30 minutes throughout the growing period. Other meteorological data captured by the data logger included air temperature, rainfall, and air pressure.

## 2.3 Soil GHG sampling

Greenhouse gas samples were collected for flux determination over two maize growing seasons using the static chamber method (Rosenstock *et al.*, 2016). Each chamber had two parts, the base and a lid, both made of PVC plastic. The lid had a small fan for adequately mixing the gases in the chamber headspace while a foam gasket was used to tightly seal the base and the lid. The balance in pressure between chamber headspace and the atmosphere was maintained using vent fixed on the lid. Additionally, the lid had a gas pooling port sealed with silicon septum and a thermometer for recording the temperature in the chamber.

In each plot, three bases were installed to 7 cm depth a week before the first GHG sampling to avoid soil disturbance-induced GHG emissions. The bases were left installed in the field throughout the sampling period except during land preparation. GHG samples were collected weekly throughout the entire season. However, sampling was done daily for five consecutive days beginning immediately after top dressing during both growing seasons. During sampling, ten metal binders were used to tightly hold the chamber base and lid. Samples were collected in the morning between 08:00 and 11:00 hours, representing the time with mean diurnal temperature to minimize daily differences in emission patterns. Four samples were collected from each plot at 15 minutes intervals. During sampling, a 60ml syringe was used to collect 20 ml of gas from each chamber while locking the syringe with a lure lock fitted at its tip. The three samples of 20ml gas from the three chambers were mixed while the lure lock is closed in each sampling campaign. Out of the 60 ml composite sample, 30 ml was used to drive out residual gas in the glass vial using an extra needle to vent while driving in the composite sample. The remaining 30 ml was stored in rubber sealed glass vials, carefully packaged, transported to and analyzed at the International Livestock Research Institute (ILRI- Nairobi Kenya) laboratory. The gas chromatography (GC) was used to determine the concentration of $N_2O$, $CO_2$ and $CH_4$ in the samples.

## 2.4 Calculation of GHG Fluxes

GHG emission (E) was determined by first converting emissions from concentration in parts per million (ppm) to weight per unit area per hour using Eq 1.

$$E = \frac{dX}{dt} \times \frac{VM}{AV_m} \qquad \text{Eq. 1}$$

*Where*: dX/dt is the accumulation rate of gas (X) in the chamber in ppm/h, A is the chamber area, V is the volume of the chamber, M is the mass of N and C per mol of gas x ( where x is either $CO_2$, $CH_4$ or $N_2O$) and $V_m$ is the molecular volume of gas ($CO_2$, $CH_4$ or $N_2O$).


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The molecular volume ($V_m$) was determined based on the ideal gas law using Eq 2.

$$PVm = nRT \quad \text{Eq 2}$$

*Where*: P is the pressure of the atmosphere (1 atm), $V_m$ is the volume of the gas (in litres), n is moles of the gas (in mol), R is gas constant (L/atm/k/mol), and T is the temperature (Kelvin).

To quantify the GHG emission rate per ha per day, we multiplied the value of E by 10000m$^2$ and 24 hours.

## 2.5 Growth and biomass measurement

Nine-square meter sub-plots in the middle of each plot were used to monitor indicators of crop growth such as plant height, the LAI and the crop yield. Plant height was determined as the height measured from where plant touches soil to the end of the highest leaves. The LAI was calculated based on the plant height and the width and length of the leaves measured every two weeks throughout the growing season. The length of the leaf was determined by measuring the distance from the point of departure from the stem to the end of the leaf, while the width of the leaf was measured at the middle most wide portion of the leaf. The leaf area per plant was determined nondestructively using Eq 3. A correction factor of 0.75 was used (Elings, 2000).

$$LA = L \times W \times 0.75 \quad \text{Eq 3}$$

*Where LA, L, W* and *0.75* stands for the leaf area, leaf length, the maximum leaf width and maize coefficient, respectively.

The area index of the leaf was calculated using Eq 4.

$$LAI = \frac{leaf\ area\ (m^2\ plant^{-1}) \times Plant\ density(plant\ ha^{-1})}{10000(m^2\ ha^{-1})} \quad \text{Eq 4}$$

*Where* plant density indicates plant population per hectare and plant population ($P_p$) is given by Eq 5 (Adebooye, Ajadi and Fagbohun, 2006).

$$Pp = \frac{(B+b)(L+l)}{lb} \times N \quad \text{Eq 5}$$

*Where L* is the length of the plot*, B* is the width of the plot*, (l ×b)* is spacing, and *N* is the number of seeds per stand.


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At harvesting maize stover, cob and grain yield were measured from the net plot. The stover and cob samples were sun-dried to constant weight and then used to extrapolate the total dry stover and cob yield. All yield measurements were converted to a per-hectare basis using Eq 6:

$$Yield(t/ha) = total\ fresh\ weight \times \frac{sample\ dry\ weight}{sample\ fresh\ weight} \times \frac{10000}{plot\ area} \times \frac{1}{1000} \quad \text{Eq 6}$$

## 2.6 Statistical analysis

The normality of the distribution of data was tested using the Shapiro-Wilks test (Shapiro and Wilk, 1965). The differences in TN and SOC across the sampled depths were compared using ANOVA whereas the variations in GHG emission, soil moisture, soil temperature, plant height, LAI, aboveground biomass, stover, cob and grain yield between SWRT and Control were compared using t-test. The significance test was done at a 5% significance level. All statistical analyses were conducted in R-Statistic (version 4.3.2; R Core Team, 2023).

# 3.0 Results

## 3.1 Soil and field conditions

Soil organic carbon and TN content ranged from 0.21 to 0.60% (mean ± standard deviation = 0.43 ± 0.11%) and 0.01 to 0.03% (mean ± standard deviation = 0.03 ± 0.004%) respectively across the soil profile. Sand, silt and clay ranged between 84.90 to 94.05% (mean ± standard deviation = 88.81± 2.45%), 1.86 to 5.93 (mean ± standard deviation = 3.98 ± 1.08%) and 2.00 to 11.18% (mean ± standard deviation = 7.20 ± 2.49%) across the soil profile, respectively. The SOC (*p = 0.32*) and TN (*p = 0.96*) remained the same across the soil profile (Fig. 2).

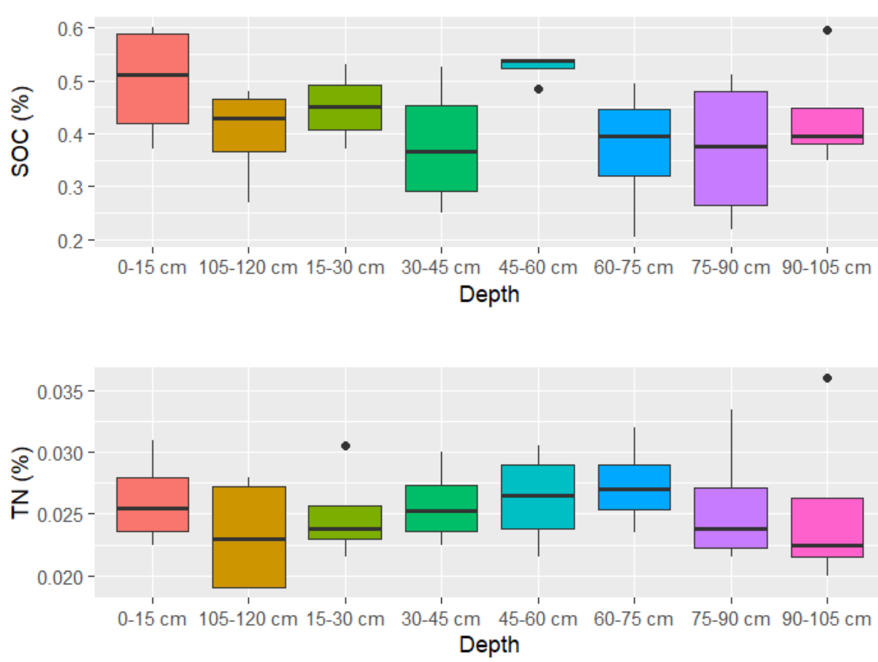



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*Fig. 2. The baseline mean total nitrogen and soil organic carbon of the experimental soils.*

During the November 2021 to March 2022 growing season, a total precipitation of 361.6 mm was recorded. The diurnal air temperature ranged between 15.92 and 42.91°C (mean ± standard deviation = 26.51±6.01°C). During April to August 2022 growing season, the total rainfall was only 10.8 mm, resulting in crop failure. The diurnal air temperature ranged from 21.18 to 27.55°C (mean ± standard deviation = 24.93±1.52°C).

The mean daily soil moisture and temperature did not vary significantly between SWRT and Control plots during the November 2021 to March 2022 growing season, while significant variations were observed during the April to August 2022 growing seasons (Fig. 3). The mean daily soil moisture (mean; SWRT = 0.089$m^3m^{-3}$, Control = 0.092$m^3m^{-3}$, *p=0.43*) and soil temperature mean; SWRT = 32.02°C, Control = 31.60°C, *p=0.14*) did not vary significantly between SWRT and Control (Fig. 3a and Fig. 3b). However, during the dry April to August 2022 growing season, the mean daily soil moisture (mean; SWRT = 0.106 $m^3m^{-3}$, Control = 0.092 $m^3m^{-3}$, $p<0.05$) and soil temperature (mean; SWRT = 28.07 °C, control = 31.60 °C, $p<0.05$) varied significantly between SWRT and Control (Fig. 3c and Fig. 3d).

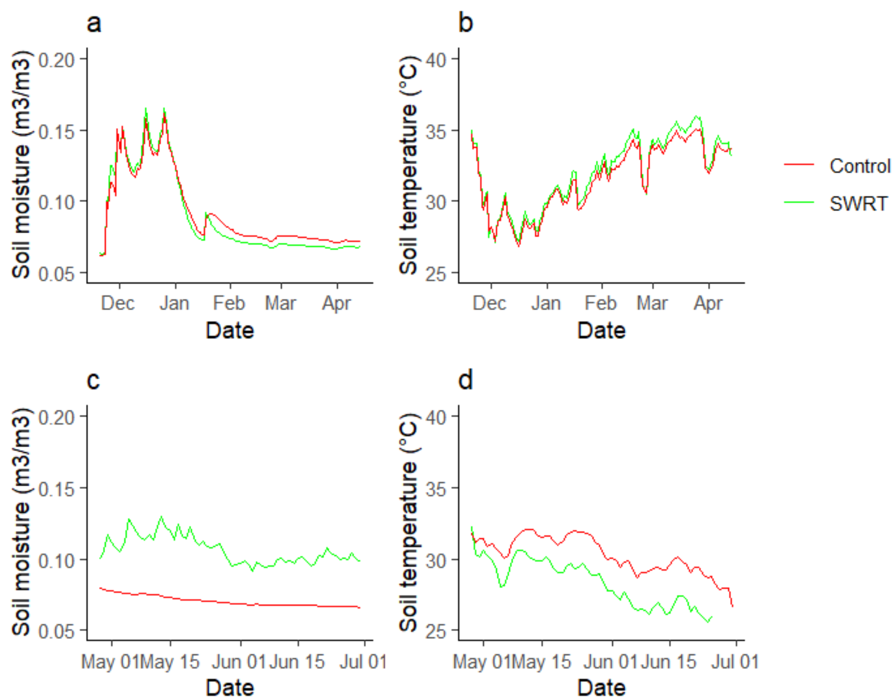


*Fig. 3: Mean daily soil moisture and soil temperature during the November 2021 to March 2022 (a and b) and the April to August 2022 (c and d) growing season.*

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### 3.2 Soil GHG fluxes

Methane emissions were dominantly below zero in both treatments during the November 2021 to March 2022 growing season. $CH_4$ uptake ranged from -40 g $CH_4$-C $ha^{-1}$ $day^{-1}$ to -0.2 g $CH_4$-C $ha^{-1}$ $day^{-1}$ in both SWRT and Control. Few $CH_4$ emissions however existed in both SWRT and Control plots in the range 0.0797 g $CH_4$-C $ha^{-1}$ $day^{-1}$ to 58 g $CH_4$-C $ha^{-1}$ $day^{-1}$ (Fig. 4c). The diurnal soil $CO_2$ emissions in both treatments ranged from 89.7 g $CO_2$-C $ha^{-1}$ $day^{-1}$ to 69712.8 g $CO_2$-C $ha^{-1}$ $day^{-1}$. A few negative $CO_2$ feedbacks were also recorded, ranging from -125520 g $CO_2$-C $ha^{-1}$ $day^{-1}$ to -159000 g $CO_2$-C $ha^{-1}$ $day^{-1}$ (Fig 4b). In both SWRT and control, $N_2O$ emissions were generally positive, ranging from 0. 14 g $N_2O$-N $ha^{-1}$ $day^{-1}$ to 957.91 g $N_2O$-N $ha^{-1}$ $day^{-1}$ (Fig. 4a). Occasionally, however, soil $N_2O$ uptakes in the range of -0. 041015 g $N_2O$-N $ha^{-1}$ $day^{-1}$ to -572.54 g $N_2O$-N $ha^{-1}$ $day^{-1}$ were observed. Peak $CO_2$ and $N_2O$ emissions were observed on the 24$^{th}$ day after planting in control plots, a week after top dressing with CAN fertilizer (Fig. 4a and Fig. 4b).

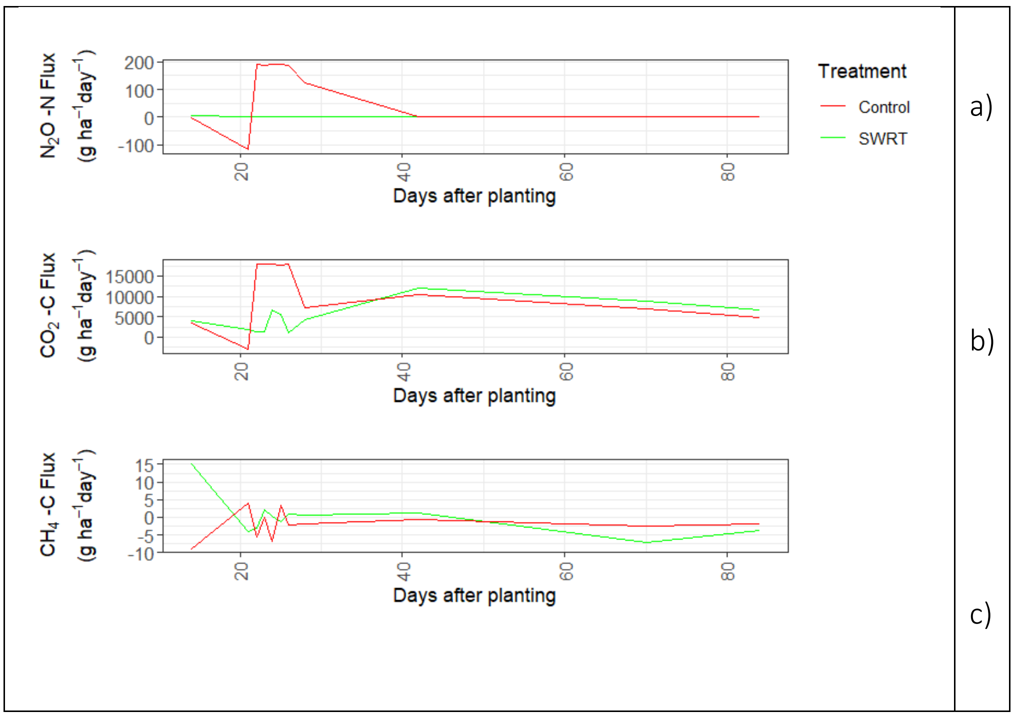


*Fig. 4: Soil (a) nitrous oxide (g $N_2O$-N $ha^{-1}$ $day^{-1}$), (b) carbon dioxide (g $CO_2$-C $ha^{-1}$ $day^{-1}$) and (c) methane fluxes (g $CH_4$-C $ha^{-1}$ $day^{-1}$) fluxes during the long rain season November 2021 to March 2022.*

During the April-August 2022 plating season, soil $CH_4$ emissions were mostly negative, implying more uptake than emission. The $CH_4$ uptake ranged between -154.7 g $CH_4$-C $ha^{-1}$ $day^{-1}$ and -3.3 g $CH_4$-C $ha^{-1}$ $day^{-1}$, while emissions ranged from 0.7 g $CH_4$-C $ha^{-1}$ $day^{-1}$ to 44.4 g $CH_4$-C $ha^{-1}$ $day^{-1}$ in both SWRT and Control (Fig. 5c). Mostly, the diurnal $CO_2$ emissions were positive despite a few uptakes. The $CO_2$ emissions ranged from 0.0102 kg $CO_2$-C $ha^{-1}$ $day^{-1}$ to 97.405 kg $CO_2$-C $ha^{-1}$ $day^{-1}$ while negative feedbacks were in the range -26210 g $CO_2$-C $ha^{-1}$ $day^{-1}$ to -138.4 g $CO_2$-C $ha^{-1}$ $day^{-1}$


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(Fig 5b). During this season, $N_2O$ emissions remained continuously below zero, with mostly positive feedback ranging from 0.2507 g $N_2O$-N $ha^{-1}$ $day^{-1}$ to 4.348 g $N_2O$-N $ha^{-1}$ $day^{-1}$ (Fig. 5a). A few $N_2O$ uptakes were observed in the range of -6.988 g $N_2O$-N $ha^{-1}$ $day^{-1}$ to -0.09588 g $N_2O$-N $ha^{-1}$ $day^{-1}$. There were no observable peaks of $CH_4$, $CO_2$ and $N_2O$ emission even after top dressing with CAN fertilizer during this season.

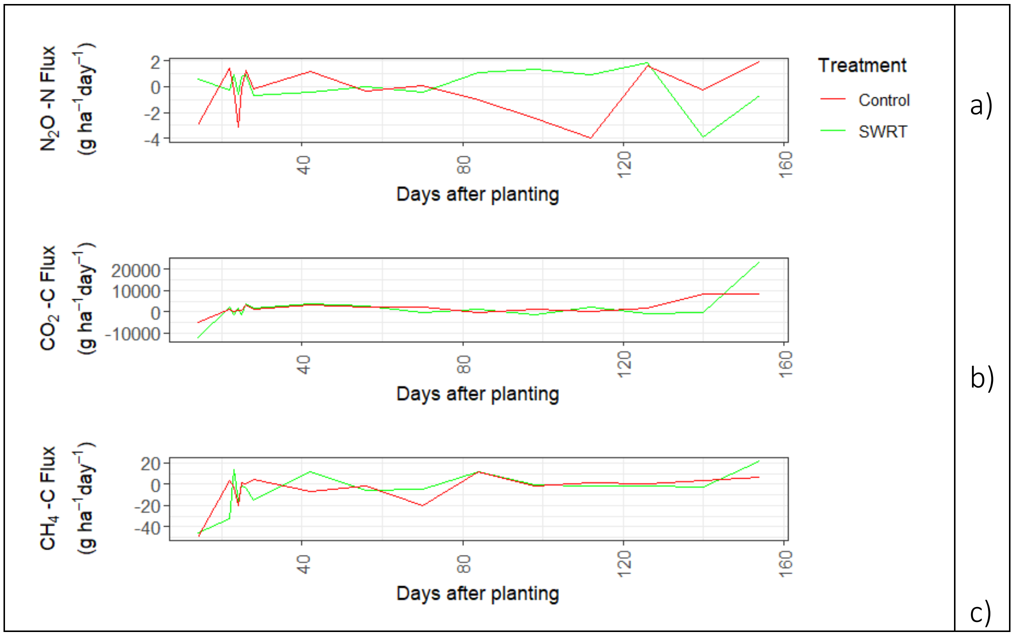


*Fig. 5: Soil (a) nitrous oxide (g $N_2O$-N $ha^{-1}$ $day^{-1}$), (b) carbon dioxide (g $CO_2$-C $ha^{-1}$ $day^{-1}$) and (c) methane (g $CH_4$-C $ha^{-1}$ $day^{-1}$) fluxes during the April to August 2022 short rain season.*

In the November 2021 to March 2022 season, the mean daily $CO_2$ and $N_2O$ emissions were higher in Control than in SWRT treatment (Table 1). However, a net $CH_4$ uptake was observed in both Control and SWRT, and a higher uptake was recorded in Control. During the dry April to August 2022 season, net $CH_4$ and $N_2O$ uptakes were observed in both Control and SWRT treatment, while positive feedback was observed for $CO_2$ emission (Table 4). There were no significant variations in emissions between SWRT and Control for $CH_4$ (*$p$ = 0.25*), $CO_2$ (*$p$= 0.49*) and $N_2O$ (*$p$=0.12*) fluxes during the rainy November 2021 to March 2022 growing season (Table 4). Similarly, during the April to August 2022 growing season, non-significant variances were observed for $CH_4$ (*$p$ =0.47*), $CO_2$ (*$p$= 0.47*) and $N_2O$ (*$p$=0.27*) fluxes between SWRT and Control.

*Table 1: Greenhouse gas fluxes between November 2021 to March 2022 (n=55) and April to August 2022 (n=24).*

| Season | Treatment | $CH_4$ (g $CH_4$-C $ha^{-1}$ $day^{-1}$) | $CO_2$ (g $CO_2$-C $ha^{-1}$ $day^{-1}$) | $N_2O$ (g $N_2O$-N $ha^{-1}$ $day^{-1}$) |
|---|---|---|---|---|
| | SWRT | -0.009 ± 5.76 | 5780 ± 5430 | 2.68 ± 10.82 |
| LR 21 | Control | -1.44 ± 4.00 | 5880 ± 10210 | 40.47 ± 115.60 |
| | *P value* | *0.27* | *0.49* | *0.12* |


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| | | | | |
|---|---|---|---|---|
| SR 22 | SWRT | -3.54 ± 16.69 | 1790 ± 8040 | -0.07 ± 1.47 |
| | Control | -4.02 ± 16.51 | 1980 ± 3610 | -0.49 ± 1.84 |
| | *P value* | *0.47* | *0.47* | *0.27* |

*LR 21 = November 2021 to March 2022 season, SR 22 = short rains April to August 2022 season. Treatment SWRT: subsurface water retention technology and Control: no subsurface water retention technology.

## 3.3 Maize growth and yield

During the April to August 2021 growing season, the mean plant height, LAI and aboveground biomass were significantly higher in SWRT than in the Control (Table 2). The mean plant height and leaf area index increased by 31.44% (from 76.07 cm in Control to 99.99 cm in SWRT, $p<0.05$) and 65.66% (from 0.99 in Control to 1.64 in SWRT, $p<0.05$) respectively, at the vegetative growth stage. During this season, maize did not mature due to prolonged dry spells and the aboveground biomass was harvested just before wilting. Aboveground biomass in SWRT was significantly higher (0.525 t $ha^{-1}$) than in the Control.

Similarly, during the November 2021 to March 2022 growing season, the observed differences in the mean plant height, LAI and aboveground biomass at the vegetative growth stage were significant (Table 2). The mean plant height and leaf area index increased by 13.85% (from 109.20 cm in Control to 124.32 cm in SWRT, $p <0.05$) and 32.86% (from 1.40 in Control to 1.86 in SWRT, $p <0.05$) respectively, at the vegetative growth stage. The aboveground biomass increased by 40.57% from 1.38 t $ha^{-1}$ in Control to 1.94 t $ha^{-1}$ in SWRT.

*Table 2: Mean plant height, leaf area index, cob, Stover, grain and total maize yields under SWRT and control treatments.*

| Growing season | Indicator | SWRT | Control | *P value* |
|---|---|---|---|---|
| April - Aug 2021 | Plant height (cm) | 99.99 ± 13.53 | 76.07 ± 14.21 | 0.0002* |
| | Leaf area index | 1.64 ± 0.38 | 0.99 ± 0.34 | 0.0001* |
| | Aboveground biomass (t $ha^{-1}$) | 0.775 ± 0.133 | 0.250 ± 0.070 | 0.003* |
| Nov 2021 - March 2022 | Plant height (cm) | 124.32 ± 15.15 | 109.20 ± 9.91 | 0.049* |
| | Leaf area index | 1.86 ± 0.35 | 1.40 ± 0.23 | 0.018* |
| | Cob yield (t $ha^{-1}$) | 0.101 ± 0.016 | 0.076 ± 0.015 | 0.258 |
| | Stover yield (t $ha^{-1}$) | 1.339 ± 0.108 | 0.944 ± 0.124 | 0.022* |
| | Grain yield (t $ha^{-1}$) | 0.497 ± 0.078 | 0.358 ± 0.073 | 0.206 |
| | Aboveground biomass (t $ha^{-1}$) | 1.937 ± 0.181 | 1.378 ± 0.201 | 0.047* |

* Means statistically significant at 5% significance level.

## 4.0 Discussion

Installation of SWRT membranes did not significantly affect soil GHG emissions from maize fields on sandy soils. The low $CH_4$ uptake in both SWRT and Control supports previous studies in East Africa that reported soils under agriculture as net methane sinks (Macharia *et al.*, 2020; Wachiye *et al.*, 2020; Lemarpe *et al.*, 2023). The low $CH_4$ uptake in SWRT could be due to the inhibition of $CH_4$ oxidation brought about by reduced microbial activity of methanotrophs occasioned by the high moisture retained by SWRT membranes (Wu *et al.*, 2021; Githongo *et al.*, 2022). On the


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contrary, the lower moisture levels in the Control could have suppressed methanogenesis, reducing methane emissions and increasing uptake (Yang *et al.*, 2014). While the higher rainfall recorded in the November 2021 to March 2022 season, amounting to 361 mm, favored methanogenesis and diminished $CH_4$ uptake, the higher uptake observed during the April to August 2022 seasons could be attributed to the recorded low rainfall (10 mm), which enhanced methanotrophy (Wu *et al.*, 2020; Guo *et al.*, 2023). The low SOC levels could have also impeded methanogenesis since SOC is a substrate for methanogenic bacteria, thus lowering methane emissions.

The higher $CO_2$ emission observed during the November 2021 to March 2022 season is attributable to the higher rainfall (361 mm), which increased microbial activity since moisture availability increases soil mineralization, causing higher $CO_2$ emissions (Ortiz-Gonzalo *et al.*, 2018). The higher moisture could also result in increased root growth, as evidenced by the high growth (shown by the significantly higher plant height and LAI) and yield (stover, cob and grain yield) observed during the November 2021 to March 2022 season, thus increasing root respiration resulting in increased $CO_2$ emissions (Moinet *et al.*, 2023). Contrarily, the low $CO_2$ emitted during the April to August 2022 season could be explained by the impeded activity of soil microbes and respiration of plant roots due to the reduced plant growth and aboveground biomass associated with low moisture resulting from diminished rainfall (10 mm). The low SOC content ranges from 0.21 to 0.60% and limited decomposition processes due to the reduced substrate, resulting in lower $CO_2$ emission in both SWRT and the control plots (Santoni *et al.*, 2023).

The soil $N_2O$ emissions were low, in corroboration with earlier studies (Ortiz-Gonzalo *et al.*, 2018). These low emissions could be due to low fertility associated with sandy soils and the low fertilizer input by farmers. The low TN content, in the range of 0.01 to 0.03%, could also explain the observed low $N_2O$ emissions due to limited substrate availability for nitrification-denitrification processes that drive soil $N_2O$ emission (Götze *et al.*, 2023; Posmanik, Nejidat and Gross, 2023). Since the soils were sandy with low SOC content (0.21 to 0.60%), the unavailability of mineralizable carbon may also have inhibited denitrifcation, resulting in the low emission of nitrous oxide. The high moisture in SWRT plots creates anaerobic conditions, reported by Wang *et al.* (2023) to enable conversion of nitrous oxide to nitride, and could explain the low amounts of nitrous oxide emitted in SWRT. By impeding deep percolation of nutrients, SWRT could increase nitrogen use efficiency by increasing nitrogen availability for plant uptake thus reducing $N_2O$ emission. High nitrogen uptake in SWRT plots is evidenced by the observed significantly higher aboveground biomass and grain yield. On the other hand, the high emissions of nitrous oxide observed in the control could be attributed to the lower moisture levels reported to enhance denitrification process (Fernández-Ortega, Álvaro-Fuentes and Cantero-Martínez, 2023). The observed low grain yield and aboveground biomass also indicate low nitrogen use efficiency and could further explain the higher $N_2O$ emission in the control plots.


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The coincidence of the peak $CO_2$ and $N_2O$ emissions and fertilization time during the November 2021 to March 2022 growing season shows the effect of fertilizer application on GHG emission. The surge in $CO_2$ emission is attributable to increased root and microbial respiration due to enhanced plant growth while the increase in $N_2O$ emission could be associated with soil endowment with ammonium and nitrate which enhance nitrification-denitrification. The unobserved effect of fertilization on methane emission implies other factors such as moisture could have had more impact than fertilizer application. This agrees with the findings by Kussainova *et al.* (2023) who found that environmental factors, particularly soil moisture and soil temperature, had more effect on methane emission than fertilizer application. According to Fernández-Ortega et al. (2023), notwithstanding soil moisture and fertilization dryland soils absorb more methan than they emit thus acting as a $CH_4$ sink. On the contrary, there were no observable $CO_2$, $CH_4$ and $N_2O$ emission peaks in both SWRT and control during the dry April to August 2022 growing season. The non-response of GHG emission to fertilization in this season could be due to limited soil moisture which inhibited soil microbial activity, root growth and respiration, methanotrophy and nitrification-denitrification (Bista *et al.*, 2023; Kaur *et al.*, 2023; Zhang et la., 2023).

## 5.0 Conclusion

There is no evidence that installing SWRT on coarse sandy soils significantly increases GHG emissions compared to soils without SWRT. The observed slight decrease in $CH_4$ and $N_2O$ emissions could be due to the SWRT membrane`s ability to retain moisture in the plant root zone, creating conditions favorable for GHG uptake rather than emission. Therefore, SWRT can be considered a climate-friendly technology for improving agricultural productivity of sandy soils without increasing GHG emissions.

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### 6.2 Conflicts of interest

The authors have no competing interests to declare.

## 7.0 References

Abdullah, A. H. and Almasraf, S. A. (2020) "Assessment Improving of Rainwater Retention on Crop Yield and Crop Water Use Efficiency for Winter Wheat," *Journal of Engineering*, 26(3), pp. 46–54. doi: https://doi.org/10.31026/j.eng.2020.03.04

Adebooye, O. C., Ajadi, S. O. and Fagbohun, A. B. (2006) "An accurate mathematical formula for estimating plant population in a four dimensional field of sole crop," *Journal of Agronomy*,


ISSN 1561-7645 (online)
doi: 10.4314/jagst.v23i5.5

5(2), pp. 289–292. doi: https://doi.org/10.3923/ja.2006.289.292

Agovino, M. *et al.* (2019) "Agriculture, climate change and sustainability: The case of EU-28," *Ecological Indicators*, 105, pp. 525–543. doi: https://doi.org/10.1016/j.ecolind.2018.04.064

Al-rawi, S. S., Mahdi, A. ibrahim and Alaa Salih Ati (2017) "The Role of Subsurface Water Retention Technology ( SWRT ) for Growing Chili Pepper in Iraqi Sandy Soils," *Journal of Environment and Earth Science*, 7(1), pp. 82–89. Available at: https://www.iiste.org/Journals/index.php/JEES/article/view/34994

Aoda, M. I. *et al.* (2021) "Novel root zone soil water retention improves production with half the water in arid sands," *Agronomy Journal*, 113(3), pp. 2398–2406. doi: https://doi.org/10.1002/agj2.20648

Aoda, M. I. A., Ati, A. S. A. and AL-Rawi, S. S. A.-R. (2018) "Subsurface Water Retention Technology (SWRT) for Water Saving and Growing Tomato in Iraqi Sandy Soils," *Journal of Zankoy Sulaimani - Part A*, 2ndInt.Con(Special Issue), pp. 127–134. doi: https://doi.org/10.17656/jzs.10659

Bista, P. *et al.* (2023) "Effect of Urea-Calcium Sulfate Cocrystal Nitrogen Fertilizer on Sorghum Productivity and Soil $N_2O$ Emissions," *Sustainability (Switzerland)*, 15(10). doi: https://doi.org/10.3390/su15108010

Bolleter, W. T., Bushman, C. J. and Tidwell, P. W. (1961) "Spectrophotometric Determination of Ammonia as Indophenol," *Analytical Chemistry*, 33(4), pp. 592–594. doi: https://doi.org/10.1021/ac60172a034

Chataut, G. *et al.* (2023) "Greenhouse gases emission from agricultural soil: A review," *Journal of Agriculture and Food Research*, p. 100533. doi: https://doi.org/10.1016/j.jafr.2023.100533

Chelangat Ronoh, L., Mihara, M., Mukundi, J. B., Ngamau, C., Aggrey Adimo, & Touch, N. (2024) "The Dynamics of Greenhouse Gas Emission during Food Waste Composting," *JOURNAL OF AGRICULTURE, SCIENCE AND TECHNOLOGY*, *23*(4), 47–64. https://doi.org/10.4314/jagst.v23i4.3

Ciais, P. *et al.* (2011) "The carbon balance of Africa: Synthesis of recent research studies," *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 369(1943), pp. 2038–2057. doi: https://doi.org/10.1098/rsta.2010.0328

Demirel, K. and Kavdır, Y. (2013) "Effect of soil water retention barriers on turfgrass growth and soil water content," *Irrigation Science*, 31(4), pp. 689–700. doi: https://doi.org/10.1007/s00271-012-0345-1

Elings, A. (2000) "Estimation of leaf area in tropical maize," *Agronomy Journal*, 92(3), pp. 436–444. doi: https://doi.org/10.2134/agronj2000.923436x

Eregae, J. E., Gichuhi, . M. W., & Mwangi, G. (2017) "QUANTIFICATION OF CARBON STOCKS WITH THE COMMON TREE GENUS IN DRYLAND FOREST IN TAITA RANCH, SOUTH EASTERN KENYA," *JOURNAL OF AGRICULTURE, SCIENCE AND TECHNOLOGY*, *17*(2), 1–20. Retrieved from https://ojs.jkuat.ac.ke/index.php/JAGST/article/view/24

Fernández-Ortega, J., Álvaro-Fuentes, J. and Cantero-Martínez, C. (2023) "The use of double-cropping in combination with no-tillage and optimized nitrogen fertilization reduces soil $N_2O$ emissions under irrigation," *Science of the Total Environment*, 857(September 2022). doi:


ISSN 1561-7645 (online)
doi: 10.4314/jagst.v23i5.5

https://doi.org/10.1016/j.scitotenv.2022.159458

García-Gutiérrez, S. *et al.* (2023) "Dry rainfed conditions are key drivers of the effect of conservation tillage and a nitrification inhibitor on N fate and $N_2O$ emissions: A field 15N tracing study," *Geoderma*, 432(November 2022). doi: https://doi.org/10.1016/j.geoderma.2023.116424

Githongo, Miriam W., Collins M. Musafiri, Joseph M. Macharia, Milka N. Kiboi, Andreas Fliessbach, Anne Muriuki, and Felix K. Ngetich. "Greenhouse gas fluxes from selected soil fertility management practices in humic nitisols of upper Eastern Kenya." *Sustainability* 14, no. 3 (2022): 1938. doi: https://doi.org/10.3390/su14031938

Götze, H. *et al.* (2023) "Effect of Incorporation Techniques and Soil Properties on $NH_3$ and $N_2O$ Emissions after Urea Application," *Agronomy*, 13(10). doi: https://doi.org/10.3390/agronomy13102632

Guo, J. *et al.* (2023) "Global Climate Change Increases Terrestrial Soil CH4 Emissions," *Global Biogeochemical Cycles*, 37(1), pp. 1–15. doi: https://doi.org/10.1029/2021GB007255

Hachem, K. El and Kang, M. (2023) "Reducing oil and gas well leakage: a review of leakage drivers, methane detection and repair options," *Environmental Research: Infrastructure and Sustainability*, 3(1), p. 012002. doi: https://doi.org/10.1088/2634-4505/acbced

IPPC, Pachauri, R. . and Meyer, L. . (2014) *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPPC, Geneva, Switzerland Core Writing Team*. https://cir.nii.ac.jp/crid/1571417124957557504

Ismail, S. M. and Ozawa, K. (2007) "Improvement of crop yield, soil moisture distribution and water use efficiency in sandy soils by clay application," *Applied Clay Science*, 37(1–2), pp. 81–89. doi: https://doi.org/10.1016/j.clay.2006.12.005

Jaja, N. (2016) "Understanding the Texture of Your Soil for Agricultural Productivity," *Virginia Cooperative Extension*, *CSES-162P*, 6. Available at: https://vtechworks.lib.vt.edu/server/api/core/bitstreams/ba419b0e-caac-435a-9f9c-33d181828e28/content

Kalu, S. *et al.* (2021) "Effects of two wood-based biochars on the fate of added fertilizer nitrogen—a $^{15}N$ tracing study," *Biology and Fertility of Soils*, 57(4), pp. 457–470. doi: https://doi.org/10.1007/s00374-020-01534-0

Kaur, N. *et al.* (2023) "How much is soil nitrous oxide emission reduced with biochar application? An evaluation of meta-analyses," *GCB Bioenergy*, 15(1), pp. 24–37. doi: https://doi.org/10.1111/gcbb.13003

Khanh, P. T., Pramanik, S., & Ngoc, T. T. H. (2024) "Soil Permeability of Sandy Loam and Clay Loam Soil in the Paddy Fields in An Giang Province in Vietnam," *Environmental Challenges*, *15*, 100907. https://doi.org/10.1016/j.envc.2024.100907

Kavdir, Y. *et al.* (2014) "Development of a new long-term drought resilient soil water retention technology," *Journal of Soil and Water Conservation*, 69(5), pp. 154A-160A. doi: https://doi.org/10.2489/jswc.69.5.154A

Kussainova, M. *et al.* (2023) "Effects of different fertilization practices on $CH_4$ and $N_2O$ emissions


ISSN 1561-7645 (online)
doi: 10.4314/jagst.v23i5.5

in various crop cultivation systems: A case study in Kazakhstan," *Eurasian Journal of Soil Science*, 12(4), pp. 363–370. doi: https://doi.org/10.18393/ejss.1344462

Lemarpe, S. E. *et al.* (2023) "Smallholder Cropping Systems Contribute Limited Greenhouse Gas Fluxes in Upper Eastern Kenya," *Nature-Based Solutions*, 4(November), p. 100098. doi: https://doi.org/10.1016/j.nbsj.2023.100098

Macharia, J. M. *et al.* (2020) "Soil Greenhouse Gas Fluxes From Maize Production Under Different Soil Fertility Management Practices in East Africa," *Journal of Geophysical Research: Biogeosciences*, 125(7), pp. 0–3. doi: https://doi.org/10.1029/2019JG005427

Miller, S. A. and Smucker, A. J. M. (2015) "A new soil water retention technology for irrigated highly permeable soils," *Joint ASABE/IA Irrigation Symposium 2015: Emerging Technologies for Sustainable Irrigation*, pp. 726–730. doi: https://doi.org/10.13031/irrig.20152147252

Moinet, G. Y. K. *et al.* (2023) "Carbon for soils, not soils for carbon," *Global Change Biology*, 29(9), pp. 2384–2398. doi: https://doi.org/10.1111/gcb.16570

Muema, E. *et al.* (2018) "Determinants of access and utilisation of seasonal climate information services among smallholder farmers in Makueni County, Kenya," *Heliyon*, 4(11), p. e00889. doi: https://doi.org/10.1016/j.heliyon.2018.e00889

Mushab, F. S. and Almasaf, S. A. (2019) "Subsurface Water Retention a Technology for Increasing the Field Use Efficiency and Water Saving Values of Cucumber Plant," *Journal of Engineering*, 25(9), pp. 54–61. doi: https://doi.org/10.31026/j.eng.2019.09.5

Ortiz-Gonzalo, D. *et al.* (2018) "Multi-scale measurements show limited soil greenhouse GAS emissions in Kenyan smallholder coffee-dairy systems," *Science of the Total Environment*, 626, pp. 328–339. doi: https://doi.org/10.1016/j.scitotenv.2017.12.247

Posmanik, R., Nejidat, A. and Gross, A. (2023) "Effects of limed manure digestate application in sandy soil on plant nitrogen availability and soil $N_2O$ emissions," *Soil and Environmental Health*, 1(1), p. 100006. doi: https://doi.org/10.1016/j.seh.2023.100006

Prakash, T. and Shimrah, T. (2023) "A Review on Soil Carbon Sequestration in Different Land Use and Land Cover," *Ecology, Environment and Conservation*, 29(2017), pp. 332–340. doi: https://doi.org/10.53550/eec.2023.v29i03s.060

R Core, T. (2023) "R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing." Vienna, Austria. Available at: https://www.r-project.org/

Recha, J. W. *et al.* (2016) "Changing rainfall patterns and farmers' adaptation through soil water management practices in semi-arid eastern Kenya," *Arid Land Research and Management*, 30(3), pp. 229–238. doi: https://doi.org/10.1080/15324982.2015.1091398

Rosenstock, T. S. *et al.* (2016) *Methods for Measuring Greenhouse Gas Balances and Evaluating Mitigation Options in Smallholder Agriculture*, *Methods for Measuring Greenhouse Gas Balances and Evaluating Mitigation Options in Smallholder Agriculture*. doi: https://doi.org/10.1007/978-3-319-29794-1

Salim, A. H. and Almasraf, S. A. (2019) "Improvement Water Productivity of Eggplant Under Subsurface Water Retention Technology," *Association of Arab Universities Journal of Engineering Sciences*, 26(2), pp. 1–5. doi: https://doi.org/10.33261/jaaru.2019.26.2.001

Santoni, M. *et al.* (2023) "Soil microbiome biomass, activity, composition and $CO_2$ emissions in a


ISSN 1561-7645 (online)
doi: 10.4314/jagst.v23i5.5

long-term organic and conventional farming systems," *Soil Use and Management*, 39(1), pp. 588–605. doi: https://doi.org/10.1111/sum.12836

Shapiro, A. S. S. and Wilk, M. B. (1965) "Biometrika Trust An Analysis of Variance Test for Normality ( Complete Samples ) Published by : Oxford University Press on behalf of Biometrika Trust Stable," *Biometrika*, 52(3), pp. 591–611. Available at: Available at: https://pdfs.semanticscholar.org/1f1d/9a7151d52c2e26d35690dbc7ae8098beee22.pdf

Smith, P., Reay, D. and Smith, J. (2021) "Agricultural methane emissions and the potential formitigation," *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 379(2210). doi: https://doi.org/10.1098/rsta.2020.0451

Wachiye, S. *et al.* (2020) "Soil greenhouse gas emissions under different land-use types in savanna ecosystems of Kenya," *Biogeosciences*, 17(8), pp. 2149–2167. doi: https://doi.org/10.5194/bg-17-2149-2020

Wang, H. *et al.* (2023) "Quantifying nitrous oxide production rates from nitrification and denitrification under various moisture conditions in agricultural soils: Laboratory study and literature synthesis," *Frontiers in Microbiology*, 13(January), pp. 1–10. doi: https://doi.org/10.3389/fmicb.2022.1110151

Wu, G. *et al.* (2020) "Effects of soil warming and increased precipitation on greenhouse gas fluxes in spring maize seasons in the North China Plain," *Science of the Total Environment*, 734(2), p. 139269. doi: https://doi.org/10.1016/j.scitotenv.2020.139269

Wu, Jiangqi *et al.* (2021) "Responses of $CH_4$ flux and microbial diversity to changes in rainfall amount and frequencies in a wet meadow in the Tibetan Plateau," *Catena*, 202(March), p. 105253. doi: https://doi.org/10.1016/j.catena.2021.105253

Yang, G. *et al.* (2014) "Effects of soil warming, rainfall reduction and water table level on $CH_4$ emissions from the Zoige peatland in China," *Soil Biology and Biochemistry*, 78, pp. 83–89. doi: https://doi.org/10.1016/j.soilbio.2014.07.013

Zhang, K. *et al.* (2023) "Moderate precipitation reduction enhances nitrogen cycling and soil nitrous oxide emissions in a semi-arid grassland," *Global Change Biology*, 29(11), pp. 3114–3129. doi: https://doi.org/10.1111/gcb.16672

Zhang, Y., Wang, W. and Yao, H. (2023) "Urea-based nitrogen fertilization in agriculture: a key source of $N_2O$ emissions and recent development in mitigating strategies," *Archives of Agronomy and Soil Science*, 69(5), pp. 663–678. doi: https://doi.org/10.1080/03650340.2022.2025588