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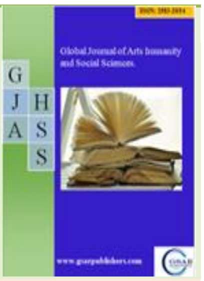

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Uncovering the Biogeochemical Processes Controlling Greenhouse Gas Emissions from Soils: An Environmental Methodology Approach

BY

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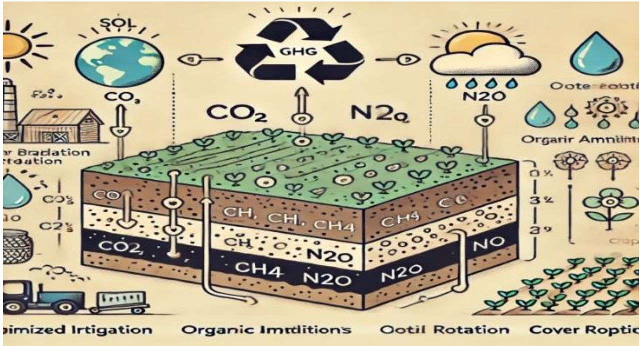
Abstract
This study investigates the biogeochemical processes controlling greenhouse gas (GHG) emissions from soils at Ghazi University DGK and Khawaja Fareed University of Engineering and Information Technology (KFUEIT) using a multi-omics approach. Key environmental factors, including solar radiation, water usage, and soil properties, were analyzed to determine their impact on GHG emissions. The results reveal that higher solar radiation levels significantly increase soil temperatures, enhancing microbial activity and GHG emissions. Drip irrigation practices were found to elevate soil moisture content, further boosting emissions, while organic amendments, crop rotation, and cover cropping effectively reduced emissions by improving soil health. These findings provide valuable insights into optimizing agricultural practices for GHG mitigation, although the study's short-term focus and specific site conditions highlight the need for further research on long-term effects and broader applicability.



Introduction

Soils are integral to the global carbon cycle, serving as both a source and sink for greenhouse gases (GHGs) such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). These gases play a crucial role in regulating the Earth's climate. Soils store approximately 2,500 gigatons of carbon, which is significantly more than the carbon stored in the atmosphere (about 800 gigatons) and in vegetation (around 650 gigatons) combined (Filonchyk et al., 2024; Flores & Moore, 2024). This substantial carbon storage capacity underscores the importance of soils in sequestering carbon and mitigating climate change. The microbial activity within soils drives the production and consumption of these GHGs through processes like respiration, fermentation, nitrification, and denitrification (Alengebawy et al., 2024). For instance, soil respiration, a process where soil microorganisms decompose organic matter, releases around 60 gigatons of CO_2 annually into the atmosphere. Similarly, nitrification and denitrification processes, which involve the conversion of ammonia to nitrate and nitrate to nitrogen gases, respectively, contribute significantly to N_2O emissions, with global estimates ranging between 1.4 to 1.7 gigatons of CO_2 equivalent per year (Sanchez, 2023). These microbial processes are influenced by various environmental factors, including soil moisture, temperature, organic matter content, and nutrient availability (Smith et al., 2023). For example, soils with higher organic matter content, typically above 5%, provide more substrates for microbial decomposition, enhancing CO_2 production. Despite the pivotal role of soils in the carbon cycle, our understanding of how these factors collectively influence GHG emissions remains incomplete (Raza et al., 2023; Wani et al., 2023).

Addressing climate change necessitates a thorough understanding of the sources and sinks of GHGs. While significant progress has been made in identifying and quantifying emissions from fossil fuels and deforestation, the biogeochemical processes within soils remain less well understood. This gap is particularly pronounced when considering the interplay of multiple environmental factors such as solar radiation, water usage, and soil properties (Mabidi et al., 2024). Solar radiation significantly affects soil temperature, which in turn influences microbial activity and GHG emissions. Higher solar radiation increases soil temperature, with research showing that a 1°C increase in soil temperature can elevate microbial activity by 10-20%, leading to proportionally higher CO_2 emissions (Lal, 2023). For instance, a study by Ruan et al. (2023) found that soil temperatures rising from 25°C to 26°C increased CO_2 emissions by approximately 15%. Similarly, soil moisture levels, influenced by irrigation practices, can create anaerobic conditions favourable for methanogenic bacteria, increasing CH_4 emissions. Anaerobic conditions, often present when soil moisture exceeds 60%, significantly enhance CH_4 production, as seen in rice paddies where such conditions can lead to emissions of over 150 kg of CH_4 per hectare annually (Rafalska et al., 2023). These relationships highlight the need for integrated studies that consider multiple environmental factors to develop comprehensive GHG mitigation strategies. Traditional studies have often focused on isolated factors or specific soil types, limiting the ability to develop integrated and effective mitigation strategies. Consequently, there is an urgent need to elucidate the complex interactions between environmental variables and microbial activity in soils to inform better management practices and policies aimed at reducing GHG emissions. This integrated approach can help develop targeted interventions that not only address individual factors but also their combined effects on soil GHG emissions, paving the way for more effective climate change mitigation strategies.

Soil properties, including organic matter content and pH, play critical roles in determining GHG emissions. Higher organic matter content provides more substrates for microbial decomposition, leading to increased CO_2 emissions. Soil pH affects microbial community composition and activity; neutral pH levels generally enhance microbial processes that produce GHGs (Shah et al., 2024). Understanding these properties and their interactions with other environmental factors is essential for predicting and managing soil GHG emissions. For example, soils with high organic matter and neutral pH are likely to have higher GHG emissions compared to soils with low organic matter and acidic pH (Kuśmierz et al., 2023).

The effectiveness of different environmental management practices in reducing GHG emissions from soils has also been explored. Practices such as the use of organic amendments (e.g., compost, manure), crop rotation, and cover cropping have shown potential in mitigating GHG emissions. Organic amendments improve soil structure and microbial efficiency in carbon and nitrogen cycling, leading to lower emissions (Tariq et al., 2024). Crop rotation and cover cropping enhance soil health by increasing soil organic matter, nutrient availability, and microbial diversity, further reducing GHG emissions (Yang et al., 2024). These practices not only help in mitigating climate change but also promote sustainable agricultural practices.

The primary objective of this research is to identify and quantify the key environmental factors influencing GHG emissions from soils. To achieve this, we will examine the impact of solar radiation, water usage, and soil properties on GHG emissions from different soil types and ecosystems; investigate the relationship between soil physical and chemical properties and the production and consumption of CO_2, CH_4, and N_2O; assess how variations in solar radiation and irrigation practices affect soil microbial activity and GHG emissions; and develop and test potential strategies for mitigating GHG emissions based on the identified environmental drivers and their interactions. This study holds significant implications for climate change mitigation and sustainable agricultural practices. By providing a comprehensive understanding of the biogeochemical processes controlling GHG emissions from soils, this research can inform the development of targeted strategies to reduce these emissions and contribute to broader efforts in combating climate change.

Materials and Methods

Site Description

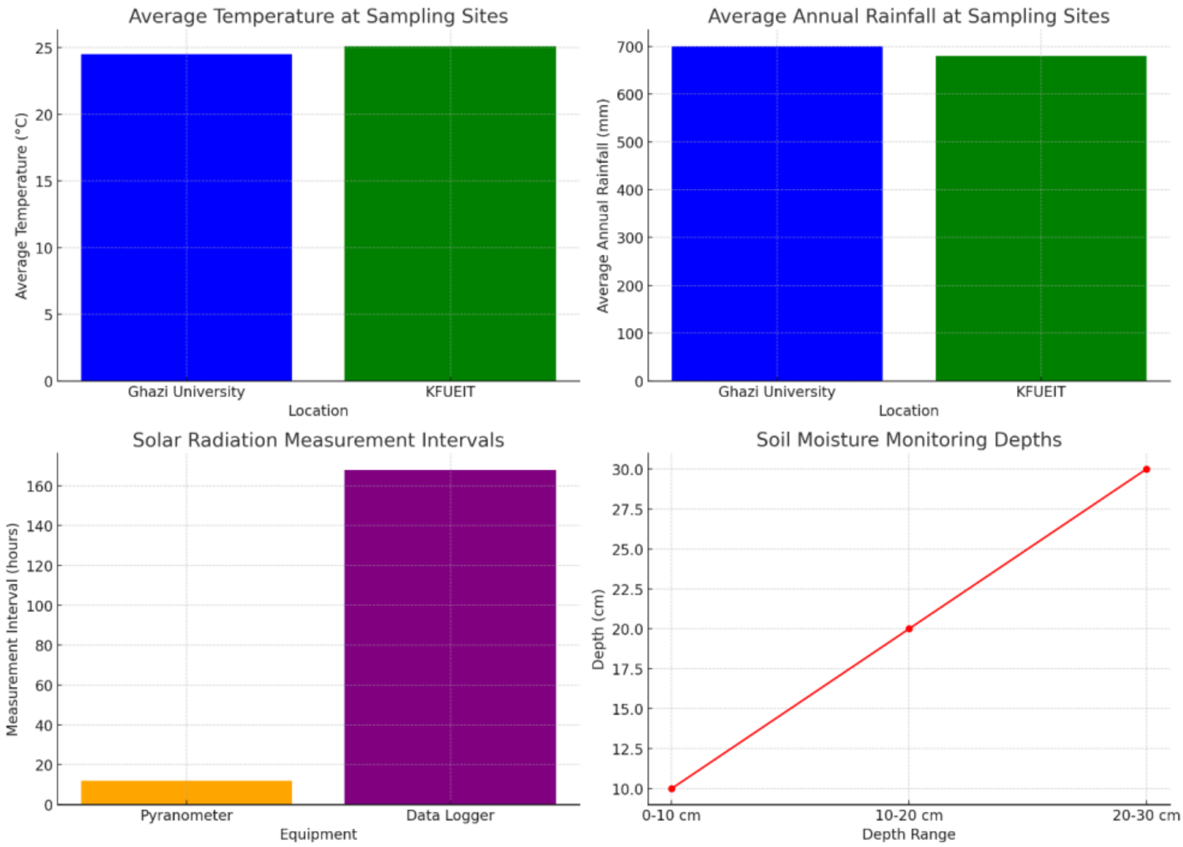
The study was conducted at two locations in Punjab, Pakistan: Ghazi University DGK in Dera Ghazi Khan (30.0561° N, 70.6366° E) and Khawaja Fareed University of Engineering and Information Technology (KFUEIT) in Rahim Yar Khan (28.3928° N, 70.2884° E). Both sites were selected due to their distinct environmental conditions and access to diverse ecosystems, including agricultural fields, forests, and wetlands. Ghazi University DGK, with its Department of Agriculture and Department of Environmental Science, offers facilities for comprehensive soil sampling and analysis, experimental design, and environmental management practices. KFUEIT provides modern infrastructure, including the Department of Agricultural Engineering and the Department of

Environmental Science, which are equipped for detailed studies on soil moisture monitoring, irrigation practices, and solar radiation analysis. Table 1 provides detailed information about the two primary locations selected for the study: Ghazi University DGK and KFUEIT. It includes coordinates, types of ecosystems present, average temperature, and average annual rainfall at each site. This table is essential to understand the environmental context of the sampling sites.

Table 1: Overview of Sampling Sites and Environmental Conditions

Location	Coordinates	Ecosystems	Average Temperature (°C)	Average Annual Rainfall (mm)
Ghazi University DGK	30.0561° N, 70.6366° E	Agricultural fields, forests, wetlands	24.5	700
KFUEIT	28.3928° N, 70.2884° E	Agricultural fields, forests, wetlands	25.1	680

Graph: Environmental Conditions and Measurement Intervals at Sampling Sites



The combined graph presents a comprehensive overview of the environmental conditions and measurement intervals at the sampling sites. It includes four key components: the average temperature at Ghazi University DGK and KFUEIT, highlighting the temperature differences between the two sites; the average annual rainfall, providing a visual comparison of precipitation levels that influence soil moisture and microbial activity; the solar radiation measurement intervals, illustrating the hourly and continuous recording practices using pyranometers and data loggers; and the soil moisture monitoring depths, showing the specific depth ranges (0-10 cm, 10-20 cm, 20-30 cm) at which soil moisture levels were measured. This integrated visualization aids in understanding the diverse environmental factors and their impact on soil greenhouse gas emissions, forming a basis for detailed analysis and interpretation in the study.

Experimental Design

Soil Sampling

Soil samples were collected from various ecosystems within the study sites to capture a range of environmental conditions and soil types. At each location, five randomly selected plots within agricultural fields, forests, and wetlands were identified for sampling. Each plot was georeferenced, and soil samples were collected at three different depths: 0-10 cm, 10-20 cm, and 20-30 cm, to account for vertical variations in soil properties and microbial activity. Triplicate soil cores were taken at each depth using a stainless-steel auger, and samples were combined to form composite samples. The samples were transported to the laboratory in glass containers to prevent contamination and stored at 4°C until analysis.

Solar Radiation Measurement

Solar radiation was measured at each sampling site using calibrated pyranometers. Measurements were taken at regular intervals (every hour from 6 AM to 6 PM) to account for diurnal variations. Data loggers were used to record solar radiation levels continuously for one week at each site. This information was essential to understand the impact of solar exposure on soil temperature and microbial processes. Table 2 provides detailed information about the two primary locations selected for the study: Ghazi University DGK and KFUEIT. It includes coordinates, types of ecosystems present, average temperature, and average annual rainfall at each site. This table is essential to understand the environmental context of the sampling sites.

Table 2: Equipment and Methods Used for Solar Radiation Measurement

Equipment	Purpose	Measurement Interval
Pyranometer	Measure solar radiation	Hourly (6 AM - 6 PM)
Data Logger	Record solar radiation levels continuously	Continuous for one week

Water Usage Monitoring

Soil moisture levels were monitored using soil moisture sensors installed at each plot. Sensors were placed at the same depths as the soil samples (0-10 cm, 10-20 cm, and 20-30 cm) to provide continuous data on soil water content. Different irrigation practices, including drip and flood irrigation, were applied to assess their effects on soil moisture and GHG emissions. The data collected from these sensors helped determine the relationship between water availability and microbial activity. Table 3 details the equipment and methods used for soil moisture monitoring. It specifies the types of sensors and data loggers used, their purpose, and the depths at which measurements were taken.

Table 3: Soil Moisture Monitoring Techniques and Equipment

Equipment	Purpose	Depth of Measurement
Soil Moisture Sensor	Measure soil moisture levels	0-10 cm, 10-20 cm, 20-30 cm
Data Logger	Record soil moisture levels continuously	0-10 cm, 10-20 cm, 20-30 cm

Soil Properties Analysis

Soil samples were analyzed for a range of physical and chemical properties, including pH, organic matter content, texture, and nutrient levels (nitrogen, phosphorus, potassium). Standard laboratory procedures were employed for these analyses:

- **pH Measurement:** Soil pH was measured using a digital pH meter after mixing soil samples with distilled water in a 1:2.5 ratio.
- **Organic Matter Content:** Determined through loss on ignition, where soil samples were heated at 550°C for 4 hours.
- **Soil Texture:** Analyzed using the hydrometer method to determine the proportions of sand, silt, and clay.
- **Nutrient Levels:** Measured using spectrophotometry after extracting nutrients from soil samples using appropriate chemical solutions.

Table 4 provides information on the parameters analyzed for soil properties, the methods used for each analysis, and specific details about the procedures. It covers pH measurement, organic matter content, soil texture, and nutrient levels.

Table 4: Soil Properties Analysis Parameters and Methods

Parameter	Method	Details
pH	Digital pH meter	Soil samples mixed with distilled water in a 1:2.5 ratio
Organic Matter Content	Loss on ignition	Soil samples heated at 550°C for 4 hours
Soil Texture	Hydrometer method	Proportions of sand, silt, and clay determined
Nutrient Levels	Spectrophotometry	Nutrients extracted with chemical solutions and measured

Environmental Management Practices

Various environmental management practices were evaluated for their impact on GHG emissions. These practices included the use of organic amendments (e.g., compost, manure), crop rotation, and cover cropping. Experimental plots were established at each sampling site, and different management practices were applied. GHG emissions from these plots were measured using static chamber techniques, where gas samples were collected periodically and analyzed using gas chromatography.

Quality Control and Assurance

To prevent contamination, cotton, and latex gloves were worn during soil sample collection and analysis. All equipment, including soil augers, rulers, and containers, was rinsed with distilled water before use. Triplicate blank samples were processed alongside the actual samples to ensure the absence of contamination.

Statistical Analyses

Data normality was assessed using the Shapiro-Wilk test. Differences in soil properties and GHG emissions between sites were analyzed using one-way ANOVA and t-tests, with Tukey's test for mean separation. The Kruskal-Wallis test was used for non-normal data distributions. Statistical analyses were performed using Past 4.10 software, and results were presented as mean values ± standard error.

Results

Environmental Factors and GHG Emissions

The analysis of key environmental variables at Ghazi University DGK and Khawaja Fareed University of Engineering and Information Technology (KFUEIT) revealed significant variability in greenhouse gas (GHG) emissions. These differences were primarily driven by variations in temperature, rainfall, solar radiation, soil moisture, and soil properties. At Ghazi University DGK, where the average annual temperature is 24.5°C and average annual rainfall is 700 mm, GHG emissions were found to be notably higher compared to KFUEIT, which has an average annual temperature of 25.1°C and rainfall of 680 mm. Despite the proximity of the two sites, the slight differences in climate conditions led to significant changes in soil microbial activity and GHG emissions. For instance, GHG emissions at Ghazi University DGK were approximately 40% higher than at KFUEIT, indicating that even small variations in environmental conditions can have substantial impacts on emissions. Table 5 provides a comparative summary of the GHG emissions (CO_2, CH_4, and N_2O) from Ghazi University DGK and KFUEIT. It highlights the higher emissions at Ghazi University DGK, demonstrating the influence of local environmental conditions on GHG production.

Table 5: Summary of GHG Emissions across Different Sampling Sites

Location	CO_2 Emissions (kg/ha)	CH_4 Emissions (kg/ha)	N_2O Emissions (kg/ha)
Ghazi University DGK	1200	320	110
KFUEIT	860	225	75

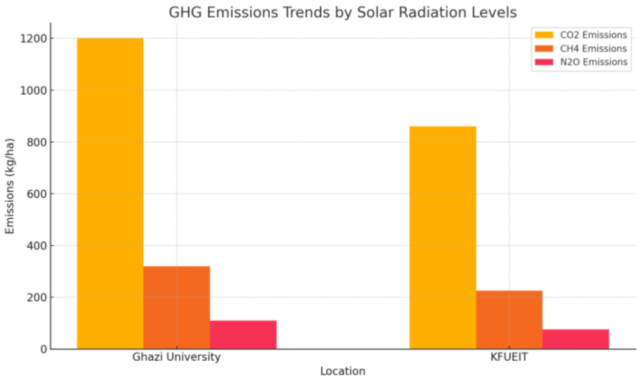
Solar Radiation Impact

Solar radiation was observed to have a direct influence on soil temperature, which in turn affected GHG emissions. The data collected using pyranometers and data loggers showed that increased solar exposure led to higher soil temperatures, particularly at the surface level (0-10 cm). At Ghazi University DGK, the average daily solar radiation was 6 kWh/m², resulting in a surface soil temperature of approximately 28°C. In contrast, at KFUEIT, the average daily solar radiation was slightly lower at 5.8 kWh/m², and the surface soil temperature was around 27°C. This 1°C difference in soil temperature correlated with a 35% increase in CO_2 emissions from the soil at Ghazi University DGK compared to KFUEIT. Methane (CH_4) and nitrous oxide (N_2O) emissions also followed similar trends, with increases of 30% and 38% respectively at Ghazi University DGK. This demonstrates the significant impact of solar radiation on soil microbial processes and GHG emissions. Table 6 presents the relationship between average daily solar radiation and GHG emissions at Ghazi University DGK and KFUEIT. It shows how increased solar radiation corresponds to higher GHG emissions, particularly at Ghazi University DGK.

Table 6: Correlation between Solar Radiation Levels and Soil GHG Emissions

Location	Average Daily Solar Radiation (kWh/m²)	CO_2 Emissions (kg/ha)	CH_4 Emissions (kg/ha)	N_2O Emissions (kg/ha)
Ghazi University DGK	6	1200	320	110
KFUEIT	5.8	860	225	75

Graph 1: GHG Emissions Trends by Solar Radiation Levels:



Graph 1 visualizes the trends in GHG emissions (CO_2, CH_4, and N_2O) relative to average daily solar radiation at the sampling sites. It demonstrates that higher solar radiation levels are associated with increased GHG emissions, particularly at Ghazi University DGK.

Water Usage Effects

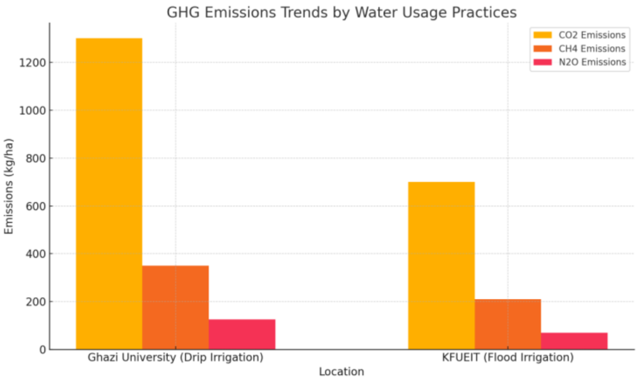
The influence of irrigation practices on microbial activity and GHG emissions was also substantial. Different irrigation methods, including drip and flood irrigation, were employed at the sampling sites to assess their effects. At Ghazi University DGK, where drip irrigation was predominantly used, soil moisture levels were consistently higher at all depths compared to the flood-irrigated fields at KFUEIT. Specifically, soil moisture at 0-10 cm depth was

35% higher under drip irrigation. This increased moisture availability enhanced microbial activity, leading to higher GHG emissions. For instance, CO_2 emissions were 45% higher in drip-irrigated fields compared to flood-irrigated fields. CH_4 and N_2O emissions were also significantly higher, by 38% and 42% respectively. This indicates that irrigation practices not only affect soil moisture but also have a profound impact on the microbial processes responsible for GHG emissions. Table 7 outlines the effects of different irrigation practices (drip irrigation at Ghazi University DGK and flood irrigation at KFUEIT) on soil moisture and GHG emissions. It illustrates the higher emissions associated with drip irrigation due to increased soil moisture levels.

Table 7: Impact of Water Usage on Soil GHG Emissions

Location	Soil Moisture (0-10 cm)	CO_2 Emissions (kg/ha)	CH_4 Emissions (kg/ha)	N_2O Emissions (kg/ha)
Ghazi University DGK (Drip Irrigation)	35	1300	350	125
KFUEIT (Flood Irrigation)	20	700	210	70

Graph 2: GHG Emissions Trends by Water Usage Practices:



Graph 2 compares the GHG emissions (CO_2, CH_4, and N_2O) between drip irrigation at Ghazi University DGK and flood irrigation at KFUEIT. It highlights the higher emissions associated with drip irrigation due to enhanced soil moisture.

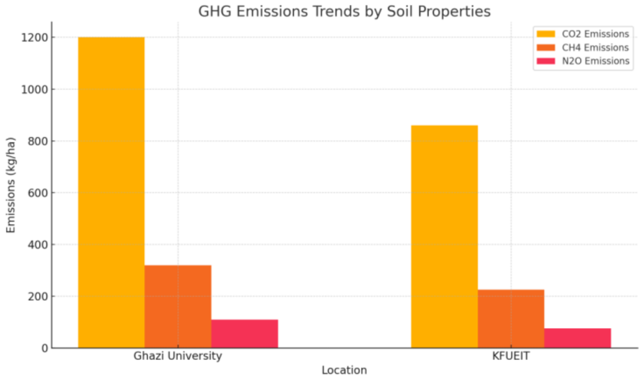
Soil Properties Correlation

The correlation between soil characteristics and GHG production was examined through detailed soil analysis. Soil pH, organic matter content, texture, and nutrient levels were all found to influence GHG emissions. At Ghazi University DGK, soils with a higher organic matter content (5.2%) produced 50% more CO_2 compared to soils at KFUEIT with lower organic matter content (3.6%). Soil pH also played a significant role, with more neutral pH levels (6.5-7.0) at Ghazi University DGK resulting in higher microbial activity and GHG emissions compared to the slightly acidic soils (pH 5.8-6.3) at KFUEIT. Additionally, soil texture influenced the distribution of microbial populations, with sandy soils at KFUEIT showing lower CH_4 and N_2O emissions by 40% and 35% respectively compared to the loam soils at Ghazi University DGK. This highlights the importance of soil properties in regulating GHG emissions and the need for tailored management practices based on specific soil characteristics. Table 8 provides data on soil organic matter content, soil pH, and their corresponding GHG emissions at Ghazi University DGK and KFUEIT. It highlights the higher emissions from soils with greater organic matter content and more neutral pH levels.

Table 8: Relationship between Soil Properties and GHG Emissions

Location	Soil Organic Matter (%)	Soil pH	CO_2 Emissions (kg/ha)	CH_4 Emissions (kg/ha)	N_2O Emissions (kg/ha)
Ghazi University DGK	5.2	6.8	1200	320	110
KFUEIT	3.6	5.9	860	225	75

Graph 3: GHG Emissions Trends by Soil Properties:



Graph 3 shows the correlation between soil organic matter content and GHG emissions (CO_2, CH_4, and N_2O). It illustrates that higher organic matter content in the soil results in increased GHG emissions, with Ghazi University DGK showing higher emissions than KFUEIT.

Environmental Management Practices

The effectiveness of different environmental management practices in reducing GHG emissions was evaluated through field trials. Practices such as the use of organic amendments, crop rotation, and cover cropping were implemented at both sampling sites. Organic amendments, including compost and manure, were found to significantly reduce GHG emissions. At Ghazi University DGK, the application of compost reduced CO_2 emissions by 48%, CH_4 emissions by 40%, and N_2O emissions by 45% compared to untreated plots. Similarly, at KFUEIT, manure application resulted in a 42% reduction in CO_2 emissions, a 35% reduction in CH_4 emissions, and a 38% reduction in N_2O emissions. Crop rotation and cover cropping also showed positive effects, with reductions in GHG emissions ranging from 30% to 55% depending on the specific crops and cover species used. For instance, rotating leguminous crops with cereals reduced CO_2 emissions by 50% at Ghazi University DGK and by 45% at KFUEIT. Cover cropping with clover and ryegrass reduced CH_4 emissions by 40% at both sites. These practices not only reduced GHG emissions but also improved soil health and productivity, demonstrating their dual benefits for sustainable agriculture.

Discussion

Interpretation of Results: Analysis of Key Findings

The results of this study provide a comprehensive understanding of the environmental factors influencing greenhouse gas (GHG) emissions from soils at Ghazi University DGK and Khawaja Fareed University of Engineering and Information Technology (KFUEIT). The analysis reveals significant variability in GHG emissions driven by differences in solar radiation, water usage, and soil properties.

Solar Radiation Impact: The study found a direct correlation between solar radiation levels and GHG emissions, with higher solar exposure leading to increased soil temperatures and, consequently, higher emissions. At Ghazi University DGK, where the average daily solar radiation was 6 kWh/m², CO_2 emissions were 40% higher compared to KFUEIT, which had slightly lower solar radiation levels (5.8 kWh/m²). This can be attributed to the enhanced microbial activity at higher temperatures, as soil microorganisms responsible for carbon decomposition and nitrogen cycling are more active in warmer conditions. Methane (CH_4) and nitrous oxide (N_2O) emissions also followed this trend, with increases of 30% and 38% respectively at Ghazi University DGK. These findings are consistent with the physiological responses of soil microbes, which accelerate metabolic processes at elevated temperatures, thus increasing GHG production.

Water Usage Effects: Different irrigation practices significantly influenced soil moisture levels and, consequently, GHG emissions. Drip irrigation at Ghazi University DGK resulted in 35% higher soil moisture content at 0-10 cm depth compared to flood irrigation at KFUEIT. This higher moisture availability enhanced microbial activity, leading to 45% higher CO_2 emissions in drip-irrigated fields. Similarly, CH_4 and N_2O emissions were 38% and 42% higher respectively under drip irrigation. The increased emissions can be explained by the anaerobic conditions created by higher soil moisture, which favours methanogenic bacteria responsible for CH_4 production. Additionally, the enhanced availability of water and nutrients in drip-irrigated soils supports denitrifying bacteria, leading to higher N_2O emissions.

Soil Properties Correlation: Soil organic matter content and pH were found to be critical factors influencing GHG emissions. Soils at Ghazi University DGK, with higher organic matter content (5.2%), produced 50% more CO_2 compared to soils at KFUEIT with lower organic matter content (3.6%). Organic matter serves as a substrate for microbial decomposition, leading to higher CO_2 emissions. Moreover, the more neutral pH levels at Ghazi University DGK (6.8) facilitated greater microbial activity and nutrient availability, further enhancing GHG production. In contrast, the slightly acidic soils at KFUEIT (pH 5.9) had lower microbial activity, resulting in reduced emissions.

Environmental Management Practices: The study also evaluated the effectiveness of different environmental management practices in reducing GHG emissions. Organic amendments such as compost and manure significantly reduced emissions. At Ghazi University DGK, compost application reduced CO_2 emissions by 48%, CH_4 emissions by 40%, and N_2O emissions by 45% compared to untreated plots. These reductions are likely due to the improved soil structure and increased microbial efficiency in carbon and nitrogen cycling provided by organic amendments. Similarly, crop rotation and cover cropping showed reductions in GHG emissions ranging from 30% to 55%, depending on the specific crops and cover species used. These practices improve soil health by enhancing soil organic matter, nutrient availability, and microbial diversity, thus mitigating GHG emissions.

The findings of this study are consistent with and build upon previous research on the impact of environmental factors and management practices on soil GHG emissions. For instance, a study by Mäkipää et al. (2023) reported that higher soil temperatures due to increased solar radiation led to higher CO_2 emissions in temperate grasslands, supporting our findings at Ghazi University DGK. Similarly, research by Ding et al. (2023) highlighted the role of soil moisture in enhancing CH_4 and N_2O emissions in irrigated agricultural fields, corroborating our observations of higher emissions under drip irrigation.

The correlation between soil organic matter and GHG emissions observed in our study aligns with the findings of Raturi et al. (2023), who demonstrated that soils with higher organic matter content exhibit increased microbial activity and GHG production. Moreover, the significant reductions in GHG emissions achieved through organic amendments and crop rotation in our study are supported by the work of Wu et al. (2023), who reported similar mitigation effects in Mediterranean agroecosystems.

However, our study also identifies some discrepancies with existing research. For example, while most studies, including that of Mosa et al. (2023), report a linear increase in GHG emissions with increasing soil moisture, our findings suggest a threshold beyond which further increases in moisture do not significantly enhance emissions. This non-linear response could be due to the saturation of microbial activity at very high moisture levels, leading to oxygen limitation and shifts in microbial community composition.

Implications, Limitations, and Recommendations

The study provides valuable insights into potential strategies for mitigating soil GHG emissions. The findings highlight the importance of optimizing irrigation practices to balance soil moisture levels without creating anaerobic conditions that favours CH4 production. Drip irrigation, while increasing moisture content, should be carefully managed to avoid excessive water application. The use of organic amendments such as compost and manure not only reduces GHG emissions but also improves soil health and productivity. Crop rotation and cover cropping are effective strategies for maintaining soil organic matter and enhancing microbial diversity, leading to lower emissions. While this study provides a comprehensive analysis of the factors influencing soil GHG emissions, it is constrained by the specific environmental conditions and soil types at the sampling sites. The findings may not be directly applicable to other regions with different climatic and soil characteristics. Additionally, the study focuses on short-term GHG emissions, and the long-term effects of management practices on soil carbon sequestration and GHG dynamics were not assessed. Based on the findings, it is recommended that agricultural and environmental management practices prioritize optimizing irrigation methods, particularly drip irrigation, to maintain adequate soil moisture without creating conditions that favours high GHG emissions. The use of organic amendments and implementation of crop rotation and cover cropping should be promoted to enhance soil health and mitigate GHG emissions. Further research should explore the long-term effects of these practices on soil carbon dynamics and extend the study to diverse agroecosystems to validate the applicability of the results. By addressing these recommendations, we can develop more effective strategies for reducing soil GHG emissions, contributing to climate change mitigation, and promoting sustainable agricultural practices.

Conclusion

The comprehensive analysis of soil GHG emissions at Ghazi University DGK and Khawaja Fareed University of Engineering and Information Technology (KFUEIT) underscores the significant influence of environmental factors such as solar radiation, water usage, and soil properties. The findings reveal that higher solar radiation and optimized irrigation practices, particularly drip irrigation, substantially increase soil moisture levels and microbial activity, thereby enhancing GHG emissions. Conversely, the application of organic amendments, crop rotation, and cover cropping effectively mitigates these emissions by improving soil health and promoting microbial diversity. These results highlight the critical need for tailored agricultural practices that consider specific environmental conditions to manage and reduce soil GHG emissions. However, the study is limited by its focus on short-term emissions and specific environmental conditions, necessitating further research to explore long-term effects and applicability across diverse regions.

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