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Effects of different fertilization practices on CH_4 and N_2O emissions in various crop cultivation systems: A case study in Kazakhstan

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Abstract

The present study investigates the effects of different fertilization practices, including chemical and organic fertilizers, on CH_4 and N_2O emissions in various crop cultivation systems in Kazakhstan. The research focuses on three staple crops: wheat, barley, and corn, which are commonly grown in the region. A randomized complete block design field trial was conducted with three replications for each crop, totaling 27 plots. Gas sampling was carried out five times between June and September 2021, with cylindrical gas sampling chambers inserted into the soil at a depth of 10 cm. The concentrations of CH_4 and N_2O were analyzed using GS-MS. Results reveal that all three crops exhibited moderate to high CH_4 and N_2O emissions, with corn consistently displaying the highest emissions. Both chemical and organic fertilizers led to increased emissions of CH_4 and N_2O compared to control plots. The organic fertilizer treatment occasionally showed slightly higher emissions compared to chemical fertilizer treatment. However, the differences in CH_4 and N_2O concentrations between fertilized and unfertilized plots were not drastically significant. Notably, environmental factors, such as soil moisture and temperature, played a more prominent role in influencing CH_4 and N_2O production than the type of fertilizer applied. These findings underscore the significance of optimizing fertilization practices to minimize greenhouse gas emissions while maintaining crop productivity and promoting sustainable agriculture in Kazakhstan.

Keywords: Greenhouse gas emissions, fertilization practices, crop cultivation, Kazakhstan.

Introduction

The rapid increase in global population over the past century has posed significant challenges to agricultural practices, leading to a surge in food demand (Hemathilake and Gunathilake, 2022). In response, modern agriculture has heavily relied on the use of chemical fertilizers to enhance crop yields and meet the growing food requirements of the world's population (Umesha et al., 2018). Crop cultivation plays a pivotal role in providing essential agricultural products such as wheat, barley, and maize. However, widespread adoption of conventional agricultural practices has resulted in adverse effects on soil health. Also, this intensified use of chemical fertilizers, while capable of enhancing crop yields, has brought about several environmental implications, including to water pollution, soil degradation, nutrient imbalance, and contribute to greenhouse gas (GHG) emissions (Tellez-Rio et al., 2017; Malyan et al., 2021). In recent years, there has been a growing emphasis on eco-friendly agricultural practices, and organic fertilizers have emerged as a notable alternative. Compared with chemical fertilizer, organic fertilizers have many positive effects on soil fertility and quality including increasing soil carbon and nitrogen, improving the soil physical structure, and enhancing crop yield and quality (Dillon et al., 2012; Zhao et al., 2014; 2020). Organic fertilizers comprise natural components such as animal manure, compost, and green manure. Utilizing organic fertilizers can improve soil productivity and

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health, and nutrient release, while reducing potential environmental impacts. Organic matter stimulates respiration and growth of microorganisms and provides carbon for denitrification. The growth of microorganisms increases oxygen consumption and anaerobic conditions for denitrification, which produces nitrous oxide (N_2O) (Jena et al., 2013). Food and Agriculture Organization (FAO) introduced organic agriculture to reduce the contribution of GHGs in agricultural sector and climate change adaptation (FAO, 2002; 2009). However, organic fertilizers can affect the production of methane (CH_4) and N_2O from soil (Anshori et al., 2020).

Carbon dioxide (CO_2), CH_4, and N_2O are prominent GHGs that contribute to the greenhouse effect, trapping heat in the Earth's atmosphere and causing global warming. Among these gases, CH_4 is of particular concern, being the second most important contributor to radiative forcing after CO_2 (Cassia et al., 2018). It possesses a significantly higher global warming potential, with a 100-year warming potential approximately 28 times that of CO_2 (Dlamini et al., 2022). Agricultural practices, especially in rice paddies, have been identified as substantial sources of CH_4 and N_2O emissions. The flooded conditions of rice fields create anaerobic environments, promoting CH_4 production through the decomposition of organic matter by methanogenic bacteria. Moreover, N_2O emissions often arise from nitrogen-based fertilizers due to nitrification and denitrification processes in the soil (Datta et al., 2014).

The situation is particularly relevant for Kazakhstan, where agriculture plays a crucial role in ensuring food security and supporting the economy. As a country with diverse climatic and soil conditions, Kazakhstan faces unique challenges in managing GHG emissions from agricultural activities. To address these challenges, sustainable and environmentally friendly agricultural practices are of utmost importance. In this context, the present study aims to investigate the effects of different fertilization practices, including chemical and organic fertilizers, on CH_4 and N_2O emissions in various crop cultivation systems, focusing on three staple crops in the region: barley, wheat, and corn. By conducting a field trial under the specific conditions of Kazakhstan, this research endeavors to quantify GHG emissions and study the impact of different fertilizers on soil fertility, nitrogen management, and the overall sustainability of agricultural practices (Kussainova et al., 2023).

Furthermore, this study represents the first scientific endeavor conducted in Kazakhstan to comprehensively assess the effects of fertilization on GHG emissions. As such, it holds significant importance for guiding future agricultural practices and policy decisions in the region. By providing unique insights into the specific challenges and opportunities faced by Kazakhstan, the research aims to contribute to the country's efforts in mitigating the environmental impact of agricultural activities while ensuring food security and sustainable development. Ultimately, the findings of this study are expected to contribute to the scientific understanding of GHG emissions in Kazakhstani agricultural systems. By identifying best practices for minimizing GHG emissions and maximizing crop productivity, the research can pave the way for the adoption of sustainable agricultural approaches tailored to the unique conditions of Kazakhstan. This can help enhance the resilience of the agricultural sector, support economic growth, and promote environmental conservation in the face of global climate change challenges.

Material and Methods

Experimental Site and Climatic Conditions

Experimental site is in “Baibulak” training and experimental farm of KazNARU located in the foothills of the dry network of Ile Alatau, Almaty oblast, Talgar district (N 43^{0}28.99’; E 43^{0}28.99’) (Figure 1). The locations of the evaluations were characterized by the continental climate (large daily and annual fluctuations in air temperature, characterized by cold winters and long hot summers), the air temperature reaches minimum values in January (-11, -13 ^{0}C), and maximum values in July (25 ^{0}C). The average number of days with a maximum air temperature equal to or above 25°C is 108.2 days, 30°C is 44.5 days, and 34°C is 9.4 days. The mean duration of periods with temperatures not exceeding 0°C is 105 days with an average temperature of -2.9°C. For temperatures not exceeding 8°C, the duration is 164 days with an average temperature of 0.4°C, and for temperatures not exceeding 10°C, the duration is 179 days with an average temperature of 0.8°C. Throughout the year, precipitation exhibits two peaks. The first peak occurs in the months of March or April, and the second peak occurs in October or November. The annual precipitation ranges from 148 to 509 mm. In some years, significant fluctuations in the amount of precipitation are observed, ranging from complete absence to abundant rainfall.

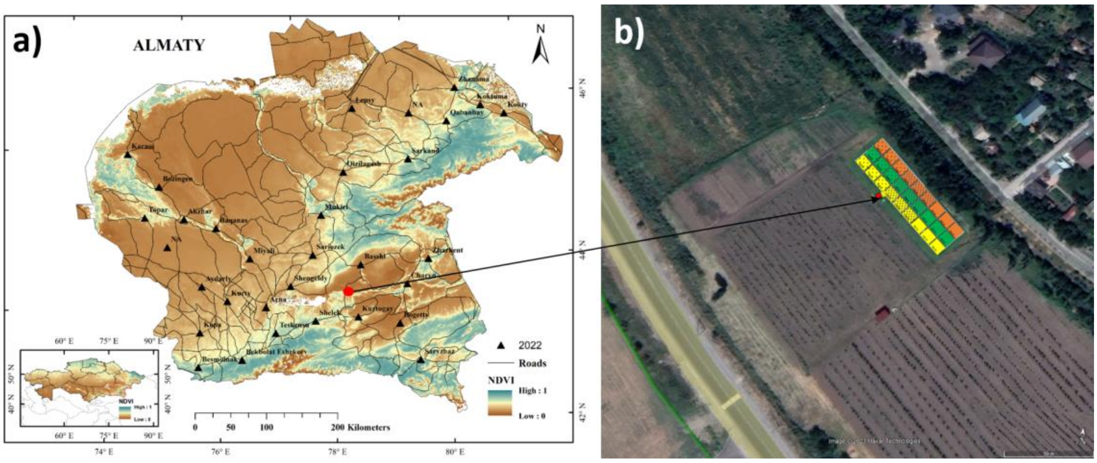

Figure 1. Location of the research site in Almaty oblast, Kazakhstan a) Elevation map of Kazakhstan and Almaty oblast b) Research site

Soil Properties of the Experimental Site

The soil type of the experimental field is "Haplic Kastanozems." In order to determine some soil characteristics of the experimental field, soil samples were taken from depths of 0-5 cm, 5-25 cm, 25-35 cm, and 35-65 cm. Particle size distribution of the collected soil samples was determined by the hydrometer method (Bouyoucos, 1962). Total organic matter was determined by the Walkley-Black method (Walkley and Black, 1934). Soil reaction was measured using a pH meter in a 1:1 soil-to-distilled water solution (Bower and Wilcox, 1965). Mineral Nitrogen was determined by Kjeldahl distillation in a 1 N KCl extract (Bremner, 1965). Available phosphorus was determined in a 0.5M $NaHCO_3$ extraction (Olsen and Dean, 1965). Available potassium was determined in a 1 N NH_4OAc extraction (Pratt, 1965).

Experimental Design

The experiment was set up in a total area of 1500 m^2 (100m x 15m) following a randomized complete block design in 2021, with three replications, totaling 27 plots (Figure 2). The study utilized Kazakhstan 435 CB variety of corn, Susyn variety of spring barley, and Zhenis variety of spring wheat, which are commonly grown in Kazakhstan, as the plant materials. The aim of the experiment was to determine the GHG emissions (CH_4 and N_2O) released from the soil under different plant cultivation practices and fertilizer applications. The chemical fertilizer Ammophos (11% N, 49% P_2O_5) and organic cattle manure (21% organic matter, 0.5% N, 0.25% $P_2O_5$and 0.6% K_2O) were used for the respective treatments, while plots without any fertilizer application were considered as controls. In the experiment, the planting of crops in the plots was carried out on May 18, 2021. Then, on June 3, 2021, the fertilizer applications (180 kg Ammophos ha^{-1} and 230 kg organic fertilizer ha^{-1}) were applied to the respective plots. The harvest of the wheat crop in the trial was on August 18th, the harvest of the barley crop was on August 23rd, and the harvest of the corn crop was done on September 22nd. The wheat trial lasted for 89 days, the barley trial for 95 days, and the corn trial lasted a total of 125 days.

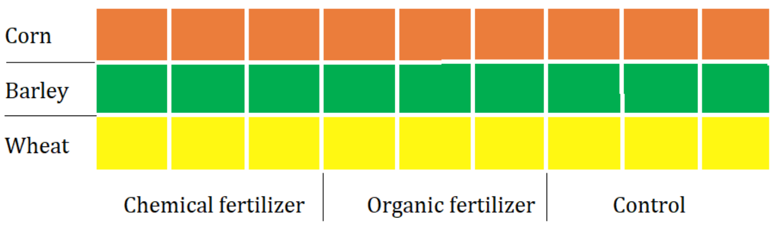

Figure 2. Experimental design

Gas Sampling and Analysis

Gas sampling was carried out five times from each plot, resulting in a total of 135 samples collected between the months of June and September 2021. Cylindrical gas sampling chambers were inserted into the soil at a depth of 10 cm between 09:00 and 11:00 in the morning. After 24 hours, the gas sampling chambers were utilized to determine the concentrations of CH_4 and N2O emitted from the soil. Gas samples were extracted from each chamber using a medical syringe through a rubber stopper and then injected into a vacuum container. CH_4 and N_2O fluxes in the gas samples were analyzed using a triple quadrupole gas chromatograph/mass spectrometer, specifically the Thermo Scientific TSQ 8000 EVO triple quadrupole mass spectrometer (MS) with a capillary column (Trace 1310 GC/TSQ 8000 Evo, Thermo Fisher Scientific). Sample separation was performed using a Supel-Q PLOT column (30m x 0.32 mm). Helium (class A) was used as the gas carrier, and 10 µl of sample was injected at a flow rate of 1 mL/min. Calibration was achieved using certified reference gas mixtures. The retention times for CH_4 and N_2O were 1.15 and 1.45 minutes, respectively. To allow sufficient time for equilibration, sample collection, injection, and data collection (IAEA, 1992), the total time per sample was set at 5 minutes.

Results

The physical and chemical properties of the soils from the experimental site with the soil type "Haplic Kastanozems" are given in Table 1 and 2. According to the obtained results, the soils of the experimental site have a loamy texture. It has been observed that as we go from the surface (0-5 cm) to the subsoil horizons, the amounts of organic matter and available N, P, and K in the soil decrease, while the soil pH increases.

Table 1. Granulometric composition of the experimental field soils

Soil depth, cm	Fraction size, mm					
	Sand		Silt			Clay
	1-0,25	0,25-0,05	0,05-0,01	0,01-0,005	0,005-0,001	<0.001
0-5	10,886	35,912	19,644	10,231	10,231	13,096
5-25	18,615	25,173	24,033	10,591	7,332	14,257
25-35	18,801	25,102	28,049	4,065	10,569	13,415
35-65	26,655	17,110	27,603	7,307	12,178	10,148

Table 2. Chemical composition of the experimental field soils

Soil depth, cm	Total Organic matter, %	Available nutrients, mg kg^{-1}			pH
		Nitrogen	Phosphorus	Potassium	
0-5	3,93	36,4	100,0	680	8,19
5-25	3,24	28,0	32,0	240	8,21
25-35	1,57	25,2	8,0	220	8,19
35-65	1,18	14,0	6,0	170	8,44

The results of the study on CH_4 and N_2O emissions from soil samples in different crop cultivation systems with various fertilization practices are presented in Figure 3 and 4.

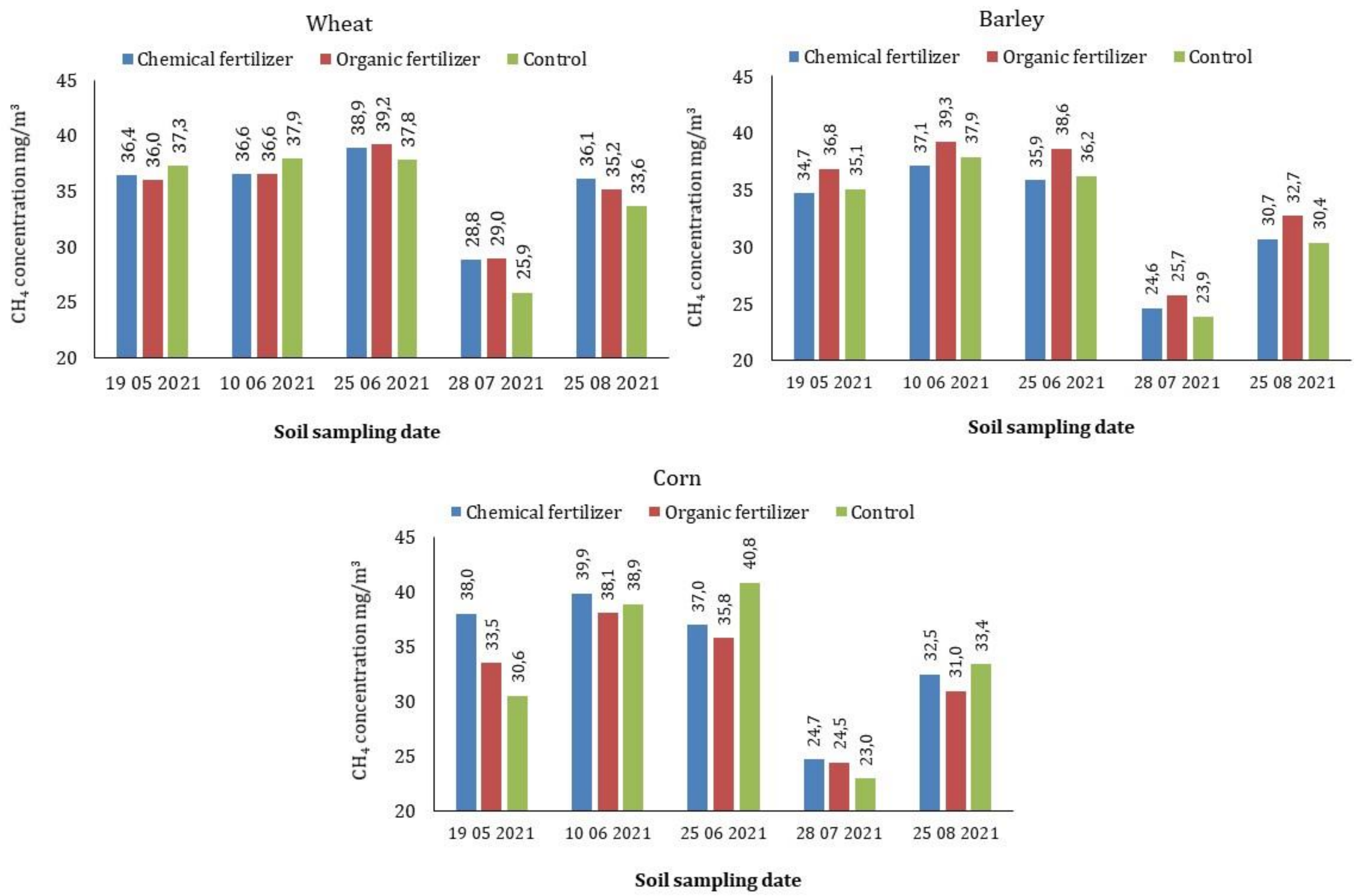

Figure 3. CH_4 concentration of soil samples from wheat growing plots at different sampling times

The measurements were taken at different sampling times between May and August 2021 for wheat, barley, and corn plots treated with chemical fertilizer, organic fertilizer, and a control group without any fertilizer application. In Figure 3, which display the CH_4 concentration of soil samples from wheat, barley, and corn growing plots, respectively, it can be observed that the CH_4 concentrations varied over time and across different fertilization treatments. For all three crops, the chemical fertilizer and organic fertilizer treatments generally exhibited higher CH_4 concentrations compared to the control plots. Notably, the organic fertilizer treatment showed slightly higher CH_4 emissions than the chemical fertilizer treatment in some cases. Regarding N_2O concentrations, Figure 4 illustrate the results for wheat, barley, and corn plots, respectively. Similar to CH_4 emissions, both chemical and organic fertilizer treatments led to elevated N_2O concentrations compared to the control plots for all three crops. The organic fertilizer treatment, in some instances, demonstrated higher N_2O emissions than the chemical fertilizer treatment.

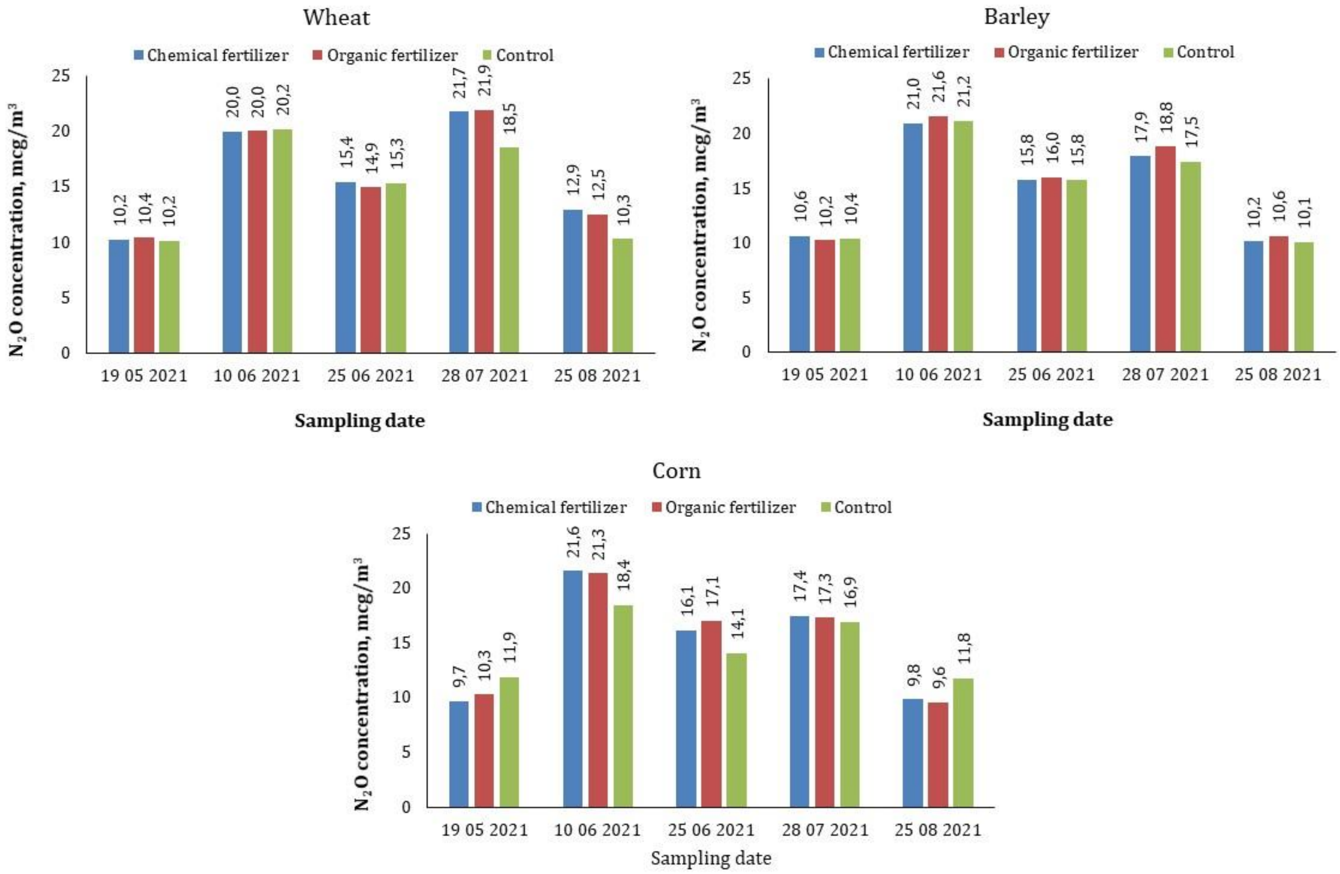

Figure 4. N_2O concentration of soil samples from wheat growing plots at different sampling times

Discussion

The present study aimed to investigate the effects of different fertilization practices on CH_4 and N_2O emissions in various crop cultivation systems of Kazakhstan, focusing on three staple crops: barley, wheat, and corn. The comparison of these crops based on the observed CH_4 and N_2O emissions provides valuable insights into the greenhouse gas dynamics and responses of each crop to varied fertilization treatments, shedding light on potential implications for soil fertility, nitrogen management, and overall agricultural sustainability.

Wheat, barley, and corn all exhibited moderate to high CH_4 emissions during the study period, consistent with the prevalence of anaerobic microbial processes in agricultural soils associated with these staple crops. Among the crops, corn consistently displayed the highest CH_4 emissions. This may be attributed to factors such as its longer growing season, higher root biomass, and potentially greater inputs of organic matter from crop residues, which create favorable conditions for methanogenic microbes. Wheat and barley showed similar CH_4 emissions, with both crops exhibiting relatively lower emissions compared to corn, likely due to their shorter growing seasons and lower root biomass. In the experiment, the lowest CH_4 emissions were determined both in plots where both chemical and organic fertilizers were applied and in control plots without any fertilizer application, during July and August. This is undoubtedly related to the region where the experiment field is located experiencing hot and low rainfall conditions during July and August, resulting in low soil moisture. CH_4 production and consumption are reported to be strongly controlled by soil moisture (van den Pol-van Dasselaar et al. 1998). Mosier et al. (1996) determined that as soil moisture content decreased in the Colorado shortgrass steppe, CH4 emissions from the soil also decreased.

Corn consistently showed the highest N_2O emissions compared to wheat and barley. The higher N_2O production in corn plots can be attributed to its higher nitrogen demand and uptake, leading to increased nitrogen availability in the soil, stimulating nitrification and denitrification processes, and subsequently resulting in higher N_2O emissions. Both wheat and barley exhibited similar N_2O emissions, with both crops showing relatively lower emissions compared to corn. The lower nitrogen demands of wheat and barley likely resulted in reduced nitrogen availability in the soil, leading to lower rates of nitrification and denitrification and subsequently reduced N_2O emissions. In the experiment, significant differences were observed in the N_2O content of the samples taken from both plots where both chemical and organic fertilizers were applied to all plants and control plots without any fertilizer application, depending on the sampling times. This indicates that environmental conditions have a more significant effect on N_2O production from soil. Increased temperature promotes nitrification and denitrification rates, and also enhances N_2O production (Granli and Bøckman 1994). Background N_2O emissions have spatial and/or inter-annual variation due to the variations in soil and climate (Lu et al., 2006; Gu et al., 2007, 2009). Gu et al. (2007) reported that background N_2O emissions from cultivated mineral soils across various soil and climatic regions were controlled by soil total N and C contents.

Overall, the application of both chemical and organic fertilizers led to elevated CH_4 and N_2O emissions compared to the control plots for all three crops. This finding emphasizes the importance of efficient and targeted nutrient management practices to minimize greenhouse gas contributions while ensuring optimal crop productivity. The organic fertilizer treatment, with its higher organic matter content, occasionally showed slightly higher CH_4 and N_2O emissions compared to the chemical fertilizer treatment. While organic fertilizers can enhance soil organic carbon content and overall soil health, they may also promote microbial activity and subsequent GHG production when applied in excessive amounts. However, the differences in CH4 and N2O concentrations between samples taken from both plots where both chemical and organic fertilizers were applied and control plots without any fertilizer application do not show a dramatic distinction. The variations in CH_4 and N_2O production in the soil are more pronounced at different sampling times. This indicates that the influence of environmental factors on CH_4 and N_2O production from the soil is more significant than the impact of fertilization activities. Similarly, in Shimizu et al. (2013), a study conducted on grasslands in Japan to investigate CH_4 and N_2O production in soils with chemical fertilizer and manure application, they found that climatic factors have a more substantial effect on CH_4 and N_2O emissions from the soil than the fertilizers applied to the soil.

Conclusion

This study aimed to investigate the effects of different fertilization practices on CH_4 and N_2O emissions in various crop cultivation systems in Kazakhstan, with a focus on three staple crops: barley, wheat, and corn. The comparison of these crops based on the observed greenhouse gas (GHG) emissions provides valuable insights into their unique responses to fertilization treatments and their implications for soil fertility, nitrogen management, and overall agricultural sustainability. The study explored the effects of varied fertilization practices on CH_4 and N_2O emissions in different crop cultivation systems of Kazakhstan, focusing on barley, wheat, and corn. Corn exhibited consistently higher CH_4 and N_2O emissions compared to wheat and barley due to its longer growing season and higher nitrogen demand. Both chemical and organic fertilizers led to increased CH_4 and N_2O emissions in all three crops, emphasizing the importance of efficient nutrient management. However, the differences in CH_4 and N_2O concentrations between fertilized and unfertilized plots were not highly pronounced, suggesting that environmental factors have a more substantial impact on gas production than the type of fertilizer used. Environmental conditions, such as soil moisture and temperature, were found to influence CH_4 and N_2O emissions significantly.

In conclusion, this study provides valuable data for developing sustainable agricultural practices to mitigate greenhouse gas emissions while ensuring optimal crop productivity in the region. Future research should further explore the interplay of environmental factors and fertilization practices on greenhouse gas dynamics for more comprehensive mitigation strategies.

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