Journal of the Korea Organic Resources Recycling Association, 30(4), pp.151-163 (2022)
ISSN 1225-6498 eISSN 2508-3015 https://doi.org/10.17137/korrae.2022.30.4.151

Original Paper

Impacts of Different Organic Fertilizers on Soil Fertility and Soil Respiration for a Corn (*Zea mays* L.) Cropping System

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옥수수 밭에서 유기질 비료가 토양 비옥도 및 토양 호흡에 미치는 영향

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(Received: Nov. 14, 2022 / Revised: Nov. 13, 2022/ Accepted: Dec. 19, 2022)

초 록: 본 연구는 친환경 농산물 생산을 위한 양분관리 자재로 유기질비료 처리에 따른 옥수수 재배 토양의 비옥도 및 토양 호흡에 미치는 영향을 분석하였다. 시험장소는 국립농업과학원 유기농업과 시험포장에서 수행하였으며 처리구는 퇴비 (Com), 발효비료 (FOF), 혼합 유박 (PC), 무비구 (NF)로 처리구당 3반복 완전임의 배치하였다. 처리량은 174kg N/ha로 옥수수 표준시비량의 질소기준에 준하여 처리하였다. 옥수수 정식 8주 후 토양분석 결과, 퇴비는 토양의 탄소 (C)와 질소 (N)를 각각 7.48 및 0.76g/kg으로 증가시켰고, 다른 처리구는 시험 전과 차이가 없었다. 또한 시험 후 토양의 화학적 특성은 무비구를 제외하고 유의한 차이는 없었다. 토양 CO_2 발생량은 발효비료 처리가 다른 처리구보다 31-76% 증가시켰으며 두 번의 제초작업 후 CH_4 발생량의 차이는 없었다. 토양의 N_2O 배출량은 발효비료 처리가 다른 처리구보다 87-96% 감소되었다. 미생물 밀도 조사 결과, 시험 전에 비해 시험 후 토양의 사상균 및 방선균 밀도를 각각 25%, 16% 증가되었다. 따라서 친환경 농산물 생산을 위한 발효비료 등 유기질 비료는 자원을 순환하며 토양 생산성을 유지하는데 기여할 것이다.

주제어: 유기농업, 유기질 비료, 토양 탄소, 토양 미생물, 토양 호흡

ABSTRACT: This study was conducted to promote organic fertilizer(s) that sustain soil productivity for corn production and protect the environment as required by the Act on the promotion of eco-friendly agriculture. It was conducted at the research station of the Organic Agriculture Division of the National Institute of Agricultural. The treatments consisted of Compost (Com), Bokashi as fermented organic fertilizer (FOF), and mixed expeller pressed cake (PC). They were applied at 174 kg N /ha to field corn, together with a ‘no fertilizer’ check in Randomized Complete Block Design. At eight weeks after transplanting (WAT) corn, compost increased soil carbon (C) and nitrogen (N) to 7.48 and 0.76 g/kg respectively, while other fertilizers maintained the initial levels (before treatment application). At corn harvest (13 WAT), soil chemical properties (total C, total N, pH, electrical conductivity, P_2O_5, Ca, K, and Mg) were similar among all organic fertilizer treatments. For soil respiration, FOF increased soil CO_2 respiration by 31-76% above other fertilizer treatments. However, there were no prominent changes in the trends of CH_4 fluxes following the two mechanical weeding operations. Fermented organic fertilizer affected N_2O emissions between 87-96% lower than other fertilizer treatments.

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Compared to the initial microbial densities, FOF increased fungi and actinomycete colony foming unit by 25 and 16% at harvest. Therefore, the additional potential of improving soil biological fertility and local availability of raw materials make FOF a better option to sustain soil productivity while protecting the environment.

Keywords: Organic farming, Organic fertilizer, Soil carbon, Soil microbes, Soil respiration

1. Introduction

Over-reliance on agrochemicals contributed to land degradation, desertification, loss of biodiversity, and air and water pollution; and made agricultural production less sustainable in South Korea in the past (Suh, 2018). In early 1990, various forms of sustainable agriculture technologies including organic farming and permaculture were re-introduced in the country (Suh, 2014). Since then, there has been a growing demand for organic foods, due to informed health and environmental concerns from consumers; which birthed the Act on Promotion of Eco-Friendly Agriculture in 1997 by the Korean government (Furuno, 2001).

Without a range of ecosystem services such as carbon sequestration in soils, clean water systems, and balanced biodiversity, sustainable food production may not be achieved (Pretty and Hine, 2009). Under the eco-friendly act, the use of inorganic fertilizers has gradually been replaced with organic fertilizers but still leaves much to be desired (Um and Lee, 2001), partly because exclusive adoption of organic fertilizers has not assured a complete prospect of making the country totally food secured in a short term. Organic fertilizers improve soil organic matter (SOM) which consequently improves soil physical and microbial properties and regulates nutrient/water retention capacities to reduce nutrient losses through pathways like greenhouse gas emissions (Mockeviciene et al., 2021; Michael, 2021; Songsong et al., 2019; Islam, 2012). These agroecosystem services make organic fertilizers invaluable. However, more research is needed to arrive at organic fertilizers that can in addition to the above-mentioned services for improving soil chemical fertility in the short term to enhance crop productivity. Since the introduction of the eco-friendly act, various organic and natural farming measures such as recycling organic waste to make fertilizer, intercropping with legumes, multi-cropping, and crop rotations among others have been practiced by farmers (Abulu, 2020). To make organic agriculture more sustainable, stakeholders (farmers, government, researchers) have adopted the use of locally available resources to make organic fertilizers. Liquid organic fertilizers are made from resources such as bone meal, fish meal, sesame oil, starfish, oil seed (castor or soybean) cake, and animal waste among others (Choi, 2020; Jayasundara et al., 2016). Composting of animal waste such as cattle, poultry, and pig manure and municipal solid waste is also a common practice under strict quality control measures to ensure environment and food safety (Um and Lee, 2001; Lee, 2000). Green manure and biochar applications have also been practiced (Kim et al., 2016; Park et al., 2015) while pressed castor or soybean cakes have been imported for use (An et al., 2020). Fermented mixed organic fertilizer locally called 'Bokashi' has been widely promoted in Asia because of its soil chemical and biological fertility benefits (An et al., 2020). It has made strides in the organic agriculture space in the Republic of Korea, particularly because its raw materials are sourced locally. To make different organic fertilizer types, it is important to evaluate the performance of these organic fertilizers in terms of soil nutrients, Soil organic matter (SOM) build-up, microbiology improvement, and environmental protection. This research was to provide baseline information to the government, farmers, and other stakeholders on which organic fertilizers to invest more resources into making cropping systems more sustainable while protecting the environment.

2. Materials and Methods

2.1. Description of the research field

The study was conducted in a corn cropping system at the research station of the Organic Agriculture Division of Rural Development Administration. There is located in Wanju-gun, Jeollabuk-do, Republic of Korea on latitude 23.5226°N and longitude 72.2579°E. During the experimental period, the research area received a total of 551 mm of rainfall with an average minimum temperature of 20°C and an average maximum temperature of 29.7°C (Wanju-gun, Jeollabuk-do, Korea weather station). Before the start of the experiment, the soil had a pH (1:5) of 6.97; electrical conductivity (EC) of 0.35 dS/m; total carbon (C), total nitrogen (N), and SOM of 5.79, 0.56, and 9.98 g/kg respectively; phosphorus pentoxide (P_2O_5) concentration of 68.35 mg/kg; and calcium (Ca), potassium (K), magnesium (Mg), sodium (Na) and cation exchange capacity (CEC) of 6.27, 0.46, 1.44, 0.12, 8.28 cmol+/kg respectively. It also contained $8.11x\ 10^7$ bacteria, $0.03x10^7$ fungi, and $0.67x10^7$ actinomycete colony form unit/g dry soil at the start of the experiment. The field had been left to follow for several years before this experimental setup.

2.2. Experimental design and treatment application

The experiment was conducted in a Randomized Complete Block Design with three replications. Four fertilizer treatments including control (NoF), fermented organic fertilizer, "*Bokashi*" (FOF), mixed expeller press cake (PC), and compost (Com) were applied. Fertilizers were applied at a Nitrogen (N) rate of 174 kg/ha, one week before corn transplanting. At fertilizer application FOF contained 30.85% total C and 4.36% total N (C: N ratio of 7.08); Com contained 31.66% total C and 3.20% total N (C: N ratio of 9.89); and PC contained 40.52% total C and 4.57% total N (C: N ratio of 8.87). There were a total of 12 plots, each measuring 3.5 m x 2.4m. The N% of each compost was determined to enable the calculation and measurement of amounts to apply. The fertilizers were weighed on a dry mass basis and applied on their designated plots by broadcasting, and evenly mixed with the surface soil by a fertilizer spreader. The following formula was used to calculate the amounts of fertilizers to apply:

$$\text{Organic fertilizer} = \frac{target\ \ N\ rate\ \left(\frac{kg}{ha}\right)\times plot\ \ area\ \ (m^2)\times 100\% \times 100\%}{area\ of\ hectare\ (m^2)\times \%N\ in\ \ fertilizer\ \times \%\ \ dry\ fertilizer\ (without\ \ moisture)} \quad \text{eqn 1}$$

2.3. Corn cultivation

Corn was transplanted to the field on May 18. It took a duration of 13 weeks to harvest. Corn plants were irrigated with fresh water from the day of planting till one month after transplanting when rainfall was sufficient and more consistent. Irrigation water usually flooded the soil (the amount was not quantified). Mechanical weeding operations on all plots occurred on June 17 and July 22.

2.4. Soil sampling and analyses after corn planting

Soil samples were collected for analysis before treatment application, at 8 weeks after transplanting (WAT) and 13 WAT (at harvest). Samples collected before treatment application and at 13 WAT were analyzed for soil total C (g/kg) and N (g/kg), pH (1:5), EC (dS/m), total C (g/kg), total N (g/kg), P_2O_5 (mg/kg) and K^+ ($cmol^+$/kg), Ca^{2+} ($cmol^+$/kg), Mg^{2+} ($cmol^+$/kg), Na^+($cmol^+$/kg) and CEC ($cmol^+$/kg), and densities of bacteria, fungi, and actinomycetes. Samples were analyzed for only total C and N at 8 WAT. At each soil sampling campaign, five random soil samples were collected from soil surface layer (0- 15 cm depth) using an auger; and composited for each plot. Soil pH was determined at a ratio of 1 part soil to 5 parts water, using the Orion model Star A211, USA pH meter. Electrical conductivity was determined with the Hanna model Hl 9932, Korea. The Dumas dry combustion method was used to determine soil total C and N, using the vario max CN, Elemental Analyzer, Germany. P_2O_5 was determined with the Lancaster method, using a UV-2450, Shimadzu, Japan. Exchangeable cations (Ca, Mg, K and Na) were determined by extraction with 1 N ammonium acetate solution at a pH of 7.0, using the Integra XL, GBC Scientific Equipment Pty Ltd., Australia. CEC was determined by calculating the sum of milliequivalents/100g dry soil of all exchangeable cations. Bacteria, fungi, and actinomycete density determinations were done by counting colony form units from plated soil solutions on Yeast-Glucose, Rose-Bengal, and Starch-Casein agar media respectively. Protocols followed for chemical properties and microbial densities analyses are Korean standard methods prescribed by RDA (2000).

2.5. Gas sampling and analyses for soil respiration

The closed static chamber method (Hwang, 2017; Rolston, 1986) was used for gas collection. Chambers were installed at the center of all 15 plots. Gases were collected weekly for the three months duration of corn growth, starting from 1 WAT. Small weeds growing in the bases of the chambers were always removed before covering them with the tops. Gases were collected with 50ml plastic syringes, 30 minutes after closing the chambers. Syringes were sealed with attached stoppers and conveyed to the laboratory to analyze gases for their concentrations of soil respiration (CO_2), methane (CH_4), and nitrous oxide (N_2O). Concentrations of the three gases were measured by gas chromatography (Shimadzu, GC- 2010, Japan) with Porapak NQ columns (Q 80-100 mesh) using 30 ml of the gas samples by manual control. A ^{63}Ni electron capture detector, thermal conductivity detector and flame ionization detector were used to quantify CO_2, CH_4, and N_2O respectively. An increase in each gas concentration per unit surface area of the closed chamber (from the soil surface to the top of the chamber cover) at 30 minutes intervals were calculated, using the closed-chamber equation (Lou et al., 2004) below. Fluxes were averaged across treatments.

$$F = \rho \times (V/A) \times (\Delta C/\Delta t) \times (273/T) \qquad \text{eqn 2}$$

Where F is the CO_2, CH_4, or N_2O flux ($mg/m^2/hr$); ρ is the gas density (mg/cm^3) of CO2, CH4, or N2O in a standardized state; V is the volume (m^3) of the chamber (from the soil surface to top of the chamber cover); A is the surface area (m^2) of the chamber; $\Delta C/\Delta t$ is the rate of increase of each gas concentration ($mg/m^3/hr$) in the chamber, and T is the absolute temperature (K) of the chamber.

2.6. Statistical analyses

Soil and greenhouse gas flux data were subjected to analysis of variance (ANOVA) using IBM SPSS Statistics 20 package. Fertilizer treatments were run as fixed factors. Measured field data were run as dependent variables and blocks/replications were run as covariates. Significant treatment means were separated using Fisher's least significant difference (LSD). Regression analysis in excel was used to determine the relationship between various measured soil and N parameters.

3. Results

3.1. Effect of fertilizers on SOM indices, other soil nutrients, and soil microbial densities

Initial soil total C was averaged at 5.79 g/kg before any treatment application. Eight weeks after transplanting corn (8 WAT), fertilizer treatments significantly affected ($p<0.01$) soil total C concentrations (Fig. 1A). Compost and PC increased total C levels, ~ 22% above initial levels (Fig. 1A). No fertilizer and FOF affected relatively lower total C content, about the same amounts of the initial level on this date (Fig. 1A). However, at corn harvest (13 WAT), all organic fertilizers affected comparable amounts of total C ($p>0.05$); about 0.03-0.7 g/kg above initial levels; while NoF reduced total C by 0.3 g/kg compared to initial soil level (Table 1). The average initial soil total N was 0.56 g/kg but increased ($p<0.01$) by 13 and 26% at 8 WAT (Fig. 1B) with applications of PC and Com respectively (Fig. 1B). On this sampling date, NoF and FOF also affected relatively lower total N similar to initial soil levels (Fig. 1B). However, at 13 WAT, all organic fertilizers maintained initial soil total N levels (Table 1). At harvest, soil pH and EC, and soil concentrations of P_2O_5, Ca^{2+}, K^+, and Mg^{2+} were comparable ($p > 0.05$) among all the fertilizer treatments (Table 1). They were averaged at 7.51, 0.28 dS/m, 82.55 mg/kg, 6.63 cmol$^+$/kg, 0.42 cmol$^+$/kg, and 1.42 cmol$^+$/kg, respectively. However, compared to the initial soil pH (6.97) before treatment application, the soil had generally become more alkaline at harvest (Table 1). There was a general decline of 11-29% in soil EC compared to the initial EC (0.35 dS/m) before treatment applications. Aside NoF which marginally reduced soil P_2O_5 concentration, all the organic fertilizers increased P_2O_5 by 4-38% above the initial level. Compost increased soil Ca^{2+} concentration by about 13%, compared to the initial level, while all other fertilizer treatments maintained about the same Ca^{2+} concentrations as before the experimental set-up (Table 1). Compared to the initial soil K^+ before experimental se-up, all but compost reduced initial soil K^+ concentration level by harvest time (Table 1). Initial soil Mg^{2+} concentration was also maintained by all the treatments at harvest (Table 1). Fermented organic fertilizer increased ($p=0.04$) soil Na^+ concentration (0.19 cmol$^+$/kg) by ~ 22% more than other fertilizer treatments at harvest (Table 1). At harvest, there were no significant differences ($p>0.05$) between the densities (colony form unit/ g dry soil) of bacteria, fungi, and actinomycetes affected by the fertilizer treatments (Table 1). However, compared to soil microbial densities before treatment applications, Com increased soil bacteria and actinomycetes densities by 10% and 15%, respectively, but did not change fungi densities (Table 1). Fermented organic fertilizer increased bacteria, fungi, and actinomycetes densities by 9%, 25%, and 16% respectively, while PC increased bacteria and fungi densities by 1% and 25% respectively (Table 1). Pressed cake, in turn, reduced soil actinomycetes concentration by 3% compared to initial actinomycetes density. Thus, altogether, FOF added the largest microbial densities to the soil at the end of the study compared to the initial microbial densities.

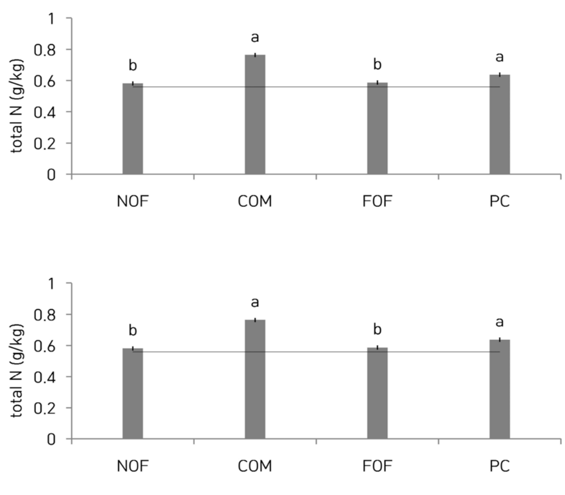

Fig. 1. Soil total carbon (A) and soil total nitrogen (B) (y-axes) affected by 'no fertilizer', compost, fermented organic fertilizer, and mixed expeller pressed cake (x-axis) at 8 weeks after transplanting corn. Straight lines across the bars represent the initial total C and total N at the start of the experiment. Error bars represent standard errors of the treatment means on sampling dates. Different lowercase letters on top of the bars show differences in treatment means at least a significant difference of $p \leq 0.05$.

Table 1. Effect of Chemical Properties and Soil Microbial Densities to Different Treatments at Corn Harvest.

	Soil property before treatment	NoF	Com	FOF	PC
pH (1:5)	*6.97*	7.48±0.08	7.78±0.04	7.34±0.13	7.43±0.04
EC (dS/m)	*0.35*	0.25±0.01	0.31±0.01	0.29±0.01	0.25±0.01
P_2O_5 (mg/kg)	*68.35*	68.29±1.84	109.43±3.02	79.33±8.43	73.16±2.73
Soil organic matter indices (g/kg)					
Total C	*5.79*	5.49±0.11	6.49±0.42	5.82±0.21	5.92±0.20
Total N	*0.56*	0.56±0.01	0.68±0.48	0.61±0.02	0.58±0.02
Exchangeable cations (cmol+/kg)					
Ca^{2+}	*6.37*	6.34±0.08	7.24±0.24	6.56±0.33	6.39±0.28
K^+	*0.46*	0.38±0.01	0.50±0.03	0.38±0.01	0.40±0.02
Mg^{2+}	*1.44*	1.40±0.03	1.39±0.09	1.44±0.04	1.46±0.03
Na^+	*0.12*	$0.15±0.01_{(b)}$	$0.14±0.01_{(b)}$	$0.19±0.01_{(a)}$	$0.15±0.01_{(b)}$
Microbial densities [colony form unit (x 10^7) /g dry soil]					
Bacteria	*8.11*	8.60±1.14	9.03±0.23	8.90±2.25	8.20±1.17
Fungi	*0.03*	0.03±0.004	0.03±0.004	0.04±0.002	0.04±0.001
Actinomycetes	*0.67*	0.52±0.20	0.79±0.45	0.80±0.14	0.65±0.25

Numbers following ± signs are standard errors of the treatment means. Different lowercase letters in parenthesis attached to means of Na^+ show differences in treatment means at least significant difference ($p \leq 0.05$).

3.2. Effect of fertilizers on soil respiration during corn cultivation

Significant differences ($p=0.04$) in soil respiration among fertilizer treatments were observed only at 12 WAT (Fig. 2B). On this date, FOF increased soil respiration by 31-76% above other fertilizer treatments. Aside from this date, all treatments affected statistically similar rates of CO_2 emissions on all the other sampling dates (Fig. 2B). However, considering the trends of soil respiration over the growing period, the sampling date (7 WAT) with the highest average temperature (43°C), but relatively lowest weekly antecedent rainfall (7 mm of rainfall without irrigation); coincided with the least soil respiration from all treatments (Figs. 2A and 2B). After the second mechanical weeding on July 22, soil respiration from all treatments rose to peak levels, up to two weekly sampling dates before CO_2 emissions started to decline.

Gas samples collected 5 WAT were the only samples that demonstrated significant differences ($p<0.01$) in CH_4 fluxes (Fig. 2C). Methane was assimilated by the soil on this date in the following order: FOF>Com>PC> NoF. Peak CH_4 emissions from all treatments occurred and coincided with a relatively higher temperature (35°C) and relatively higher total weekly antecedent rainfall amount (98 mm) at 6 WAT. Methane was assimilated by all the fertilizer treatments, almost half the sampling times. There were no prominent changes in the trends of CH_4 fluxes following the two mechanical weeding operations (Fig. 2C).

Significant differences were observed among N_2O emissions by the fertilizer treatments on 10 WAT and 13 WAT (Fig. 2D). At 10 WAT, fertilizer treatments affected N_2O emission in the order NoF> PC> Com > FOF. Fermented organic fertilizer affected N_2O emissions between 87-96% lower than other fertilizer treatments on this date. At 13 WAT, fermented organic fertilizer again affected the least N_2O emission (Fig. 2D). Nitrous oxide emissions on sampling dates other than the above-mentioned were comparable for all fertilizer treatments. Generally peak N_2O emissions from all the treatments were observed within the first few weeks of study when

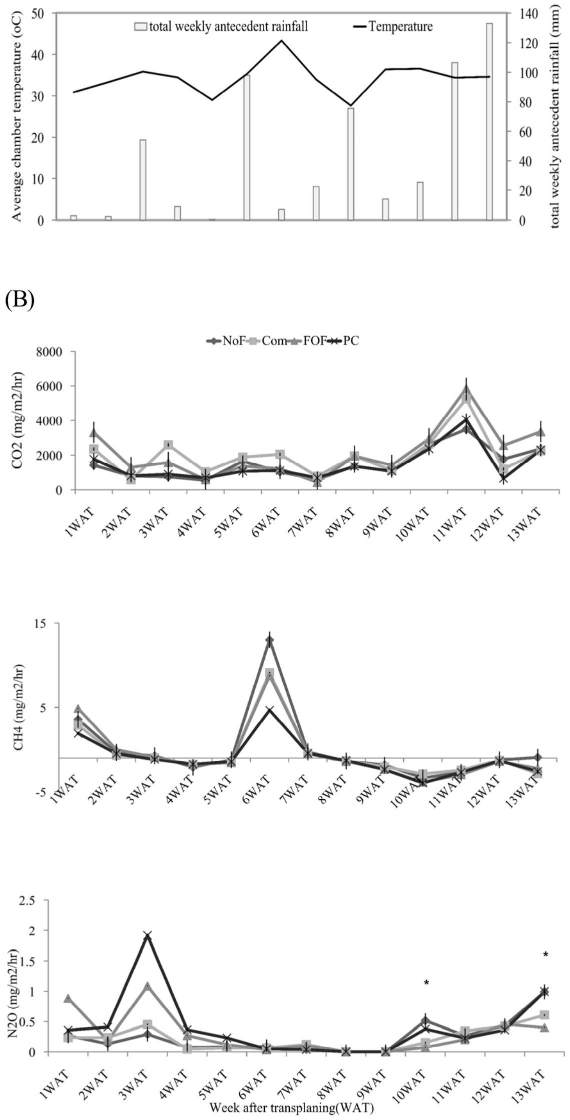

Fig. 2. Weekly average chamber temperatures (primary vertical y-axis) and total weekly antecedent rainfall (bar graph; secondary vertical y-axis) over corn growing period (A); Weekly soil respiration (B), methane fluxes (C) and nitrous oxide emissions (D) (line graphs) from the soil affected by ‘no fertilizer’, compost, fermented organic fertilizer, mixed expeller pressed cake and mineral fertilizer during the growth period of corn. X-axes represent weekly sampling dates. Error bars represent standard errors of the treatment means on each sampling date. Sampling dates with asterisks shows significant differences between treatment means at least significant difference of $p \leq 0.05$. The double-ended arrow in 2A shows the duration of irrigation before the onset of sufficient amounts of rainfall.

corn crops were being irrigated, and in the last few weeks to harvest, after the second mechanical weeding. Trends in N_2O emission after the second mechanical weeding seemed to follow the pattern of an increase in amounts of total weekly antecedent rainfall (Figs. 2A, 2D). Thus, the higher the rainfall amounts, the higher the rise in N_2O emission (Fig. 2D). Peak temperatures (Fig. 2A) did not seem to influence N_2O emissions.

4. Discussion

Higher total C affected by Com and PC in the soil samples collected at 8 WAT (Fig. 1A) is only an artifact of relatively higher C content per unit N in them. Compost and PC had C: N ratios of 9.89 and 8.87 compared to a C: N ratio of 7.08 in FOF. This observation is in line with the findings of Wingeyer (2007), who reported relatively higher soil C content after the application of organic residues with a higher C: N ratio compared to soybean residue with a lower C: N ratio. Our observation suggests that Com and PC may have added more organic matter to the soil around this time since SOM constitutes ~58% of total C (USDA, 2022). Additionally, the abundance of labile N forms in FOF, due to the anaerobic fermentation process used in making it (Merfield, 2012), may have caused a rapid N loss from it, leading to a low total N affected by it on this date. Previous studies have reported rapid C and N losses due to the abundance of labile organic matter and fast mineralization rates of some organic soil inputs (Yang et al., 2022; Wang et al., 2017). Continuous use of N by plants for their physiological needs (Muratore et al., 2021), and continuous soil respiration throughout the growing period caused the general reduction in total C and total N from all the fertilizer treatments by the end of the study (at harvest).

It is usually the norm that organic fertilizers add soluble salts and raise the EC of soils (Mylavarapu et al, 2020; Provin et al., 2001), however, the contrary was observed in our study. The general reduction in soil EC observed at the end of the study (Table 1) could be the combined effect of the leaching of salts by excess irrigation water supplied to the crops at the beginning of the experiment and the uptake of nutrients in the form of soil salts by the crops (Roy et al., 2020; Provin et al., 2001). Only about a total of 558 mm of water is required to grow the highest yield for corn cultivation (Kruger, 2021), and our field received a total of 551 mm of rainfall during the corn-growing period. This suggests that the field received lots of excess water during the one month of irrigation with fresh water; even though it was the best option then because the rains were delayed. The general decline in EC implies a reduction of the amounts of soluble salts and H^+ ions (in the chemical composition of some of the salts such as $NaHCO_3$, $CaSO_4.2H_2O$, $CaCl_2.2H_2O$) which may have caused the general increase in soil pH observed. Our results confirm the negative correlation between soil EC and pH reported by Provin et al. (2001). Highest Na^+ (0.19 cmol+/kg) concentration affected by FOF must have been associated with the decline in concentrations of other cations affected by FOF (compared to the initial; Table 1) because increasing Na^+ concentration displaces other cations (Botta, 2016). However, Na^+ concentration of 0.19 $cmol^+/kg$ which extrapolates to 2.5% exchangeable sodium percentage in our soil did not put it in a sodic category (MacDonald, 2021), hence FOF is not problematic. Though non-essential, Na^+ may be beneficial for the electrical neutralization of inorganic and organic anions and macromolecules, pH homeostasis, control of membrane electrical potential, regulation of cell osmotic pressure and turgor-driven cell movements in plants (Nieves-Cordones et al., 2016). Thus, FOF application could offer these benefits to growing crops with a slight Na^+ increase. The presence of microbes in the organic fertilizers jump-started microbial growth (Ojo et al., 2015) and caused increases in microbial densities in fertilizer-applied plots by the end of the study compared to the initial (Table 1). Additionally, FOF relatively increased microbial densities among other fertilizers because at the application it supplied more labile forms of nutrients which enhanced microbial growth. Our result is in line with the findings of Goyal et al. (1999), who also reported increased microbial biomass C and N after applying fermented organic fertilizer to spinach, compared to other fertilizers. Increased microbial densities in FOF-applied plots indicate the better potential to increase the abundance of beneficial microbes for soil biological fertility improvement. Increased microbial density is a key potential to increase microbial activities in the soil, such as biological nitrogen fixation, phosphorus solubilization and availability, nutrient cycling, and disease control among others (Shah et al., 2021; Toor and Adnan, 2020) with consistent FOF application. The field generally had a relatively higher percentage increase in fungi cell counts at the end of the study, compared to other microbes (Table 1), because the soil had become more alkaline by the end of the harvest. Silva-Sanchez et al. (2019) also reported a shift toward fungi dominance in their experiment, when soil pH increased.

Factors such as availability of soil C, mineralization rate of soil inputs, soil moisture availability, temperature, and soil disturbance, and control soil respiration (CO_2 emission) (Ray et al., 2020; Raich and Tufekciogul, 2000; Conant et al., 2000). The order of importance of these factors in affecting soil respiration follows the sequence: C availability > soil moisture/ temperature> soil disturbance (Conant et al., 2000; Bridgham and Richardson, 1992). A faster mineralization rate of FOF (due to the lowest C: N ratio) and relatively higher amounts of weekly antecedent rainfall (106.5 mm; Fig. 2A) together with favorable temperature (34°C) led to the highest soil respiration affected by FOF at 12 WAT. Ray et al. (2020) also observed the highest CO_2 emissions from chicken manure and milorganite compared to dairy manure, a few weeks after application, because of their lower C: N ratios. The insufficient antecedent weekly rainfall on 07.07.22 (7 mm; Fig. 2A) resulted in the least CO_2 emission from all the fertilizer treatments even with the highest temperature (43°C; Fig. 2A) on that sampling date. This is because soil moisture and temperature must interact to affect soil respiration (Fig. 2B) (Brempong et al., 2019; Conant et al., 2000). Moreover, dry heat above 40°C may have caused the denaturation of some microbial enzymes, leading to reduced soil respiration (Skiba, 2008). Peak CO_2 emissions from all fertilizer treatments, up to two sampling dates after the second mechanical weeding, is the combined effect of increased oxidation of C following soil disturbances and adequate rainfall. Previous studies have identified increased CO_2 emission with varying degrees of soil disturbances, due to the rapid oxidation of C (Cai and Chang, 2020; Bista et al., 2017; Grave et al., 2015).

Methane assimilation occurring on several sampling dates (Fig. 2C) is a typical characteristic of upland soils because they have abundant oxidizing agents that favor methanotrophic activities (Kim et al., 2012). Soil moisture is the most important factor controlling CH4 flux processes; followed by soil C content (Korkiakoski et al., 2022), therefore, statistically significant CH_4 assimilation by all the fertilizer treatments on the sampling date with the least amount of total antecedent rainfall (5WAT) was expected. The highest CH_4 assimilation from FOF on this date is because soil C affected by FOF around this time had reduced, judging from Fig. 1A. Peak CH_4 emissions from all the treatments at 6 WAT are because the soil was saturated with relatively high total weekly antecedent rainfall which reduced soil redox potential, and encouraged methanogenesis (Valero et al., 2018; Wang et al., 1993). It can be inferred from Fig. 1A and Table 1 that soil C reduced with time in the growing period, hence the reduced magnitude in CH_4 emission even with higher rainfall amounts, close to the end of the growing period.

Suitable mineral N substrates and the prevalence of anaerobic conditions are major determinants of N_2O emissions from agricultural soils (Wang et al., 2021; Smith et al., 2000). As time progressed through the study, continuous N uptake by plants and the rapid mineralization of FOF from the onset of the study may have led to lower N availability and consequent lower N_2O emission (0.07 and 0.40 mg/m^2/hr respectively) from it at 10 and 13 WAT (Fig. 2D). A steady increase in the trends of N_2O emission from all the treatments, following the same increasing order of total weekly antecedent rainfall, after the second mechanical weeding on 22.07.22 (Fig. 2D), is the result of soil disturbance from the weeding and creation of more anaerobic soil microsites with moisture addition. Such anaerobic microsites host microorganisms that use alternative sources of oxygen like NO_3^- to carry out N reduction processes (Bergsma et al. 2011). The disturbance may have also caused temporal destruction or dis-continuum of soil macro and micro pores leading to a burst out in N_2O emission (Lehrsch et al. 2016).

5. Conclusion

This study was conducted to identify and promote the best-performing organic fertilizer among conventional compost, fermented organic fertilizer, and mixed expeller pressed cake in terms of soil fertility improvement, and soil respiration. From our results, all three fertilizers affected similar total C and total N concentrations by the end of the study; which suggests the same effect on soil organic matter. They also affected similar pH and EC, and soil P_2O_5, Ca^{2+}, Mg^{2+}, and K^+ concentrations at the end of the study. For soil respiration, FOF increased soil CO_2 respiration by 31-76% above other fertilizer treatments. There were no prominent changes in the trends of CH_4 fluxes following the two mechanical weeding operations. Fermented organic fertilizer affected N_2O emissions between 87-96% lower than other fertilizer treatments.

However, in terms of soil microbiology, fermented organic fertilizer stands out because it increased soil fungi and actinomycetes densities by relatively higher margins than other fertilizers at the end of the study, compared to soil microbial properties before treatment applications. Thus, aside from improving soil organic matter and nutrient concentrations in the same measure as other organic fertilizers, and making no significant contribution to global warming, fermented organic fertilizer also has the potential to improve soil biological fertility. This indicates that with consistent fermented organic fertilizer application, there is a high potential to improve soil microbial activities like biological nitrogen fixation, phosphorus solubilization, and availability, nutrient cycling processes, and enhance crop disease resistance among other benefits. Moreover, its raw materials are locally sourced and it takes relatively very few days to make. Therefore, fermented organic fertilizer (Bokashi) is recommended to farmers and other stakeholders.

Acknowledgment

This project was supported by Korea-Africa Food and Agriculture Cooperation Initiative (KAFACI) and the Organic Agriculture Division of National Institute of Agricultural Science, Rural Development Administration, under the project number, PJ015990012022.

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