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Methane (CH_4) emissions exceeding the threshold from chilli cultivation mulching practices in Sleman Regency, Indonesia

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ABSTRACT

Methane (CH_4) is a potent greenhouse gas contributing to global warming, although there is limited information on its emissions dynamics in dryland horticulture. Chilli cultivation practices comprising fertilization and mulching may influence CH_4 emissions through alterations in soil temperature and moisture. Therefore, this study aimed to evaluate the effect of different mulching practices on CH_4 emissions and determine the threshold for sustainable chilli cultivation in tropical dryland conditions. A field experiment was conducted in Sleman, Indonesia, using a randomized block design with three mulch treatments. These included unmulched treatment (M0), organic mulch (M1), and plastic mulch (M2), each replicated three times. Gas sampling was performed biweekly for 112 days using the closed chamber method. Soil temperature and Volumetric Water Content (VWC) were recorded using in situ sensors. The results showed that mulch treatments significantly influenced CH_4 emissions ($p < 0.001$). M1 produced the highest average CH_4 flux (0.114 mg m^{-2} h^{-1}), followed by M2 (0.043 mg m^{-2} h^{-1}) and M0 (0.016 mg m^{-2} h^{-1}). All treatments exceeded the calculated CH_4 threshold of 0.145 mg m^{-2} h^{-1} under certain conditions. These results showed the need for careful mulching selection to reduce environmental impact and support the development of CH_4 emissions threshold for sustainable dryland horticulture.

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1. INTRODUCTION

Greenhouse gas (GHG) emissions are among the challenges faced in recent decades, contributing to climate change. The agriculture sector contributes to GHG emissions because of various cultivation practices through several sources, such as methane (CH_4) (Molina et al., 2023). Among various practices, chilli cultivation on dryland is economically valuable (Karyani et al., 2020), but contributes to GHG emissions due to intensive tillage practices, fertilizer use, and mulching (Song et al., 2021; Voltr et al., 2021; Yang et al., 2023). Mulching influences soil microclimate, particularly temperature and moisture, which directly affects microbial activity related to CH_4 production. Organic mulch also enhances anaerobic microsites and provides additional labile carbon, stimulating methanogenic archaea and increasing CH_4 fluxes (Akhtar et al., 2019). However, plastic mulch alters water retention and limits oxygen diffusion, which can variably affect CH_4 emissions depending on substrate availability (Lee et al., 2020; Zhao et al., 2022).

In Indonesia, Sleman is the main chilli producing area in the Special Region of Yogyakarta, with year-round production unaffected by seasonality (Lubis et al., 2019). The consistency of production, along with the large area of chilli farmland, potentially contributes to CH_4 emissions. Moreover, the rate of emissions tends to peak during the rainy season, when

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environmental conditions are more favorable for methanogenesis in soil (Jeffrey, 2019). This shows the need to understand how agricultural practices, including the use of mulch, affect GHG emissions in chilli cultivation as climate change mitigation efforts.

Studies on CH_4 emissions in dryland, particularly chilli cultivation, often receive less attention than GHG in irrigated paddy fields. Although previous reports have shown that CH_4 gas is produced in flooded paddy fields, there is no information regarding the potential occurrence in dryland (Kim et al., 2022). The occurrence of CH_4 in dryland is attributed to the activity of microorganisms in soil that break down organic matter under partially anaerobic conditions, using organic matter inputs (Anshori et al., 2018). This material is obtained from compost fertilizer farming practices and the use of plastic mulch or straw (Jeong et al., 2018; Lee et al., 2019; Liu et al., 2016).

Previous studies have shown that mulching practices significantly affect both GHG emissions and soil quality, depending on type and environmental conditions. Yagioka et al. (2015) reported that the use of organic mulch in vegetable cultivation increased CH_4 emissions compared to the control, because of enhanced microbial decomposition under semi-anaerobic conditions. However, organic mulch contributed positively to long-term soil health through improved organic matter content. Chaudhary and Sharma (2024) found that plastic mulch tended to reduce CH_4 emissions by limiting carbon input and controlling soil water, although the impact on soil fertility is minimal.

In another study, the use of plastic and organic mulch increased crop yields, alongside CH_4 and N_2O emissions, compared to the unmulched treatment. The combination of plastic and organic mulch is known to be effective in reducing GHG emissions, but with a tendency to decrease soil organic carbon (SOC) stocks (Kim et al., 2017; Lee et al., 2020). Organic mulch, such as straw, has been shown to provide significant benefits to soil nutrition and health through increased SOC (Shinde et al., 2014). This increase in SOC improves soil quality and contributes to the reduction of GHG emissions, particularly CH_4, thereby serving as a more environmentally friendly option for farmland management (Khazimov et al., 2021).

Despite the numerous reports, studies specifically focusing on chilli cultivation and the comparison of different mulching practices with CH_4 emissions are limited. This shows the need to explore the best agricultural practices that are environmentally friendly and the threshold for CH_4 emissions in chilli cultivation fields. Therefore, this study aimed to evaluate the effectiveness of different mulching practices in mitigating CH_4 emissions in chilli cultivation. The analysis statistically identified the threshold for emissions under different mulching treatments, addressing a gap in current studies where only nitrous oxide (N_2O) had been associated with a defined threshold and emission factor (EF), as reported by Della Chiesa et al. (2022). According to the IPCC provisions, the threshold for GHG emissions is global warming potential (GWP), EF, and greenhouse gas intensity (GHGI) (Alengebawy et al., 2022; Mathivanan et al., 2021; Sapkota et al., 2021). Establishing the threshold for CH_4 emissions is essential for assessing whether agricultural practices implemented by farmers contribute to environmental pollution or correlate with sustainable standards.

2. MATERIAL AND METHODS

2.1. Field and design of the experiment

This study was conducted in Sleman Regency, Yogyakarta, Indonesia, a well-known chilli production area in a tropical dryland agroecosystem. The area is situated at an elevation of approximately 450 m above sea level, with average daily temperatures ranging from 22°C to 30°C and relative humidity between 70% and 85% during the growing season. These environmental conditions are within the optimal range for chilli growth, making the area representative and suitable for studying agronomic responses, including CH_4 emissions under mulching practices (Lubis et al., 2019).

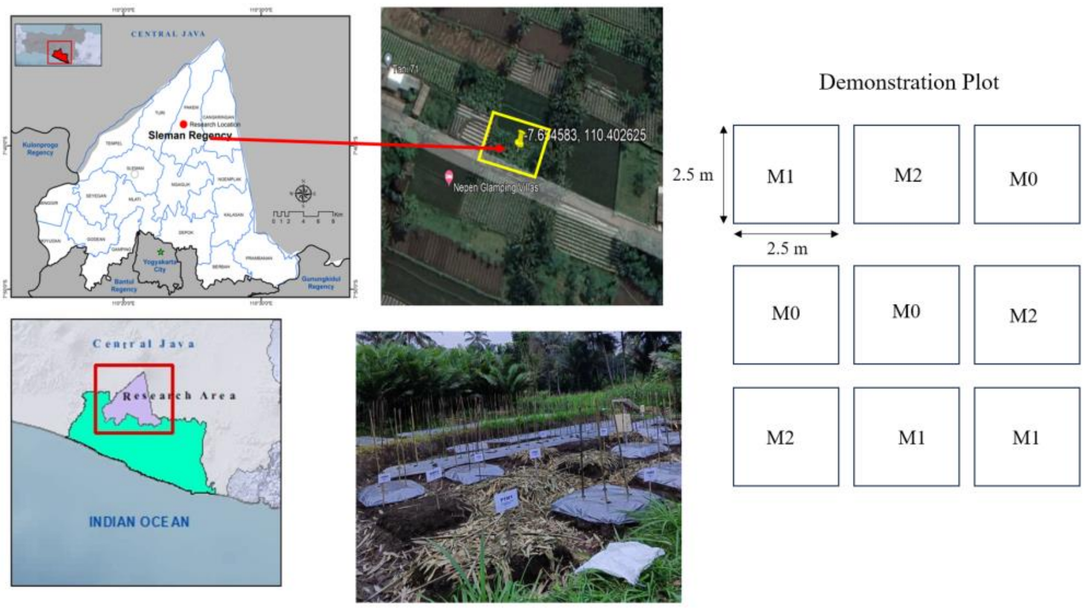

Figure 1. Experimental design and chili cultivation field in Sleman, Special Region of Yogyakarta, Indonesia

Figure 2. Closed chamber

In line with the experiment, this study used demonstration plots with mulch treatment and three replications. The size of the demonstration plot used in gas sampling was 2.5 x 2.5 m^2, as shown in Figure 1. The treatments given were the use of organic mulch (M1), plastic mulch (M2), and unmulched treatment (M0). Measurements were taken from the first planting to the second harvest of chili, totaling eight gas samples. This study was conducted from 27 June to 31 October 2024, and CH_4 gas data were collected every two weeks (Hall et al., 2014). Subsequently, a soil monitoring system (SMS) equipped with RS485 soil sensors installed at a depth of 15 cm from the soil surface was used to collect soil temperature and volume water content (VWC) data. Soil water and temperature were measured biweekly alongside greenhouse gas measurements (Shaukat et al., 2019). A rain gauge observatory was also used to monitor daily rainfall data.

Soil preparation in each chili cultivation plot followed standard protocols based on locally established practices. These included the use of dolomite, compost, and NPK fertilizer, selected through the practical experience and assessments of local chili farmers. Basic fertilizers consisted of dolomite at a dose of 2 kg and manure (compost) at 4 kg per plot, applied 2 weeks before planting. For chemical fertilizer needs, NPK (Nitrogen, Phosphorus, Potassium) with Yaramila brand was applied 5 days after planting. This fertilizer contained 16% nitrogen, 16% phosphorus, and 16% potassium, with a recommended dose of 250 grams per demonstration plot.

2.2. GHG Measurement

Greenhouse gas measurements, specifically CH_4, were carried out by using the closed chamber method in accordance with internasional atomic energi agency (IAEA) requirements (Zaman et al., 2021). The chamber used for this procedure had dimensions of 61 cm in length, 41 cm in width, and 71 cm in height (Fig. 2). It was outfitted with a fan to ensure proper air circulation within the enclosed space (Huang et al., 2021; Shaukat et al., 2019). Gas sampling used a 10 ml syringe with a 27G needle size and was inserted into a 10 ml vial bottle. The bottle was sealed under vacuum conditions to secure accurate and uncontaminated samples. Furthermore, the collected samples were analyzed through gas chromatography (Shimadzu 14 B) equipped with a flame Ionization detector (GC-FID) at the laboratory of the Agricultural Instrument Standardization Agency (BSIP) of the Ministry of Agriculture. CH_4 gas concentration data from laboratory results were calculated for emissions value/flux coming out of chilli cultivation farmland using the formula in Equation 1.

$$F = \frac{dC}{dt} \times h \times \frac{mW}{mV} \times \frac{273.2}{273,2+dT} \quad [1]$$

where : F = Flux / Emissions of CH_4 (mg m^{-2} h^{-1}); dC/dt = change in CH_4 concentration per unit time (ppm h^{-1}); h = height of closed chamber; mW = molecular weight of CH_4 gas (g/mol); mV = volume constant of gas molecules (22.4 liter); T = closed chamber temperature at the time of gas sampling (°C).

In Equation 1, dC/dt represents the rate of change in CH_4 concentration over time (ppm h^{-1}). The value was calculated using the linear regression of gas concentration measurements obtained at 0, 10, and 20 minutes after the chamber was closed. Subsequently, CH_4 concentrations were analyzed using a Shimadzu GC-14B gas chromatograph equipped with a Flame Ionization Detector (FID).

2.3. Statistical Analysis

The ANOVA (Analysis of Variance) method was used to test significant differences between the means of more than two treatment groups, with CH_4 emissions as tested data. When the results were significant, the Tukey HSD (Honestly Significant Difference) test was conducted to compare treatment pairs using confidence intervals. This analysis was used to identify statistically significant differences in means and provide insights into the contribution of mulching treatments to CH_4 emissions.

Z-score is used to determine the threshold for identifying data deviating from the main distribution, such as outliers in GHG fluxes (Muhamediyeva, 2023). The calculation of Z-score was by comparing each data against the mean of the distribution, normalized through the standard deviation using Equation 2. Since the sample used was only eight times of CH_4 gas collection, emissions data were resampled using the bootstrap method (Breivik & Aarnes, 2017), with 1000 data to determine the threshold more objectively.

$$Z = \frac{X - \mu}{\sigma} \quad [2]$$

where Z = the Z-score (standard score) shows how far a data point (X) is from the mean (μ) in terms of standard deviations (σ), X = the value of an individual data point being evaluated, μ = the mean of the entire CH_4 emissions dataset, σ = the standard deviation of the dataset.

Table 1. Physical and chemical properties of soil at the Pakem Station

Parameter	Value
Soil Water Content (%)	5,18 ± 0.01
pH	6,01 ± 0.02
Electrical Conductivity (EC) (dS m^{-1})	0,02
Total Nitrogen (N-total) (%)	0,35 ± 0.01
Available Phosphorus (P-available) (ppm)	20,71 ± 0.02
Available Potassium (K-available) (me %)	0,22 ± 0.02
Organic Carbon (C-organic) (%)	1,18 ± 0.01

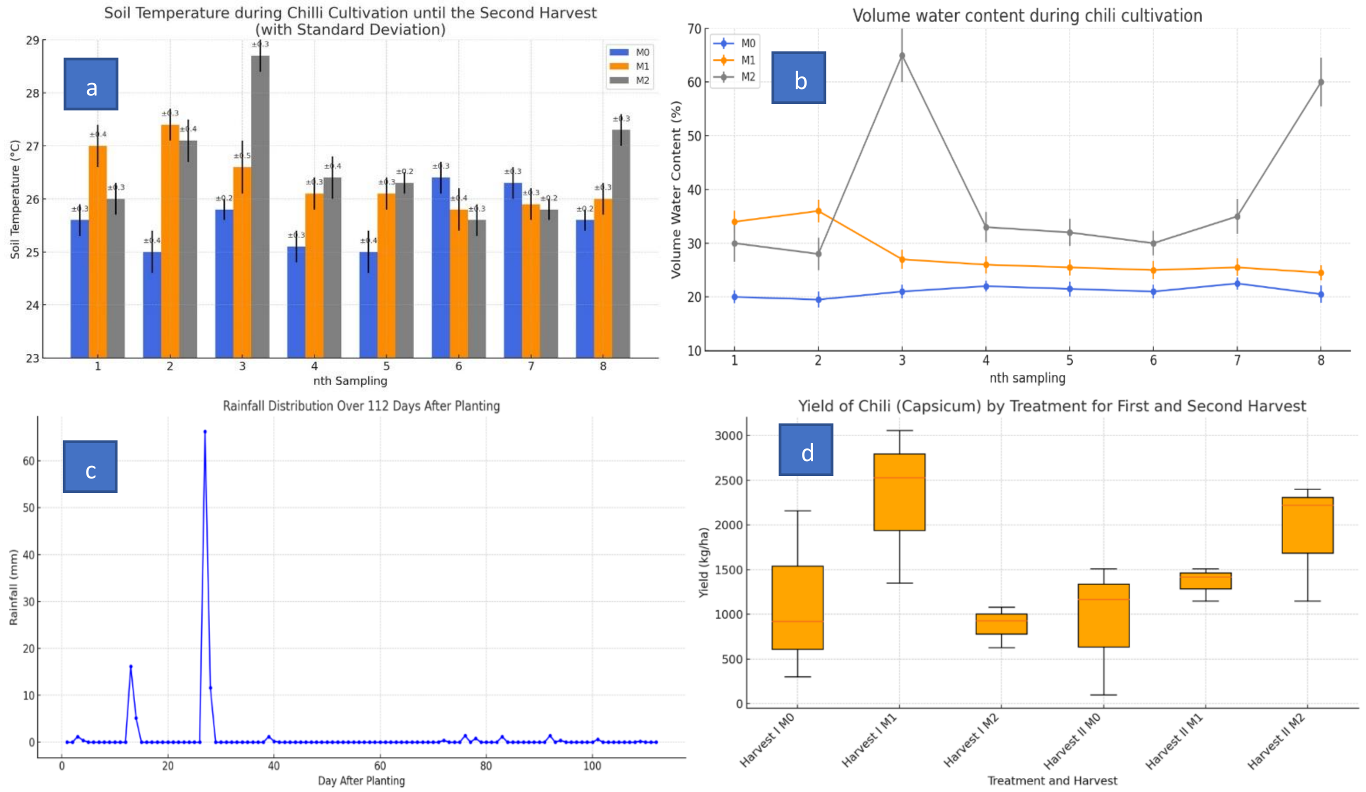

Figure 3. The environmental conditions and yield of chili cultivation (a) soil temperature; (b) volume water content (VWC); (c) rainfall; (d) yield

In addition to treatment-based comparisons, this study analyzed the relationship between CH_4 emissions and selected soil properties, namely temperature and volumetric water content (VWC). A linear regression analysis was conducted to quantify the impact of environmental factors on CH_4 emissions under different mulching treatments. This statistical method aimed to support the mechanistic interpretation of emissions observed in the field.

3. RESULTS

3.1. Environmental conditions and productivity of chilli cultivation

Based on sample analysis, the soil type in this study area was identified as regosol. Before conducting intensive tillage (such as forming beds or mounds), composite soil samples were collected to assess the initial physical and chemical properties of the soil. The texture analysis showed that the soil consisted of 72.06% sand, 15.38% silt, and 12.56% clay, showing a sandy soil structure. Detailed results of the physical and chemical characteristics are presented in Table 1. These initial conditions are important to understand soil responsiveness to mulching treatments during cultivation.

Figure 3a shows the variation in soil temperature throughout the chilli growing season, to the second harvest, with three different treatments (M0, M1, and M2). The trend of soil temperature is observed to fluctuate between sampling, with the M2 treatment generally showing higher soil temperature compared to others, although not consistently across all sampling points. During sampling 6th and 7th, M2 treatment records slightly lower soil temperatures than M0. This shows that the warming effect of plastic mulch varies depending on weather conditions and radiation intensity. The M0 and M1 treatments tended to be more stable with smaller fluctuations, particularly at the 5th to 7th sampling. These results show that M2 tended to increase soil temperature, but not consistently throughout the season. The influence of plastic mulch on temperature is modulated by external environmental factors such as rainfall and solar radiation.

VWC showed that the water content in M0 remained relatively stable at approximately 20%, while M1 had mild fluctuations with a stable trend close to 30%. However, M2 showed much higher fluctuations, reaching a peak of approximately 60% in the third sampling before declining and rising significantly in the last sampling (Fig. 3b). These results showed that M2 had a major impact on the dynamics of water content in soil, compared to the more stable M0 and M1. The data showed that M0 produced the most stable and low VWC, while M1 had a moderate increase and provided better stability than M0. Meanwhile, M2 produced VWC, but with significant fluctuations, particularly in some sampling points. This suggested that plastic mulch was more effective in retaining water.

Figure 3c presents the rainfall pattern during the 112 days after planting, showing considerable variability in precipitation intensity. Although dry periods were predominant throughout the growing season, a few distinct rainfall events occurred on days 12, 27, and 28, with the highest intensity recorded at 66.2 mm. These intermittent rainfall peaks played a significant role in altering surface water conditions and contributed to fluctuations in soil VWC observed in the earlier analysis. The timing and intensity of rainfall events were critical in regulating soil microclimate dynamics, particularly under different mulch treatments where surface cover influenced water infiltration and retention.

In Figure 3d, chilli yield shows significant differences between treatments M0, M1, and M2 in the first and second harvests. In the first harvest, M2 produced the highest average, reaching 2160 kg/ha, showing optimal conditions for early chilli production. M1 also recorded a high yield with a maximum of 2530 kg/ha, while M0 had the lowest yield, only 1350 kg/ha. In the second harvest, yield declined in all treatments, including M0 and M1, which recorded 1150-1510 kg/ha. However, M2 remained superior with a yield reaching 1510 kg/ha, showing consistency in productivity. Based on the results, M2 proved to be more effective than M0 and M1 in supporting sustainable chilli productivity.

3.2. Effect of treatment on methane gas emissions

The results of the ANOVA showed that mulching treatments (M0, M1, and M2) had a significant effect on CH_4 emissions ($F = 154.1$, $p = 6.96 \times 10^{-6}$). The Sum of Squares and Mean Squares values for the treatments (0.015345 and 0.007672, respectively) were significantly higher than the residuals (0.000299 and 0.000050), confirming that the variation in CH_4 emissions was explained more by the different mulch treatments than random factors. This result showed that different mulch treatments had a significant effect on the level of CH_4 emissions. The results of methane gas emissions for M0, M1, and M2 were analyzed using ANOVA and presented in Table 2. Although M0 did not have a mulch application, it served as the control treatment and was included in the statistical comparison to evaluate the effect of mulching practices.

The Tukey test was conducted to evaluate significant differences between mulch treatments and CH_4 emissions. The results showed that there was a significant difference in CH_4 emissions between M1 and M0, as well as between M2 and M1 treatments. Additionally, the difference between M2 and M0 was significant but with a smaller value (Table 3). The confidence intervals (Lower and Upper) for each comparison excluded zero, showing that the results were statistically significant, causing an increase in statistical significance.

In Figure 4, the analysis of differences in mean CH_4 emissions between treatments using a family-wise 95% confidence level showed significant results. The confidence interval graph showed that M1 had consistently higher CH_4 emissions than M0, with statistically significant mean differences (confidence intervals did not include zero). Meanwhile, the comparison between M2 and M0 showed a significant difference, although the mean value was smaller than the difference between M1 and M0. The difference between M2 and M1 was smaller, showing a confidence interval that included zero. This suggested that there was no statistically significant difference between these two treatments. The results also confirmed that M1 had the most significant impact on increasing CH_4 emissions, while M2 showed a response pattern more similar to M1 than M0. This supported the previous results, where M1 created conditions that were more favorable to CH_4 production. In comparison, M0 with a negative difference showed that the untreated conditions tended to limit CH_4 emissions.

Table 2. Anova test results of the effect of mulch treatment on methane gas emissions

Source of Variance	Df	Sum of Squares	Mean Squares	F-value	p-value
Treatment	2	0.015345	0.007672	154.1	6.96e-06
Residuals	6	0.000299	0.000050		

Remark: Sign. <0.05

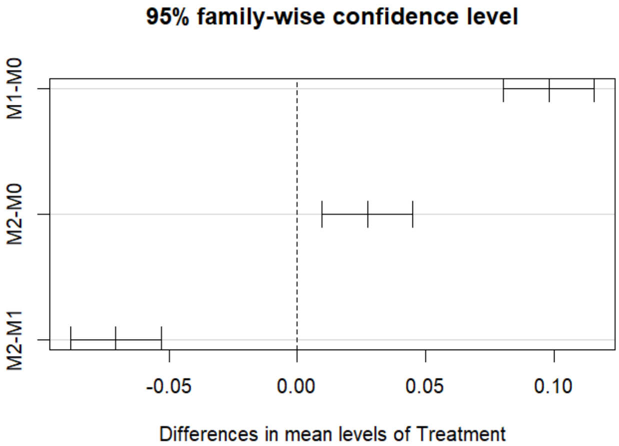

Figure 4. Confidence Interval plot for differences in mean levels of treatments

3.3. CH_4 emissions in chilli cultivation field

Analysis of CH_4 emissions data during the study period provided information on the effect of mulch treatment applied in chilli cultivation. Figure 5 shows a graph of CH_4 fluctuations from the day after chilli planting to 112th day based on the different mulch treatments. The graph showed significant differences in emissions during the 112-day period after planting. Specifically, M1 produced the highest CH_4 emissions consistently compared to the other treatments, on day 28, where the peak reached 0.075 mg CH_4 m^{-2} h^{-1}. M0 showed the lowest and most stable emissions over time, while M2 fluctuated with significant spikes on days 42 and 112. The average seasonal GHG emissions were 0.016 mg m^{-2} h^{-1} for M0, 0.114 mg m^{-2} h^{-1} for M1, and 0.043 mg m^{-2} h^{-1} for M2, with M1 producing the highest average seasonal CH_4 emissions compared to M0 and M2.

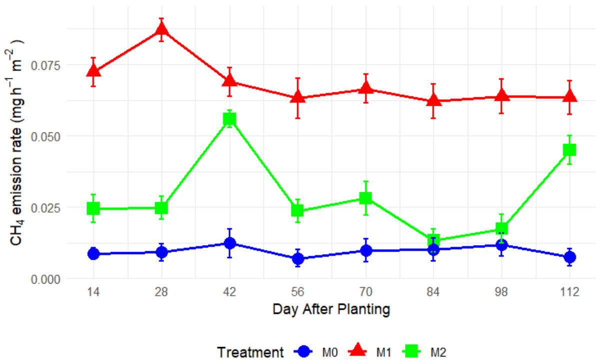

Figure 5. Methane gas emissions during chilli cultivation period with various treatments

Table 3. Tukey test results

Comparison	Diff	Lower	Upper	p-adj
M1-M0	0.09800000	0.080324719	0.11567528	0.0000061
M2-M0	0.02733333	0.009658052	0.04500861	0.0075808
M2-M1	-0.07066667	-0.088341948	-0.05299139	0.0000441

Table 4. Statistical relationship between soil properties and CH_4 emissions

Treatment	Variable	R	R^2	Slope	Intercept	p-value	Sign
M0	CH_4 – Soil Temperature	0.718	0.516	0.00144	-0.00366	0.0447	*
M0	CH_4 – VWC	0.611	0.374	0.00032	0.024647	0.1072	
M1	CH_4 – Soil Temperature	0.925	0.855	0.01642	-0.36243	0.0010	*
M1	CH_4 – VWC	0.991	0.982	0.00186	0.0187	<0.0001	*
M2	CH_4 – Soil Temperature	0.817	0.667	0.01281	-0.26986	0.0134	*
M2	CH_4 – VWC	0.994	0.989	0.00107	0.03006	<0.0001	*

Remark: *) Significance p-value < 0.05

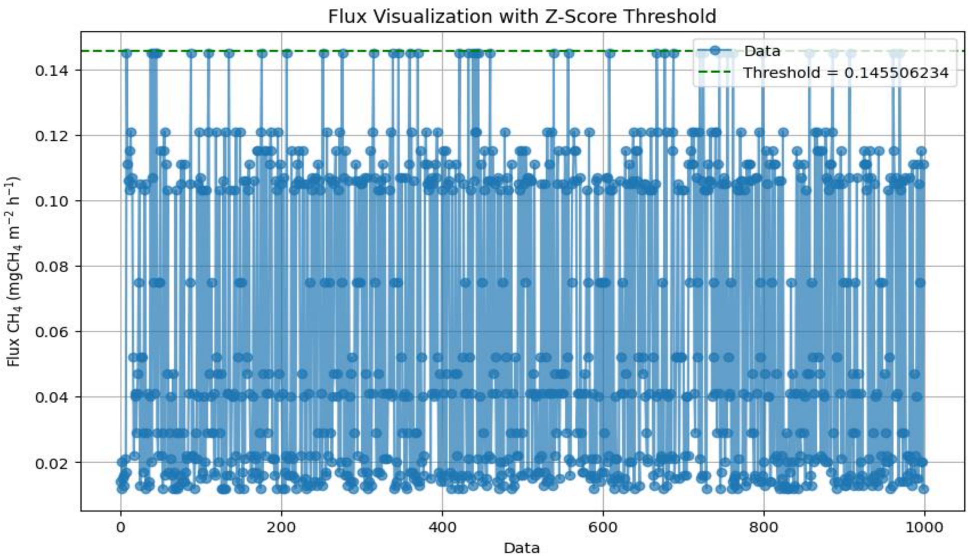

Figure 6. Visualization of Z-score calculation of methane flux to determine the threshold

The difference in results shows a significant effect of treatment on CH_4 emissions. M1 includes treatment that increases anaerobic microbiological activity, such as the availability of organic matter or environmental conditions favoring methanogenesis. However, the low emissions in M0 show condition that is less favorable for CH_4 production. M2 with fluctuating patterns shows a dynamic response to certain treatments that can change depending on planting time or other environmental factors. These results show the effect of mulch treatment on the level of CH_4 emissions dynamics in chilli cultivation agricultural system.

3.4. The threshold of CH_4 Emissions in chilli cultivation field

The threshold of CH_4 emissions visualized using a Z-score method shows significant data variability with the value at 0.145506234 mg CH_4 m^{-2} h^{-1} (Fig. 6). Most of the data are distributed below this threshold, but there are a number of spikes (outliers) above the value. These outliers show extreme emissions due to changes in environmental conditions, such as fluctuations in soil temperature, water, microbiological activity, or specific land treatments (Kim et al., 2017; Perez-Coronel & Michael Beman, 2022; Rajendran et al., 2024; Yagioka et al., 2015). However, outliers can potentially originate from noise or measurement errors, making evaluation of data quality an essential step.

The Z-score method used to detect outliers is effective in identifying data that deviates from the main distribution pattern. However, validation of the statistical distribution of the dataset is required to confirm the assumptions used, particularly when data distribution is not normal. From the results, the values of CH_4 emissions for all treatments exceed the threshold. Treatment M1 produces the highest emissions of 0.114 mg m^{-2} h^{-1}, followed by M2 and M0 at 0.043 mg m^{-2} h^{-1} and 0.016 mg m^{-2} h^{-1}, respectively.

3.5. Relationship between Soil Environmental Factors and CH_4 Emissions

In order to elucidate the environmental drivers influencing CH_4 emissions across treatments, a linear regression analysis was performed between the rate of emissions and soil temperature as well as VWC. Based on the regression results in Table 4, both variables significantly influenced CH_4 emissions under mulching treatments (M1 and M2). The strongest correlation was observed between CH_4 and VWC under M1 (R^2 = 0.982, $p < 0.001$) and M2 (R^2 = 0.989, $p < 0.001$), showing the significant role of soil water in supporting methanogenic activity. Temperature also showed a significant positive relationship, particularly in M1 (R^2 = 0.855, p = 0.001) and M2 (R^2 = 0.667, p = 0.0134). The unmulched treatment (M0) showed only a moderate correlation between CH_4 and soil temperature (R^2 = 0.516, p = 0.045), and a non-significant correlation with VWC (p = 0.1072). This suggested that, under better-aerated soil conditions without mulching, CH_4 emissions were less responsive to water dynamics.

4. DISCUSSION

The results of the ANOVA showed that the treatment of agricultural practices with mulch (M0, M1, and M2) had a highly significant effect on CH_4 emissions. Similarly, Kim et al. (2017); Lee et al. (2020); Yagioka et al. (2015) showed that mulch treatments significantly affected CH_4 production. CH_4 is generated through biogeochemical processes in soil, including under aerobic conditions, as described by Perez-Coronel and Michael Beman (2022). In agricultural practices without mulching, CH_4 is produced in lower quantities, due to the interaction of natural processes in the environment (Li, 2007; Li et al., 1992). Complex biogeochemical processes in the environment interact to influence soil microbial activity, which is a major key factor in CH_4 generation (Rajendran et al., 2024).

In this study, M1 produced the highest level of CH_4 emissions consistently compared to others. This was due to the interaction between the application of inorganic fertilizer and the use of bamboo leaf mulch (straw), which enhanced the process of organic matter decomposition and soil microbial dynamics (Wei et al., 2022). The combination created more favorable conditions for methanogenic microbial activity, thereby increasing CH_4 emissions.

M2 showed a reduction in CH_4 emissions compared to M1, with an average rate of 0.043 mg m^{-2} h^{-1} during one growing season. This varied significantly compared to 0.114 mg m^{-2} h^{-1} when using organic mulch. The use of plastic mulch provided a physical barrier effect, which reduced the release of CH_4 into the atmosphere (Chae et al., 2022). Additionally, plastic mulch modified soil temperature and water and affected soil microbial activity contributing to CH_4 production (Yu et al., 2021). M0 produced the lowest emissions compared to others. However, this treatment was also associated with lower yields (Wang et al., 2021; Wei et al., 2022). A recommendation for policymakers is to consider the use of mulch that is environmentally friendly and supports high productivity. The selection of mulch types needs to be performed by considering its impact on the environment, particularly GHG emissions, as well as crop yields.

In Figure 5, the peaks of CH_4 emissions on the 28^{th} and 42^{nd} days after sowing observed in M1 and M2 treatments were due to soil environmental dynamics and microbiological activities (Kirchman, 2024). This was shown by the data in Figures 3a, 3b, and 3c, where the peak of CH_4 emissions in treatment M1, rainfall on days 12, 13, 27, and 28, reached the highest precipitation of the growing season at 66 mm (Fig. 3c). The rainfall made soil water also high because the organic mulch did not provide tight coverage, making soil moist due to high water content of 34% in the first side and 39% in the second measurement (Fig. 3b). The results showed that the combination of high rainfall and loosely covered soil in M1 treatment created conditions conducive to increased soil water and microbiological activity, leading to significant CH_4 emissions (Munawaroh et al., 2022; Senapati et al., 2016). This shows the significant role of soil water dynamics and organic mulch management in influencing CH_4 emissions during cultivation (Ni et al., 2019; Venturini et al., 2022).

The interaction of straw decomposition and fertilizer use is a factor supporting the increase in CH_4 emissions (Gonzaga et al., 2019; Syamsiyah et al., 2016; Zeng et al., 2020). The use of fertilizers, particularly nitrogen-based ones, can modify microbial activity in soil. Nitrogen fertilizers increase the denitrification process, which indirectly affects methanogenesis due to electron competition between denitrifying microorganisms and methanogens (Liu et al., 2024).

In M2, the peak emissions increase on the 42^{nd} and 112^{th} day was caused by environmental factors. The use of plastic mulch improved microenvironmental conditions, significantly influencing soil temperature and VWC dynamics under the cover, as shown in Figures 3a and 3b. Moreover, different mulch treatments influenced soil temperature and water dynamics throughout the growing season. M2 increased soil temperature compared to M1 and M0 due to the ability to reduce heat loss and suppress evaporation. This correlated with previous results, where plastic film mulch created a more stable thermal environment by raising daytime temperatures and retaining warmth at night (Li et al., 2022; Zhang et al., 2022). In comparison, organic mulch buffered soil thermal fluctuations by reducing peak daytime temperatures and increasing nighttime minima (Vieira et al., 2020). The higher soil water under M2 was due to reduced evaporation, leading to improved VWC. These microclimatic modifications play a critical role in microbial activity and CH_4 emissions under each mulch treatment.

Plastic mulch acts as a barrier that reduces evaporation and minimizes heat loss, causing consistently higher soil water and temperature compared to other treatments (Yang et al., 2022). This elevated soil temperature accelerates microbial activity and decomposition rates. Meanwhile, the reduced water fluctuation stabilizes water availability, creating an optimal environment for plant growth but potentially increasing CH_4 emissions under anaerobic conditions. The process of using plastic mulch can limit soil evaporation and increase water retention, leading to higher soil water and VWC. The observed increase in soil water under M2 is attributed to reduced evaporative losses. This causal direction has been revised to reflect that water content is the driver of measured soil water levels.

The factors contributing to VWC are significantly observed in 42^{nd} and 112^{th} days after planting. Increased water content in soil can affect microbial activity, thereby improving CH_4 emissions (Lee et al., 2022; Nayna et al., 2022). The results also showed that the use of plastic mulch had higher chilli production. The highest productivity in both the first and second harvests was achieved with M2 treatment, showing an average yield of 1510–2160 kg/ha. This suggested that using plastic mulch was an effective mitigation strategy to reduce GHG emissions while maintaining high productivity (Lee et al., 2022; Zhang et al., 2022).

The results provide information on the interaction between soil engineering treatments, microbiological activity, and environmental factors in influencing CH_4 emissions dynamics in cultivated agricultural systems (Lage Filho et al., 2023). For future studies, there is a need to measure environmental variables such as microclimate and soil attributes (Feng et al., 2020), to determine the factors influencing CH_4 emissions.

Determining the threshold for CH_4 emissions is very necessary due to its significant role as an indicator in cultivation fields (Riddick et al., 2022). With the threshold, monitoring can be performed to determine whether the cultivation environment is environmentally friendly or contributes to global warming in agriculture. Currently, there are no regulatory requirements governing the threshold of CH_4 emissions to the atmosphere (Stern et al., 2014).

In comparison, N_2O gas has an EF threshold indicator in accordance with IPCC provisions. The default EF recommended by the IPCC for direct N_2O emissions from agricultural soil is 1% of applied nitrogen (N) (Della Chiesa et al., 2022; Wei et al., 2015). The statistical Z-score for the CH_4 emissions is 0.145 mg CH_4 m^{-2} h^{-1}. Based on this study, the calculation of CH_4 emissions on chilli cultivation land in Sleman exceeded the threshold according to the statistical method. Determination of the threshold of methane gas emissions in agriculture can be agreed upon internationally. The threshold can be used as a reference for measuring and monitoring emissions in other agricultural fields to minimize environmental impacts, low emissions, high production, and sustainability.

The regression analysis supported the role of soil temperature and VWC as key drivers of CH_4 emissions across mulch treatments. In M1 and M2, stronger correlations between CH_4 and VWC were observed. This suggested that mulch application modulated soil water retention, thereby promoting semi-anaerobic conditions favorable to methanogenic activity. Similarly, Akhtar et al. (2019) and Wei et al. (2022) reported how organic mulch enhanced labile carbon availability and water, both of which stimulated microbial decomposition and CH_4 production. Soil temperature also showed a significant positive relationship with CH_4 emissions, corroborating the notion that elevated temperatures under mulched conditions enhanced microbial metabolic rates and accelerated methanogenesis.

The control treatment (M0), with relatively stable and lower soil water and temperature, showed weaker or non-significant correlations, indicating that CH_4 emissions were limited by the lack of optimal environmental stimuli. These results were consistent with previous studies conducted in both dryland and paddy systems, emphasizing the interplay of soil microclimate and microbial activity in determining CH_4 emissions under agricultural settings.

5. CONCLUSION

In conclusion, this study confirmed that mulching practices significantly influenced CH_4 emissions in chilli cultivation. Among the treatments, M1 produced the highest CH_4 emissions due to increased microbial decomposition. Meanwhile, M0 had the lowest emissions but was associated with reduced yields. M2 offered a balanced outcome, generating moderate CH_4 emissions while enhancing crop productivity. All treatments exceeded the calculated threshold of 0.145 mg m^{-2} h^{-1} under specific environmental conditions. The elevated emissions observed in M1 treatment were strongly associated with higher soil temperature and water, showing that microclimatic factors under mulching could intensify methanogenic activity. Therefore, selecting mulching strategies must consider both emissions mitigation and yield optimization. These results contributed to the understanding of the CH_4 threshold in horticultural systems and supported plastic mulch as a sustainable option for dryland agriculture. Moreover, future studies should investigate seasonal variability and long-term effects of mulching on soil health and greenhouse gas dynamics.

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Declaration of Competing Interest

The authors declare that no competing financial or personal interests may appear to influence the work reported in this paper.

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