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Mitigating methane emissions in chili farming with sustainable agricultural practices

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ABSTRACT

The appropriate use of fertilizers and mulches can reduce methane emissions in chili cultivation. This research seeks to assess the impact of various conditions on methane emissions, encompassing chili cultivation under the following scenarios: absence of fertilizers, application of organic fertilizers, use of NPK (nitrogen, phosphorus, and potassium) fertilizers, absence of mulch, utilization of organic mulch, and application of inorganic mulch. Fertilizer application was combined with mulching to assess their impact on methane emissions. The study was conducted at two different sites with similar soil types. NPK levels were also measured to determine their correlation with methane emissions. The findings show that applying NPK fertilizers boosts the levels of soil nutrients, such as nitrogen (N), phosphorus (P), and potassium (K), while organic fertilizers contribute to an increase in soil organic carbon content. The application of organic mulch increases soil NPK levels while reducing methane emissions. In contrast, the use of plastic mulch significantly increases methane emissions, particularly when combined with NPK fertilizers. Soil nitrogen levels show a correlation with methane emissions exceeding 90%, while phosphorus and potassium exhibit moderate relationships with methane emissions (72%). The results of this research are anticipated to offer valuable insights into optimal fertilization and mulching practices for chili cultivation, with the aim of reducing methane emissions.

Keywords: chili cultivation, mulching, fertilizer, NPK, methane emissions.

INTRODUCTION

Climate change is a global challenge that threatens the sustainability of ecosystems and the survival of living things (Ostad-Ali-Askari et al., 2017; Rosenzweig and Tubiello, 2007). A significant contributor to climate change and global warming is the rise in greenhouse gas (GHG) concentrations in the atmosphere, driven by human activities (Yoro and Daramola, 2020). Today, global warming is an environmental crisis that impacts countries around the world. On a global scale, the energy sector represents the primary source of GHG emissions, whereas the agriculture sector accounts for a substantial proportion, contributing approximately 10–12% of the total emissions (Huang et al., 2019).

The agricultural sector faces various environmental challenges due to human activities that utilize natural resources intensively and put great pressure on ecosystems. One of the most prominent environmental issues is the contribution of the agricultural sector to GHG emissions into the atmosphere (Foley et al., 2011; Gilbert, 2012; Zhou et al., 2019). The global rise in GHG emissions is predominantly attributed to human activities, including the combustion of fossil fuels, the application of nitrogen-based fertilizers in agriculture, and livestock production systems (Jose et al., 2016). The agricultural sector generates emissions comprising carbon dioxide, methane, and nitrous oxide. Methane is a major concern due to its much higher Global Warming Potential (GWP) than carbon dioxide (Molina et al., 2023).

Indonesia is known as an agricultural country rich in natural resources, supported by a tropical climate, abundant water availability, and fertile soil (Hilmawan and Clark, 2019). Sleman Regency, located in the central part of Java Island, has the characteristics of a tropical monsoon climate and fertile soil, making chili peppers a major agricultural commodity that is widely cultivated in the region (Rahayu and Febriani, 2021). Chili cultivation requires the use of large amounts of nitrogen fertilizer and manure to achieve optimal productivity (Kim et al., 2022; Zhang et al., 2023). Despite the great potential of chili cultivation amidst the challenges of climate change, the agricultural sector faces the problem of greenhouse gas (GHG) emissions, one of which is methane emissions. Research shows that chili cultivation can produce GHG emissions, where methane emissions account for about 52–83% of the total of GWP (Tao et al., 2024).

Previous studies reported that agricultural practices such as soil tillage (Pandey et al., 2012; Bhattacharya et al., 2023; Rafique et al., 2014; Voltr et al., 2021; Yagioka et al., 2015), straw and organic fertilizer management (Gonzaga et al., 2019; Huang et al., 2020; Liu et al., 2016; Song et al., 2021), irrigation water management (Islam et al., 2020; Song et al., 2021), compost fertilizer application (Jeong et al., 2019, 2018), the use of mulching (Chiesa et al., 2022; Kim, et al., 2017b; Lee et al., 2019; Yagioka et al., 2015), and the management of chemical/nitrogen fertilizers (Kim et al., 2017a; Lee et al., 2019; Song et al., 2021; Wang et al., 2018; Yang et al., 2023) play a role GHG emissions from agricultural land. However, earlier studies have identified several limitations, particularly in integrating these practices. To establish low-emission farming systems, further research is essential to develop integrated agricultural approaches that combine elements such as fertilisers, mulch, straw, and minimal tillage.

Study on methane emissions in drylands, especially chilli cultivation, often receives less attention than GHG emissions in irrigated paddy fields. So far, it is known that methane gas is emitted from flooded paddy fields. However, methane emissions can also occur in drylands, such as in chili cultivation (Kim et al., 2022). This is due to the activity of microorganisms in the soil that decompose organic matter under partially anaerobic conditions, utilizing organic matter inputs (Dassonville et al., 2004). This organic matter comes from the practice of fertilizing with compost as well as the use of plastic mulch or straw (Jeong et al., 2018; Lee et al., 2019; Liu et al., 2016).

Studies on the combined impact of fertilizer types (organic and NPK) and mulches (organic and plastic) on methane emissions are limited, especially in chili cultivation. Previous studies have mostly focused on individual aspects of fertilizer or mulch use without holistically investigating how the interaction between the two affects GHG emissions, especially methane. In addition, the direct relationship between nitrogen, phosphorus and potassium levels in the soil and methane emission levels has not been quantitatively explained. Therefore, there is a knowledge gap that needs to be filled to identify the most effective farming methods to minimize methane emissions while still maintaining crop productivity.

This research aims to fill the gap by examining the impact of organic fertilizer, NPK fertilizer and organic mulch on methane emissions, and revealing the pattern of interrelationships between nitrogen, phosphorus and potassium levels in soil and methane emissions. This research is expected to contribute to the development of sustainable agricultural practices that are optimal and environmentally friendly. The results of this study are anticipated to offer valuable scientific insights for farmers, practitioners, and policymakers in devising strategies to mitigate greenhouse gas emissions, particularly within the context of chili cultivation.

MATERIALS AND METHODS

Research location

Figure 1 shows the location sites of this study. This study was conducted during dry season (Juni untill October 2024) in Sleman Regency, Special Region of Yogyakarta, Indonesia. The Special Region of Yogyakarta is a chili production center that contributes significantly to national chili production in Indonesia. The research was carried out at two sites, namely Mlati (7°39'16.5"S 110°24'09.5"E, 450 msl) and Pakem (7°43'50.2"S 110°21'12.3"E, 182 msl). These locations were selected because they share the same soil type (regosol) and are key chili production areas in Sleman Regency (Figure 2).

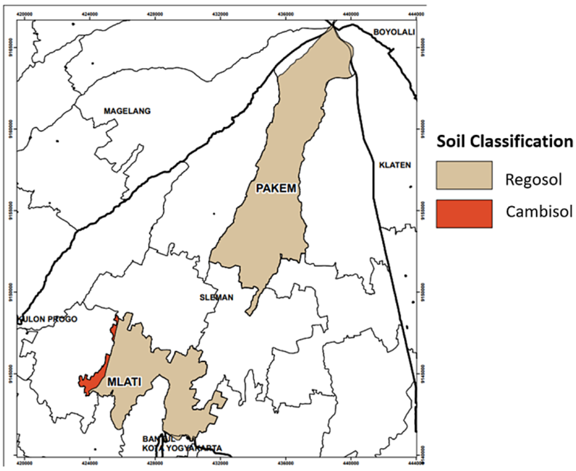

Figure 2. Soil classification map of research area

Research design

This study was carried out on experimental demonstration plots (demplots) measuring 1 × 1 meter, organized in a randomized block design (RBD) with three replications (Figure 3). The cultivation of curly red chili in each plot utilized the Electra variety. The Electra variety was chosen based on its resistance to diseases, fungi, and viruses when cultivated during the dry season with fluctuating temperature and humidity conditions. The treatments applied in this study combined the use of mulch and fertilizers. The specific treatments implemented are as follows: treatment without fertilizer (P0), treatment without mulch (M0), treatment with organic fertilizer (P1), treatment with organic mulch (M1), treatment with inorganic fertilizer (P2), and treatment with inorganic mulch (M2).

Treatment P1 involves the application of agricultural practices utilizing organic fertilizer and pesticide management, specifically employing eco-enzyme fertilizer, which is more environmentally friendly and serves as a mitigation effort for GHG emissions in agricultural fields (Benny et al., 2023). Treatment P2 involves the use of chemical inorganic fertilizers, specifically NPK, at a 100% recommended dosage. Treatment M1 refers to the use of organic mulch derived from straw management using bamboo leaf residues, which has been shown to enhance crop production and effectively suppress weeds (Huang et al., 2020). The thickness of the dried bamboo leaf mulch is set at 3 cm. In contrast, M2 involves the use of plastic mulch. P0

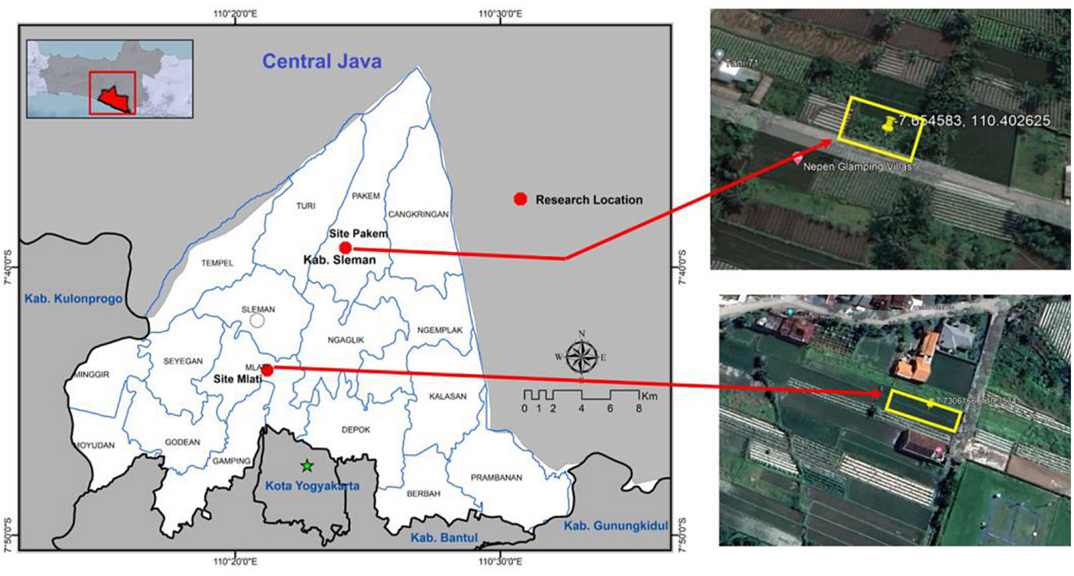

Figure 1. Study sites

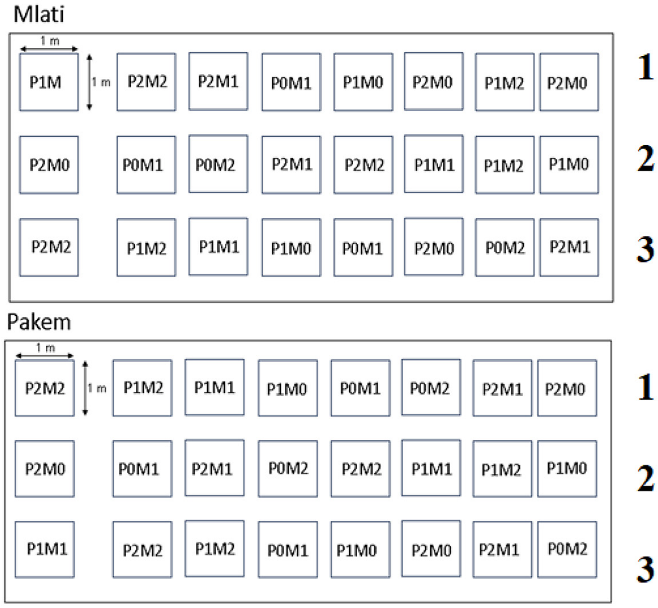

Figure 3. Research design

represents treatment without fertilizer, while M0 denotes treatment without mulch. Both organic and inorganic fertilization processes are conducted weekly (Jeong et al., 2019).

Analytical methods

Methane gas measurements were conducted using the closed chamber method (Collier et al., 2014; Zaman et al., 2021). The chamber dimensions were 61 cm in length, 41 cm in width, and 71 cm in height, and it was equipped with a fan to circulate air within the chamber (Huang et al., 2020; Shaukat et al., 2022), which was operated for 10 minutes. A 27G syringe was used to extract air from the chamber and transfer it into a 10 mL vial. The vial was then vacuum-sealed to ensure precise gas sampling results. The samples were analyzed using Gas Chromatography (Shimadzu 14 B) equipped with a flame ionization detector (GC-FID).

This research utilizes IoT technology equipped with soil sensors to measure various soil attributes, the tool is called Soil Monitoring System. Data on soil properties, including temperature, soil moisture, pH, electrical conductivity (EC), and NPK content, were obtained through measurements using an RS485 soil integrated sensor. This advanced 7-in-1 sensor serves as a comprehensive tool, enabling the simultaneous assessment of multiple soil parameters critical for understanding and optimizing soil health and productivity. Images of the enclosed space and soil monitoring system are presented in Figure 4. Sampling was conducted four months after planting and the illustration of data collection is presented in Figure 5.

The relationship between soil NPK concentration and methane (CH_4) emissions was analysed using the simple linear regression method, with methane emissions being the dependent variable and soil NPK as the independent variable. Regression coefficients were calculated using the least squares method to measure the effect of NPK on methane emissions, while the coefficient of determination (R^2) was used to evaluate the extent to which the model could explain the variability of methane emissions. Significance testing was conducted using a t-test to ensure the relationship between the independent and dependent variables was not random, by comparing the p-value against the 0.05 significance level.

RESULTS AND DISCUSSIONS

Soil characteristics

Table 1 presents the soil characteristics at the research sites. At both research sites, the soil texture predominantly consists of sand and silt, while clay constitutes less than 15% of the soil composition. Soil moisture ranges from 5.20% to 7.34%, with a slightly acidic pH (below 7). The electrical conductivity (EC) falls within a moderate range. The soil's NPK content is classified as high, with

Figure 4. Closed chamber and soil monitoring system

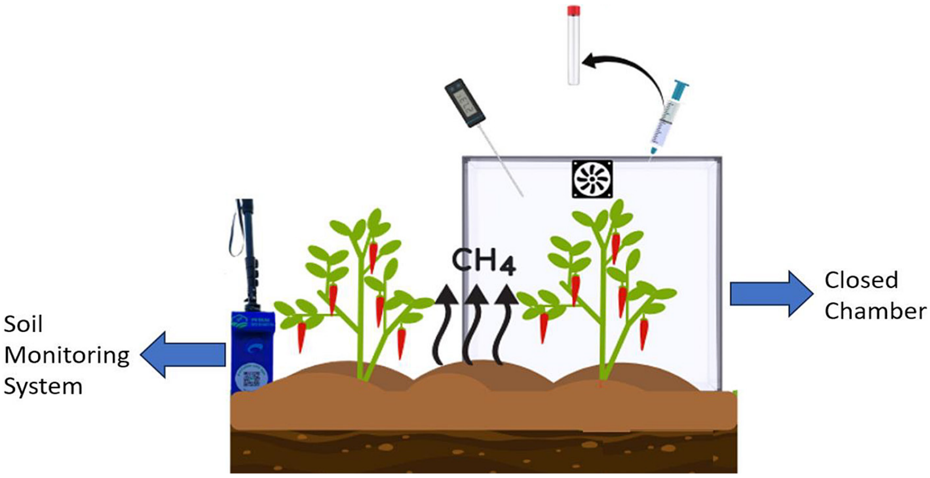

Figure 5. Mechanism for soil attributes and methane gas data collection

Table 1. Soil characteristics

Parameters	Mlati	Pakem
Soil composition		
Sand (%)	62.40	72.06
Dust (%)	28.25	15.38
Clay (%)	9.35	12.56
Soil moisture (%)	7.34	5.20
pH	6.38	6.02
EC (µS/cm)	49	26
NPK content		
Nitrogen (%)	0.14	0.35
Phosphate (ppm)	15.05	20.72
Potassium (%)	0.31	0.34
Organic carbon (%)	1.29	1.19

Note: Soil sampling results (2024).

The Pakem sites exhibited a significant contribution. Soil moisture and pH are critical factors influencing the biochemical and geochemical processes associated with methane emissions from the soil. Biogeochemistry is centred around four fundamental principles—abundance, landscape, repetition, and cycles—that shape the interactions between living organisms and their surrounding environment (Li et al., 1992). The concentration of soil organic carbon (SOC) at both sites is categorized as low to medium. The availability of SOC is a key indicator of fertile and healthy soil (Bationo et al., 2007; Bhunia et al., 2018). Raising SOC levels is an essential approach for alleviating the effects of global warming. This is accomplished by improving the availability of SOC to capture carbon dioxide, thereby preventing its emission into the atmosphere and facilitating its long-term storage in the soil. This process, referred to as soil carbon sequestration, entails the conversion of atmospheric carbon dioxide into the soil, where it is stored as organic matter and retained over time (Lal, 2004). Soil carbon sequestration is considered one of the most effective and cost-efficient methods for reducing GHG emissions to the atmosphere, thereby contributing to efforts to mitigate global warming and climate change (Agus, 2013). Changes in soil carbon stocks are significantly influenced by soil management practices, including crop rotation, fertilization, irrigation, organic matter addition, tillage, and others (Lal et al., 2015; Smith, 2008).

Effect of research scenario on NPK concentration

Figure 6 illustrates the effects of the research scenarios on soil NPK levels. The application of inorganic fertilizers and inorganic mulch (P2M2), which inherently have high NPK levels, resulted in the highest increase in NPK content at both sites. This was followed by the use of inorganic fertilizers combined with organic mulch (P2M1) and inorganic fertilizers without mulch (P2M0). The Mlati site (Figure 6a) exhibited the highest

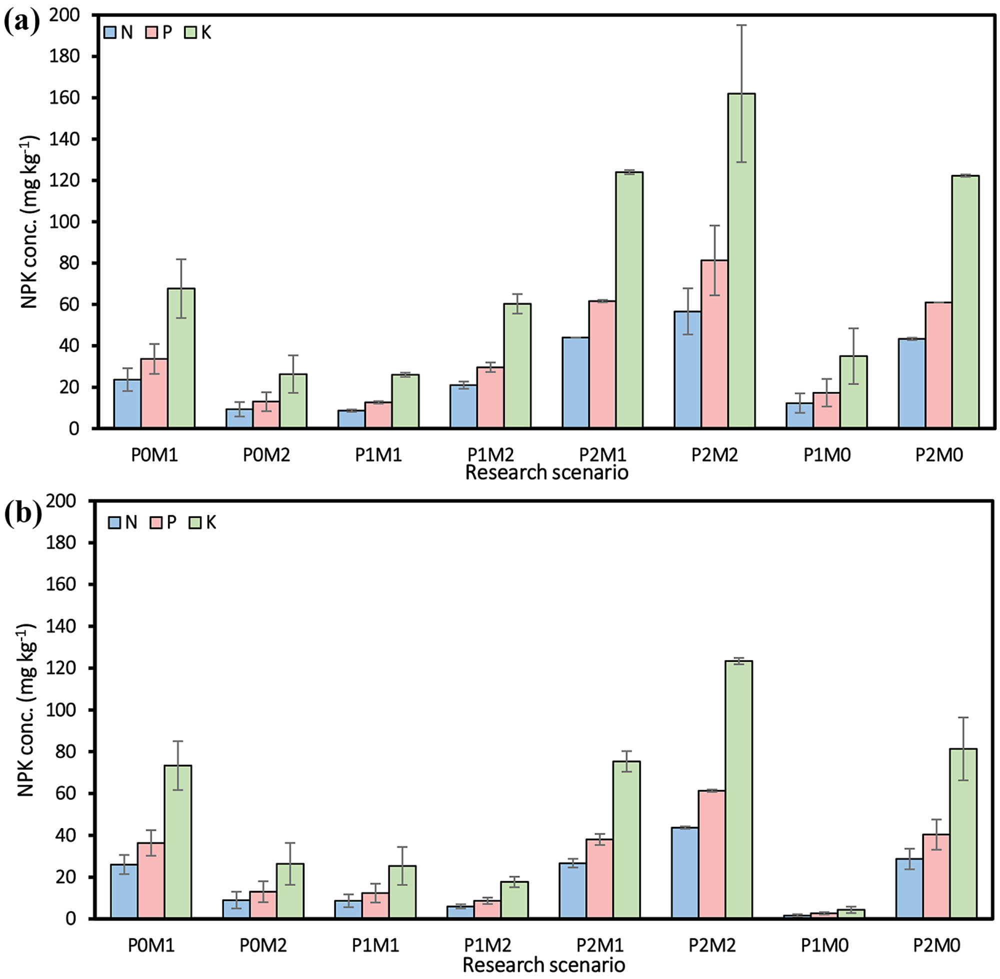

Figure 6. NPK concentration in soil: (a) Mlati, and (b) Pakem sites

NPK levels under these scenarios compared to the Pakem site (Figure 6b).

At both study sites, the NPK content of chili plants grown with organic mulch without fertilizer (P0M1) was higher than that of those with inorganic mulch without fertilizer (P0M2). Organic mulch may contain varying levels of nutrients such as nitrogen, phosphorus, and potassium. Apart from its NPK composition, bamboo leaves have also been found to be rich in organic carbon and calcium. Incorporating bamboo leaves into the soil facilitates nutrient recycling and enhances soil organic carbon levels, potentially reducing the need for fertilizers in subsequent cropping cycles.

The use of organic fertilizer without mulch (P1M0) resulted in relatively low NPK content at the Mlati site and the lowest at the Pakem site. This may be attributed to the fact that organic fertilizer alone does not provide additional nutrients to the soil, unlike organic mulch. On the other hand, the combination of inorganic mulch with organic fertilizer also failed to improve soil NPK content.

Effect of research scenario on Methane emission

The application of bamboo leaves as organic mulch effectively reduced methane emissions in chili fields as shown in Figure 7. Among the scenarios, P1M1 resulted in the lowest methane emissions, followed by P0M2 at the Mlati site (Fig. 7a) and P1M0 at the Pakem site (Fig. 7b), compared to other scenarios across both study sites. Conversely, the P2M2 scenario exhibited the highest methane emissions. The reduction in methane emissions was influenced not only by the use of organic mulch but also by the absence of fertilizer Soil mulching can effectively reduce surface soil evaporation and increase water retention in the root zone, thereby promoting methane production and emissions (Guo and Liu, 2022). Methane was consumed through microbial oxidation in the no-mulching cultivation process (Cuello et al., 2015). Inorganic mulch such as plastic film can increase the methane emission due to the increase of soil temperature that favorable

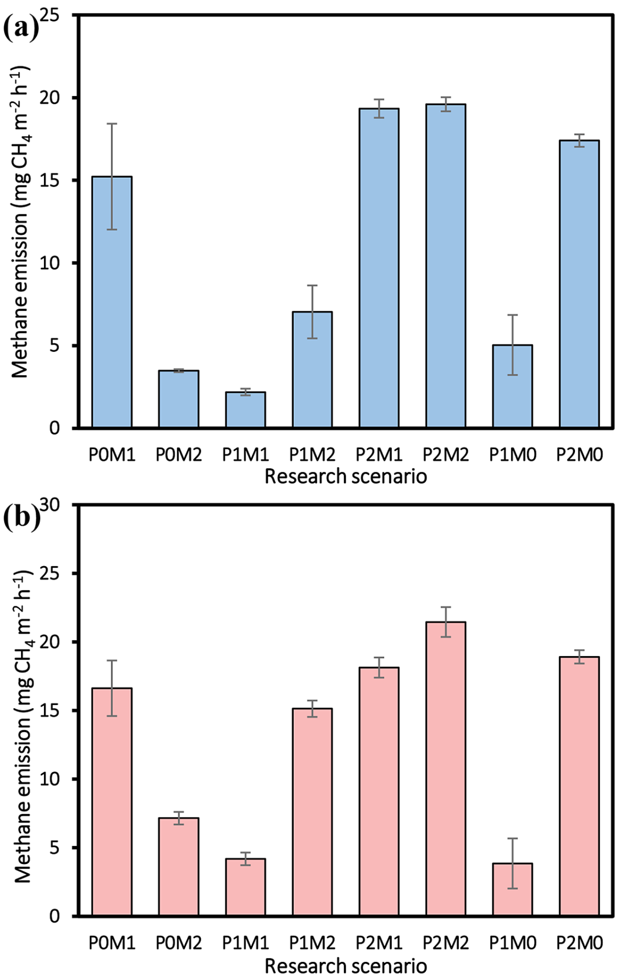

Figure 7. Methane generation: (a) Mlati, and (b) Pakem sites

conditions for microbial activity (Cuello et al., 2015; Li and Sarah, 2003).

In contrast to organic mulch, the use of NPK fertilizer tended to increase methane emissions due to the greater availability of substrates for methanogens (Zhang et al., 2018) and a reduction in soil redox potential (Olufemi et al., 2022). Methane emissions are determined by the net balance between the activities of methanogens and methanotrophs (Zhang et al., 2018). Methanotrophs are gram-negative bacteria that use methane as their carbon and energy source (Ma et al., 2013). Nitrogenous fertilizers can enhance methane production while inhibiting methane oxidation (Yuan et al., 2018) (Figure 7).

Relationship between NPK concentration and methane generation

NPK content showed moderate to high correlations with methane emissions. Nitrogen had the strongest correlation with methane emissions in both study sites, with coefficients of determination (R^2) of 0.9148 and 0.9638 for Mlati (Fig. 8a) and Pakem (Fig 8b) respectively. Phosphorus also shows a high correlation with methane emissions in the Mlati location ($R^2 = 0.871$) (Figure 8c), while at the Pakem location the correlation is moderate ($R^2 = 0.7278$) (Figure 8d). Potassium content showed an almost identical correlation pattern with phosphorus in both study sites with R2 value of

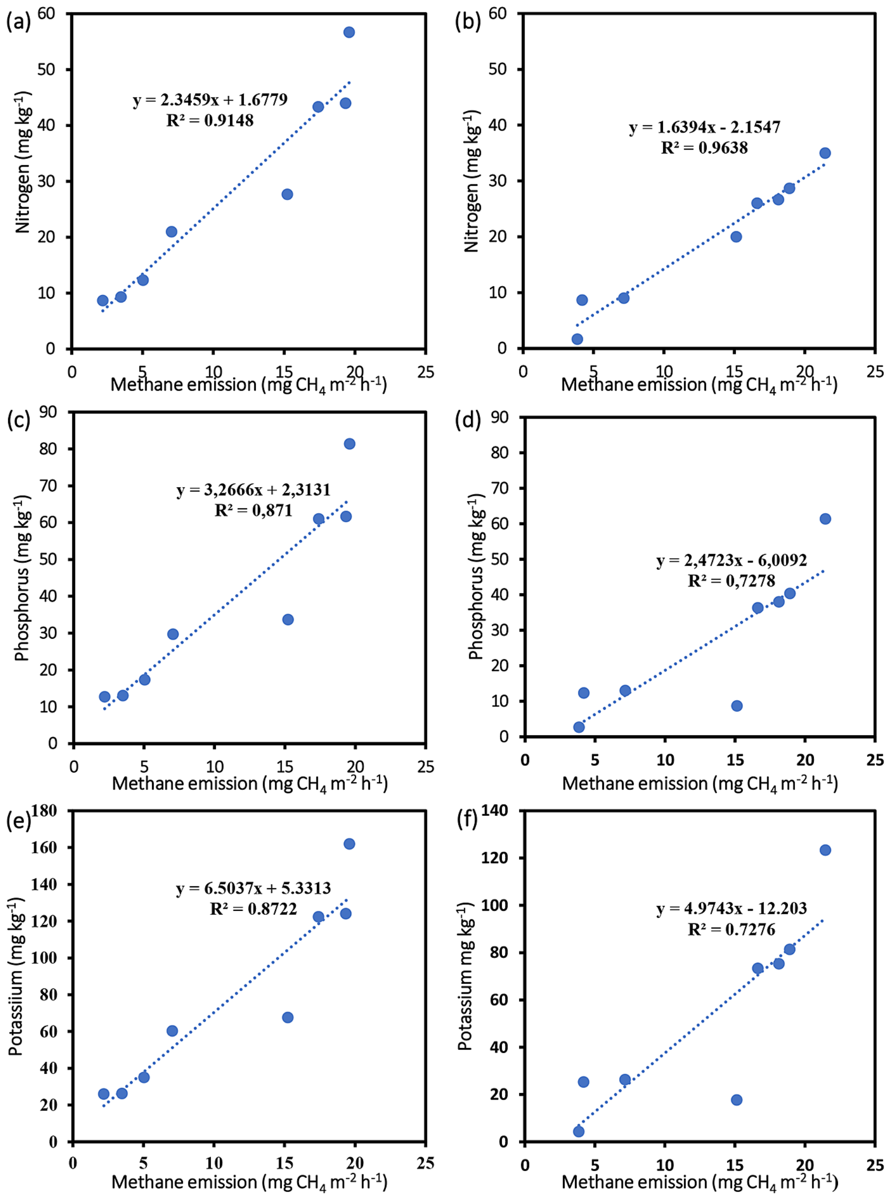

Figure 8. Relationship between NPK concentration and methane generation: (a) N-Mlati, (b) N-Pakem, (c) P-Mlati, (d) P-Pakem, (e) K-Mlati, and (f) K-Pakem

0.8722 and 0.7276 for Mlati (Fig. 8e) and Pakem (Fig. 8f) sites respectively. These results suggest that the measurement of NPK content, particularly nitrogen, is potentially a reliable predictor of methane emissions during the cultivation process.

The slope value of all regression coeficient are higher than zero indicates that there is a positive correlation between methane emission and soil NPK content. The intercept coeficient have positif value in all Mlati sites data indicates that the predicted value of the Methane emission when the soil NPK content is zero is positive. On the other hand, all intercept coeficient in Pakem sites has negative value indicates that the predicted value of methane emission when soil NPK is zero is negative. In this case, the regression line crosses the y-axis below the zero value.

Then to ensure that the relationships between the dependent and independent variables are highly correlated, statistically significant, and not random, a t-test was conducted. The results of the analysis showed that all relationships between CH_4 emissions and soil NPK levels were significant with p values less than 0.05, as shown in Table 2. These findings indicate a strong correlation and statistical significance between CH_4 emissions and soil NPK levels.

The R^2 value (ranging from 0.7276 to 0.9638) in the linear regression relationship between methane emissions and NPK parameters indicates that methane emissions have a linear increasing relationship that can explain variations in nutrient concentrations. Nitrogen showed the strongest relationship with methane emissions, followed by phosphorus and potassium. Positive regression slopes in all sub-plots indicate that increasing methane emissions are associated with increasing nutrient concentrations, with the largest response seen for potassium based on higher slope values.

The results of this study are in line with findings reported in previous studies, which showed that NPK levels in soil have a direct influence on methane emissions from cultivated land. Research by Petaja et al., 2023 and Wu et al., 2023 also revealed that increasing concentrations of nitrogen (N), phosphorus (P) and potassium (K) in the soil can stimulate methanogenic microbial activity, which contributes to increased methane emissions. This systematic relationship is consistent with biogeochemical processes affecting soil nutrient quality, so nutrient measurements, especially nitrogen, can be used as a practical and relevant indicator in monitoring methane emissions in cultivation practices across different sites.

The application of organic mulch reduces methane emissions, while the use of fertilizers, especially inorganic NPK fertilizers, increases methane emissions. The combination of these factors results in varying methane emissions, which exhibit a linear correlation with nitrogen content and methane emissions.

Theoritical mechanism

Figure 8 illustrates the mechanism of methane gas formation based on the research scenarios. The application of NPK fertilisers in agricultural fields has been found to significantly increase methane emissions. However, the use of organic fertilisers, as highlighted in this study, can help reduce methane emissions. Both organic and inorganic fertilizers influence methane emissions, with the extent of their impact being contingent on several factors, such as soil temperature and pH. In tropical regions, replacing inorganic fertilisers with organic alternatives has been reported to substantially decrease methane emissions (He et al., 2023). Several studies suggest that organic fertilisers may reduce greenhouse gas emissions

Table 2. Results of t-test relationship between CH_4 emission variables and soil NPK

Variable relationship	t-calculated	p-value	Sign
Mlati			
CH_4 Emission - N	-9.325	0.0021	*
CH_4 Emission - P	-13.505	0.0024	*
CH_4 Emission - K	-24.546	0.0020	*
Pakem			
CH_4 Emission - N	-4.097	0.0047	*
CH_4 Emission - P	-7.241	0.0189	*
CH_4 Emission - K	-16.407	0.0072	*

Note: Significance level $^{*}p < 0.05$.

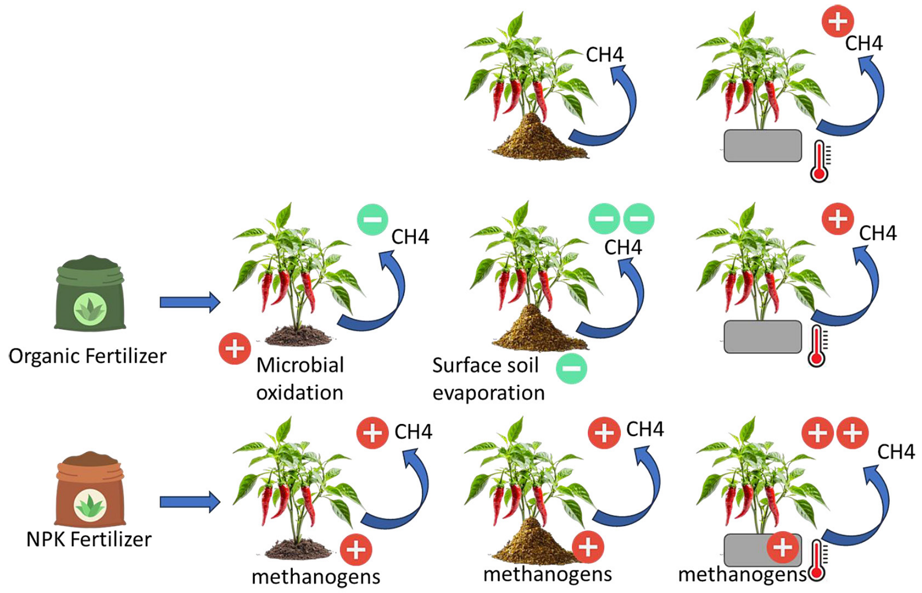

Figure 9. Theoritical mechanism

(Linquist et al., 2012; Smith et al., 2020). This is primarily because organic fertilisers minimise environmental impacts and reduce reliance on chemical nitrogen fertilisers, thereby lowering the GHG emissions associated with their production (Smith, 2016).

The use of organic mulch can significantly reduce methane emissions compared to using plastic mulch or no mulch. When combined with organic fertiliser, the use of organic mulch can further increase the reduction of methane emissions. The breakdown of organic mulch provides accessible carbon and nitrogen, promotes the release of carbon dioxide (Bavin et al., 2009), and helps reduce emissions of methane and nitrous oxide (Yagioka et al., 2015). In contrast, plastic mulching can expedite the microbial decomposition of soil organic matter, potentially depleting soil organic carbon stocks (Chen et al., 2017) and contributing to an increase in greenhouse gas emissions (Jia et al., 2021; Ma et al., 2018) (Figure 9).

CONCLUSIONS

This study reveals findings on the effects of different fertiliser and mulching practices on methane emissions during chilli cultivation. The findings showed that the use of NPK fertilisers significantly increased methane emissions in chilli cultivation. In contrast, the use of organic fertilizers leads to reduced methane emissions when compared to NPK fertilizers. The application of organic mulch, like dried bamboo leaves, enhances soil NPK concentrations and organic carbon content, simultaneously lowering methane emissions. Conversely, plastic mulch significantly increases methane emissions, particularly when combined with NPK fertilizers. Soil NPK levels exhibit a high (> 90%) to moderate (> 70%) correlation with methane emissions. The combination of organic fertilizers and organic mulch has been shown to significantly reduce methane emissions.

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