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Environmental Factors and Mulching Effects on Soil Nitrogen in Organic Curly Chili (*Capsicum annuum* L.) Cultivation for Sustainable Agriculture

Indah Retno Wulan[1], Bayu Dwi Apri Nugroho[1,✉], Chandra Setyawan[1], Aristya Ardhitama[1,2], Jeane Claudea Tanjung[1]

[1] Department of Agricultural and Biosystem Engineering, Gadjah Mada University, Yogyakarta, INDONESIA.
[2] BMKG – Climatology Station of Yogyakarta, Jl. Kabupaten Km. 5.5 Duwet, Sendangdadi, Mlati, Sleman, Yogyakarta, INDONESIA.

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Corresponding Author:
✉ bayu.tep@ugm.ac.id
(Bayu Dwi Apri Nugroho)

ABSTRACT

Nitrogen availability is a critical determinant of chili yield, and its dynamics are influenced by environmental conditions and cultivation practices such as mulching. This study aimed to evaluate the combined effects of environmental factors and mulching on soil nitrogen levels in curly chili (Capsicum annuum L.*) cultivation using organic fertilizer under a sustainable agriculture framework. The experiment used a randomized block design with 24 plots and three treatments: no mulch (P1M0), organic mulch with bamboo leaves (P1M1), and inorganic mulch with plastic (P1M2). Monitoring was conducted for 4 months on soil pH, volumetric water content (VWC), electrical conductivity (EC), temperature, rainfall, solar radiation, humidity, and wind speed. Results showed that soil nitrogen was highest in no mulch (31.1 mg/kg), followed by organic mulch (28.8 mg/kg), and lowest in inorganic mulch (25.6 mg/kg). ANOVA confirmed that organic mulch was comparable to no mulch, but significantly better in maintaining nitrogen than inorganic mulch. Regression analysis identified electrical conductivity as the strongest positive predictor across all treatments, while soil pH showed negative effects and average temperature tended to reduce nitrogen under no mulch conditions. Model accuracy was strong (R^2: P1M0 = 0.799, P1M1 = 0.799, P1M2 = 0.699). The use of bamboo leaves can be an alternative in maintaining soil nitrogen availability. Mulching practices adapted to environmental conditions can enhance soil fertility and support sustainable chili production.*

1. INTRODUCTION

Chili (*Capsicum annuum* L.) is believed to have originated in Mexico before spreading to regions such as South America, Central America, and Europe. It is commonly consumed in various forms, including fresh, dried, or processed, serving as both a vegetable and a spice. Beyond its culinary uses, chili also plays a significant role in the pharmaceutical industry. Nutritionally, chili provides essential compounds, including 1.0 g of protein, 0.3 g of fat, and 7.3 g of carbohydrates, along with important minerals like calcium (29 mg), phosphorus, and iron. Additionally, it contains 18 mg of vitamin C, 0.05 mg of vitamin B1, and bioactive alkaloid compounds, particularly capsaicin, which contributes to its characteristic heat (Rubatzky & Yamaguchi, 1999).

Nitrogen (N) as one of the macro nutrients that were essential for plants was found in the soil in organic form, which was about 90% (Jansson & Persson, 1982; Haynes, 1986). The mineralization of organic N in the soil greatly determines the availability of N and soil fertility (Nadelhoffer, 1990; Gaiser *et al*., 1994), and was also the main source for the N needs of plants (Purnomo *et al*., 2000).

Organic farming is a production system that minimizes or eliminates synthetic fertilizers, pesticides, and growth regulators, instead relying on crop rotation, residues, livestock manure, legumes, green manure, organic waste, mechanical weeding, mineral-rich rocks, and biological pest control to maintain soil productivity and fertility (Nengparmoi *et al*., 2023). Nitrogen is a critical nutrient for plant growth and must be available in balanced amounts to ensure proper root, stem, and leaf development. Excess nitrogen promotes excessive vegetative growth, making plants susceptible to disease, while deficiency leads to chlorosis and reduced growth (Leiwakabessy *et al*., 2003). Ecoenzymes, produced from fermenting organic waste with sugar and water, contain enzymes, organic acids, and essential minerals such as N, P, and K. Studies show their application increases soil nitrogen and enhances organic matter mineralization, improving nutrient availability and acting as biofertilizers that support soil health and crop productivity (Lubis *et al*., 2022; Nugroho *et al*., 2020; Suwandi *et al*., 2024).

Mulching is another key cultivation method, functioning as soil cover to retain moisture, suppress weeds, improve water use efficiency, protect roots, and reduce erosion (Iqbal *et al*., 2020; Prosdocimi *et al*., 2016). Field studies show that Plastic Photo Mulch (PFM) can increase corn yields by 45–95%, particularly under organic fertilization due to higher nutrient input (Lee *et al*., 2019). In chili cultivation, plastic mulch improves growth conditions by conserving moisture and controlling weeds (Zhao *et al*., 2023; Salama & Geyer, 2023). However, long-term use causes environmental concerns due to non-biodegradable residues. Natural mulches such as bamboo leaves provide a sustainable alternative by retaining soil moisture, enhancing organic matter, and reducing environmental risks. Nevertheless, most studies have analyzed mulching or fertilization separately, without integrating environmental factors such as temperature, moisture, and solar radiation in their impact on soil nitrogen—especially in organic curly chili systems.

Environmental factors, especially climate and soil conditions, play a role in plant growth and development processes (Joswig *et al*., 2022). Variations fundamentally influence the weather and climate conditions in a region in the distribution of solar radiation energy. Changes in the intensity of solar radiation received on Earth shape climate patterns over various periods. In addition to affecting weather and climate, solar radiation patterns also had significant impacts in various sectors such as agriculture, particularly on plant productivity which plays a role in the processes of photosynthesis and respiration (Setiawan, 2009). Various environmental factors such as climate, solar radiation, temperature, and humidity play an important role in plant growth processes and soil nitrogen mineralization. For example, mulching can regulate soil temperature and moisture, thereby stimulating microbial activity and enhancing nitrogen availability (Qin *et al*., 2015). A meta-analysis of 74 studies reported that mulching significantly increased crop yields, water use efficiency, and nitrogen use efficiency by up to 60% compared with no mulching. Organic mulches also improve soil fertility through their decomposition (Qin *et al*., 2015). Moreover, the use of plastic mulches has been shown to increase soil microbial nitrogen biomass and enrich C–N cycling-related microorganisms, thereby supporting enhanced mineralization and nutrient availability (Wang *et al*., 2021).

While numerous studies have examined the effects of mulching or environmental factors separately on soil nitrogen, little research has integrated both aspects under organic curly chili cultivation in a sustainable agriculture context. The objective of this study was to determine the effect of different mulching materials and key environmental parameters on soil nitrogen content in organic curly chili under sustainable agriculture practices. This study is among the first to evaluate the combined influence of environmental parameters and mulching practices on soil nitrogen levels in organically grown curly chili within tropical agroecosystems. This approach is expected to provide a more comprehensive understanding in an effort to improve fertilizer efficiency, preserve the environment, and support a sustainable agricultural system.

2. RESEARCH MATERIALS AND METHODS

2.1. Research Location

The research location was in Sleman Regency, Special Region of Yogyakarta, where the region was a chili production center that contributes 2.25% on a national scale in 2020 (Ministry of Agriculture of the Republic of Indonesia, 2021). According to data, Kapanewon Pakem in 2023 produced 24.73 kw/ha (One quintal is equivalent to 100 kilograms*)*. The research was located in Kemendung Hamlet, Candibinangun Village with an elevation of 450 meters above sea level with a soil texture consisting of 72.06% sand, 15.38% dust, and 12.56% clay. The research location map can be seen in Figure 1. The research was conducted during the dry season of 2024, namely May-October 2024.

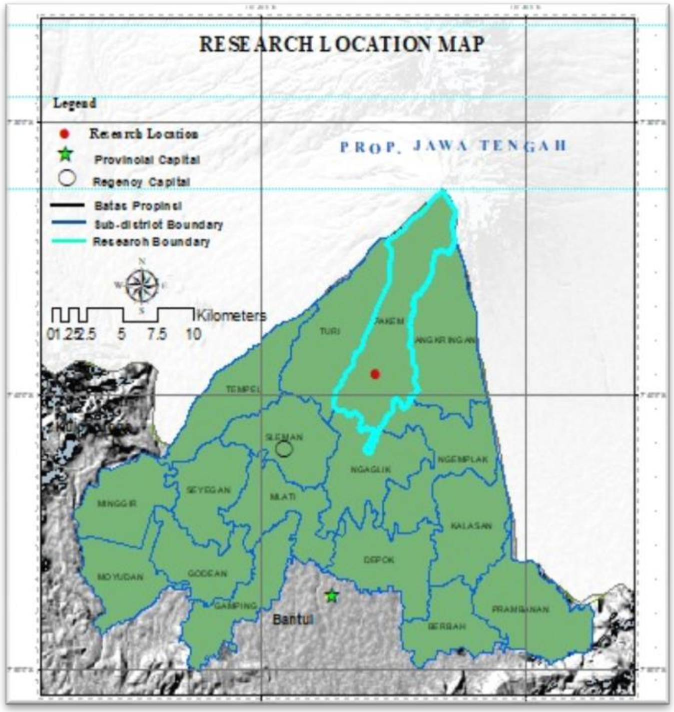

Figure 1. Research location map

2.2. Materials and Tools

The materials used in this study were curly chili seeds Electra variety, organic fertilizer in the form of ecoenzyme, organic mulch in the form of bamboo leaves, and inorganic mulch in the form of silver plastic. The fertilizer used was ecoenzyme fertilizer with a concentration of 30 ml/L of water. Fertilization was carried out once a week with a volume of 90 ml poured on the soil and sprayed on the leaves. The tools used were sprayer, hoe, shovel, bamboo, paranet, signboard, watering can, cellphone, and laptop. Environmental measurements used Automatic Weather Station (AWS) and soil sensors. The technical specifications of AWS and soil sensors used in the study were presented in Table 1.

Table 1. Technical specifications of an Automatic Weather Station and soil sensor.

Component Name	Specification	
	Trade Mark	**Type**
Data Logger	Campbell Scientific	CR1000X
Baterai	Panasonic	VRLA 12VDC 28Ah
Regulator	Victron Energy	MPPT 75/15
Solar Panel	Cansela	Solar Cell
Tipping Bucket Sensor	HS HyQuest Solutions	TB4/0.2mm
Solar Radiation Sensor	Kipp&Zonen	CMP 3
Temperature and Average Humidity Sensor	Campbell Scientific	HygroVUE 10
Soil Sensor	RK520-01 (*soil moisture and temperature sensor*), RK500-22 (*soil pH sensor*), RS-NPK/RS-485 (*Soil NPK Sensor and soil EC).*	

2.3. Research Methods

This study was conducted using randomized block design with 24 plots and 3 mulch type treatments. Each plot measured 1 m × 1 m and received one of three mulching treatments: M0 (without mulch), M1 (bamboo leaves mulch/organic), M2 (plastic mulch/inorganic). The combination of treatments produced 135 samples. The parameters observed included N-total content, soil temperature, soil pH, EC (electrical conductivity), air temperature, rainfall, solar radiation, air humidity, and maximum wind speed measured every one week. The data was processed using Excel for the first time to facilitate the processing using R Studio v.12 and the Python language via Google Colabs.

The RS-NPK (RS-485) sensor is a soil sensor designed to measure the concentrations of essential nutrients, namely nitrogen (N), phosphorus (P), and potassium (K). Several studies have reported that the measurements obtained from these sensors can be validated against laboratory analyses, with differences of approximately 10% for nitrogen, indicating sufficient reliability for field research (Kumar *et al*., 2025; Chinembiri *et al*., 2025). Such validation provides scientific legitimacy for the use of RS-485 NPK sensors as a rapid alternative for in situ measurements under field conditions. In addition, technical specifications from manufacturers indicate that these sensors have a measurement range of 1–1999 mg/kg with an accuracy of ±2% FS, and support data communication through the Modbus-RTU protocol, facilitating integration with IoT devices and automated data recording systems (Shandong Renke Control Technology, 2021; Changsha Zoko Link Technology Co., Ltd. (n.d); Indonusa Tekno, 2025). Therefore, the use of RS-485 NPK sensors is not only practical and efficient but also scientifically validated as relevant for sustainable agricultural research. Soil nitrogen was measured at 15 cm depth. Measurements were taken between 07:00–09:00 under field-moist conditions. Previous studies have demonstrated that the RS-NPK sensor is effective for rapid and practical monitoring of soil nutrient availability. For example, research on guava cultivation in India reported that the use of NPK sensors significantly improved fertilizer efficiency and crop yield (Adak, 2025). Similarly, an Indonesian study developed a portable RS-NPK–based prototype, which was proven sensitive in detecting variations in soil nitrogen, phosphorus, and potassium (Sulaeman *et al*., 2024). These findings support the use of the RS-NPK sensor in this study to measure available soil nitrogen.

The data was first tested for assumptions (normality, homoscedasticity, autocorrelation, and multicollinearity) to determine the appropriate analysis method. After that, visualization analysis (scatter plot) and descriptive statistics were carried out, followed by Analysis of Variance (ANOVA), which included the simultaneous test (F-test) to assess the overall significance and pairwise comparisons (Tukey's post hoc test) to evaluate differences among treatments. Finally, Pearson correlation analysis was conducted to examine the relationships between variables. Multiple regression models are used to predict the value of the dependent variable (response) based on the value of more than one variable. When more than one independent variable (predictor) the regression model is called multiple regression. According to Li *et al*., (2022), the functional relationship between the predictor variable (variable X) and the response variable (Y) is a linear function, so the corresponding linear model is

$$Y = a + b_1X_1 + b_2X_2 + b_3X_3 + U \quad (1)$$

where Y is soil nitrogen content; X_1, X_2, $X3$ are environment variables; b_1, b_2, b_3 are regression coefficients; and U is disturbance term (error term).

The determination coefficient aims to determine how much the independent variable was able to explain the dependent variable. The R^2 value ranges from 0 to 1, the closer it was to 1, the greater the diversity of dependent data explained by the independent variable. The correlation coefficient (r) was used to determine the linear relationship between the independent variable (X) and the dependent variable (Y). In addition, the correlation coefficient (r) was used to measure the strength (closeness) of a relationship between variables.

3. RESULT AND DISCUSSION

Climate plays an important role in determining the types and cultivars of plants that can be cultivated and in determining the final yield. Successful crop production requires efficient use of climate resources, such as sunlight, carbon dioxide, and water. The phenology and rate of development of a plant depend on climate factors such as temperature, day length, and water supply. Likewise, in the chili plants used in the study.

The data obtained from the chili fields were visualized using scatter plots. Scatter plots were a visualization method for understanding the relationship between two variables in a dataset and identifying the type of relationship between variables (linear or non-linear), and finding outlier values. As a data exploration tool, scatter plots were used to visualize experimental data and compare them with hypotheses or expected models (Montgomery *et al*., 2012; Cleveland, 1993; Tukey, 1977; McGill *et al*., 1978).

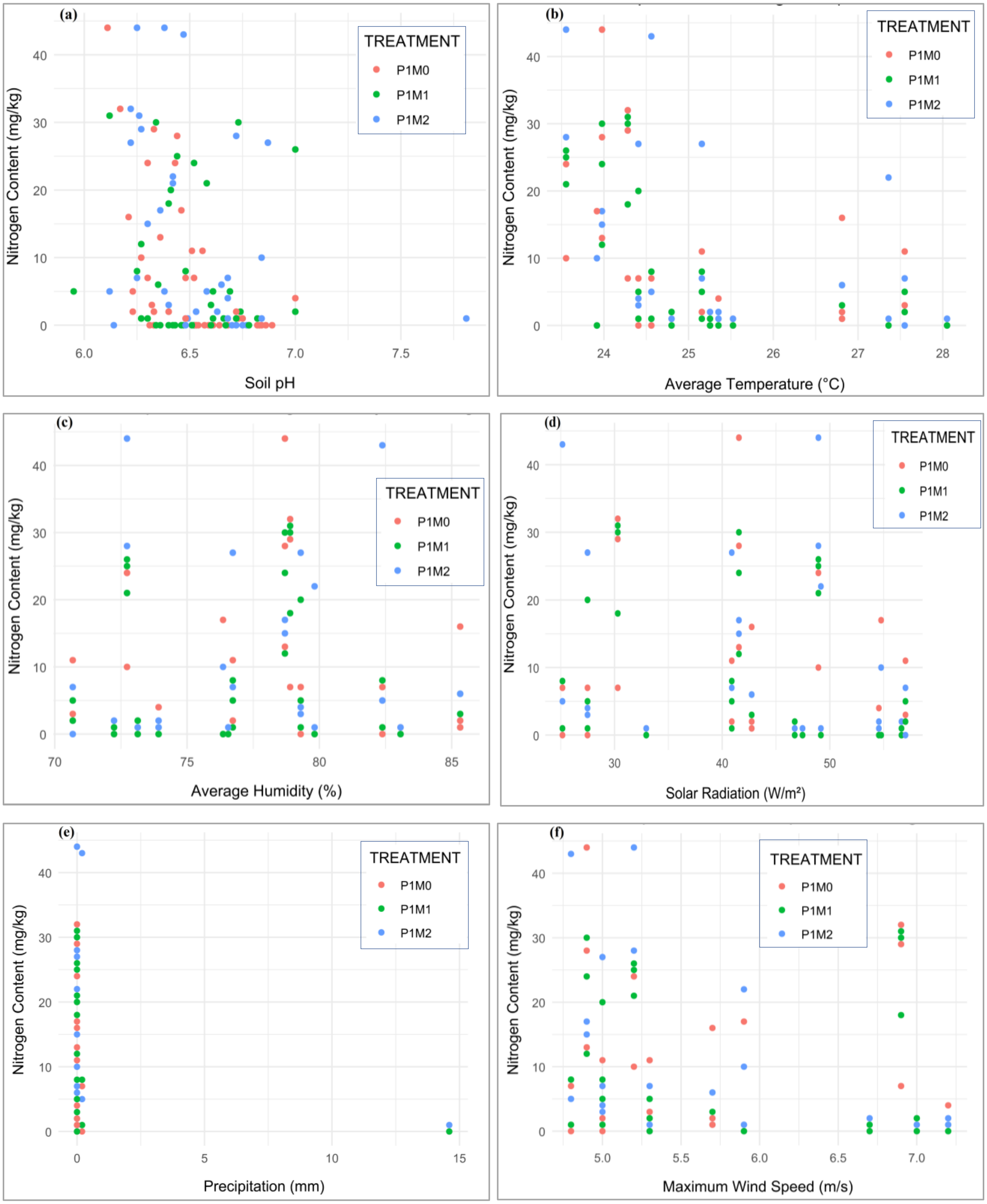

Figure 2. Scatter plot of soil pH, average temperature, average humidity, solar radiation, precipitation, and maximum wind speed on soil nitrogen content

Figure 2a shows the relationship between soil pH and nitrogen levels. Each dot represents one sample, with different colors indicating the treatments given. It appears that nitrogen levels tend to be high at soil pH around 6.2 to 6.5 and decrease at higher pH. This suggests that more acidic soil pH conditions support higher nitrogen levels. Figure 2b shows the relationship between average temperature and nitrogen levels. It appears that nitrogen levels had large variations at temperatures between 23°C and 25°C, while at higher temperatures, nitrogen levels tend to be lower.

Figures 2c and 2d show the relationship between average humidity and solar irradiance on nitrogen content. It can be seen that nitrogen levels vary from 70% to 85% humidity, with some extreme values at higher humidity. There were certain patterns (e.g., an upward or downward trend), which could indicate that solar irradiation and presipitation influenced nitrogen levels (Figures 2d and 2e). There was a clear pattern, this could be an indication that moisture was affecting the weathering process or nitrogen release. There was no clear pattern, possibly because wind speed was not a major factor affecting nitrogen levels.

Table 2 shows important patterns in environmental variables and soil nitrogen content across the three treatments (P1M0: no mulch, P1M1: organic mulch, P1M2: inorganic mulch). Average nitrogen was highest in the no mulch treatment (31.09), followed by organic mulch (28.75), and lowest in inorganic mulch (25.6). Nitrogen variability was considerable across all treatments, with a minimum value of 0 and a maximum between 140 - 163.

Table 2. Descriptive statistics of soil and environmental parameters under treatments P1M0, P1M1, and P1M2.

Parameters/	Mean			Std. Deviation			Std. Error			Min			Max		
Treatments	P1M0	P1M1	P1M2	P1M0	P1M1	P1M2	P1M0	P1M1	P1M2	P1M0	P1M1	P1M2	P1M0	P1M1	P1M2
Nitrogen (mg/kg)	31.1	28.8	25.6	24.4	20.2	18.5	1.6	1.5	2.0	0.0	0.0	0.0	163.0	150.0	140.0
pH	6.3	6.3	6.2	0.2	0.2	0.2	1.6	1.5	2.0	5.6	5.8	5.8	7.2	7.1	7.1
VWC (%)	35.8	32.5	30.1	20.7	18.5	16.8	2.4	2.7	2.5	7.5	8.0	7.0	228.0	200.0	190.0
EC (dS/m)	0.5	0.5	0.5	0.1	0.1	0.1	11.2	20.9	28.5	0.2	0.3	0.3	0.8	0.8	0.7
Average Temperature (°C)	25.5	24.9	24.5	1.3	1.2	1.2	0.2	0.2	0.2	23.6	23.0	22.5	28.9	28.0	27.5
Rainfall (mm)	2.7	2.8	2.5	6.5	5.8	5.2	0.5	0.5	0.5	0.0	0.0	0.0	22.0	20.0	18.0
Solar Radiation (W/m^2)	93.6	95.2	91.8	10.3	9.8	9.9	1.5	1.5	1.5	68.8	70.0	68.0	100.0	98.0	96.0
Average Humidity (%)	78.4	79.1	77.5	11.5	10.9	10.3	0.6	0.6	0.6	37.7	40.0	38.0	94.2	92.0	90.5
Max Wind Speed (m/s)	7.4	7.4	7.2	0.9	0.9	0.8	0.1	0.1	0.1	5.5	5.8	5.6	8.7	8.5	8.2

Based on the data Table 2, soil parameters such as pH (6.2–6.3), volumetric water content (VWC), and electrical conductivity (EC) remained relatively stable across treatments. The no-mulch treatment (P1M0) showed the highest mean values for soil nitrogen (31.1 mg/kg), pH, VWC, air temperature, humidity, and solar radiation, whereas inorganic mulch (P1M2) generally produced the lowest values. This indicates that mulching can influence the surface soil microclimate, which in turn affects microbial activity involved in organic matter decomposition and nitrogen mineralization. Optimal climatic conditions, such as adequate temperature and moisture, enhance microbial activity, thereby increasing nitrogen availability for plants (Karamina *et al*., 2017; Aprimonika *et al*., 2024; Serlina, 2020).

Additionally, differences in VWC and solar radiation among treatments suggest that organic mulch (P1M1) tends to better maintain soil moisture compared to inorganic mulch, even though its nitrogen content is slightly lower than the control (no-mulch treatment). Therefore, while the no-mulch treatment produced the highest nitrogen accumulation, the use of organic mulch remains important for stabilizing soil conditions and supporting sustainable crop production.

Figure 3 shows that based on the regression diagnostic plots, the model meets the basic assumptions of linear regression, namely residual normality, linearity, and homoscedasticity. The Residuals vs Fitted plot shows a random distribution with no particular pattern, indicating linearity and relatively constant residual variance. The Q-Q plot shows that the residuals mostly follow a normal distribution, although there are slight deviations at the ends of the curve. The Scale-Location plot confirms that the residual variance is fairly homogeneous, while Residuals vs Leverage identifies some highly leveraged points that do not significantly exceed the Cook's distance limit. Therefore, this

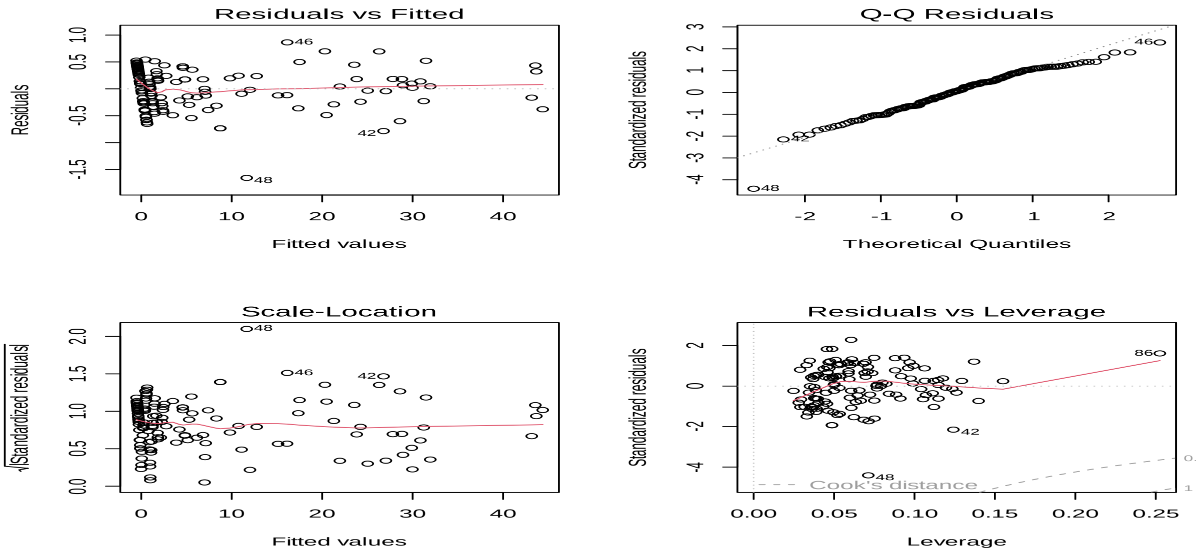

Figure 3. Regression diagnostic plots for the multiple linear regression model of Nitrogen with predictors (pH, VWC, EC, average temperature, rainfall, solar radiation, average humidity, and maximum wind speed)

regression model can be considered feasible and does not suffer from serious assumption violations (Ghozali, 2018; Kutner *et al*., 2005).

Based on the ANOVA test results obtained, it appears that the treatment has a significant effect on the observed variables. This is indicated by the F value of 4.03 with degrees of freedom of treatment (df = 2) and residual (df = 132), as well as a p-value of 0.027 which is smaller than the 0.05 significance level. Thus, the null hypothesis stating that there is no difference in means between treatments is rejected, and it can be concluded that at least one treatment has a significantly different mean than the other treatments. The Sum of Squares value for treatments of 939 and Mean Square of 565.0 indicates that the variation between treatment groups is quite large compared to the variation within groups (Mean Square of residual of 125.0). The ratio of treatment Mean Square to residual Mean Square yielded an F value high enough to indicate a statistically significant difference. This is shown in Table 3.

Table 3. Analysis of Variance (ANOVA) of Nitrogen Content

Source	Df	Sum Sq	Mean Sq	F value	Pr(>F)
TREATMENT	2	939	469.5	4.03	0.027
Residuals	132	16500	125		

Note: * = significant at α = 0.05.

Table 4. Mean Nitrogen Content of Treatments with Tukey's Test Grouping

Treatment	Mean	SE	Letters
P1M0	31.1	1.58	a
P1M1	28.8	1.47	a
P1M2	25.6	2.02	b

Note: Means followed by the same letter are not significantly different according to Tukey's test at the 95% confidence level.

Tukey's test at Table 4 showed that treatment P1M2 (inorganic mulch) significantly increased nitrogen content (10.02 ± 2.02) compared to P1M0 (no mulch, 6.78 ± 1.58) and P1M1 (organic mulch, 6.90 ± 1.47). This suggests that inorganic mulch provided the highest nitrogen accumulation, while the effect of organic mulch was not markedly different from the control. Previous studies also confirmed that inorganic mulches, such as plastic film, enhance nitrogen uptake by improving soil temperature and moisture (Yan *et al*., 2021). Conversely, organic mulches like straw or compost contribute more to long-term fertility by improving soil organic matter, microbial activity, and nutrient cycling, while reducing plastic-related risks (Akhtar *et al*., 2023). Therefore, while P1M2 showed the highest nitrogen content in this study, P1M1 should not be disregarded, as organic mulching supports soil health and sustainability, and its performance was not significantly inferior compared to inorganic mulch. This highlights the complementary role of both mulching strategies in sustainable crop production.

The Figure 4 revealed that soil nitrogen exhibited a perfect positive correlation with EC (r = 1.0), suggesting a strong linear dependence or possible redundancy between these two variables. In addition, soil nitrogen was negatively correlated with soil pH (r = –0.34) and average temperature (r = –0.46), indicating that higher soil pH and elevated temperatures tend to reduce nitrogen availability. Other environmental variables, including rainfall, humidity, solar radiation, and wind speed, showed only weak relationships with nitrogen (r values generally between –0.2 and 0.2). These findings are consistent with previous studies reporting that soil pH and temperature regulate nitrogen dynamics by influencing nitrification and denitrification pathways (Davidson *et al*., 2000; Smith *et al*., 2003). Furthermore, the strong association between EC and soil nitrogen may reflect the influence of soluble ions and nutrient availability in regulating nitrogen content, as highlighted by Zhang & Wienhold (2002). These results indicate that higher EC is associated with greater nitrogen availability, whereas higher temperature and more alkaline conditions tend to reduce soil nitrogen levels.

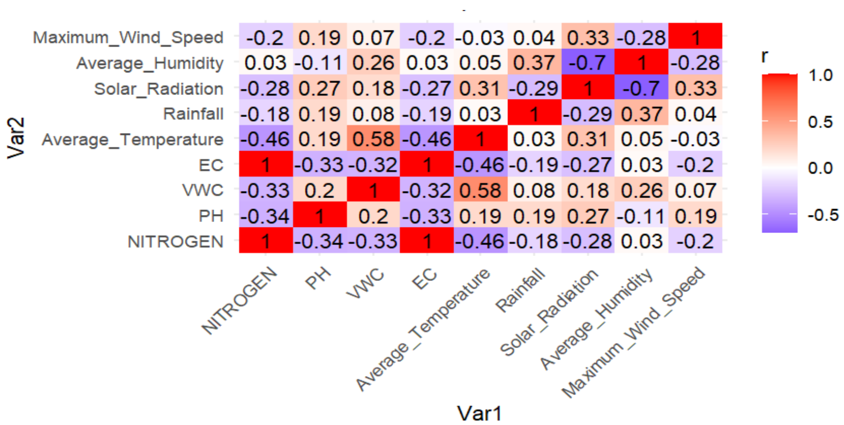

Figure 4. Correlation heatmap of soil properties and climatic variables

From the partial test results, the p-value of each predictor helps to determine which variables were statistically significant. Electrical conductivity (EC) was the most consistently significant predictor across all three treatments. In all three treatments, the p-value for EC was very small ($p < 0.001$), indicating that EC has a strong influence on nitrogen levels. Precipitation was significant in P1M0 ($p = 0.027$, indicating that precipitation played a role in determining nitrogen levels in this treatment, as seen in Table 5. Under P1M1 treatment (Table 6), EC also shows a strong influence on nitrogen levels with p-value = 0.001.

Table 5. Partial test results in multiple regression analysis of nitrogen levels for treatment P1M0 (without mulch)

Variable	**Estimate**	**Std. Error**	**t value**	**Pr(>|t|)**	
(Intercept)	6.3224	3.1059	2.0360	0.0494	*
PH	-0.6199	0.3418	-1.8140	0.0783	
VWC	0.0006	0.0048	0.1280	0.8986	
EC	0.0712	0.0005	152.119	0.0015	***
Average_Temperature	-0.0641	0.0577	-1.1110	0.2743	
Rainfall	0.0404	0.0175	2.3040	0.0273	*
Solar Radiation	0.0041	0.0086	0.4780	0.6354	
Average Humidity	-0.0150	0.0203	-0.7390	0.4647	
Maximum_Wind_Speed	-0.0056	0.0792	-0.0710	0.9439	

Notes: The p value indicates the significance level of the regression result (*** = $p < 0.001$; ** = $p < 0.01$; * = $p < 0.05$).

Table 6. Partial test results in multiple regression analysis on nitrogen content for P1M1 (organic mulch) treatment

Variable	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	2.7053	3.7171	0.7280	0.4710	
PH	-0.4204	0.2875	-1.4620	0.1520	
VWC	0.0016	0.0050	0.3210	0.7500	
EC	0.0706	0.0005	133.5780	0.0011	***
Average_Temperature	0.0068	0.0574	0.1190	0.9060	
Rainfall	0.0244	0.0182	1.3390	0.1890	
Solar Radiation	-0.0021	0.0109	-0.1910	0.8500	
Average Humidity	-0.0147	0.0278	-0.5280	0.6010	
Maximum_Wind_Speed	0.129073	0.078935	1.635	0.111	

Notes: The p value indicates the significance level of the regression result (*** = $p < 0.001$; ** = $p < 0.01$; * = $p < 0.05$).

Table 7. Partial test results in multiple regression analysis on nitrogen content for P1M2 (inorganic mulch) treatment

Variable	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	1.8577	2.9569	0.6280	0.5338	
PH	-0.0929	0.2524	-0.3680	0.7148	
VWC	0.0011	0.0053	0.2060	0.8378	
EC	0.0708	0.0004	167.4180	0.0011	***
Average_Temperature	0.0453	0.0631	0.7180	0.4773	
Rainfall	0.0089	0.0195	0.4550	0.6519	
Solar Radiation	-0.0298	0.0109	-2.7490	0.0092	**
Average Humidity	-0.0281	0.0258	-1.0870	0.2843	
Maximum_Wind_Speed	0.1059	0.0876	1.2090	0.2344	

Notes: The p value indicates the significance level of the regression result (*** = $p < 0.001$; ** = $p < 0.01$; * = $p < 0.05$).

Table 7 shows that sunlight was only significant in P1M2 (p = 0.009), indicating that in this treatment, sunlight had a measurable influence on nitrogen levels. Other variables such as PH, VWC, mean temperature, mean humidity, and maximum wind speed were generally not significant across the three treatments, indicating that they may not had a major influence on nitrogen levels in this dataset.

Thus, certain environmental factors, especially EC, average temperature, rainfall, and average humidity, had a greater contribution in determining soil nitrogen levels in this study. Several studies had mentioned the correlation between soil EC values and nitrogen, phosphorus, potassium and pH contents. The correlation between EC and nitrogen showed a value of -0.4, indicating a negative relationship between the two. This means that the higher the EC value, the lower the soil nitrogen content (Sari *et al*., 2019). According to Setiawan & Hariyono (2022), high air humidity can affect the transpiration rate of plants. Although not directly related to soil nitrogen content, changes in air humidity can affect the activity of soil microorganisms that play a role in the nitrogen mineralization process.

Soil nitrogen levels were found to be higher in plots treated with organic mulch compared to those with inorganic mulch. The use of organic mulch also contributed to an increase in soil organic carbon (C-organic) levels when compared to the initial soil conditions before the experiment began. Research findings indicate that during the dry season, C-organic content increased by approximately 0.24% to 0.43%. This improvement is largely driven by the decomposition of organic matter by microorganisms, which break down complex polysaccharides into simpler short-chain saccharides. This process facilitates the faster release of nutrients, making them more readily available for plant uptake. A decrease in the C/N ratio of the organic complex was characteristic of decomposition (Jansson & Persson, 1982). The increase in total soil N content with organic mulch treatment proves that plant organic matter was the main source of soil N after organic matter decomposes. The increase in soil N content was in line with the statement of Li *et al*. (2022) that the decomposition of organic matter will produce compounds containing N, including nitrate, nitrite and nitrogen gas. According to Li *et al*. (2022), total soil N levels increased with the application of organic fertilizers.

According to Tables 5, 6 and 7 above, the results of the regression equation of environmental elements with soil nitrogen levels in each treatment were summarized in Table 8. In this table *Y* is soil nitrogen content (ppm), and X1 to

X8 is respectively soil pH, VWC (%), EC (dS/m), average temperature (°C), rainfall (mm), solar radiation (W/m²), average humidity (%), and maximum wind speed (m/s).

Table 8. Summary of regression equation for N-total content

Treatment	Regression Equation	
P1M0	$Y = 6.322 - 0.62X_1 + 0.001X_2 + 0.071X_3 - 0.064X_4 + 0.040X_5 + 0.004X_6 - 0.015X_7 - 0.006X_8$	(2)
P1M1	$Y = 2.705 - 0.42X_1 + 0.002X_2 + 0.071X_3 + 0.007X_4 + 0.024X_5 - 0.002X_6 - 0.015X_7 + 0.129X_8$	(3)
P1M2	$Y = 1.858 - 0.093X_1 + 0.001X_2 + 0.071X_3 + 0.045X_4 + 0.009X_5 - 0.030X_6 - 0.028X_7 + 0.106X_8$	(4)

The regression results (Tables 8) revealed differences in the influence of environmental factors on soil nitrogen levels across treatments. In P1M0 (no mulch), electrical conductivity (EC, 0.071) emerged as the dominant factor increasing nitrogen, while pH (-0.62) and mean temperature (-0.064) showed negative effects. Other variables such as rainfall (0.040), humidity (-0.015), and solar radiation (0.004) had relatively minor impacts. In P1M1 (organic mulch), EC remained dominant, pH (-0.42) still exhibited a negative influence though less pronounced, while maximum wind speed (0.129) showed the strongest positive effect. In P1M2 (inorganic mulch), EC continued to play a role, but irradiation (-0.03) and humidity (-0.028) exerted stronger negative effects compared to the other treatments.

The high R^2 values (P1M0: 0.7991; P1M1: 0.7988; P1M2: 0.6992) indicate that the models explained soil nitrogen variation effectively. The correlation coefficients ($R \approx 0.79$) also suggest a very strong linear relationship between environmental variables and soil nitrogen. Differences in intercepts indicated that initial nitrogen was highest in P1M0 (6.322), followed by lower values in P1M1 (2.705) and P1M2 (1.858).

Plastic mulch has been shown to increase soil temperature by reducing evaporation, thereby maintaining more stable soil moisture (Ibarra-Jimenez *et al*., 2011; Montgomery, 2007). Meanwhile, EC is influenced by fertilizers and nutrient solutions; excessively high EC can hinder nutrient uptake (Ding *et al.,* 2018; Heinen *et al*., 2002). These findings are consistent with Mirzakhaninafchi *et al*. (2022), who demonstrated that EC can serve as an accurate indicator of soil nitrogen status.

Organic mulch tends to improve soil pH, enhance organic matter content, and support microbial activity that sustains nitrogen availability (Laia *et al*., 2025). This aligns with Verma & Pradhan (2024) as well as Wang *et al*. (2015), who emphasized the critical role of organic mulching in soil health and nutrient balance. Thus, the combination of organic fertilizer and organic mulch holds potential to enhance nitrogen availability while promoting the sustainability of agricultural systems.

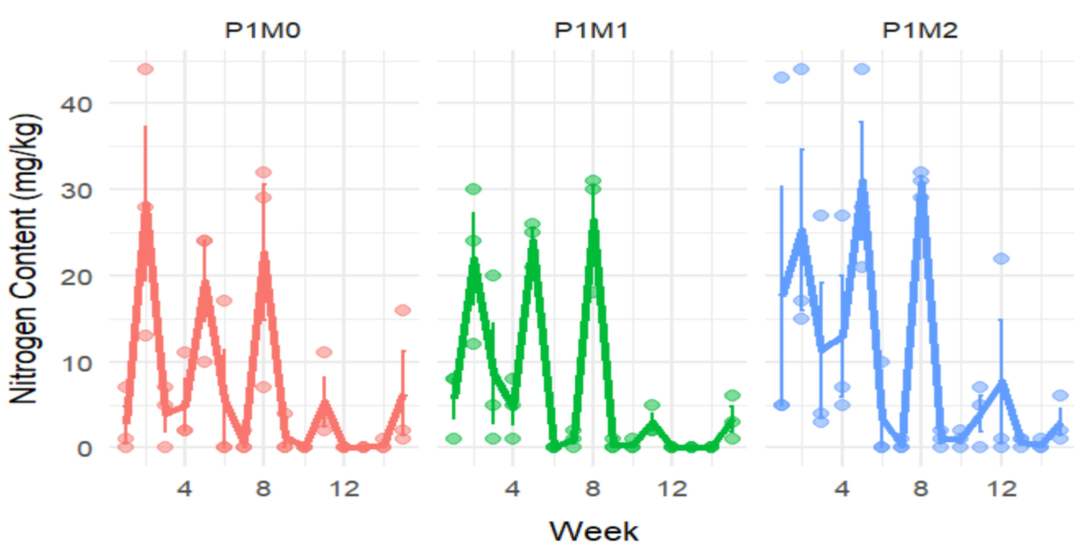

Figure 5. Soil Nitrogen trends across organic and inorganic fertilizer–mulch combinations

As illustrated in Figure 5, the temporal dynamics of soil nitrogen varied substantially across treatment combinations. Under P1M0 (organic fertilizer without mulch), nitrogen content exhibited pronounced fluctuations, characterized by a sharp early-season peak followed by a rapid decline. In contrast, P1M1 (organic fertilizer with organic mulch) demonstrated relatively stable nitrogen dynamics, with moderated fluctuations that ensured more consistent availability throughout the growing period. Meanwhile, P1M2 (organic fertilizer with inorganic mulch) was associated with elevated initial nitrogen levels, which subsequently declined steeply, indicating a rapid but inefficient release of nitrogen into the soil system. These empirical observations are consistent with the results of multiple regression analysis, which identified soil nitrogen as a significant predictor of N_2O emissions ($p < 0.05$). Treatments characterized by unstable nitrogen dynamics (e.g., P1M0 and P1M2) tended to increase the risk of nitrogen loss through greenhouse gas emissions. Conversely, organic mulch application (P1M1) not only maintained soil nitrogen availability but also effectively mitigated N_2O release.

These findings corroborate earlier evidence. Choudhary *et al*. (2002) demonstrated that unstable soil nitrogen dynamics directly contribute to elevated N_2O emissions via denitrification. Similarly, Snyder *et al*. (2014) and Shcherbak *et al*. (2014) emphasized that variability in soil nitrogen availability is a primary determinant of agricultural greenhouse gas emissions. More recent studies, such as Wang *et al*. (2019), highlighted the role of organic mulching in improving nitrogen retention and reducing nitrogen losses, while Chen *et al*. (2013) confirmed that the positive association between soil mineral nitrogen and N_2O emissions can be effectively captured using multiple regression and machine learning approaches.

4. CONCLUSION

The study revealed that soil nitrogen content was highest under no mulch (P1M0, mean = 31.1 mg/kg, followed by organic mulch with bamboo leaves (P1M1, mean = 28.8 mg/kg), and lowest under inorganic mulch with plastic (P1M2, mean = 25.6 mg/kg). ANOVA confirmed significant differences ($F = 4.03$, $p = 0.027$), with organic mulch maintaining nitrogen 3.2 mg/kg higher than inorganic mulch and comparable to no mulch. Regression analysis confirmed that electrical conductivity (EC) was the dominant positive predictor of nitrogen levels, while soil pH and average temperature negatively influenced nitrogen availability. These findings demonstrate that mulching practices, when integrated with environmental factors, significantly affect soil nitrogen dynamics in organic curly chili cultivation, supporting the objective of optimizing soil fertility under sustainable agriculture. In practical terms, organic mulching offers a more sustainable option than inorganic mulch by maintaining higher nitrogen levels and contributing to soil health, while further studies are needed to assess its long-term effects on soil carbon–nitrogen balance, microbial activity, and crop productivity under different climatic conditions.

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