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SOIL RESPIRATION MODEL IN PINEAPPLE PLANTATIONS SUPPORTING CARBON MARKET IMPLEMENTATION

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ABSTRACT

The contribution of pineapple (Ananas comosus) plantations to reducing carbon emissions has been widely reported in global studies; however, the reverse relationship remains less explored. This study aimed to develop a soil respiration model as a function of rhizosphere biota, specifically mesofauna (M_FAU), earthworms (E_WORM), and microorganisms (C_MICR), as well as respiration models based on soil moisture, pH, and temperature. The study was conducted in a pineapple plantation in Southern Sumatra, Indonesia, from February to May 2024, using a randomized design with three replicates. Laboratory analyses at the Soil Science Laboratory, University of Lampung, included soil moisture, respiration, microbial carbon (C_MICR), and mesofauna analysis. Temperature, pH, and earthworm populations were measured and sorted directly in the field. The results showed that microbial content (C_MICR) could be significantly estimated from rhizosphere conditions, particularly temperature (TEMP), soil acidity (pH), and soil moisture (WATER), with the following equation: [C_ MICR]i = -27.2 + 0.460 [TEMP]i + 0.0651 [WATER]i + 2.780 [pH]i quad (P=0.000). Microorganisms (C_MICR) were positively correlated with soil respiration (RESP) (P=0.087), whereas mesofauna (M_FAU) and earthworms (E_WORM) showed no significant effect. The respiration model was expressed as: [RESP]i=2.91-0.0226[M_ FAU]i+0.169[C_ MICR]i-0.043[E_ WORM]i. Further research is recommended to examine the influence of other soil biota on soil physicochemical characteristics.

KEYWORDS: Carbon accounting, Microorganisms, Soil temperature, Soil pH, Southern Sumatra

1. INTRODUCTION

Global climate change has become a central issue in sustainable development, especially because of the increased concentration of greenhouse gases (GHGs) in the atmosphere, which impacts the Earth's climate system. The agricultural sector plays a dual role in this dynamic, both as a source of GHG emissions and as a potential carbon sink through biological processes and soil ecosystem management (Abs et al., 2025; Li et al., 2025). Tropical plantations, including pineapple (Ananas comosus) plantations, have unique edaphic and biological characteristics that make them potentially strategic for land-based climate change mitigation (Mishra et al., 2023).

Soil respiration is one of the largest components of the terrestrial carbon cycle and contributes significantly to the flux of carbon dioxide (CO_2) into the atmosphere. This process reflects the metabolic activity of soil microorganisms, soil fauna, and their response to physical and chemical conditions of the soil (Varshney, Mohan, & Dahiya, 2020). In tropical ecosystems, soil respiration rates tend to be higher because the temperature and humidity conditions support biological activity year-round (Li et al., 2025a).

Soil microorganisms are the main contributors to soil respiration through organic matter decomposition and carbon mineralization. Microbial biomass carbon (C_MICR) is widely used as a sensitive indicator of soil biological activity and carbon dynamics because it reflects the size and metabolic potential of soil microbial communities (Bruni et al., 2025; Dhakal, Parajuli, Jian, Li, & Nandwani, 2022). In pineapple plantation systems, the unique rhizosphere conditions can modulate microbial community structure and metabolic activity, making the relationship between C_MICR and soil respiration a key aspect of understanding soil carbon flux.

In addition to microorganisms, mesofauna and earthworms play a role in the carbon cycle through the fragmentation of organic matter, soil structure modification, and their interactions with microbial communities (Astuti, PW, Sidik, & IrawanIrawan4, 2026). However, recent synthesis of knowledge suggests that the direct contribution of these biota groups to soil respiration is often inconsistent and highly dependent on environmental conditions and the availability of carbon-containing substrates. As such, their influence is generally indirect through the stimulation of microbial activity rather than being a primary source of respiration (Ruess, Kolb, Eisenhauer, & Ristok, 2025; Stevance et al., 2020).

Environmental factors, such as soil temperature, moisture, and pH, are key regulators of microbial activity and soil respiration (Munyepwa, 2025). Temperature regulates enzymatic reaction rates, whereas moisture and pH affect nutrient availability and microbial habitat conditions (Khan, Supronienė, Žvirdauskienė, & Aleinikovienė, 2025; Ma et al., 2024). Variability in these factors in tropical pineapple plantations has the potential to cause significant fluctuations in soil CO_2 emissions. Although numerous studies have examined soil respiration in agricultural ecosystems, research specifically integrating microbial biomass carbon, environmental factors, and the role of soil biota in pineapple plantation systems remains limited. This gap leads to uncertainty in carbon accounting and the development of applicable soil respiration models for tropical plantations in general. Therefore, this study aimed to develop a soil respiration model based on C_MICR and environmental variables as a scientific basis for GHG accounting and sustainable carbon management in pineapple plantations.

2. RESEARCH METHODOLOGY

2.1. Time and Location

This study was conducted from February to May 2024 in a pineapple plantation in Lampung, Southern Sumatra, Indonesia.

Figure 1: Research location.

2.2. Data Collection

Data were generated using a Randomized Block Design as the basis for field data collection. The collected data included biological, physical, and chemical variables. Laboratory analysis was conducted at the Soil Science Laboratory, University of Lampung, covering measurements such as soil respiration using the Fumigation-Incubation method, microbial biomass carbon (C_MICR) using the Verstraete method, soil moisture by Gravimetry, and soil mesofauna by Berlesse-Tullgre. Field measurements included soil pH using a soil pH meter, soil temperature using a soil thermometer, and earthworms through hand sorting.

2.3. Analysis Approach and Model Specification

Data analysis was conducted using a linear regression modeling approach with the Ordinary Least Squares (OLS) method. All statistical tests were performed at a 90% confidence level ($\alpha = 0.10$), commonly used in soil ecology studies to capture the sensitivity of dynamic biological processes. Two empirical models were developed to test the causal relationships between variables:

2.3.1. Model I: Soil Respiration Model

This model was designed to analyze the effect of soil biota on soil respiration using the following equation:

$$[RESP]i = \alpha 0 + \alpha 1\ [M\_FAU]i + \alpha 2\ [C\_MICR]i + \alpha 3\ [E\_WORM]i + \varepsilon i$$

Where:
1. [RESP]i = soil respiration,
2. [M_FAU]i = soil mesofauna,
3. [C_MICR]i = microbial biomass carbon,
4. [E_WORM]i = earthworms,
5. εi = random error.

The hypothesis tested in Model I is as follows:

$$H_1: \alpha 1 \neq \alpha 2 \neq \alpha 3 \neq 0$$

This indicates that at least one component of the soil biota significantly affects soil respiration**.**

2.3.2. Model II: Microbial Biomass Carbon Model

This model was used to evaluate the effects of soil physical and chemical factors on microbial biomass carbon using the following equation:

$$[C\_MICR]i = \beta 0 + \beta 1\ [TEMP]i + \beta 2 [WATER]I + \beta 3\ [pH]i + ui$$

Where:
1. [TEMP]i = soil temperature,
2. [WATER]i = soil moisture content,
3. [pH]i = soil acidity,
4. ui = random error.

The hypothesis developed in Model II is as follows:

$$H_2: \beta 1 \neq \beta 2 \neq \beta 3 \neq 0$$

This indicates that soil physical and chemical variables partially affect microbial biomass carbon**.**

2.4. Hypothesis Testing and Model Evaluation

The feasibility and goodness-of-fit of both models were tested using the F-test to simultaneously assess the significance of the independent variable effects. Then, a t-test was used to evaluate the significance of each regression parameter's partial effect. All estimation and model parameter optimization processes were conducted using Minitab software version 16, with statistical testing criteria set at a confidence level of ≥ 90%.

3. RESULTS AND DISCUSSION

3.1. Results

Table 1 shows that the biological soil variables exhibited a higher level of variation than the environmental variables. Soil respiration had an average value of 3.14 with a standard deviation of 1.41, indicating moderate variation across observations. Microbial biomass carbon (C_MICR) had an average of 2.72 and a standard deviation of 1.89, reflecting relatively high heterogeneity in soil microbial activity. Soil mesofauna also showed considerable variation, with a standard deviation of 0.86, whereas the presence of earthworms was relatively low, with an average value of 0.11, and most observations were zero.

Table 1: Descriptive statistics of soil biological and environmental variables

Variable	Symbol	Units	N	Mean	SD	Min	Max
Mesofauna	[M_FAU]	Individuals.dm^{-3}	72	0.99	0.86	0.00	36
Microbial biomass carbon	[C_MICR]	Mg CO_2 Me 100g soil^{-1}	72	2.72	1.89	0.00	5.99
Soil respiration	[RESP]	Mg CO_2 Me 100g soil^{-1}	72	3.14	1.41	0.54	7.26
Soil water	[WSTER]	%	72	20.59	3.17	14.99	30.13
Soil temperature	[TEMPERATUR]	°C	72	30.24	1.04	28.00	32.00
Soil Acidity	[pH]		72	6.13	0.36	5.50	7.00
Earthworms	[E_WORM]	tail m^{-2}	72	0.11	0.32	0.00	1.00

In contrast, the environmental variables of the soil are relatively homogeneous. The soil moisture had an average value of 20.59% with a standard deviation of 3.17, whereas the soil temperature showed a narrow variation with an average value of 30.24°C and a standard deviation of 1.04. The pH of the soil was slightly acidic to neutral, with an average of 6.13 and a standard deviation of 0.36. Overall, the minimum and maximum value ranges for each variable (Table 1) reflect relatively stable soil biological and environmental conditions, although with varying biological dynamics at the research site.

Table 2: F-test Analysis of variance (F-test) for the soil respiration regression model ([RESPI]$_i$) with biotic predictors

Source	DF	SS	MS	F	P
Regression	3	12,948	4,316	2,29	0,087
Residual Error	68	128,382	1,888		
Total	71	141,330			

Based on Table 2 (F-test Model I), the analysis results show that the regression model with three independent variables has an F-value of 2.29 and a p-value of 0.087. At the 90% confidence level (α = 0.10), this p-value indicates that the regression model is significant simultaneously, meaning that the independent variables have an effect on the dependent variable. The regression Mean Square value of 4,316 compared to the residual Mean Square value of 1,888 shows that the variation explained by the model is greater than the unexplained variation, although the model's strength is considered moderate.

Table 3: T-test results for regression coefficients (Model I)

Symbol	Predictor	Coefficient	SE	t-value	p-value
[M_FAU]	Mesofauna	−0.023	0.021	−1.12	0.268
[C_MICR]	Microbial biomass C	0.169	0.094	1.81	0.075
[E_WORM]	Earthworms	−0.043	0.526	−0.08	0.935

Based on Table 3 (t-test results for Model I) at the 90% confidence level (α = 0.10), microbial biomass carbon ([C_MICR]) showed a positive and significant partial effect on the response variable with a coefficient of 0.169 (t=1.81; p=0.075). In contrast, soil mesofauna ([M_FAU]) and earthworms ([E_WORM]) had negative coefficients, but they were not statistically significant (p > 0.10); therefore, neither of these variables significantly affected soil respiration in Model I at this confidence level.

Table 4: F-test Analysis of variance (F-test) for the soil respiration regression model ([RESPI]$_i$) with biotic predictors

Symbol	Predictor	Coefficient	SE	t-value	p-value
[TEMP]	Soil temperature	0.460	0.212	2.17	0.034
[WATER]	Soil water content	−0.065	0.055	−1.18	0.243
[Soil pH]	Soil Acidity	2.780	0.633	4.39	0.000

Based on Table 4 (t-test results for Model II), soil temperature ([TEMP]) had a positive and significant effect on the response variable with a coefficient of 0.460 (t = 2.17; p = 0.034), indicating that an increase in soil temperature tended to increase the observed response. Soil moisture ([WATER]) had a negative coefficient but was not statistically significant (t = −1.18; p = 0.243); therefore, it did not have a partial effect in the model. Conversely, soil pH (acidity) showed a highly significant positive effect with a coefficient of 2.780 (t = 4.39; p = 0.000), suggesting that changes in soil pH are a dominant factor in explaining the response variation in Model II.

Table 5: T-test results for regression coefficients (Model II)

Source	DF	SS	MS	F	P
Regression	3	47,247	15,749	8,89	0,000
Residual Error	62	109,881	1,772		
Total	65	157,129			

Based on the F-test results from Model II, the analysis shows that the regression model with three independent variables is significant simultaneously, indicated by an F-value of 8.89 and a p-value of 0.000. This indicates that, at a high confidence level (α ≤ 0.05), all predictor variables significantly affect the response variable. Additionally, the comparison of the regression Mean Square (15,749) being larger than the residual Mean Square (1,772) suggests that the model has a relatively strong explanatory power, with Model II providing a better fit to the data than the unexplained variation.

3.2. Discussion

The F-test results showed that Model I (soil biota → soil respiration) was significant at the 90% confidence level (p = 0.087), whereas Model II (physical-chemical factors → microbial carbon) was strongly significant (p = 0.000). These findings affirm that soil respiration, as a source of CO_2 emissions, is indirectly controlled by environmental factors through the modulation of microbial biomass carbon (C-mik), which acts as a proximate driver of soil carbon emissions, especially because temperature and changes in edaphic conditions can alter microbial biomass/activity, ultimately affecting heterotrophic respiration (Qu et al., 2023). Furthermore, the strong role of soil pH in shaping microbial biomass reinforces the argument that soil chemistry can be a key "lever" in biological carbon dynamics (Jiang et al., 2024). In the context of carbon accounting, these results are relevant because estimating CO_2 emissions from the land/agriculture sector requires methodological consistency and an understanding of the biophysical processes controlling fluxes, given the differences in approach and sources of uncertainty between model-based estimates and GHG inventories (Boton, Nitschelm, Juillard, & van der Werf, 2025).

The t-test in Model I showed that microbial biomass carbon (C-mik) had a positive and marginally significant effect on soil respiration (p = 0.075), whereas mesofauna and earthworms did not show significant partial effects. These results are consistent with empirical studies that emphasize that soil microorganisms are the main controllers of heterotrophic respiration, as they directly mineralize organic carbon into CO_2 via their metabolic activities (Qu et al., 2023; Tao et al., 2023). High microbial metabolic activity generally increases CO_2 flux from soil to the atmosphere, particularly when environmental conditions support substrate availability and optimal temperatures for microbial growth.

However, other findings suggest that an increase in microbial biomass does not always correlate with increased soil respiration if the microorganisms show high carbon use efficiency (CUE). CUE represents the proportion of carbon allocated by microorganisms for growth (biomass) compared to the amount released as CO_2. When CUE is high, more carbon is stored in the microbial biomass and stable microbial products; therefore, respiration per unit biomass does not always increase proportionally (Tao et al., 2023). This phenomenon has also been observed in studies reporting that CUE variability is highly influenced by soil texture, substrate availability, and other environmental factors, affecting the relationship between microbial biomass and soil respiration (Dang, 2024). These differences suggest that the relationship between C-mik and soil respiration is contextual, depending on the availability of organic substrates, quality of organic matter, and environmental pressures such as temperature and pH. In the context of carbon accounting, this finding is important because it indicates that an increase in microbial carbon stock does not always imply an increase in CO_2 emissions; instead, microorganisms may act as a temporary carbon buffer by retaining carbon in the form of biomass and stable microbial products. Therefore, carbon accounting models based solely on microbial biomass or soil respiration may be less accurate if carbon-use efficiency is not explicitly considered.

The lack of significance of mesofauna and earthworms in Model I does not necessarily negate their roles in the ecosystem. Recent literature emphasizes that soil fauna often operate through indirect pathways, such as organic residue fragmentation, modification of soil porosity/aggregation, redistribution of organic material through bioturbation, and regulation of microbial communities (e.g., through grazing and the formation of microbial "hotspots" in casts/drilosphere). Because their mechanisms are chain-like and cross-scale, linear regression approaches that capture only direct effects may fail to detect the contribution of fauna as regulators of the carbon stabilization-mineralization process (Angst et al. 2024).

Several studies have also reported seemingly contradictory results, where earthworms may enhance soil respiration and CO_2 emissions through increased substrate-microbe contact and the release of labile compounds in casts that trigger the priming effect. However, the magnitude of these effects is highly influenced by earthworm species/ecological groups, moisture conditions, litter/organic matter quality, observation time, and earthworm density; meta-analyses have even shown that the impact of earthworms on carbon mineralization can change over time (e.g., strong in the early phase, then decreasing/reversing over longer durations) (Irshad & Frouz, 2024). In the context of carbon accounting, this implies that soil fauna, particularly earthworms, are better positioned as regulators of the balance between carbon loss (CO_2 emissions) and the formation of protected carbon (e.g., MAOM/mineral-associated carbon), rather than merely as direct emission sources. This explains why some field studies have found that the effect of earthworms on respiration is not always significant when their density is low or habitat conditions are less favorable (Jiang et al., 2024).

Model II showed that soil temperature and pH had a significant effect on microbial biomass carbon (C-mik), whereas soil moisture was not significantly correlated in the partial analysis. The positive effect of soil temperature reflects the acceleration of enzymatic reactions and increased microbial growth rates under higher thermal conditions, which ultimately enhances the soil respiration potential and CO_2 emissions. This pattern aligns with the literature that places temperature sensitivity as a key parameter to describe soil respiration responses to warming and to improve predictions of soil carbon feedback at ecosystem to global scales (Liu et al., 2021; Yang et al., 2023). Thus, an increase in soil temperature due to climate change or land management practices may accelerate soil carbon loss through heterotrophic respiration, particularly when microbial responses and substrate availability support higher decomposition rates (Qu, 2023).

Soil pH had the strongest effect on C-mik, indicating that soil chemical conditions are the main limiting factors for microbial community stability and structure. Soil with more favorable pH conditions allows microorganisms to maintain better metabolic activity and carbon use efficiency, which directly impacts soil carbon storage and mineralization dynamics (Jiang et al., 2024) Malik et al., 2020). In carbon accounting, this finding emphasizes that pH changes due to land management practices, fertilization, or soil amelioration can shift the balance between carbon sequestration and CO_2 emissions; therefore, they must be considered in agricultural carbon balance assessments.

In contrast, the non-significance of soil moisture suggests that, during the study period, moisture likely remained within an optimum range for microbial activity and thus did not act as the primary limiting factor. Near-optimal moisture conditions are known to stabilize microbial respiration because oxygen diffusion and substrate availability are balanced. This finding contrasts with several studies reporting that soil moisture is a key regulator of soil respiration under extreme conditions, such as drought or water saturation, which can limit microbial activity due to water stress or oxygen diffusion constraints (Jian et al. 2016; Patel et al. 2021). This difference highlights that soil carbon emission responses to moisture are highly contextual, depending on climate regimes, observation seasons, and soil physical characteristics. Thus, the interpretation of soil respiration results must consider the specific environmental conditions of the study location and time.

Overall, this study suggests that soil carbon accounting based on CO_2 emissions needs to include biological indicators, specifically C-microbes, as a key variable. This is in line with the literature that positions microorganisms as the main controllers of carbon partitioning between growth (biomass/necromass) and loss as CO_2, making microbial indicators and parameters such as carbon use efficiency (CUE) important to understand whether soil is functioning as a carbon source or sink (Schimel, Weintraub, & Moorhead, 2022). Approaches relying solely on physical factors or total carbon stock risk overlooking the microbial process dynamics that mediate the input of organic carbon, stabilization (e.g., through microbial byproducts), and respiration as emissions (Tao et al., 2023). This finding also supports a new paradigm in carbon accounting, in which soil is treated as a living system and not just a passive carbon reservoir. In this framework, land management practices that stabilize microbial biomass and increase carbon use efficiency, such as strategies that strengthen the formation of more stable microbial byproducts, have the potential to reduce CO_2 emissions while improving the credibility of carbon balance calculations in agricultural/plantation systems (Beattie, et al., 2024).

Based on the regression coefficient estimates in Model I, changes in soil respiration responded differently to increases in each soil biota variable. Microbial biomass carbon (C-mik) had a positive coefficient of 0.169, indicating that a one-unit increase in C-mik would be followed by a 0.169-unit increase in soil respiration, assuming other variables were constant (ceteris paribus). This finding is consistent with several studies showing that an increase in microbial biomass carbon (C-mik) is associated with increased soil respiration, supported by empirical evidence from observational and experimental studies that demonstrate a positive correlation between microbial biomass and soil respiration rates in various soil systems. For example, their study showed that soil microbes, along with temperature and enzymatic activity, are the main drivers of soil respiration, and that soil microbial biomass is an important element in the proposed respiration model (Qu, et al., 2023). Additionally, literature shows an explicit positive relationship between microbial biomass carbon (MBC) and respiration rates in several field systems, indicating that increased MBC is often aligned with increased soil respiration as more active microbes decompose organic material into CO_2 (Babur, Ozlu, & Uslu, 2025). Therefore, the quantitative results of this model, which show a positive regression coefficient for C-mik, support the empirical findings that heterotrophic microbes are key components in controlling CO_2 fluxes from the soil.

In contrast, soil mesofauna had a regression coefficient of −0.023, indicating that a one-unit increase in mesofauna is associated with a 0.023-unit decrease in soil respiration, assuming that C-mik and earthworms remain constant. Although not statistically significant, this negative direction suggests that the role of mesofauna in soil respiration is indirect, primarily through their influence on organic matter fragmentation, soil aggregation, and spatial regulation of microbial activity. Recent literature synthesis shows that small soil fauna contribute more to carbon stabilization and microbial substrate redistribution than as direct drivers of CO_2 emissions, meaning that their influence is often not captured as a partial effect in linear regression models (Filser et al., 2016).

Similarly, earthworms showed a regression coefficient of −0.043, indicating that a one-unit increase in earthworm population could potentially decrease soil respiration by 0.043 units, assuming that other variables remain unchanged. This small and insignificant effect suggests that the contribution of earthworms to soil respiration in this model was marginal and indirect. Recent literature emphasizes that earthworms' primary role is not as direct CO_2 emission drivers but as soil engineers that modify soil structure, enhance aggregation, and facilitate organic carbon stabilization, thus protecting some carbon from rapid mineralization into CO_2 (Filser et al., 2016). However, literature synthesis also shows that under certain conditions—particularly when labile organic material is abundant or in the early decomposition phase—earthworm activity can increase soil respiration by enhancing labile carbon flow and stimulating microbial activity (priming effects). This difference in response direction highlights that the influence of earthworms on soil respiration is highly contextual, depending on substrate quality, environmental conditions, and observation time scale, making the non-significance of earthworm effects in this model consistent with contemporary soil ecology understanding (Sanchez et al., 2024; (Irshad & Frouz, 2024).

Comparatively, the analysis results show that the quantitative influence of microbial biomass carbon (C-mik) on soil respiration is much more dominant than the contribution of mesofauna or earthworms. These findings suggest that increased soil respiration in the studied system is primarily controlled by changes in microbial biomass and metabolic activity, which are the main agents of organic material mineralization and CO_2 release (Bruni et al., 2025; Zhang et al., 2025). Conversely, changes in soil fauna communities showed relatively weaker and more indirect effects, even associated with opposite response directions under certain conditions. This aligns with conceptual studies asserting that soil fauna, including mesofauna and earthworms, play a larger role as modulators of microbial processes through organic matter fragmentation, soil structure modification, and trophic interactions rather than as primary drivers of soil respiration (Angst et al., 2024; Mittmannsgruber et al., 2025). Comparisons with recent studies have also shown that soil respiration responses to biotic variables are highly contextual, influenced by soil biological community structure, abiotic environmental conditions, and the quality and availability of organic material as respiration substrates (Wang, Cui, Liu, & Xu, 2023; Zhang et al., 2025). Thus, the dominance of C-mik as a driver of soil respiration in this study reflects a key mechanism in the soil carbon cycle but should still be interpreted within the specific ecological framework of the location and management systems.

Regression analysis showed that abiotic variables had different effects on soil respiration. Soil temperature had a positive coefficient of 0.460 and was significant at the 5% level ($p = 0.034$), indicating that a one-unit increase in soil temperature (°C) was followed by a 0.460-unit increase in soil respiration, assuming that other variables remained constant. This finding reinforces the role of temperature as a primary controller of soil microbial metabolic activity and organic matter decomposition rates, where temperature increases accelerate enzymatic reactions and respiration. This pattern is consistent with several recent studies showing that soil respiration responses to temperature are positive and relatively strong, particularly in soil systems with adequate carbon substrate availability (Carey et al., 2016).

In contrast, soil moisture showed a negative coefficient of −0.065, which was not statistically significant ($p = 0.243$). Quantitatively, this result shows that a one-unit increase in soil moisture only reduces soil respiration by 0.065 units, but this effect is weak and not significantly different from zero. This suggests that within the moisture range of the studied system, soil moisture was not the primary limiting factor for respiration and potentially reduced oxygen diffusion when approaching saturation. Recent studies have emphasized that the effect of moisture on soil respiration is often nonlinear and highly contextual, depending on soil texture, porosity, and interactions with temperature and microbial biomass (Kim, Kim, Woo, & Min, 2025).

Soil pH showed a very strong positive effect, with a coefficient of 2.780, which was highly significant ($p = 0.000$). This indicates that every one-unit increase in soil pH is followed by a 2.780-unit increase in soil respiration, making it the variable with the largest quantitative effect in this model. This finding indicates that improving soil acidity directly enhances microbial metabolism efficiency, enzyme stability, and nutrient availability, ultimately accelerating soil respiration processes. Recent literature consistently reports that pH is a key factor controlling the structure and function of soil microbial communities; therefore, small changes in pH can result in large respiration responses (Rousk & Brangarí, 2022) ; (Delgado-Baquerizo et al., 2025).

Overall, these results confirm that soil respiration in the studied system is more sensitive to changes in environmental quality (temperature and pH) than to fluctuations in soil moisture, and reinforce the view that abiotic factors play a major role in modulating biological activity in soil. The dominance of pH and temperature influences also indicates a close interaction between soil physicochemical conditions and biological processes in regulating CO_2 emissions from the soil.

4. CONCLUSION

4.1. Conclusion

This study demonstrates that soil respiration in pineapple plantations is primarily controlled by soil microbial biomass carbon (C_MICR) and soil physicochemical conditions, particularly temperature and pH. The positive and significant effect of C_MICR underscores the role of soil microbes as the main drivers of carbon mineralization processes and CO_2 emissions from soil. In contrast, mesofauna and earthworms did not show significant effects, indicating that the contribution of soil fauna to respiration is indirect and context-dependent. These findings emphasize that soil microbiological indicators are more representative in modeling soil respiration and are highly relevant for the development of land-based greenhouse gas accounting in plantations.

4.2. Suggestions

Future studies should integrate both biological and physicochemical soil indicators simultaneously and evaluate the temporal dynamics of soil respiration under various management conditions.

From an applicative perspective, the results of this study can be used as a foundation for developing a process-based soil respiration model to improve the accuracy of carbon emission estimates and support the implementation of a Measurement, Reporting, and Verification (MRV) system in the plantation sector.

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