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Impact of Regenerative Agriculture on Soil Biological Performance in Arabica Coffee (*Coffea arabica*) Cultivation

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Abstract

Soil health is a crucial factor in the sustainability of Arabica coffee production, particularly in addressing the challenges of land degradation caused by conventional agricultural practices. One practical approach to naturally enhance soil fertility is implementing a regenerative farming system, which focuses on increasing the diversity of soil microbes to support a healthy and productive ecosystem. This study aims to analyze and compare the diversity of soil microbes in Arabica coffee fields managed under regenerative farming systems versus those under conventional farming systems. It will identify the dominant types of microbes in each system and examine how their presence influences soil fertility. Additionally, the study will assess the impact of regenerative farming on the balance of the soil microbial ecosystem and the health of coffee plants. The methodology employed is comparative, involving soil sampling through random sampling techniques. Microbial diversity will be analyzed using culture methods, with soil microbial observation parameters including bacteria, fungi, phosphorus-solubilizing bacteria, nitrogen-fixing bacteria, respiration rates, and the carbon-to-nitrogen (C/N) ratio. Laboratory data will be analyzed using comparative statistical tests, specifically the t-test. The study aimed to identify microbial distribution patterns using PCA-Bi Plot analysis. The results indicated that the total number of bacteria, fungi, total microbes, and soil respiration rates were significantly higher in the regenerative farming system than in the conventional system. The dominant soil microbes in the regenerative farming system included nitrogen (N) fixing bacteria and decomposer fungi. A strong positive correlation ($r = 0.938$, $p < 0.01$) was observed between total microbes and soil respiration. The regenerative farming system not only increases the number of soil microbes but also enhances the biological activity of the soil. These findings underscore the potential of regenerative agriculture as a viable alternative for improving soil quality in Coffea arabica cultivation, aligning ecological benefits with agricultural productivity.

Keywords: *Conventional Agriculture, Soil Ecosystem, Soil Biology, Soil Health, Regenerative Agriculture*

1. Introduction

Coffea arabica is one of the leading commodities in the global plantation industry, including Indonesia. The quality and productivity of coffee plants are highly dependent on soil conditions, particularly the biological aspects of the soil, which encompass microorganisms, soil fauna, and biogeochemical activity. The sustainability of this soil ecosystem is becoming an increasingly important concern in modern agricultural systems, especially with the implementation of regenerative agriculture based on Good Agricultural Practices (GAP).

The growing concern over soil degradation caused by conventional agricultural practices threatens the long-term sustainability of *Coffea arabica* cultivation. Arabica coffee, a high-value commodity and a vital source of income for millions of farmers in tropical regions, is highly dependent on healthy, biologically active soils. Conventional farming methods often lead to reduced soil fertility, loss of microbial diversity, and disrupted soil structure. In contrast, regenerative agriculture offers a sustainable alternative by enhancing soil biological health through natural processes. However, scientific data comparing soil microbial performance between regenerative and conventional systems, particularly in coffee plantations, remains limited.

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This research aims to fill that gap by providing evidence on how regenerative practices can restore soil health, improve coffee plant vitality, and support ecological balance and agricultural productivity.

Regenerative agriculture is an approach that emphasizes improving soil health by increasing organic matter, crop diversification, and reducing synthetic inputs. This approach aligns with Good Agricultural Practices (GAP) principles, prioritizing sustainable agricultural practices focusing on efficient use of resources, ecosystem balance, and food security (Nora, S, et al., 2025). However, there are still many coffee plantations that implement non-GAP systems, which tend to use conventional practices with minimal attention to regenerative aspects.

Studies comparing soil biology in Arabica coffee plantations with GAP and non-GAP systems in regenerative agriculture are still limited. Therefore, this study aims to understand how these different farming systems affect soil biology, including microbial populations, enzymatic activity, and respiration. The results of this study are expected to provide scientific recommendations for coffee farmers on increasing agricultural productivity and sustainability. Soil biology is one of the leading indicators in maintaining soil fertility and plant health. Soil microorganisms, such as bacteria and fungi, are essential in nutrient cycling, organic matter decomposition, and pathogen control (Sherwood and Uphoff 2000). In addition, soil fauna such as earthworms contribute to increasing soil structure and porosity (Ingham and Slaughter 2004)

This research differs from previous studies in several important aspects. Most previous studies have focused primarily on the physical and chemical aspects of soil in coffee farming systems, without deeply exploring biological indicators of soil, such as microbial activity, soil respiration, or the presence of functional microorganisms (eg, phosphate-solubilizing bacteria and nitrogen-fixing bacteria). Additionally, earlier research tended to compare organic and conventional systems, whereas this study examines explicitly regenerative agriculture, which includes holistic approaches such as cover crop integration, compost application, and agroforestry.

This study also combines quantitative soil microbial analysis with advanced statistical methods, such as PCA-Bi Plot, to identify microbial distribution patterns and their correlation with biological soil parameters. This approach has not been widely used in previous studies, which typically report microbial presence without linking it deeply to ecosystem function and coffee plant health. Through this approach, this research offers a new contribution to understanding the role of regenerative agriculture in improving the soil ecosystem in *Coffea arabica* cultivation.

One way to increase soil fertility naturally is to implement a regenerative farming system, which emphasizes increasing the diversity of soil microbes to support a healthy and productive ecosystem. According to Schreefel et al. (2020), the need for Regenerative agriculture is because the loss of soil fertility and the world's biodiversity, as well as the loss of seeds, is a deadly threat to our survival in the future. Applying regenerative farming principles can improve soil health and biodiversity, increase yields and the quality of agricultural products, and increase resilience to climate change.

Coffee plants produce litter and twigs as a source of organic material after going through a weathering process where organic matter acts as a soil fertilizer chemically, physically, and biologically. Organic matter can increase root absorption, retain water, and affect the diversity of biota species.

The abundance of soil microorganisms is also influenced by microclimate conditions such as temperature, air humidity, soil moisture, lighting, and aeration. Changes in microclimate can significantly impact the population and activity of soil microorganisms around coffee plants. Soil microorganisms, such as bacteria, fungi, and nematodes, are essential in nutrient cycling, organic matter decomposition, and overall soil health.

Soil microbes are essential in nutrient cycling, soil structure, and plant resistance to disease. However, little research compares the diversity of soil microbes in Arabica coffee fields that implement regenerative agriculture with conventional farming systems. Therefore, this study aims to explore the differences in soil microbes in the two farming systems to understand the ecological and agronomic benefits of regenerative agriculture.

Research on soil health shows that the implementation of organic farming systems can improve soil health and the quality of agricultural products (Muksin and Anasaga 2021), and the biodiversity of soil microorganisms is positively correlated with soil (Praxis 2022), where earthworms can improve soil health and soil fertility.

This study aims to analyze and compare the diversity of soil microbes in Arabica coffee fields with regenerative farming systems and conventional farming systems, identify the dominant types of microbes in each system and how their presence affects soil fertility and assess the impact of regenerative farming on the balance of the soil microbial ecosystem and coffee plant health.

2. Material and Methods

The research location is around the Lake Toba area, precisely in Karo Regency (3.2215 N; 98.4204 E), Simalungun Regency (2.8013 N; 98.8551 E), Dairi Regency (2.7454 N; 98.4888 E), and North Tapanuli Regency (2.2526 N; 98.9820 E), at altitudes ranging from 1,000 to 1,250 meters above sea level and above 1,250 meters above sea level from April to December 2024. This location was chosen considering the type of Arabica coffee commodity with different management, including coffee cultivation with regenerative and conventional farming.

This research is a comparative study with a field experiment approach to compare the diversity of soil microbes in Arabica coffee fields that implement a regenerative farming system with land that uses a conventional farming system.

The Independent Variable is the farming system used (regenerative with conventional). The Dependent Variable is the diversity of soil microbes, such as the number of microbes, bacteria, fungi, and soil respiration.

Soil samples were taken using a random sampling technique in one coffee planting area. Each location was taken 5 sample points diagonally, which were then mixed to obtain a composite sample. Samples were stored in sterile containers and analyzed within 24 hours to maintain the accuracy of microbiological results. Soil samples were taken near the roots, namely between rows of coffee plants with a volume of 20 cm x 20 cm x 20 cm, then placed in a plastic bag, labeled, and immediately stored in an ice box to avoid high temperatures.

The biological properties of the soil that were observed were:

a) Total number of microbes

Culture techniques were used to isolate and count the total number of microbes in the soil.

b) Total number of bacteria

Using bacterial culture techniques to isolate and count the total number of bacteria in the soil.

c) Total number of fungi

Using fungal culture techniques to isolate and count the total number of fungi in the soil

d) Soil Respiration

Measuring the amount of carbon dioxide produced by the respiration activity of microbes in the soil

The data analysis technique used in this study is a descriptive analysis technique to describe the data collected through field surveys and laboratory analysis results. Laboratory data were analyzed using comparative statistical tests. The T-test is the statistical analysis used to see significant differences between the application of regenerative and conventional agriculture. To identify patterns of differences in the distribution of microorganism communities in both agricultural systems, Multivariate analysis (PCA-Principal Component Analysis) was used with the statistical software R Studio and R version 4.4.0.

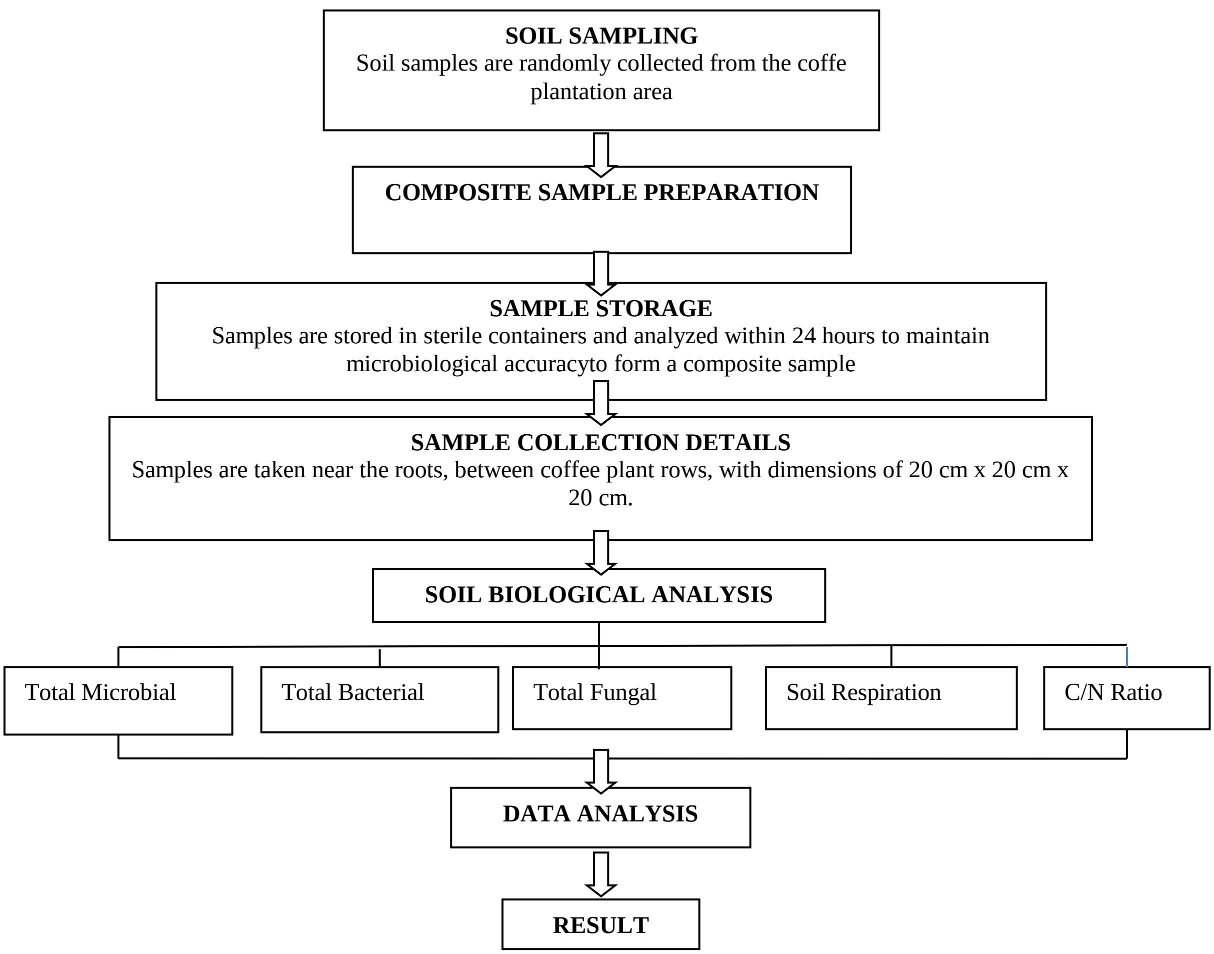

Figure 1. Research Flow Diagram

3. Results and Discussion

3.1. Analysis of Soil Biological Diversity

Table 1 presents the findings from the study on soil biology in Arabica coffee cultivation, comparing the effects of regenerative agriculture and conventional agriculture.

Table 1. Results of Analysis of Soil Biological Characteristics of *Coffea arabica*

No.	Sample	Bacteria (CFU/ml)	Fungi (CFU/ml)	P-Solubilizing Bacteria (CFU/ml)	N-Fixing Bacteria (CFU/ml)	Microbes (CFU/ml)	Respira tion (mgCO $_{/day}$)	C/N ratio (%)	n
1	D1	8.73 x 10 ^{7}	58 x 10 ^{7}	2.5 x 10 ^{5}	2.1 x 10 ^{7}	44.76 x 10 ^{7}	3,197	12.24	3
2	D2	3.27 x 10 ^{7}	26 x 10 ^{7}	3.1 x 10 ^{5}	1.5 x 10 ^{7}	25.07 x 10 ^{7}	1,880	11.59	3
3	K1	9.85 x 10 ^{7}	39 x 10 ^{7}	2.0 x 10 ^{5}	5.1 x 10 ^{7}	46.95 x 10 ^{7}	2,524	9.00	3
4	K2	1.15 x 10 ^{7}	9 x 10 ^{7}	1.5 x 10 ^{5}	3.4 x 10 ^{7}	12.5 x 10 ^{7}	1,447	8.58	3
5	S1	7.85 x 10 ^{7}	38 x 10 ^{7}	5.0 x 10 ^{5}	4.5 x 10 ^{7}	31.85 x 10 ^{7}	2,114	7.15	3
6	S2	3.5 x 10 ^{7}	21 x 10 ^{7}	1.7 x 10 ^{5}	3.7 x 10 ^{7}	22.5 x 10 ^{7}	1,724	9.17	3
7	T1	9.49 x 10 ^{7}	56 x 10 ^{7}	2.6 x 10 ^{5}	5.0 x 10 ^{7}	48.69 x 10 ^{7}	2,974	13.51	3
8	T2	2.2 x 10 ^{7}	27 x 10 ^{7}	1.1 x 10 ^{5}	1.7 x 10 ^{7}	20.2 x 10 ^{7}	1,785	11.32	3

Description: D (Dairi), K (Karo), S (Simalungun), T (North Tapanuli), Number 1 (Regenerative Agriculture), Number 2 (Conventional Agriculture)

The table above shows that the number of bacteria in K1 and T1 is the highest with the application of regenerative agriculture, and the lowest in K2 and T2 with the application of conventional agriculture. The highest P-solubilizing bacteria were found in Location S1 with the application of regenerative agriculture, and the lowest in T2 with the application of conventional agriculture. N-fixing bacteria are found in K1, which is the location with the application of regenerative agriculture and are at their lowest in Location D2 with conventional agriculture.

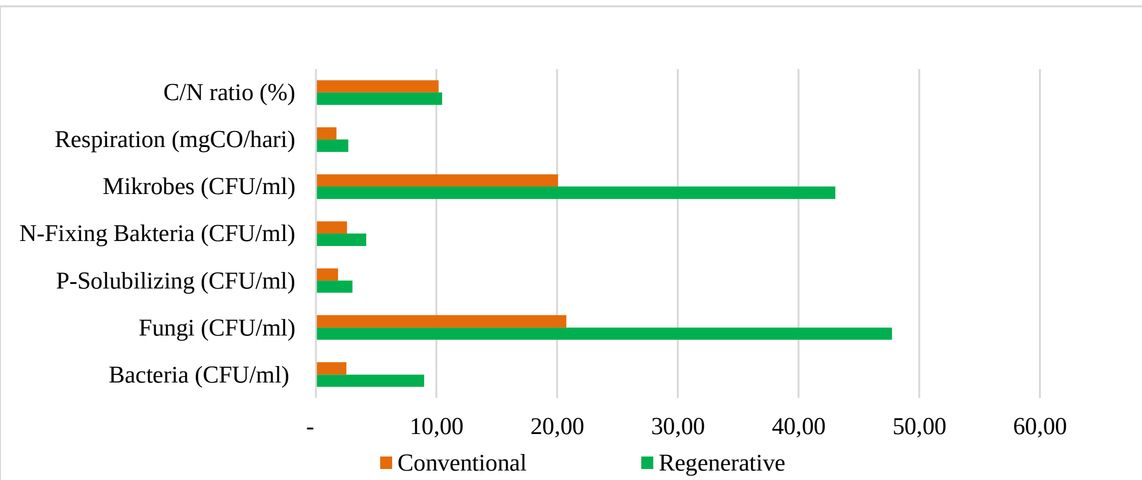

Figure 2. Differences in the distribution of biological soil properties with the application of regenerative and conventional agricultural systems.

In Figure 2 The total number of bacteria, fungi, microbes, and respiration in coffee plant cultivation with regenerative agriculture is higher than in conventional agriculture. Soil and air temperatures also tend to be lower, so coffee plants with shade can maintain the humidity around the coffee plants. Regenerative land has higher respiration activity, meaning that microorganisms are more active in processing organic matter. The average C/N ratio is slightly higher in the regenerative system, indicating that sufficient organic matter (carbon) is still available to support microbial activity without a nitrogen deficit.

The abundance of soil microorganisms is also influenced by microclimate conditions such as temperature, air humidity, soil moisture, lighting, and aeration. Changes in microclimate can significantly impact the population and activity of soil microorganisms around coffee plants. Soil microorganisms, such as bacteria, fungi, and nematodes, are essential in nutrient cycling, organic matter decomposition, and overall soil health.

Some bacteria are very effective in dissolving phosphate from phosphate rock and phosphate residues in the soil. For example, Bacillus megaterium var. phosphaticum has been formulated as a phosphobacterin inoculant. This inoculant has been successfully used to increase available P in soils. Almost every soil ecology finds free-living bacteria that can fix nitrogen from the air. These bacteria are usually associated with plants, water systems, and sediments.

Soil respiration is the process of releasing carbon dioxide (CO2) from the soil into the atmosphere. Soil respiration is an essential indicator of a soil ecosystem. Soil respiration is also an indicator of nutrient cycling and soil health. Nutrients not yet available to plants are broken down by microorganisms so that nutrients can be used for plants, and the respiration rate can be used to assess soil health (Pane et al. 2023).

The main factor in soil respiration is the activity of microbes in the soil. According to Gmbh (2018), Environmental factors affecting coffee plants' growth include altitude, rainfall, sunlight, wind, and soil. Increasing canopy cover can regulate air temperature and soil humidity (Pradiko et al. 2020), creating favorable conditions for the development of soil organisms. (Evizal and Prasmatiwi 2024) ,

The nature of plant leaves can affect litter decomposition, nutrient cycling, and soil cover (Yelli et al. 2020). The agroforestry coffee planting system can be one of the measures for soil and water conservation, in addition to producing several types of products that have high economic value (Teixeira et al. 2021)

In addition to vegetation, different land management practices also affect physical properties. Soil cultivation can damage soil aggregation and reduce organic matter content due to mechanical damage from processing tools (Prabowo and Subantoro 2008), increasing canopy cover can regulate air temperature and soil humidity (Pradiko et al. 2020), creating favorable conditions for developing soil organisms. (Evizal et al, 2012), The nature of plant leaves can affect litter decomposition, nutrient cycling, and soil cover (de Carvalho et al. 2021). The primary key in a healthy soil ecosystem is the flow of energy in the food web and the supply of organic substrates as a source of chemical energy for primary decomposer organisms. Decomposer organisms have a special role and function in maintaining soil quality, such as physical, chemical, and biological fertility, making the soil optimal for plant growth and development (Murray et al. 2009).

3.2. Differences in soil microbes in Arabica coffee plantations with the application of regenerative and conventional farming

A T-test was used to determine the differences between the application of regenerative and conventional farming systems. The following table presents the differences between regenerative farming (RA) and conventional farming on Arabica coffee plants' soil microbes.

Table 2. Comparison of the application of regenerative farming (RA) and conventional farming on soil property variables in 8 locations

Variable	**T-test**	**Mean + *standard* error**	
		Regenerative Agriculture	**Conventional Agriculture**
Soil Biological Properties			
Total bacteria (CFU/ml)	0.0001**	8.98 x 10 $\pm$ 0.88 x 10 ^{7}	2.53 x 10 $\pm$ 1.08 x 10 ^{7}
Total Fungi (CFU/ml)	0.0072**	47.75 x 10 $\pm$ 10.71 x 10 ^{7}	20.75 x 10 $\pm$ 8.26 x 10 ^{7}
Total microbes (CFU/ml)	0.0027**	43.06 x 10 $\pm$ 7.64 x 10 ^{7}	20.06 x 10 $\pm$ 5.42 x 10 ^{7}
Respiration (mgCO/day)	0.0085**	2.7 $\pm$ 0.48 x 10 ^{7}	1.7 $\pm$ 0.19
Total P-solubilizing Bacteria (CFU/ml)	0.192ns	$3.03 \times 10^5 \pm 6.71 \times 10^4$	$1.85 \times 10^5 \pm 4.35 \times 10^4$
Total N-fixing Bacteria (CFU/ml)	0.127ns	$41.75 \times 10^7 \pm 3.82 \times 10^7$	$25.75 \times 10^7 \pm 2.71 \times 10^7$
C/N Ratio (%)	0.8586ns	10.48 $\pm$ 1.46	10.27 $\pm$ 0.76

Description: * = significantly different at α 0.05, ns = not significantly different at α 0.05; ** = significantly different at α 0.01

The data table above shows that the regenerative agricultural system has an average number of microbes (43.06 x 107) much higher than the conventional system (20.06 x 107). The total bacteria and fungi in the regenerative system are also higher than conventional. Soil microbial respiration is greater in the regenerative system (average 2.70 x 107mgCO/day) than in conventional (average 1.71 x 107 mgCO/day), indicating higher biological activity.

Total bacteria, fungi, microbes, and soil respiration showed significant differences ($p < 0.05$), meaning that the regenerative agricultural system significantly increased microbial diversity and soil biological activity compared to conventional agriculture. Total phosphate-solubilizing and nitrogen-fixing bacteria did not show significant differences ($p > 0.05$), although their numbers were higher in the regenerative system.

These results support the idea that regenerative agriculture creates a healthier and more productive soil ecosystem. Regenerative agriculture practices have a significant positive impact on the lives of soil microorganisms. Regenerative agriculture creates an environment more conducive to the growth and development of soil microorganisms. An increase in bacteria, fungi, and microbes indicates this.

Regenerative agriculture is an agricultural approach that aims to improve and restore soil health, ecosystems, and biodiversity. Unlike conventional agriculture, which often drains natural resources, regenerative agriculture seeks to work with nature to create sustainable agricultural systems.

Prayogo et al. (2021) found that Higher soil microbes are associated with more sustainable agricultural practices. Regenerative methods increase soil microbes and biological activity (Le et al. 2021), and microbial activity is higher in regeneratively managed soils (Sherwood and Uphoff 2000)

Higher soil respiration on regenerative agricultural land indicates higher biological activity. This means that soil microorganisms on regenerative land are more active in decomposing organic matter and carrying out other biogeochemical processes. High soil microorganism populations and high biological activity contribute to increased soil fertility. Microorganisms help decompose organic matter, nitrogen fixation, and other nutrient cycles. (Matondang, et al., 2015)

Microbes such as bacteria and fungi break down organic matter, releasing carbon dioxide as a respiratory product. Environmental factors that can affect the rate of soil respiration are climate and soil properties. Soil properties greatly influence soil respiration. (Pane et al. 2023) added that differences in land cover can significantly affect the rate of soil respiration through various factors, including organic matter input, soil microorganism activity, and microclimate factors that are formed.

3.3. Relationship between soil microbial variables in Arabica coffee plantations with the application of regenerative and conventional agriculture

The relationship between soil microbial variables in Arabica coffee plantations with the application of regenerative and conventional farming is presented through PCA-Bi Plot analysis in the image below.

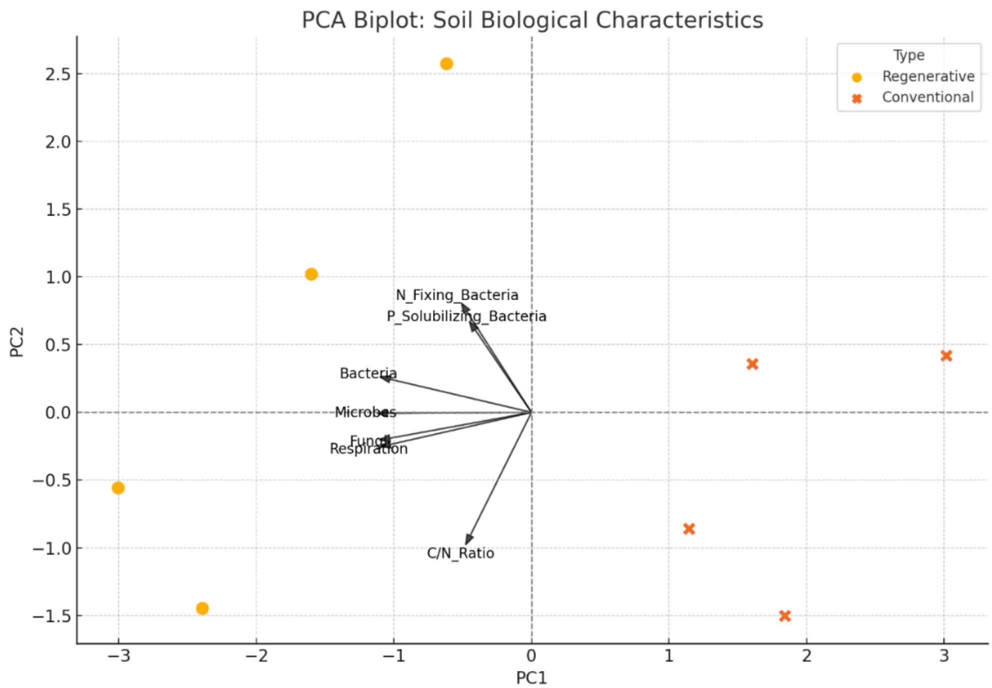

Figure 2. Relationship between Soil Biology observation variables (PCA Bi-Plot)

Long vectors in the bacteria and microbes variables significantly contribute to differentiating samples. Short vectors indicate variables that contribute less to data separation. Variables that point in the same direction, namely bacteria and fungi, have a positive relationship and are correlated.

A strong positive correlation ($r = 0.938$, $p < 0.01$) between total microbes and soil respiration indicates that the microbial ecosystem in the regenerative farming system is more active and balanced, contributing to long-term soil health and coffee plant productivity.

The results of this study provide compelling evidence that regenerative farming practices significantly enhance soil health, particularly in biological aspects. The increase in the population and activity of soil microorganisms in regenerative lands has beneficial implications for soil fertility, agricultural productivity, and the overall environment.

Regenerative and conventional farming methods seem distinctly different, exhibiting significant variations in soil microbial characteristics. Long vectors (bacteria and microbes) indicate variables that play a substantial role in differentiating the samples.

4. Conclusion

The research deduces the following conclusions:

a. Compared to conventional farming, regenerative farming exhibits significantly greater bacteria, fungi, microbes, and soil respiration rates.
b. The predominant soil microorganisms in the regenerative farming system consist of nitrogen (N) fixing bacteria and decomposer fungi.
c. The results indicate a significant positive correlation ($r = 0.938$, $p < 0.01$) between the number of microbes and soil respiration, suggesting that the regenerative farming system's microbial ecosystem is more active and harmonized.

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