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Reactivating the Potential of Lima Bean (*Phaseolus lunatus*) for Enhancing Soil Quality and Sustainable Soil Ecosystem Stability

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Abstract: *Background*: This study explores the role of leguminous crops like lima bean in enhancing soil quality and ecosystem stability. Despite existing studies on agronomic aspects, there is a significant research gap on its impact on soil organic matter level, microbial activity, soil health, and nutrient availability. Therefore, this study examines the capacity of lima bean to reactivate soil quality, focusing on its impact on soil organic matter level, microbial activity, soil health, and nutrient availability. *Methods*: The experimental area was set up in 2023 using three replicates and a randomized block design. Two treatments were used: lima bean-planted plots and control plots with various weeds and without lima bean. Post-harvest soil samples were collected from various agroecological zones and sterilely packed, and physical, chemical, and biological indices were examined. *Results*: lima bean significantly affected nutrients, enzymes, soil microbial respiration, and other markers. Amylase activity (0.41**) was positively correlated with urease activity (0.73**), while dehydrogenase activity positively correlated with both. Dehydrogenase activity was negatively correlated with total nitrogen (0.66**) and sulfur (0.60**). Lima bean significantly affected soil quality, with all locations showing higher ratings (55–77%) than wild land, except for location D (Ilora). A total of 70% of total nitrogen variation may be attributed to soil quality (r^2 = 0.696). Lima bean enhanced soil quality, potentially enhancing productivity and reducing dependence on inorganic nitrogen inputs. *Conclusions*: The symbiotic relationship between lima bean and nitrogen-fixing bacteria improves nutrient cycling, enhancing agricultural productivity and environmental conservation. Future research should explore the economic viability of integrating lima bean into crop rotations or agroforestry systems for sustainable agricultural practices, providing valuable information for farmers.

Keywords: lima bean; soil quality; soil ecosystem stability; enzyme activity; soil microbial communities; sustainable agricultural management

1. Introduction

Soil is a complex and dynamic ecosystem that serves as a vital reservoir of nutrients, a habitat for a myriad of macro and microorganisms, and the bedrock of global food production systems [1,2]. The quest for sustainable agricultural practices has gained unprecedented importance in recent years due to the increasing challenges posed by environmental degradation, dwindling natural resources, and the increasing global demand for food production [3]. Soil health and quality emerge as critical determinants in achieving sustainable agricultural systems; therefore, maintaining soil health is essential to ensure long-term agricultural productivity, environmental stability, and food security [4,5]. The relationships that exist within soil ecosystems support a number of biological processes that are essential to the ability of ecosystems to function and adapt to changing environmental conditions [6–8]. Thus, the importance of soil health and quality in relation to agricultural productivity and environmental sustainability has garnered substantial attention from researchers.

The stability of soil ecosystems is influenced by a variety of physical, chemical, and biological soil variables, or markers of soil health [9]. Soil structure, nutrient cycle, microbial diversity, and organic matter content are key determinants of soil stability [10]. Furthermore, external factors, such as changes in land use, climate variability, and human activities, can significantly affect soil stability. Complex interactions between soil organisms, nutrient cycling, and physical properties contribute to ecosystem adaptability and the ability to withstand disturbances [11,12]. Recognizing the interconnectedness of soil health, soil quality, biodiversity, and ecosystem resilience underscores the importance of sustainable soil management practices in protecting the stability and long-term sustainability of our ecosystems [13]. The physical, chemical, and biological properties of the soil matrix have a major impact on the total productivity and stability of agroecosystems and are directly related to the health and quality of the soil [14].

The physical structure of the soil influences water retention, drainage, and aeration. Adequate water regulation improves the resistance of soil ecosystems to droughts and floods, contributing to overall stability and quality [15]. A stable soil structure prevents erosion and supports plant root systems, promoting plant establishment and growth [16]. The cycling of nutrients within soil ecosystems sustains plant growth and productivity, ultimately influencing soil ecosystem stability. Plants and soil organisms also contribute to the stability of the soil ecosystem by participating in intricate feedback loops. Plants discharge organic substances into the soil, which in turn mold microbial populations. Therefore, these microorganisms have an impact on the availability of nutrients and the health of plants [17]. Microorganisms form intricate networks within the soil matrix, which contribute to the availability of nutrients through processes such as mineralization and nitrogen fixation [18,19]. These soil microbial communities are essential for the stability of the soil ecosystem and help to preserve the general performance of the soil ecosystem.

The degradation of soil health and quality through erosion, the depletion of nutrients, and the loss of microbial diversity has the potential to disrupt soil structure, nutrient cycling, and water-holding capacity [2,20]. Incorporation of leguminous plants into agricultural systems offers a multifaceted approach to address these challenges, owing to their unique ability to enrich soil nitrogen content through symbiotic interactions with nitrogen-fixing bacteria. The lima bean (*Phaseolus lunatus* L.), is the second most important domesticated species of *Phaseoulus* globally and has significant potential as a valuable alternative resource for food security, quality, and sustainability in the face of climate change [21]. Its symbiotic relationship with rhizobia microorganisms offers an attractive strategy for soil fertility restoration, soil health and quality improvement, and sustainable agricultural practices [22]. This legume crop is known to establish symbiotic relationships with nitrogen-fixing rhizobia bacteria, mainly of the *Bradyrhizobium genus*, which can contribute to soil fertility and ecosystem sustainability [22,23]. It possesses distinctive attributes that contribute to its role as a soil quality restorer, particularly its capacity to enrich the soil with readily available

nitrogen [24], reducing the dependence on synthetic fertilizers and its subsequent ecological consequences [25].

Recent studies have highlighted the complex bottom-up effects of lima bean plants on their associated biotic communities, including direct and indirect defense mechanisms that can influence higher trophic levels [18,26]. These findings suggest that the lima bean could serve as an important model system to understand the role of legumes in promoting the stability of the soil ecosystem. In addition, the presence of leguminous crops such as lima bean in crop rotations has shown promise to enhance soil organic matter content, promote microbial diversity, and improve soil structure and aeration [13,20,27]. Its deep-rooted growth habit and abundant biomass production facilitate the creation of stable soil aggregates, which improves water infiltration, drainage, and overall soil porosity [22,28]. Consequently, the cultivation of the leguminous lima bean may serve as a natural soil protection mechanism, mitigating erosion risks and fostering a healthier soil environment for subsequent crops. Its impact on soil microbial communities and biodiversity underscores its potential to promote robust soil health. Furthermore, exudates released by its roots can provide a rich substrate for diverse microbial populations, facilitating the establishment of beneficial microorganisms that promote nutrient cycling, disease suppression, and overall stability of the soil ecosystem [29–31].

Complex interactions between soil organisms, nutrient cycling, and physical properties contribute to ecosystem adaptability and stability. In the face of increasing environmental challenges, research on the mechanisms by which lima bean contribute to soil nutrient enrichment, microbial dynamics, and overall soil ecosystem stability is imperative for sustainable agricultural intensification. This research seeks to provide valuable information on the pivotal role of lima bean as a legume-based strategy in maintaining soil ecosystem stability in different agroecologies as well as provide information on the potential of lima bean as a cover crop or intercrop to increase soil fertility and resilience through field tests, lab investigations, and data modeling. The research work aims to explore the multifaceted interactions between lima bean cultivation and soil health/quality reactivation for soil ecosystem stability. Through an assessment of its effects on nutrient dynamics, microbial abundance, soil structure enhancement, and its broader implications for sustainable agricultural systems, it will be a valuable contribution to the growing body of knowledge on the role of leguminous crops in soil health/quality restoration.

2. Materials and Methods

2.1. Study Location and Experimental Layout

The lima bean was planted in 2023 in five (5) agroecological zones in the Southwestern part of Nigeria, namely, transition agroecology (Ibadan: 7°22′ N; 4°33′ E), high-rain forest (Ife: 7°73′ N; 4°33′ E), derived savanna (Ilora: 7°52′ N; 3°85′ E), the southern Guinea savanna (Kishi: 9°69′ N; 3°51′ E), and Ikenne (6°40′ N; 3°33′ E). Three replicates and a randomized complete block design were used to set up the experimental area. Two treatments were used: a plot planted with lima bean (LB) and control plots and fallow plots with various weeds and without lima bean (WLB). Samples of post-harvest soil were aseptically taken from every plot in each of the various agroecological zones, placed in sterile containers, and sent straight to the laboratory for examination.

2.2. Determination of Soil Microbiological Indicators

Soil Microbial Respiration: Microbial activity was measured as heterotrophic respiration in the absence of plant roots using an incubation-alkaline absorption technique [32]. Subsamples of compost weighing 50.0 g dry weight were placed in 1 L Mason jars with a suspended beaker containing 10 mL of 0.05 M sodium hydroxide (NaOH) after the moisture content was adjusted to approximately 60% water holding capacity. The jars were sealed, then left in the dark and incubated at 25 °C for three days. After the incubation period, the CO_2 that had been trapped in NaOH was titrated with 0.05 M HCl. The method of [32] was used to calculate the respiration rate. The final value was expressed in terms

of the amount of CO_2 that developed from the bacteria present per gram of soil per hour (μg CO_2 g^{-1} soil h^{-1}).

Enzyme Activities of Soil Samples: The moisture content of the soil from which enzyme assessments were performed was 20–30%. The enzyme assessment tests were conducted after the soil physicochemical tests using the same soil. The enzyme activity of the soil in the samples was measured using colorimetric assays, which involve the addition of specific substrates to the enzymes. The process involved the measurement of soil samples, preparing a soil extract, selecting an enzyme assay, adding the substrate, incubating the mixture under controlled conditions (such as pH and temperature being maintained during the tests to indicate potential enzyme activities), and measuring the resulting reaction using spectrophotometry. The enzyme activity was calculated based on the rate of reaction observed, and quality control was included to ensure accuracy and reliability [33].

Amylase activity: A 50 mL Erlenmeyer flask containing 5 g of the substance (cornstarch) was filled with 1.5 mL of toluene. After giving the mixture a gentle shake and letting it stand for 15 min to allow complete extraction, 10 mL of distilled water and five milliliters of a 2% soluble starch solution were added. This allowed the amylase enzyme to react with the starch, and the activity was assessed [33].

Dehydrogenase activity: Soil samples were evaluated for dehydrogenase activity. The TTC reduction technique developed by [33] was employed. In a test tube, one gram of fresh soil, one milliliter of 1% TTC solution, and 0.1 g of calcium carbonate ($CaCO_3$) were added. The liquid was shaken, then sealed with a rubber stopper and placed in an incubator set at 30 °C for 24 h. For each sample, three duplicates were kept. After that, the slurry was poured onto Whitman filter paper No. 1 and extracted with incremental aliquots of methanol that had been concentrated. After the filtrate was made up to a volume of 50 mL, its optical density was measured at 485 nm using a Hitachi Spectrophotometer (220), with methanol extract serving as a reference.

Urease activity: Urease activity was measured using the technique described by [33]. To ensure complete penetration of toluene into the soil, 100 mL of a volumetric flask containing 1 g of fresh soil was filled with 1 mL of toluene, and the mixture was left to stand for 15 min. After adding 10 mL of pH 7 buffer solution and 5 mL of 10% urea solution, the flask was shaken and allowed to incubate for three hours at 37 °C in an incubator. Instead of adding a urea solution, 10 mL of distilled water was added to the control treatment. Following incubation, distilled water was added to get the amount down to 100 mL. After the contents of the flask were properly mixed, Whitman filter paper was used to filter the mixture. Indophenol blue was used to measure the amount of urease activity in the filtrate.

Phosphatase activity: FA A 100 mL conical flask was filled with five grams of air-dried dirt and 1.5 mL of toluene. The mixture was shaken well and allowed to stand for fifteen minutes. Ten milliliters of 0.1 M Tris-HCl buffer and five milliliters of 0.013 m disodium phenylphosphate in Tris-HCl buffer (pH 7.0) were added. After sealing the flask and keeping it at 37 °C for three hours, the phosphate activity was determined.

2.3. Determination of Soil Physicochemical Indicators

Physicochemical analyses of the soil samples were determined after air drying and sieving (2.0 mm sieve). The pH, exchange bases (Ca, Mg, K, Na), CEC, phosphorus, organic carbon, % total nitrogen, S, and trace elements (Mn, B, Cu, Fe, and Zn) were determined using dry analysis of the mid-infrared (MIR) dry analysis. The modified Boyoucos hydrometer method was used to determine the particle sizes of clay, silt, and sand [34–36]. Bulk density was determined using the fundamental method [37,38]. Equation (1), which describes the relationship established by [39], was used to infer total porosity from the bulk.

$$POR_t = 1 - \frac{\rho b}{\rho s} \quad (1)$$

where ρs is the density of the particle, which is assumed to be 2.65 mg/m^3, ρb is the bulk density of the soil, and POR_t is the total porosity of the soil.

Using a constant head permeameter in the laboratory, the saturated hydraulic conductivity of the collected core samples was also ascertained [40]. Equation (2), which was used to estimate the available water capacity stated on a gravimetric basis, describes the difference between the field capacity (FC), measured at 10 kPa (100 cm water), and the permanent wilting point (PWP), calculated at 1500 kPa (15,000 cm water):

$$AWC = (\theta FC - \theta PWP) \quad (2)$$

where θFC is the gravimetric moisture content (%) in the field capacity, and θPWP is the gravimetric moisture content (%) at the permanent wilting point.

2.4. Assessment of Soil Quality

The procedures and soil quality indicators were combined to create the value of the quality index (Table 1). Each signal that had an impact on a specific process was collected, assigned relative weights, and scored according to its significance. Indicator scores were added and then multiplied by the appropriate weights to determine the process evaluation of soil quality. The soil quality rating of each procedure was further multiplied by a suitable weight using a model originally developed by [41]. This produced a matrix, which was then added together to produce the soil quality index. These changes were made to the model:

$$SQI = \frac{n}{\Sigma WS} = qt.nav \times wt.nr \times wt + qt.rp \times wt + qt.be \times wt\, e \; = \; 1 \quad (3)$$

where SQI = soil quality index, W = average soil quality weight; S represents the factors' respective scores; qt. are the soil quality ratings for the nutrient availability, and retention processes are represented by the letters nav, qt, and rp, respectively. The letter qt stands for the soil quality rating for the root penetration process and the biotic environment process grade for soil quality.

Table 1. Minimum data set for quality indicators and soil processes is used to determine the relative weights of these indicators and soil quality.

Soil Quality-Related Soil to Processes	Weight (g)	Indicators (Soil Quality)	Relative Weight (%)
Nutrient availability	0.3	pH	0.25
		Avail. P	0.30
		K	0.25
		CEC	0.20
Nutrient retention	0.3	Organic matter	0.50
		ECEC	0.30
		SHC	0.20
Root penetration	0.2	Bulk density Total	0.40
		Porosity	0.40
		SHC	0.20
Biotic environment	0.2	Soil respiration	0.25
		Phosphatase activity	0.25
		Urease activity	0.20
		Dehydrogenase activity	0.30

2.5. Statistical Analysis

To determine characteristics related to soil quality, quality procedures were scored, and the score variables were then analyzed with analysis of variance (ANOVA) using statistical application software [42]. Following the use of Duncan's multiple range test to separate the means, all results were given as mean ± standard deviation of three measures. Associations between various soil chemical and microbiological markers were investigated using bivariate correlations (Pearson, two-tailed).

3. Results

3.1. Influence of Lima Bean on Soil Microbial Indicators of Soil Quality

3.1.1. Influence of Lima Bean on Soil Microbial Respiration

The soil respiration results observed at the different locations for soils with lima bean (LB) and control soils without lima bean (WLB) are reported in Figure 1a. The soil respiration results in Ibadan were 5.7 and 2.4 mg $CO_{2/}$g soil for LB and WLB, respectively, while in Ife, LB and WLB were 4.9 and 3.2 mg $CO_{2/}$g soil, respectively. In Ikenne, soil respiration was 8.99 and 8.29 mg $CO_{2/}$g soil for LB and WLB, respectively. The microbial soil respiration in Kishi was 6.8 and 3.8 mg $CO_{2/}$g soil for LB and WLB, respectively. Unlike the other location, Ilora recorded higher microbial soil respiration for WLB when compared to LB, with soil respiration values of 1.5 and 0.74 mg $CO_{2/}$g of soil, respectively.

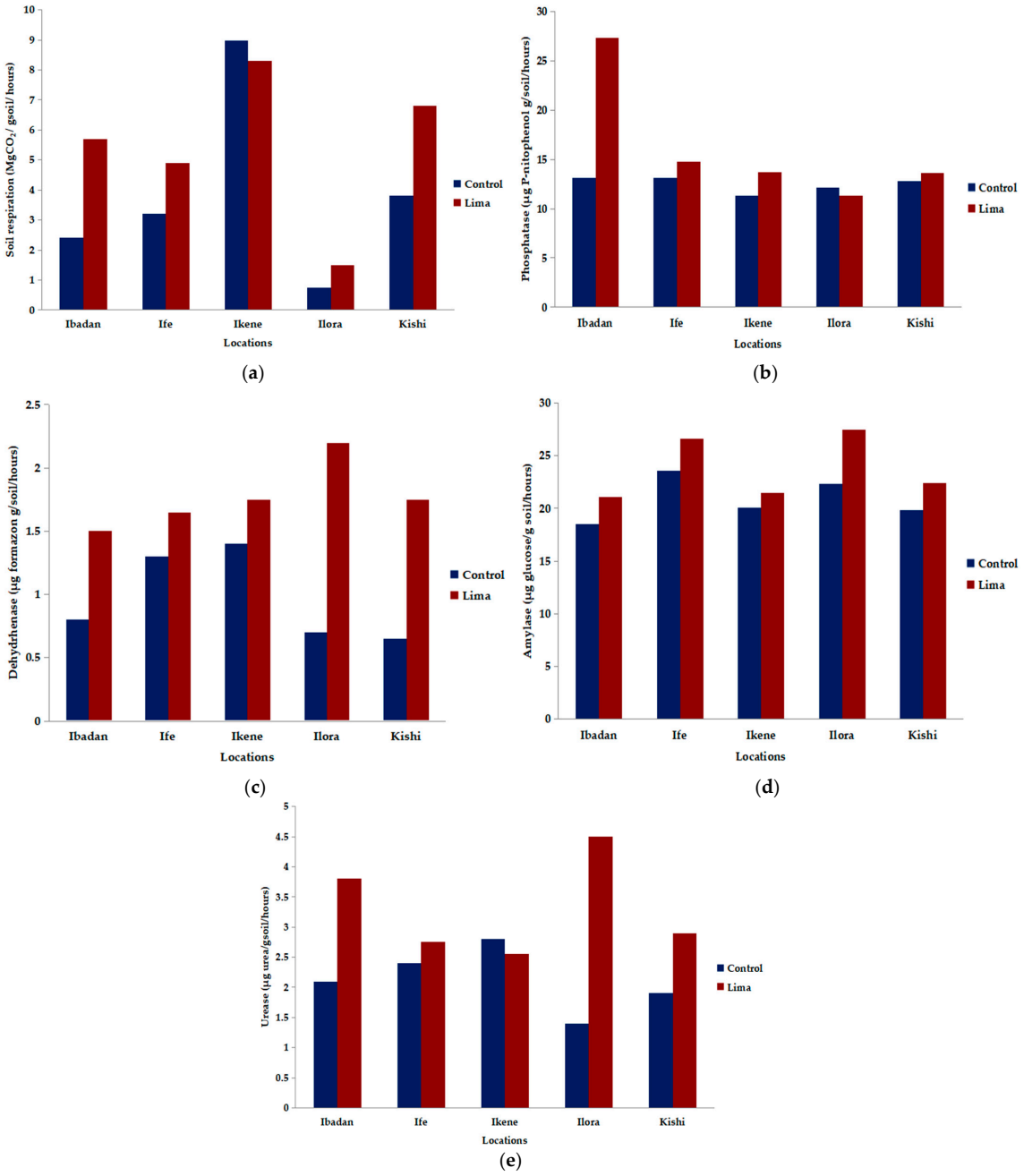


Figure 1. Influence of lima bean on (**a**) microbial soil respiration, (**b**) soil phosphatase activities, (**c**) soil dehydrogenase activities, (**d**) soil amylase activities, (**e**) soil urease activities.

3.1.2. Influence of Lima Bean on Soil Microbial Enzymes

The influences of lima bean on the activity of phosphatase, dehydrogenase, urease, and amylase in the soil were also evaluated. The phosphate activity results are presented in Figure 1b; the results showed higher enzyme activities in the soil with lima bean (LB) in all locations except Ilora, compared to the control (WLB). The results obtained in Ibadan from LB were significantly different from all other locations and also significantly higher than those of WLB; however, there was no apparent disparity in the results between the treatments in the other locations (Ife, Ikenne, Ilora, and Kishi). The results of the dehydrogenase activity also showed that all locations had significantly greater dehydrogenase activity in LB compared to WLB (Figure 1c).

Higher amylase activities were also observed in soils incorporated with lima bean (LB) across all locations compared to the control (WLB); however, no significant differences were observed in the activities between LB and WLB except for Ilora, which showed significantly higher amylase activity in LB than was obtained in both treatments at all locations (Figure 1d). The results of urease activities are presented in (Figure 1e), the results obtained from LB in Ibadan, Kishi, and Ilora were significantly higher ($p \leq 0.05$) when compared with WLB, while in Ife and Ikenne, the results were not significantly different ($p \leq 0.05$).

3.2. Correlation of Soil Respiration and Enzyme Activities

Table 2 provides an overview of the microbial activities in the soils from the various locations and shows the correlation coefficients between the various enzyme activities. Data on the soil respiration rates and enzyme activities (Amylase, phosphatase, dehydrogenase, and urease) in the lima bean were recorded and analyzed to calculate the coefficients between soil respiration and each of the enzyme activity with a correlation coefficient value ranging from −1 to 1. Positive values indicate a positive relationship (as one variable increases, the other also increases), and negative values indicate a negative relationship (as one variable increases, the other decreases). Also, the closer the value is to 1 or −1, the stronger the correlation, and a value near 0 suggests no linear relationship. The results of soil microbial respiration (SMR) revealed a non-significant connection with urease (0.03), dehydrogenase (0.03), and phosphatase (0.15), and a negative correlation that was not significant with amylase activity (−0.20). In addition to the strong positive connection with urease (0.41**) and dehydrogenase (0.37*), amylase activity also showed a non-significant negative correlation with phosphatase activity (−0.17). Phosphatase activity did not have any significant correlation with any of the other enzyme activities, while a negative correlation was observed with amylase; it showed a positive correlation with dehydrogenase (0.04) and urease (0.32). Also, a strong positive association (0.73**) was found between urease and dehydrogenase activities.

Table 2. Correlation Table for Soil Respiration and Enzyme Activities.

	Soil Microbial Respiration	Amylase	Phosphatase	Dehydrogenase
Amylase	−0.20			
Phosphatase	0.15	−0.17		
Dehydrogenase	0.03	0.37 *	0.04	
Urease	0.03	0.41 **	0.32	0.73 **

* The correlation is significant at the two-tailed 0.05 level. ** At the two-tailed 0.01 significance level, the correlation is significant.

3.3. Influence of Lima Bean on Soil Chemical Indicators of Soil Quality

The results of the soil pH were slightly higher in the soil with lima bean when compared to the soils without lima bean (Figure 2a). The soil pH of the soil with lima bean ranged between 5.9 and 6.1, while those of the soil without lima bean ranged between 5.3 and 5.9. The results of the sulfur level in the soil were not significantly different compared

to the soil without lima bean, while there was a significant increase in the phosphorus level in the soil with lima bean when compared to the one without lima (Figure 2b). The potassium, magnesium, calcium, and sodium content of the soil is presented in Figure 2c, and their results showed a slight increase in the levels of the mentioned nutrients in the soil with lima bean when compared to those without lima bean. Comparable patterns were observed for the total nitrogen concentration and the percentage of organic matter in the soil (Figure 2d). The percentage of organic carbon was also higher in most of the locations compared to soil from the areas without lima bean. The results of the impacts of lima bean on some soil micronutrients in the soil are presented in Table 3 which represents the total concentration data. Although the soil with lima bean increased slightly, a comparison of the results indicated that there were no discernible differences between the soil with and without lima bean at any of the locations. The results of hydrogen ions were also not significantly different in some of the locations when the results on soil with lima bean and those without lima were compared, except in Ikene and Kishi.

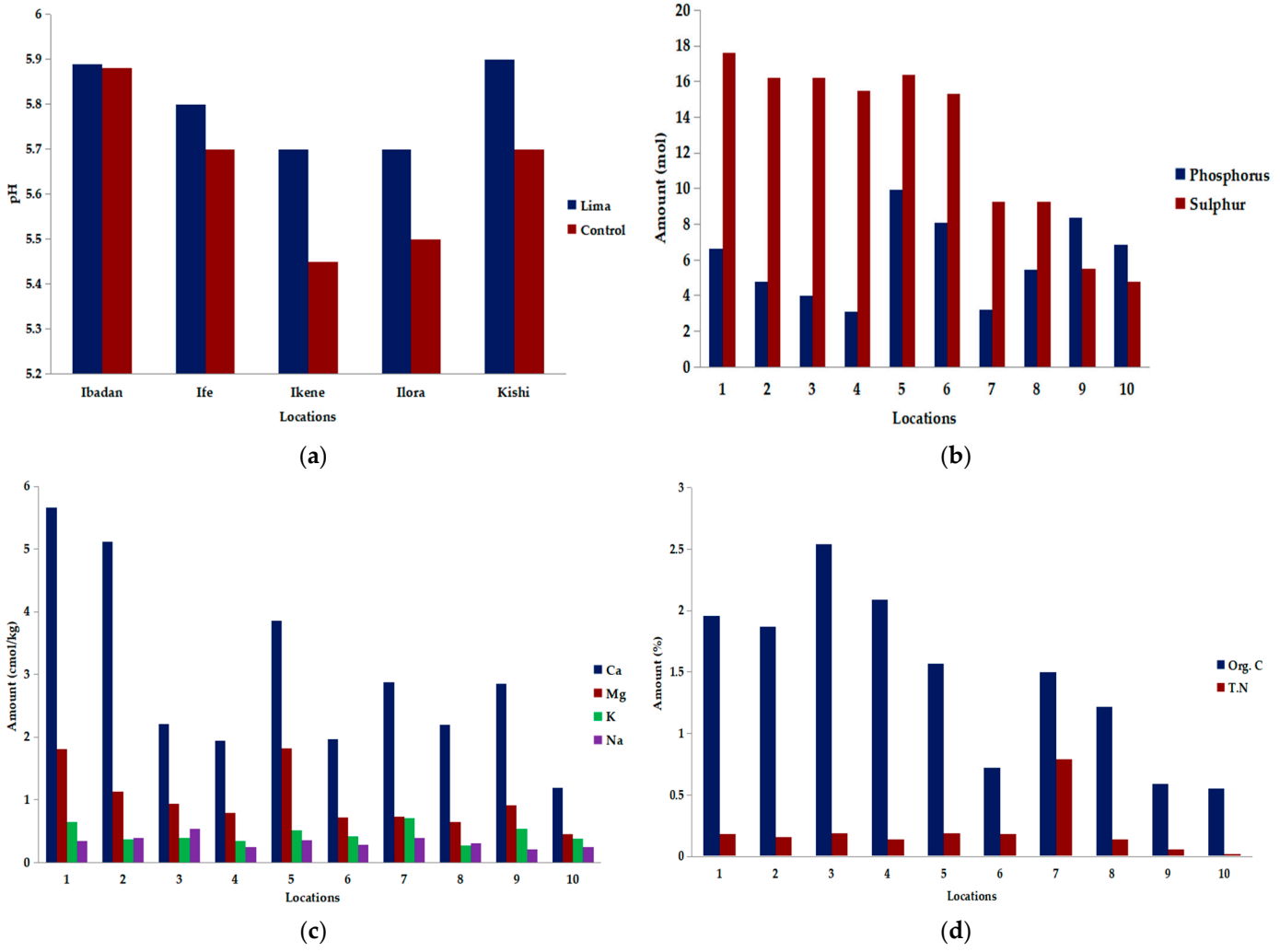


Figure 2. Influence of lima bean on chemical indicators (**a**) Soil pH, (**b**) soil phosphorus and sulfur, (**c**) soil exchangeable bases, (**d**) soil organic carbon and total nitrogen. Note: Locations 1, 3, 5, 7, and 9 are for plots without lima bean treatments (WLB), while locations 2, 4, 6, 8, and 10 are for plots with lima bean treatments for Ibadan, Ife, Ilora, Ikenne, and Kishi, respectively.

Table 3. Effect of lima bean on soil H^+ and some micronutrients.

Agroecology	Location	Treatment	H^+	CEC cmol/Kg	Mn ppm	B ppm	Cu ppm	Fe ppm	Zn ppm
Transition zone	Ibadan	WLB	0.120 ^{a}	7.52 ^{a}	54.8 ^{a}	0.07 ^{a}	1.66 ^{a}	146.4 ^{a}	2.85 ^{a}
		LB	0.130 ^{a}	8.37 ^{a}	54.9 ^{a}	0.08 ^{a}	1.26 ^{b}	159.1 ^{b}	1.17 ^{b}
High-rain forest	Ife	WLB	0.085 ^{b}	2.73 ^{b}	58.0 ^{b}	0.09 ^{a}	0.71 ^{c}	123.4 ^{c}	1.54 ^{b}
		LB	0.095 ^{b}	3.95 ^{b}	59.2 ^{b}	0.10 ^{b}	0.85 ^{c}	145.5 ^{ab}	1.40 ^{b}
Derived savannah	Ilora	WLB	0.130 ^{c}	5.1 ^{c}	40.0 ^{c}	0.16 ^{c}	0.92 ^{d}	148.1 ^{ab}	2.30 ^{ab}
		LB	0.130 ^{c}	6.67 ^{d}	41.3 ^{c}	0.19 ^{c}	1.02 ^{d}	157.9 ^{bc}	1.53 ^{b}
Rainforest	Ikenne	WLB	0.090 ^{d}	3.61 ^{e}	50.8 ^{d}	0.02 ^{d}	0.63 ^{e}	116.3 ^{d}	1.20 ^{b}
		LB	0.135 ^{e}	4.75 ^{e}	51.8 ^{d}	0.04 ^{e}	0.86 ^{e}	166.8 ^{e}	2.15 ^{c}
Guinea Savannah	Kishi	WLB	0.125 ^{f}	2.36 ^{f}	55.0 ^{e}	0.03 ^{de}	0.30 ^{f}	153.6 ^{f}	1.01 ^{d}
		LB	0.130 ^{f}	4.66 ^{g}	56.7 ^{e}	0.05 ^{f}	0.73 ^{g}	162.5 ^{g}	1.38 ^{d}

Different letters indicate significant differences among treatments within a column across the different locations at $p \leq 0.05$, according to the Duncan multiple range test (DMRT).

3.4. Correlation of Microbial Activities and Soil Chemical Indicators of Soil Quality

Table 4 shows the correlation coefficients between various chemical indicators and different enzyme activities. Data on enzyme activities and chemical indicators of soil quality were collected with laboratory analysis to test the significance of the correlation coefficient and determine the relationship between enzyme activities and various soil qualities. pH (H_2O) shows non-significant positive correlations (between 0.34 and 0.66) with all enzyme activities and also soil microbial respiration (SMR) (0.12). Ca, Mg, and K showed mixed non-significant correlations with different enzyme activities, while Na and H^+ (Hydrogen ion concentration) showed non-significant negative correlations with all enzymes and SMR. Cation exchange capacity (CEC) and phosphorus (P) showed non-significant mixed correlation patterns, while CEC showed positive correlations with phosphatase activity, urease activity, and SMR; P was positively correlated with dehydrogenase activity, urease activity, and SMR. Organic carbon was negatively correlated with all enzyme activities, though not significant, while it showed a weak positive correlation with SMR (0.05). The % total N (total nitrogen) was negatively correlated with all enzyme activities but only showed a strong significant correlation with dehydrogenase activity (0.66**) with a very weak positive non-significant correlation with SMR (0.02). Mn, S, Cu, Fe, and Zn showed mixed non-significant correlation patterns with various enzyme activities and SMR; however, S showed a strong negative correlation with dehydrogenase activity (0.60**). Boron showed a negative non-significant correlation with all enzyme activities and SMR.

Table 4. Correlation table for biological and chemical indicators of soil quality.

Chemical Indicators	Amylase	Phosphatase	Dehydrogenase	Urease	CO_2 Evolution
pH (H_2O)	0.66	0.46	0.37	0.34	0.12
Ca	−0.13	0.39	−0.08	0.13	0.30
Mg	−0.28	0.18	−0.39	−0.14	−0.14
K	−0.27	0.06	0.05	−0.03	0.31
Na	−0.03	−0.21	−0.51	−0.31	−0.03
H^+	−0.06	−0.46	−0.37	−0.34	−0.12
CEC	−0.21	0.33	−0.20	0.03	0.23
P	−0.20	−0.08	0.13	0.09	0.15
Org. carbon	−0.01	−0.09	−0.63	−0.24	0.05
% Total N	−0.16	−0.16	−0.66 **	−0.33	0.02
Mn	−0.14	0.07	−0.55	−0.37	−0.28
S	−0.12	0.02	−0.60 **	−0.25	0.14
B	−0.14	−0.25	−0.53	−0.53	−0.49
Cu	−0.08	0.13	−0.41	−0.12	0.19
Fe	0.30	−0.13	−0.06	0.20	−0.25
Zn	0.16	0.14	−0.51	−0.08	0.20

** At the two-tailed 0.01 significance level, the correlation is significant.

3.5. Influence of Lima Bean on Soil Physical Indicators of Soil Quality

Table 5 illustrates the impact of lima bean on soil physical markers of soil quality at various locations. The addition of lima bean improved the soil pore size distribution and decreased its density in the various locations. Soils in the LB plots had higher bulk densities and porosities than those in the WLB plots. A range of 1.2 to 1.58 Mg/m^3 and 0.404 to 0.547 m^3/m^3 were observed for bulk density and total porosity, respectively, in LB, while a range of 1.33 to 1. 53 Mg/m^3 and 0.404 to 0.498 m^3/m^3 were observed for soils under WLB. The available water capacity (AWC) and the saturated hydraulic conductivity (SHC) were impacted by legume systems; developments between total porosity and bulk density, respectively, were mirrored in the responses of SHC and AWC to the legume system as markers of soil quality. For soil LB and WLB, respectively, the geometric mean SHC values ranged from 0.71 × 10−3 to 8.72 × 10^{-3} cm/s^{-1} to 1.42 × 10−3 to 9.81 × 10^{-3} cm/s^{-1} throughout the regions. AWC was better influenced by lima bean, with higher values observed in LB compared to WLB, while a range of 0.09 to 0.16% was observed for LB, and a lower range of 0.09 to 0.14% was observed in WLB soils.

Table 5. Effect of lima bean on some soil physical indicators of soil quality.

Agroecology	Location	Treatment	Texture	Bulk Density ($Mg\ m^{-3}$)	Total Porosity ($m^{-3}\ m^{-3}$)	Saturated Hydraulic Conductivity ($10^{-3}\ cm\ s^{-1}$)	Available Water Capacity (%)
Transition zone	Ibadan	LB	SCL	1.32 ^{ab}	0.502 ^{ab}	2.39 ^{c}	12 ^{a}
		WLB	SCL	1.43 ^{a}	0.460 ^{b}	8.10 ^{a}	11 ^{ab}
High-rain forest	Ife	LB	SL	1.20 ^{b}	0.547 ^{a}	8.72 ^{a}	16 ^{a}
		WLB	SL	1.33 ^{ab}	0.498 ^{ab}	9.81 ^{a}	14 ^{a}
Derived Savannah	Ilora	LB	SL	1.58 ^{a}	0.404 ^{c}	3.01 ^{b}	12 ^{a}
		WLB	SL	1.38 ^{ab}	0.479 ^{b}	4.92 ^{b}	10 ^{ab}
Rainforest	Ikenne	LB	SCL	1.27 ^{b}	0.521 ^{a}	3.90 ^{b}	12 ^{a}
		WLB	SCL	1.37 ^{ab}	0.483 ^{ab}	8.21 ^{a}	11 ^{ab}
Guinea Savannah	Kishi	LB	SL	1.49 ^{a}	0.438 ^{b}	0.71 ^{d}	9 ^{b}
		WLB	SL	1.53 ^{a}	0.423 ^{bc}	1.42 ^{cd}	9 ^{b}

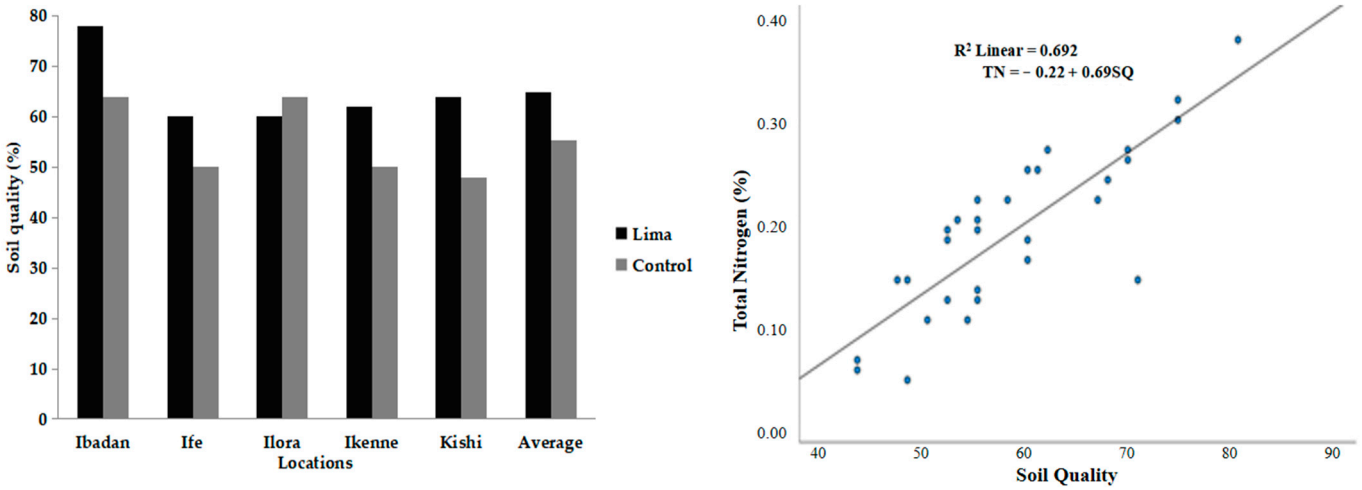
Different letters indicate significant differences among treatments within a column at different locations at $p \leq 0.05$ according to the Duncan multiple range test (DMRT). SCL = sandy clay loam; SL = sandy loam.

3.6. Influence of Lima Bean on Soil Quality

The influence of lima bean on soil quality at the different locations is shown in Figure 3a. There were significant differences between LB and WLB in relation to their soil qualities at all locations except in Ilora. The soil quality of LB plots in the different locations was higher than the WLB plots by 18.0 to 27.7%, the soil quality under LB in Ilora was, however, slightly lower than the WLB plots by 5.1%, although without significant difference. The soil quality in the LB plots was 18.0%, 22.2%, 22.4%, and 27.7% higher than the WLB plots in Ife, Ibadan, Ikenne, and Kishi, respectively, and these were higher than the average increase of 16.7% observed.

3.7. Soil Quality and Total Nitrogen

Total nitrogen in the soil is a reflection of the biological nitrogen fixation capacity of the lima bean as a legume. Although there was no significant difference in total nitrogen compared to LB and WLB in almost all locations except Ikenne and Kishi (Figure 3a), the quality of the soils influenced total nitrogen. Total nitrogen and soil quality had a substantial and positive association, according to the Pearson product-moment correlation ($r = 0.832^{**}$, $p < 0.01$). Approximately 70% of total nitrogen is related to soil quality ratings, according to the correlation coefficient ($r^2 = 0.696$) determined for the linear relationship between the two attributes (Figure 3b).



(**a**) (**b**)

Figure 3. Influence of lima bean on soil quality (**a**), evaluations of the soil quality as impacted by lima bean (**b**), relationship between soil quality and total nitrogen as affected by lima bean.

4. Discussion

The lima bean has great potential to improve soil health and soil quality, and this is evident in the improved biological activities in soils from lima bean (LB)-incorporated plots compared to that of fallow plots with various weeds and without lima bean (WLB). Higher soil respiration rates in LB are an indication of improved microbial activities, which may be the result of improved metabolic activities of microorganisms in the area, and a rapid transformation of organic waste into nutrients for plants. Though, studies have been reported on the increased microbial activities in soils with leguminous crops and consistently higher soil respiration in the legume-based rice wheat plot than in the fallow-based rice plot [43–46]. Also, the higher values of enzyme activities in LB indicated that lima bean influenced microbial activities, as its presence in the soil can lead to increased microbial respiration because fixes and organic compounds are released into the soil, which aids various microorganisms present in the rhizosphere [47].

From the results obtained, lima bean significantly influenced changes in nutrients, enzymes, soil microbial respiration, and other physicochemical markers. Amylase activity (0.41**) showed a positive association with urease activity (0.73**), while dehydrogenase activity showed a strong positive correlation with both urease and amylase activity. Dehydrogenase activity also showed a significant negative correlation with total nitrogen (0.66**) and sulfur (0.60**). These enzyme activities are indications of various metabolic processes that occur in the soil, and enhanced microbial activity boosts nutrient cycle and decomposition processes, leading to improved soil structure and fertility [48]. For example, phosphatase enzymes are crucial for the mineralization of soil organic P and plant nutrition because they catalyze the hydrolysis of H_3PO_4 esters and anhydrides [49–51].

Lima bean significantly affected soil quality, and all locations showed higher soil quality ratings in LB locations, and the majority of the variation in total nitrogen is attributed to soil quality ($r^2 = 0.696$). Furthermore, the results of soil microbial respiration (SMR) revealed a non-significant connection with urease (0.03), dehydrogenase (0.03), and phosphatase (0.15) and a negative correlation not significant with amylase activity. Elevated levels of metabolic microbial activity in the soil augment soil phosphatase sources and result in elevated enzyme synthesis [49,52]. In addition to the strong positive connection with urease and dehydrogenase, amylase activity also exhibited a non-significant negative correlation with phosphatase activity. The distribution of urease and dehydrogenase activity in this study also suggests that lima bean considerably increased soil microbial metabolism in most locations.

The anticipated outcomes of this study include a better understanding of how lima bean contributes to improved soil quality through various mechanisms such as nutrient cycling, water retention, microbial activity, and aggregate stability, which are in are consistent with those of [47,53,54], who found that legume green manure soils of the winter wheat production systems in eastern Washington always have higher levels of dehydrogenase than the chemically fertilized soils. The urease enzyme, which catalyzes the hydrolysis of urea in CO_2 and HN_3, is crucial for managing nitrogen availability for plants [55]. The significant increase in urease activity under LB in some locations may be a result of the addition of crop residues that stimulate microbial activities, which indicates that lima bean improve soil quality through nitrogen fixation, where rhizobia bacteria colonize root nodules and convert N_2 into NH_3 that benefit the beans and enrich the soil quality with nitrogen, promote plant growth, produce substrate, and improve overall soil quality [25,48,53]. Studies have found that green legume crops have higher dehydrogenase (202%), phosphatase (171%), and arylsulfatase (287%) microbial activities than fallow-wheat systems [56].

The results of the chemical indicators of soil quality show a higher pH, percentage of organic carbon and total nitrogen, exchangeable bases, phosphorus, and sulfur contents, and a relatively higher level of micronutrients in LB soils compared to WLB in most locations. Studies have reported a slight increase in the physicochemical properties of soils with leguminous crops compared to the control, with improved soil nutrients and micronutrients and an increase in total nitrogen in soils with leguminous crops [9,57–59]. Hence, the increase in % of total nitrogen observed in all locations is a good indication that lima bean has the potential to fix nitrogen and increase the nitrogen content of the soil.

The potential of lima bean as a legume-based system in rebuilding soil structural quality is shown by the soil physical indicators measured, as the lower bulk density observed in LB soils could be a result of the higher amount of biomass from leguminous crops, which enhances the soil's looseness and porosity. This explains the higher porosity observed in LB soils compared to WLB soils, an important indicator of soil structural quality. Low saturated hydraulic conductivity values can result from the presence of organic compounds in certain plant species such as legumes, which are hypothesized to promote water repellency [13,58,60], which may be responsible for the lower SHC values observed under LB in the present study. All of these improvements raise the water-holding capacity (WHC) of the soil, which was observed in the present research where LB soils had higher WHC than WLB soils.

The interplay between soil enzymes and microbial composition is intricate and interconnected, where soil enzymes can influence microbial activity by providing substrates for their growth or altering their chemical environment (microbial metabolism), while microbes affect enzyme production and activity through their interactions with organic matter in the soil [6,33,51]. Additionally, the incorporation of lima bean as a legume into the soil significantly maintains a better soil quality, as observed under LB in all locations, than soils under WLB except Ilora, where a non-significant but higher soil quality was observed in WLB. The improved soil quality can be attributed to the influence of the lima bean on the enhancement of the physical, chemical, and biological characteristics of the soil, particularly the organic carbon, porosity, and other physical structural parameters of the soil.

Additional research has shown that lima bean can be used effectively as cover crops and green manure to improve soil quality, such as with nutrients recycling, increasing soil natural matter, decreasing soil pH, and improving soil porosity, soil structure, microscopic biodiversity, and sustainability [61,62]. The nitrogen-fixing capabilities of LB-rhizobia symbioses, as well as the plant's ability to suppress weeds and improve soil structure, make it a valuable component in sustainable agricultural systems [63]. A total of 69.6% of the fixed total nitrogen is attributable to changes in soil quality, according to an analysis of the Pearson correlation between total nitrogen and soil quality, which revealed a substantial and positive linear association. This suggested that using lima bean to regulate soil quality indicators could improve soil quality and simultaneously increase total nitrogen.

5. Conclusions

The strength of this study lies in its comprehensive approach to evaluating the potential of lima bean for enhancing soil quality and ecosystem stability, providing new insights into the crop's benefits for sustainable agriculture. Leguminous crops, such as lima bean, are gaining attention due to their ability to improve soil health and quality through beneficial interactions. The results from this study demonstrated the significant potential of lima bean in improving soil health, nitrogen-fixing capability, the enhancement of the biological, chemical, and physical properties of the soil, organic matter, and soil structure, and in reducing soil bulk density, increasing soil water holding capacity, and promoting soil microbial diversity and activity, leading to enhanced soil ecosystem stability, making it a promising candidate in enhancing soil quality. Therefore, it can be concluded that incorporating lima bean into agroecosystems offers benefits, such as nitrogen-enriched soil for subsequent crops and reduced synthetic fertilizer use, and their link between soil health and quality, biodiversity, and soil ecosystem stability highlights the importance of sustainable soil management. However, more research is needed to understand how these legume-based management strategies, such as how the incorporation of lima bean into ecosystems can enhance overall soil ecosystem stability, especially amid global environmental changes. Recognizing these connections underscores the need for strategies that promote long-term ecosystem sustainability by promoting soil health and quality.

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