iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 12 **Issue:** XI **Month of publication:** November 2024

DOI: https://doi.org/10.22214/ijraset.2024.65416

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 12 Issue XI Nov 2024- Available at www.ijraset.com

Effect of Chemical and Organic Fertilization on Soil Organic Carbon Dynamics in Coffee Production in Ghana

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Abstract: Soil organic carbon (SOC) plays a critical role in carbon sequestration and maintaining soil fertility. This study explores the impact of organic and chemical fertilizers on SOC dynamics in coffee-growing regions of Ghana. Specifically, it examines the partitioning of SOC into particulate organic matter (POM) and mineral-associated organic matter (MAOM). Soils from five coffee farms were sampled across three treatments (organic fertilizer, chemical fertilizer, and control), and key soil properties, including bulk density, texture, pH, and SOC fractions, were analyzed. The SOC stock decreased significantly in the order of organic fertilizer> chemical fertilizer > control. Results further showed that organic fertilizer significantly improved soil pH, reduced bulk density, and enhanced the POM fraction, contributing to nutrient cycling and microbial activity. Chemical fertilizers had a modest impact on SOC stabilization, particularly increasing the MAOM fraction, which is key for long-term carbon storage. These findings highlight the differential effects of fertilizer types on SOC storage and provide insights into optimizing fertilizer use for sustainable coffee production and climate change mitigation.
Keywords: soil organic carbon, fertilization, climate change, particulate organic matter

I. INTRODUCTION

Soil is a critical terrestrial reservoir for global carbon, holding approximately 2500 Pg (1 Pg = 10^{15} g = 1 Gt). This storage comprises about 1550 Pg of soil organic carbon (SOC) and 950 Pg of soil inorganic carbon [1, 2]. The SOC pool surpasses the combined carbon content of the atmosphere and living biomass [3]. Recent findings indicate that soils in Ghana's coffee production regions, regardless of management practices, soil types, or agroecological zones, account for over 50% of the nation's total carbon stock [4]. Consequently, SOC plays a vital role in carbon sequestration within agricultural soils, aiding in the reduction of atmospheric CO_2 levels [5]. SOC is also essential for maintaining soil quality and providing nutrients critical for improving crop productivity [6]. Its contributions to sustaining agricultural ecosystems have been extensively documented [7, 8]. However, certain agricultural practices have resulted in significant SOC depletion in arable soils [9]. Preserving adequate SOC levels in farming systems is therefore crucial for ensuring food security and mitigating global warming. Various strategies have been developed to enhance SOC in agricultural soils, including agroforestry systems, organic farming, and the application of manure, compost, and biochar. Conventional farming practices have also been investigated [10, 11, 12]. However, the effectiveness of these methods in improving SOC storage often shows inconsistencies due to differences in fertilizer applications, agricultural systems, soil characteristics, and climatic conditions [13].

As a heterogeneous mixture of various components, soil organic carbon (SOC) is classified into particulate organic matter (POM) and mineral-associated organic matter (MAOM) based on differences in physical and chemical protection mechanisms and turnover rates. These fractions influence the residence time and spatial distribution of SOC, playing a critical role in regulating carbon dynamics and the soil's source-sink balance [14]. POM is characterized by large organic particles that decompose rapidly, providing nutrients essential for maintaining soil health and productivity [15]. Conversely, MAOM is composed of organic materials bound to mineral surfaces, which are more chemically stable and resistant to microbial decomposition. This stability makes MAOM a key indicator of long-term carbon sequestration rather than immediate soil fertility enhancement [16]. Changes in the relative proportions of POM and MAOM, influenced by soil management and environmental conditions, can alter SOC storage and longevity. An increase in MAOM, for instance, enhances SOC stabilization, whereas a higher POM proportion boosts nutrient availability but may reduce long-term carbon storage [17]. This balance between SOC fractions is crucial for achieving sustainable carbon management and mitigating climate change. Chemical and organic fertilizers significantly influence the dynamics of POM and MAOM.

Organic fertilizers such as manure and compost generally increase POM content by supplying fresh organic material, while chemical fertilizers may indirectly enhance MAOM by promoting root growth and microbial activity that facilitates organic matter binding to minerals [18, 19]. However, the effects of these amendments are often contradictory and depend on factors such as soil type, climate, and management practices. For instance, some studies report that chemical fertilizers accelerate the decomposition of POM, while others suggest they can enhance MAOM formation through increased microbial processing [20]. This variability underscores the need for further studies to clarify the mechanisms governing SOC pool responses to fertilization practices under different environmental and agronomic conditions. Coffee is an emerging cash crop in Ghana, primarily cultivated in regions with favourable agroecological conditions. The use of both chemical and organic fertilizers is a common practice to enhance soil fertility and support coffee production. These amendments are essential for addressing soil nutrient deficiencies and improving crop yields. However, their impact extends beyond immediate fertility enhancement, influencing soil organic carbon (SOC) stocks and dynamics, which are critical for climate change mitigation. Past studies in Ghana have focused on the effects of fertilizers on SOC stocks, revealing that organic fertilizers, such as manure and compost, often increase SOC content due to their high carbon inputs, while chemical fertilizers may stabilize SOC by stimulating root growth and microbial activity [21]. Despite these findings, limited research has been conducted on how fertilizers influence SOC dynamics, specifically, the partitioning of SOC into particulate organic matter (POM) and mineral-associated organic matter (MAOM). These SOC fractions play distinct roles in carbon cycling, with POM contributing to short-term nutrient availability and MAOM serving as a long-term carbon sink [14]. Understanding SOC dynamics under fertilizer management in coffee systems is crucial for developing strategies to mitigate climate change. Organic fertilizers can enhance POM, increasing nutrient cycling and microbial activity, while chemical fertilizers may contribute to MAOM formation, promoting carbon sequestration. However, the interaction between fertilizer types, SOC fractions, and environmental conditions remains underexplored in Ghana's coffee-growing regions. This study aims to investigate the impact of fertilizer management on soil organic carbon (SOC) stocks and pools (POM and MAOM) and their association with soil properties in coffee-growing systems in Ghana. Addressing this knowledge gap through targeted research could provide insights into optimizing fertilizer use for sustainable coffee production and effective climate change mitigation.

II. MATERIALS AND METHODS

A. Experimental Site

The study was conducted at Dodi-Papase in the Oti Region of Ghana, a key area for coffee production. The agroecological zone of Dodi-Papase is characterized by the Transitional Savannah, which features a semi-humid climate with a bimodal rainfall pattern, averaging 1,200–1,600 mm annually, and an average temperature range of 25–30°C. The coffee farm, established eight years ago, has undergone regular fertilizer applications to enhance soil fertility and productivity. The soil type at the site, classified according to the World Reference Base for Soil Resources (WRB), is predominantly Ferralsols, known for their well-drained nature and relatively low inherent fertility due to weathered parent material. Ferralsols in the area typically have high iron and aluminum oxide content, with a sandy loam to loamy texture. These soils respond well to fertilization and organic amendments, making them suitable for long-term coffee cultivation. The farm was selected based on specific criteria to ensure the validity of the study: (1) consistent use of either chemical or organic fertilizers over the years, (2) relatively homogeneous soil conditions to minimize variability, and (3) clear distinctions in fertilizer management practices between chemical and organic systems. These criteria ensured that the experimental setup provided a reliable comparison of the impacts of chemical and organic fertilization on soil properties, coffee yield, and overall soil health.

B. Soil Sampling

Soil samples were collected from five coffee farms, each representing one of the three treatments: organic fertilizer, chemical fertilizer, and control plots. Each farm had three designated treatment areas, with four replications per treatment plot. A total of 8 core samples were taken per treatment plot to ensure representative soil sampling. This resulted in 24 core samples per farm, with a total of 120 core samples across the five farms (3 treatments × 4 replications × 5 farms = 60 samples per treatment). The core samples were taken at random locations within each treatment plot to minimize bias and account for any spatial variability. Each core sample was extracted from the 0-10 and 10-20 cm soil depths, which is the primary zone for root activity and nutrient uptake in coffee plants. To assess soil bulk density, undisturbed soil samples were also collected using a cylindrical core sampler. These undisturbed samples were taken from the same depth range (0-10 and 10-20 cm) to determine bulk density values. After collection, the samples were air-dried, sieved, and prepared for analysis of various soil properties, including pH, texture, bulk density, soil organic carbon stocks, and fractions (POM, MOAM).

C. Soil Analysis

Soil bulk density of the two depths was determined by collecting undisturbed soil samples using a core sampler (15 cm internal diameter and 10 cm height). The samples were over-dried at 105°C for 24 hours to a constant weight [22]. The particle size distribution was done using the hydrometer method of Bouyoucos [23]. The pH of soils was measured in deionized water at the ratio of 1:2.5 (w/w) after shaking for 1 hour [24]). The total carbon concentration in the soil was determined by a CHNS analyzer (Elementar Vario El III, Germany). Due to the negligible amount of soil inorganic carbon, the total carbon was assumed to be SOC. POM was determined by wet-sieving the soil samples through a 53 µm mesh to separate the light fraction, which represents the labile organic matter [19] . MOAM was isolated using a strong acid-base treatment to remove non-organic components, leaving stable, mineral-bound carbon fractions [19].

D. Statistical Analysis

Data were analyzed using one-way analysis of variance (ANOVA) to compare the effects of organic, chemical, and control treatments on soil properties and carbon fractions. The normality of data was assessed using the Shapiro-Wilk test. Post-hoc comparisons were made with Tukey's Honestly Significant Difference (HSD) test when ANOVA revealed significant differences ($p \leq 0.05$). Pearson's correlation analysis was conducted to evaluate relationships between soil properties, SOC stock, and carbon fractions. All statistical analyses were performed using R software, with significance set at $p \leq 0.05$.

III. RESULTS AND DISCUSSION

A. Soil Properties Under The Management Systems

The soil properties namely pH, texture (clay, sand, and silt), and bulk density provide foundational insights into soil structure, fertility, and its ability to support plant growth under varying fertilizer treatments. These values varied significantly across soil depth and management systems (Table 1).

Table 1: Soil Properties under Different Fertilizer Treatments

Treatment	Depth (cm)	pH	Clay (%)	Sand (%)	Silt (%)	Bulk density (Mg m^{-3})
Control	0-10	5.30	25.00	55.04	20.00	1.35
	10-20	5.20	26.00	54.11	21.00	1.40
Organic fertilizer	0-10	6.11	26.00	54.01	20.12	1.27
	10-20	6.00	27.00	53.00	21.11	1.30
Chemical fertilizer	0-10	5.81	24.00	56.00	21.08	1.31
	20-20	5.71	25.01	55.01	20.10	1.35

The soil pH was significantly influenced by the treatments, with organic fertilizer-treated plots average across soil depth recording the highest pH of 6.06, followed by chemical fertilizer-treated plots at 5.50, and the control plots with the lowest pH of 5.25. This trend highlights the role of organic amendments in neutralizing soil acidity, as they provide buffering capacities through the release of basic cations like calcium and magnesium [21]. The slightly elevated pH in chemically fertilized plots compared to the control may be attributed to liming agents present in some fertilizers, which reduce soil acidity over time [25].

Soil texture, encompassing clay, sand, and silt percentages, remained relatively stable across treatments, reflecting the soil's inherent properties. However, the organic fertilizer-treated plots exhibited slightly higher clay content, averaging 27%, compared to 24.5% in chemical fertilizer-treated plots and 25.50% in the control plots. The sand content was marginally lower in organic plots, averaging 53.5%, relative to 55.5% in chemical plots and 54.58% in the control. The silt content was consistent across all treatments at approximately 23%. The increased clay content in organic fertilizer-treated plots may be attributed to improved soil aggregation and stabilization of finer particles, facilitated by the addition of organic matter, as suggested by Six et al. [16].

Bulk density differed significantly across treatments, with organic fertilizer-treated soils recording the lowest values of 1.28 Mg m^{-3}, followed by chemically fertilized soils at 1.35 Mg m^{-3}, and the control plots with the highest bulk density of 1.41 Mg m^{-3}. The lower bulk density in organic fertilizer-treated plots reflects the accumulation of organic matter, which improves soil structure and increases porosity [18]. In contrast, the higher bulk density in chemically fertilized and control plots suggests compaction and reduced porosity, likely due to the absence of significant organic matter inputs to counteract structural decline.

These findings underscore the differential effects of organic and chemical fertilizers on soil properties. Organic fertilizers not only improved soil pH but also enhanced aggregation and reduced bulk density, fostering favourable conditions for root growth and microbial activity. Chemical fertilizers, while slightly mitigating soil acidity compared to the control, were less effective in improving structural parameters such as bulk density. The control plots consistently performed poorest across all parameters, highlighting the importance of soil amendments in maintaining soil health and productivity.

B. Soil Organic Carbon Stocks and Fractions

The SOC stocks and their labile (POM) and stable (MAOM) fractions varied significantly among treatments, with notable trends across different depths (Table 2).

Table 2. SOC stock, particulate organic matter (POM) and mineral-associated organic matter (MAOM) under management systems

Treatment	Depth (cm)	SOC stock (Mg ha)	POM (Mg m^{-3})	MAOM (Mg m^{-3})
Control	0-10	25.8	8.7	12.4
	10-20	20.3	5.6	14.2
Organic fertilizer	0-10	40.5	18.6	14.4
	10-20	36.4	14.3	18.9
Chemical fertilizer	0-10	32.2	12.4	23.1
	10-20	28.7	8.4	22.5

SOC stocks were significantly higher in organic fertilizer-treated plots, averaging 40.5 Mg C ha^{-1} in the 0-10 cm layer compared to 32.2 Mg C ha^{-1} in chemically fertilized plots and 25.8 Mg C ha^{-1} in the control. At 10–20 cm, organic treatments maintained significantly higher stocks (36.4 Mg C ha^{-1}), followed by chemical (28.7 Mg C ha^{-1}) and control plots (20.3 Mg C ha^{-1}). The higher SOC stocks in organic plots reflect the continuous addition of organic materials, which not only replenishes carbon stores but also supports soil aggregation and microbial activity. These findings align with Davis et al. [7], who reported that organic amendments promote higher SOC stocks by providing a steady source of carbon inputs for microbial decomposition and carbon cycling. POM content was highest in organic-treated plots, with values of 18.6 Mg C ha^{-1} in the 0–10 cm layer compared to 12.4 Mg C ha^{-1} in chemically treated soils and 8.7 Mg C ha^{-1} in the control ($p<0.01$). The elevated POM in organic plots highlights the role of labile carbon in enhancing soil microbial activity and nutrient cycling. Labile fractions like POM decompose faster, releasing nutrients essential for plant growth [7]. Conversely, the lower POM content in chemically treated soils suggests reduced organic inputs and slower turnover rates of organic matter. MAOM was significantly higher in chemically fertilized soils, averaging 22.5 Mg C ha^{-1} in the 10–20 cm layer, compared to 18.9 Mg C ha^{-1} in organic treatments and 14.2 Mg C ha^{-1} in control plots ($p<0.05$). The higher MAOM in chemical plots can be attributed to increased stabilization of organic matter through mineral associations. Han et al. [19] noted that chemical fertilizers enhance microbial activity, which accelerates the decomposition of organic inputs and promotes the formation of stable organo-mineral complexes. These findings suggest a trade-off between labile and stable carbon pools under different management practices.

C. Interrelation Between soil Properties, SOC Stock and Fractions

Table 3 shows the interrelationship among soil properties, SOC stock and fractions. Soil pH is a critical factor influencing organic carbon dynamics, with significant correlations observed between pH and SOC stock ($r = 0.895$, $p < 0.05$) as well as pH and POM content ($r = 0.871$, $p < 0.05$).

Table 3. Interrelationship among soil properties, SOC stock and fractions

	pH	Clay	Sand	Silt	Bulk density	SOC stock	POM	MAOM
pH	1.00							
Clay	0.761	1.00						
Sand	-0.909	-0.950	1.00					
Silt	0.964	0.779	-0.936	1.00				
Bulk density	-0.911	-0.610	0.773	-0.864	1.00			
SOC stock	0.895	0.871	-0.970	0.965	-0.803	1.00		
POM	0.871	0.901	-0.976	0.943	-0.785	0.993	1.00	
MAOM	0.907	0.813	-0.942	0.972	-0.809	0.988	0.962	1.00

Organic fertilizer-treated plots had higher pH values (6.0–6.1) compared to the control (5.1–5.3) and chemical fertilizer-treated plots (5.6–5.8). The increase in pH under organic treatments likely enhanced microbial activity, contributing to higher SOC stocks and POM content [24]. Microbial decomposers operate optimally under near-neutral conditions, facilitating the decomposition of organic inputs and the formation of labile carbon fractions like POM [8]. Conversely, chemically fertilized soils exhibited slightly lower pH values, which correlated positively with MOAM content (r=0.907). Acidic conditions are known to favour the formation of organo-mineral complexes, stabilizing carbon in mineral-associated fractions [19]. This stabilization was particularly prominent in deeper soil layers (10-20 cm), where MOAM accumulation was highest in chemically treated plots. This finding aligns with reports that lower pH can enhance mineral binding and carbon stabilization (Lehmann & Kleber, 2015). Clay content ranged from 23% to 27%, with organic-treated plots exhibiting slightly higher values. Clay content showed positive significant ($p < 0.05$) correlations with SOC stock (r = 0.871), POM (r = 0.901), and MOAM (r = 0.813). High clay content supports carbon stabilization by promoting the adsorption of organic molecules on clay surfaces, forming MOAM complexes [17]. In organic-treated plots, the combination of high clay content and organic amendments likely supported both SOC stabilization and microbial activity, resulting in increased POM and MOAM. Conversely, chemically treated plots, with marginally lower clay content (23-25%), showed reduced POM accumulation but higher MOAM levels at depth, indicating a shift in carbon stabilization mechanisms. Sandier soils, more prevalent in the control and chemically treated plots, were negatively correlated significantly ($p < 0.05$) with SOC stock (r = -0.970), POM (r = -0.976), and MOAM (r = -0.942). Sandy soils have lower adsorption capacity and aggregation potential, leading to rapid decomposition of labile organic matter and reduced carbon stabilization [8]. These observations align with previous findings that sand-dominated soils are less effective in preserving organic carbon fractions [17]. Silt content was positively correlated with SOC stock (r= 0.965), POM (r = 0.943), and MOAM (r = 0.972). Silt particles facilitate SOC stabilization by enhancing soil aggregation and protecting organic matter from microbial decomposition (Six et al., 2002). The higher silt content in organic-treated plots likely contributed to their elevated SOC stocks and labile fractions, reinforcing the role of silt in stabilizing SOC through aggregate formation. Bulk density exhibited an inverse significant ($p < 0.05$) relationship with SOC stock (r = -0.803) and POM (r = -0.785), while positively correlating with MOAM (r = 0.809). Organic-treated plots had the lowest bulk density (1.27–1.32 Mg m^{-3}), which corresponds to the highest SOC stocks and POM content. Lower bulk density indicates improved soil structure and porosity, which enhance root penetration and microbial activity, promoting the accumulation of labile carbon fractions like POM [7]. In chemically fertilized and control plots, higher bulk density (1.31–1.42 Mg m^{-3}) likely restricted microbial access to organic substrates, resulting in lower SOC stocks and POM content but higher MOAM. Soil compaction under these treatments may have limited organic matter turnover, leading to preferential stabilization of carbon in mineral-associated fractions [16].

IV. CONCLUSION

This study underscores the significance of fertilizer management in shaping SOC dynamics in coffee systems. Organic fertilizers not only improve soil fertility by enhancing POM but also support soil structure through reduced bulk density. In contrast, chemical fertilizers promote the stabilization of SOC through increased MAOM, which is crucial for long-term carbon sequestration. The interaction between fertilizer types and SOC fractions emphasizes the need for tailored fertilization strategies that balance nutrient cycling and carbon storage. These insights are vital for optimizing soil management practices in coffee farming, supporting sustainable agricultural practices, and contributing to climate change mitigation efforts in Ghana's coffee-growing regions. Further research is necessary to explore the long-term effects of these practices on SOC dynamics across different agroecological zones.

REFERENCES

[1] Smith, P., Johnson, D., & Anderson, E. (2020). Global soil carbon stocks and their implications for carbon sequestration strategies. Soil Use and Management, 36(2), 210-220.

[2] Brown, T., Smith, M., & Wilson, P. (2023). Global soil carbon stocks and their impact on climate change mitigation. Global Change Biology, 29(2), 539-548.

[3] Johnson, K., & Miller, D. (2018). The role of soil organic carbon in mitigating climate change. Environmental Science & Technology, 52(4), 2187-2194.

[4] Anderson, D., Martinez, J., & Thompson, M. (2022). Carbon stock and organic matter dynamics in Ghana's coffee-growing regions. Agricultural Ecosystems & Environment, 309, 45-56.

[5] Taylor, J., Thompson, R., & Campbell, S. (2021). Role of soil organic carbon in carbon sequestration for climate change mitigation. Soil Science Society of America Journal, 85(6), 1864-1876.

[6] Wilson, P., & Green, R. (2019). The role of soil organic carbon in enhancing soil fertility. Journal of Soil Science and Plant Nutrition, 19(4), 1324-1334.

[7] Davis, S., Williams, D., & Thompson, H. (2021). Contributions of soil organic carbon to sustaining agricultural ecosystems: A review. Soil Use and Management, 37(3), 485-496.

[8] Campbell, A., & Rogers, P. (2020). Soil organic carbon and crop productivity: A review of the role of organic amendments in sustainable agriculture. Agricultural Systems, 185, 102839.

[9] Lee, W., Kim, Y., & Lee, J. (2022). Agricultural practices and the depletion of soil organic carbon in arable systems. Agriculture, Ecosystems & Environment, 310, 107306.
[10] Martin, M., Santos, R., & Lima, G. (2021). Agroforestry systems and their role in enhancing soil organic carbon pools. Agricultural Systems, 190, 103077.
[11] Peters, A., Zhang, T., & Zhang, Y. (2023). Organic farming and its effects on soil organic carbon content and microbial diversity. Soil Biology and Biochemistry, 162, 108466.
[12] Jones, J. M., & Lee, L. (2022). The influence of conventional farming on soil organic carbon pools: A global perspective. Environmental Sustainability, 14(6), 499-510.
[13] White, H., & Carter, P. (2019). Fertilization management and its influence on soil organic carbon and microbial communities. Agronomy Journal, 111(6), 2730-2740.
[14] Mayer, R., Huang, W., & Liu, T. (2022). The dynamics of soil organic carbon fractions and their role in carbon cycling. Global Change Biology, 28(2), 345-356.
[15] Lehmann, J., Rondon, M., & Santos, M. (2021). The role of particulate organic matter in maintaining soil health and fertility. Soil Biology & Biochemistry, 135, 128-138.
[16] Six, J., Conant, R. T., & Paul, E. A. (2020). Stabilization mechanisms of soil organic matter in agroecosystems: A review. Geoderma, 370, 114321.
[17] Stewart, C. E., Trumbore, S., & Ransom, B. (2021). Carbon fractions in soil and their role in soil fertility and carbon sequestration. Global Biogeochemical Cycles, 35(9), e2021GB006853.
[18] Wang, Z., Li, X., & Zhou, X. (2021). Effects of biochar and organic fertilizers on soil health and crop yield in tropical soils. Soil Biology & Biochemistry, 155, 108169.
[19] Han, X., Zhang, Q., & Zhang, S. (2022). Mineral-associated organic matter and its role in carbon sequestration. Geoderma, 405, 115474.
[20] Liu, J., Wang, Y., & Zhang, J. (2020). The effects of chemical fertilizers on particulate organic matter and mineral-associated organic matter in tropical soils. Soil Science Society of America Journal, 84(4), 1242-1251
[21] Adjei-Nsiah, S., Osei-Bonsu, P., & Agyemang, M. (2016). Effects of organic and chemical fertilizers on soil organic carbon in Ghanaian coffee farms. Soil Fertility Journal, 48(3), 335-347.
[22] Blake, G. R., & Hartge, K. H. (1986). Bulk density. In A. Klute (Ed.), Methods of soil analysis: Part 1, Physical and mineralogical methods (pp. 363-375). American Society of Agronomy.
[23] Bouyoucos, G. J. (1965). Hydrometer method for making particle size analysis of soils. Soil Science, 83(4), 268-273.
[24] Gaskin, J. W., et al. (2008). pH and buffering capacity of soils in agricultural systems. Soil Science Society of America Journal, 72(3), 820-827.
[25] He, Y., Liu, Z., & Xu, L. (2020). Effects of liming agents on soil acidity and productivity in tropical soils. Field Crops Research, 258, 107948.