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Soil Carbon Sequestration in Agroforestry Systems as a Mitigation Strategy of Climate Change: A Case Study from Dinajpur, Bangladesh

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Abstract

The study was carried out in three different locations in Dinajpur district, Bangladesh, to observe soil carbon sequestration in agroforestry systems as a mitigation strategy for climate change. A total of 108 composite soil samples were collected at 0-30 cm in different study area sites. The total number of samples comprised three agroforestry systems (cropland agroforestry, homestead agroforestry, and orchard agroforestry), where 36 samples were collected from each agroforestry system. Three adjacent soil samples were collected from each agroforestry system and mixed to get composite soil samples. The outcomes revealed that the soil organic carbon (SOC) and soil organic matter (SOM) changes over the age of the orchard. Moreover, the results indicated that there are significant differences among the systems. The highest SOC (1.60%) was found in Eucalyptus woodlot-based agroforestry system, and the lowest SOC (0.29%) was found in the Mahogany woodlot-based agroforestry system although both organic carbon and organic matter are deficient compared to the optimum level. Furthermore, in the case of soil pH, the highest value (5.45) was recorded under the Mango tree, while the lowest value (5.12) was recorded under the Mahogany tree. Based on the findings, the study determined that all the collected samples were acidic. The investigation concluded that most species of homestead agroforestry systems provide maximum SOC and SOM as compared to cropland and orchard. The present study provides significant recommendations for soil carbon enrichment and environmental safety practices in the agroforestry systems to mitigate climate change through soil carbon management.

Keywords

Agroforestry systems; climate change mitigation; soil carbon; carbon management

1. Introduction

A result of human activity related to climate change is the escalating atmospheric concentration of greenhouse gases (GHGs), especially those containing carbon [1, 2]. The carbon sinks in the soil and plants offset some of the anthropogenic carbon emissions [3, 4]. SOC is dynamic, though, and anthropogenic influences on soil can change it from being a net producer of GHGs to a net sink. With the understanding that soil can reduce the concentration of carbon dioxide (CO_2) in the atmosphere (through sequestration of organic carbon in the soil) and by releasing this CO_2 back into the atmosphere, the role of soil in preventing climate change is being recognized more and more (through mineralization of soil organic matter) [5, 6]. As organic carbon is carried in SOM, the soil has around three times as much carbon as the atmosphere. Depending on its characteristics, temperature, and land use, soil can act as a carbon source or sink over a decade or more [7, 8].

SOC is crucial for its contributions to food production, climate change mitigation and adaptation, and the accomplishment of sustainable development objectives as a measure of soil health (SDGs). A high SOM concentration increases water availability and supplies nutrients to plants, both increasing soil fertility and ultimately increasing food production [9, 10]. Additionally, SOC increases the integrity of the soil's structural structure by encouraging the production of aggregates, which, in conjunction with porosity, ensures adequate aeration and water infiltration to sustain plant growth [11, 12]. According to reports, just 10% of the world's SOC pool might be mineralized, equaling around 30 years of anthropogenic emissions [13]. This emphasizes the necessity of stopping carbon release (loss) from the soil resource. In the top meter of the soil profile, there is a significant carbon pool estimated to be about 1500 Gt of organic carbon. This is twice as much carbon as in the atmosphere and far more than the biotic pool's 560 Gt of carbon [14]. The soil is avoiding CO_2 buildup in the atmosphere, which will exacerbate the problem of climate change by storing this enormous amount of carbon [15].

Given that 24% of global and 50% of agricultural soils are already degraded globally, there is a tremendous possibility for long-term atmospheric carbon sequestration in soil. Even though the fact that most agricultural soils already deteriorate, they are thought to be capable of storing up to 1.2 billion tons of carbon annually [16]. In the interim, until more efficient methods are discovered, carbon sequestration in the soil can help reduce the amount of CO_2 in the atmosphere [13]. Research efforts in sequestration have largely concentrated on geological and vegetative carbon capture and storage while paying little attention to the role of soil as a viable carbon sink, despite the enormous carbon deposit in the soil ecosystem globally [15].

By 2050, the temperature increase will be limited to 1.5-2.0°C according to global models that link the concentration of atmospheric CO_2 to temperature [17]. This is the point at which climate change would become significantly more relevant [18]. The carbon stores in the top 30 cm of soil might be increased by 0.4% (4 per 1000) per year to meet this annual decline in atmospheric CO_2 concentration [19]. In this regard, the COP21 effort on soil carbon sequestration for food security and the environment seeks to bring together governmental and non-governmental parties committed to enhancing soil carbon stock management. Through the common goal of increasing carbon stock on a global scale in agricultural areas (croplands, grasslands, and forests), on which human behavior can be oriented toward carbon storage, positive effects on food security and climate change are anticipated [19].

Science has made tremendous strides toward comprehending and explaining SOC dynamics. Howeverthere are still significant obstacles to effective on-the-ground policy creation and regionally tailored execution in protecting and monitoring SOC supplies at the national and global levels. As a result, the current study explores the conceptual foundation and process of carbon capture and sequestration in the soil, in addition to tracing the history of carbon sequestration as a viable climate change mitigation strategy. The study's goals included locating the current agroforestry systems in Bangladesh's Dinajpur district, determining the SOM and SOC in various agroforestry systems, and examining the connection between agroforestry practices and soil carbon sequestration. The advantages and difficulties of carbon sequestration in soil are also fully examined. Finally, some tried-and-true management techniques and methods for improving soil carbon stocks beneath agricultural and forest ecosystems are described.

2. Materials and Methods

2.1 Experimental Sites

The study was carried out in three different locations of Dinajpur district, namely Hajee Mohammad Danesh Science and Technology University (HSTU) campus, Birol Upazila, and Sadar Upazila, from January 2019 to June 2019 to observe soil carbon sequestration of agroforestry systems a mitigation strategy of climate change in Dinajpur district, Bangladesh. Figure 1 presents the map of the study area.

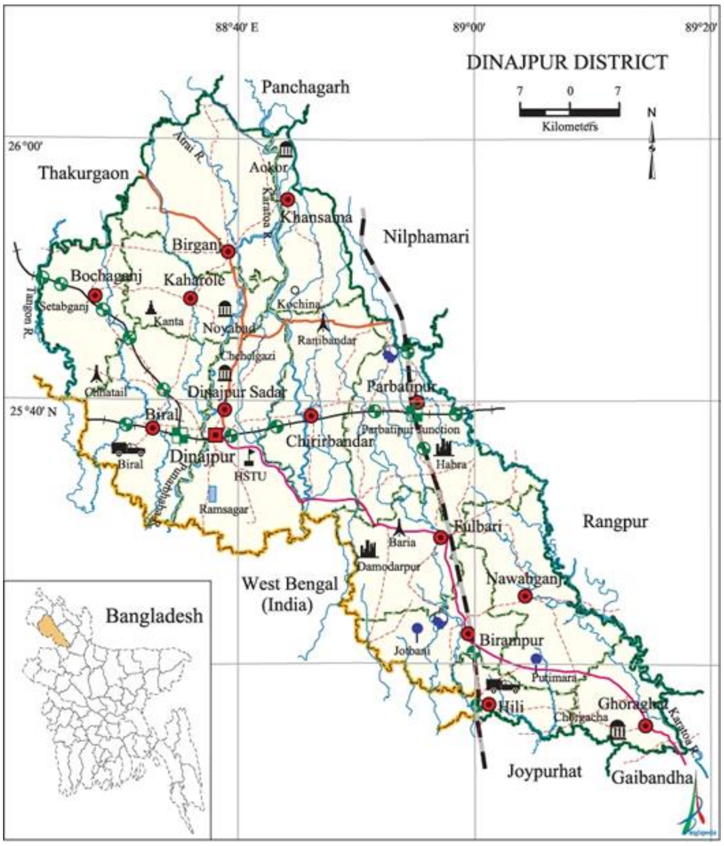

Figure 1 Map of the study area.

2.2 Sampling

A total of 108 composite soil samples were collected at 0-30 cm in different study area sites. The total number of samples was composed of three agroforestry systems (cropland agroforestry, homestead agroforestry, and orchard agroforestry), where 36 samples were collected from each agroforestry system. Three adjacent soil samples were collected from each agroforestry system and mixed to get composite soil samples. The samples were obtained randomly from three agroforestry systems, and some agroforestry species were selected, such as Mango (*Mangifera indica*), Litchi (*Litchi chinensis*), Mahogany (*Swietenia macrophylla*), and Eucalyptus (*Eucalyptus camaldulensis*) in each of these systems. Table 1 presents the age distribution of the samples based on locations and agroforestry systems. The trees from the homestead agroforestry systems were older than those from cropland and orchard agroforestry systems.

Table 1 Age distribution of the samples based on locations and agroforestry systems.

Tree species	Sadar Upazila			Birol Upazila			HSTU campus		
	Homestead	Orchard	Cropland	Homestead	Orchard	Cropland	Homestead	Orchard	Cropland
Mango	22	14	5	30	15	10	31	17	12
Litchi	22	15	10	30	14	5	31	17	12
Mahogany	18	10	3	27	13	6	30	16	8
Eucalyptus	20	10	3	23	13	4	25	14	5

2.3 Data Recording and Experimental Description

This experiment first weighed the moist soil to determine soil moisture and dry weight. experiment first weighed the moist soil. Then, dried the soil overnight at 105°C in the oven and reweighted. This experiment
calculated the soil moisture content for each of the replicate samples using the following equation:

$$\%\ \text{Moisture content} = \frac{\text{Weight of moist soil} - \text{Weight of dry soil}}{\text{Weight of dry soil}} \tag{1}$$

Wet oxidation was used to measure the amount of organic matter in the soil [20]. Converting the total organic carbon content to the organic matter content is important. Historically, the ratio of organic carbon to the organic matter in soils has been calculated using the premise that organic matter contains 58% organic carbon [20]. There isn't, however, a single conversion factor that applies to all soil types or all soil horizons within a given soil. The kind of organic matter present in the sample also influences the variation. The conversion factors accounted for ranged from 1.724 to 2.5 [20].

2.4 Statistical Analysis

STATISTIX10 statistical analysis program used a complete randomized design (CRD) with equal replications to examine the data. The Tukey HSD test separated means . The standard error of the mean (± SE Mean) in the bars of each graph and the coefficient of variations (CV in %) were included in the result. In addition, an ANOVA test was conducted for cross-location (three different locations) comparisons to indicate that the interactions are insignificant.

3. Results and Discussion

3.1 Soil Carbon Sequestration under Mango-based Agroforestry System

The effect of the age of the mango garden on the SOC and SOM is presented in Figure 2. The results show that the SOC and SOM changed over the change of ages. For instance, a 5-year-old mango garden had SOC and SOM of 0.5% and 0.6%, respectively, while the SOC and SOM were 1.1% and 1.4% in a 31-year-old mango garden. Furthermore, a 22-year-old mango-based agroforestry system has low SOC and SOM, which may be due to local soil and edaphic, climatic situations. It's interesting to note that a recent short-term study found that the tree's root had an inhibitory effect, which eventually enhanced its influence on the development of humus and would signify positive priming by root residues [21]. At this moment, the scavenging of nitrogen from the soil's organic matter to produce more organic carbon was probably the main effect of adding organic carbon to the soil. Higher levels of organic carbon would encourage more microbial activity, raising the scale of the organic carbon in terms of the residue added.

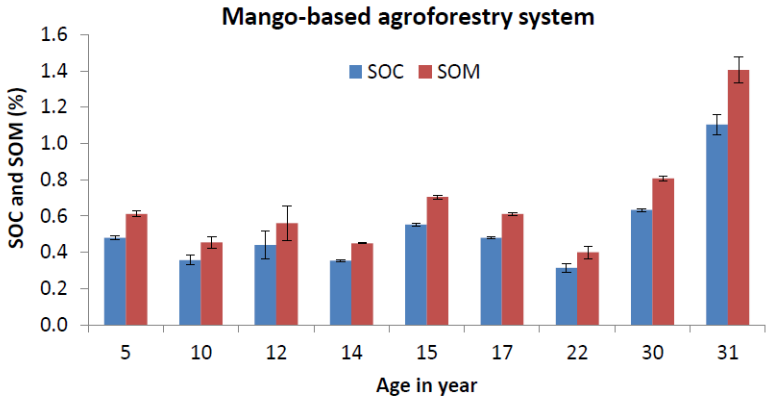

Figure 2 Effect of age of mango garden on the SOC and SOM (CV for SOC and SOM are 11.39 and 11.40).

Furthermore, the effect of different mango-based agroforestry systems (cropland, homestead, and orchard) on SOC and SOM are presented in Table 2. The results show that there is no significant difference among the systems. The highest SOC (0.77%) was found in the homestead agroforestry system, and the lowest SOC (0.39%) was found in the cropland agroforestry system. Moreover, the highest Moreover, homestead agroforestry recorded the highest SOM (1.34%). In contrast, the lowest SOM (0.67%) was recorded in the orchard agroforestry system, although both organic carbon and organic matter are very low compared to the optimum level. Plant productivity, increased soil carbon inputs from root biomass, and enhanced mineralization of plant residues are all factors that may be more pronounced in soil associated with cropland or agroforestry systems with high diversity [22]. Storage of SOC is an important ecosystem function directly linked to these factors. Changes in the agroforestry system must result in carbon inputs from plant vegetation that are greater than carbon outputs for there to be a net gain in soil carbon sequestration (i.e., the sum of soil respiration, dissolved carbon leached from the soil, and soil carbon lost through wind or water erosion). When agroforestry species are introduced to cropland, a farmhouse, or an orchard, the residue from these species can be a significant source of organic carbon for the soil [23].

Table 2 Agroforestry systems based on mangos' impact on the SOC and SOM.

Agroforestry systems	Number of observations	SOC (%)	SOM (%) *	SE mean
Homestead	3	0.77	1.34	0.26
Orchard	3	0.45	0.79	0.26
Cropland	3	0.39	0.67	0.35
CV%		15.00	9.00	

*Standard level of SOM: very low when ≤1.0, low = 1.0-1.7, medium = 1.7-3.4, high = 3.4-5.5, very high when ≥5.5

3.2 Soil Carbon Sequestration under Litchi-based Agroforestry System

The effect of the age of the litchi-based agroforestry system on the SOC and SOM is presented in Figure 3. The findings show that the SOC and SOM increased over the ages. For instance, a 3-year-old litchi garden had SOC and SOM of 0.28% and 0.49%, respectively, while a 30-year-old litchi garden had SOC and SOM of 1.33% and 2.24%. However, a 33-year-old litchi-based agroforestry system provided low SOC and SOM, possibly due to the local soil and edaphic, climatic situation. SOM comprises bacteria, fungus, and other soil-dwelling microorganisms, feces, decaying plant and animal tissues, and compounds created during their decomposition. Fresh plant remains and humus, a material that has undergone extensive decomposition, are included in the heterogeneous combination known as SOM. Organic molecules with a high carbon content make up SOM. Additionally, SOC levels are frequently used to quantify the amount of organic matter in soils because they are directly related to the amount of organic matter in soil [24].

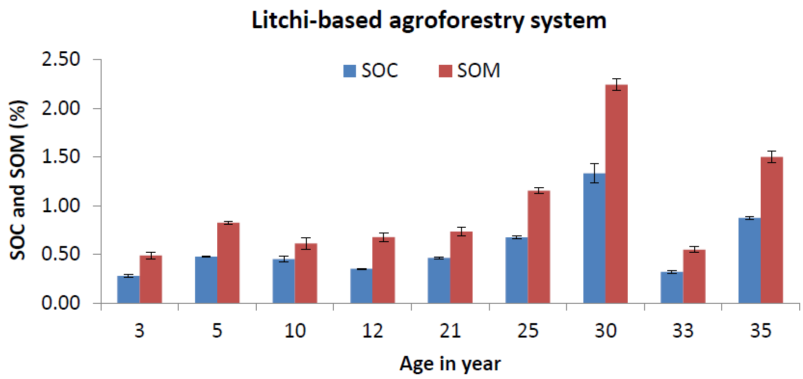

Figure 3 Effect of age of litchi garden on the SOC and SOM (CV for the age of litchi garden are SOC 10.90 and SOM 7.76).

Furthermore, Table 3 shows the impact of litchi-based agroforestry systems such as cropland, homestead, and orchard on SOC and SOM. The highest SOC was found (0.97%) in the homestead agroforestry system, and the lowest SOC was found (0.32%) in the cropland agroforestry system. In addition, the highest SOC was recorded (1.67%) from the homestead agroforestry system, while the lowest soil organic matter (0.55%) was from the cropland agroforestry system. Due to the activity of the microbial decomposer community and elevated soil temperatures brought on by the warming of the ground after the forest canopy has been removed, SOM decomposes in agroforestry systems in the absence of continuous rates of carbon intake from the growth of forest flora [25].

Table 3 Effect of the litchi garden's agroforestry system on SOC and SOM.

Agroforestry systems	Number of observations	SOC (%)	SOM (%) *	SE mean
Homestead	3	0.97	1.67	0.24
Orchard	3	0.44	0.76	0.24
Cropland	3	0.32	0.55	0.16
CV%		10.00	8.00	

*Standard level of SOM: very low when ≤1.0, low = 1.0-1.7, medium = 1.7-3.4, high = 3.4-5.5, very high when ≥5.5

3.3 Soil Carbon Sequestration under Mahogany-based Agroforestry System

The effect of the Mahogany woodlot age difference on SOC and SOM is presented in Figure 4. The findings show that the SOC and SOM increased over the ages. For example, the 3-year-old

Mahogany garden had SOC and SOM of 0.15 and 0.30, respectively, while the 30-year-old Mahogany woodlot had SOC and SOM of 1.87% and 3.23%, respectively. The increased temperature may affect the carbon cycle by reducing available water and lowering photosynthetic rates. If water is not a concern, on the other hand, temperature rise can increase in plant productivity, which would affect the carbon balance [26]. As a result of the rising temperature and greater rates of SOM decomposition, which could release more CO_2, climate change may be positively impacted [27].

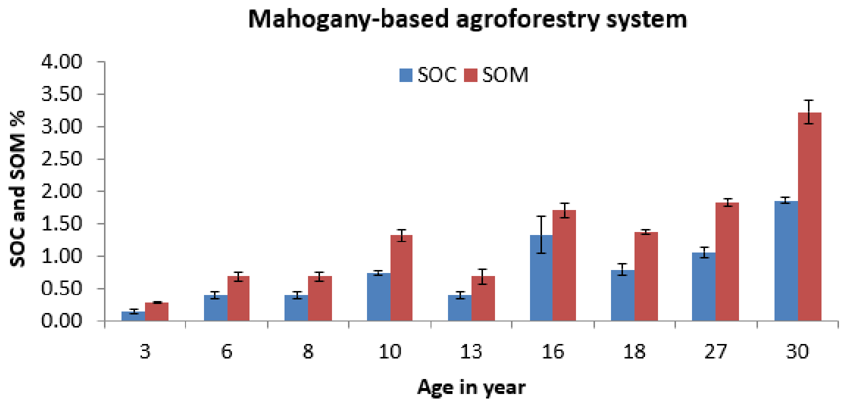

Figure 4 Effect of Mahogany species age difference on SOC and SOM (CV for the age of Mahogany garden are SOC 23.67 and SOM 12.40).

Moreover, Table 4 shows the impact of the Mahogany woodlot on SOC and SOM. The results show that the SOC and SOM vary among different agroforestry systems. For example, the highest SOC was recorded (1.31%) from the homestead agroforestry system, while the lowest (0.29%) was from the cropland agroforestry system. In addition, the highest soil organic matter was recorded (2.26%) from the homestead agroforestry system, and the lowest soil organic matter was recorded (0.50%) from the cropland agroforestry system. Local constraints on ecosystem processes may impact on the soil's ability to store carbon at the scale of a watershed or agricultural field. Due to landscape heterogeneity, processes such as rainfall infiltration, soil erosion, sediment deposition, and soil temperature can change locally. These processes all impact on the rates of carbon input and carbon loss, which causes variations in SOC levels along topographic gradients [28]. For instance, the slope location affects soil moisture and nutrient levels, which then affects plant root development and may have an effect on soil carbon.

Table 4 Effect of Mahogany Garden's agroforestry systems on SOC and SOM.

Agroforestry systems	Number of observations	SOC (%)	SOM (%) *	SE mean
Homestead	3	1.31	2.26	0.44
Orchard	3	0.65	1.12	0.76
Cropland	3	0.29	0.50	0.11
CV%		12.10	13.12	

*Standard level of SOM: very low when ≤1.0, low = 1.0-1.7, medium = 1.7-3.4, high = 3.4-5.5, very high when ≥5.5

3.4 Soil Carbon Sequestration under Eucalyptus Based Agroforestry System

The effect of age Eucalyptus woodlot-based agroforestry systems on SOC and SOM is presented in Figure 5. The findings show that the SOC and SOM increased over the ages. For example, a 3-year-old Eucalyptus garden had SOC and SOM of 0.31% and 0.41%, respectively, while a 23-year-old Eucalyptus woodlot had SOC and SOM of 1.99% and 3.44%, respectively. A shortfall in soil carbon has been caused by SOC depletion, and this presents a chance to store carbon in soil using a range of land management techniques. However, a number of factors, such as climate influences, historical land use patterns, present land management practices, and topographic variability, influence potential soil carbon change in the future [24].

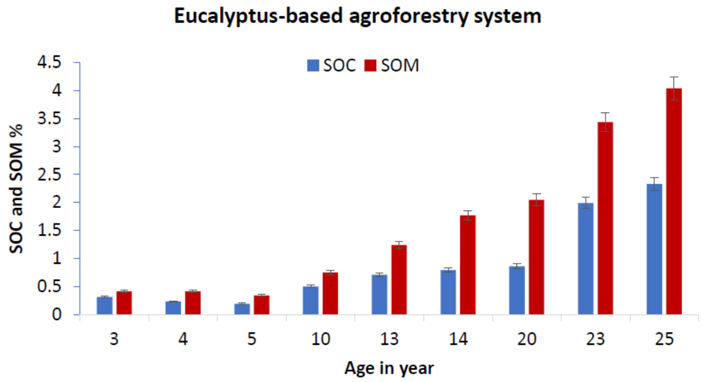

Figure 5 Effect of Eucalyptus species age on the SOC and SOM (CV for SOC and SOM are 43.91 and 13.03).

Furthermore, Table 5 shows the impact of eucalyptus woodlot-based agroforestry systems on SOC and SOM. The results show that the carbon percentage varied among different eucalyptus gardens depending on the agroforestry systems. The highest SOC was found (1.60%) in the cropland agroforestry system, and the lowest SOC was found (0.32%) in the orchard agroforestry system. In addition, the highest SOM was recorded (2.75%) from the cropland agroforestry system, and the lowest soil organic matter (0.55%) from the orchard agroforestry system. However, SOC is positively correlated with numerous soil properties that are essential to agroforestry productivity, including soil structural stability, water retention, and nutrient and pH buffering. Because the balance between soil carbon inputs and outputs in grazed rangelands varies widely among the various agroforestry systems, it is challenging to generalize the effect that agroforestry has on soil carbon dynamics. Studies have indicated that agroforestry systems have variable effects on SOC [29].

Table 5 Effect of Eucalyptus garden agroforestry systems SOC and SOM.

Agroforestry systems	Number of observations	SOC (%)	SOM (%) *	SE mean
Cropland	3	1.60	2.75	0.41
Homestead	3	0.48	0.83	0.69
Orchard	3	0.32	0.55	0.1
CV%		8.0	9.5	

*Standard level of SOM: very low when ≤1.0, low = 1.0-1.7, medium = 1.7-3.4, high = 3.4-5.5, very high when ≥5.5

3.5 Comparison of SOC in Different Agroforestry Systems

Table 6 presents the comparison of SOC in different agroforestry systems. Litchi-based agroforestry systems displayed the highest SOC compared to the agroforestry system based on other tree species. On the other hand, Mango-based agroforest systems showed the lowest SOC among the four types of tree species-based agroforestry systems. Furthermore, cropland agroforestry systems indicated the highest % of SOC, followed by homestead and orchard agroforestry systems.

Table 6 Comparison of SOC (%) in different agroforestry systems.

Agroforestry systems	**SOC (%) under tree species**			
	Mango	Litchi	Mahogany	Eucalyptus
Cropland	0.77	1.67	1.31	1.60
Homestead	0.45	0.76	0.65	0.48
Orchard	0.39	0.55	0.29	0.32

The present study's findings revealed that increasing soil carbon sequestration in agroforestry systems has enormous potential as a mitigation strategy for climate change in Bangladesh. Our findings are supported by several studies [30-36] that reported that carbon management through absorbing atmospheric CO_2 by agricultural and forest land could increase the climate change mitigation potential while increasing the carbon stock. Therefore, the negative effects of global warming and climate change on the environment and human health [37-40] can be reduced by lowering emissions through practicing and encouraging appropriate agroforestry systems.

Furthermore, Table 7 presents the results of the ANOVA test for cross-location comparisons. The finding from the ANOVA test revealed that the p-value is greater than 0.05, which indicates that the interactions between the age of the agroforestry systems in three different locations are not significant.

Table 7 Results of the ANOVA test.

Source of variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between groups	182.8889	2	91.44444	1.252144	0.299121	3.284918
Within groups	2410	33	73.0303			
Total	2592.889	35				

3.6 Effect on Soil pH

The effect of agroforestry species on the soil pH is presented in Figure 6. The soil pH was found, to be the same across all agroforestry species. The highest pH was recorded at 5.45 under the mango tree, while the lowest was at 5.12 under the Mahogany tree. The present study's findings show that Mahogany trees adversely affect the soil pH. Based on the findings, the study concluded that all the samples collected were acidic because the pH was below 7.

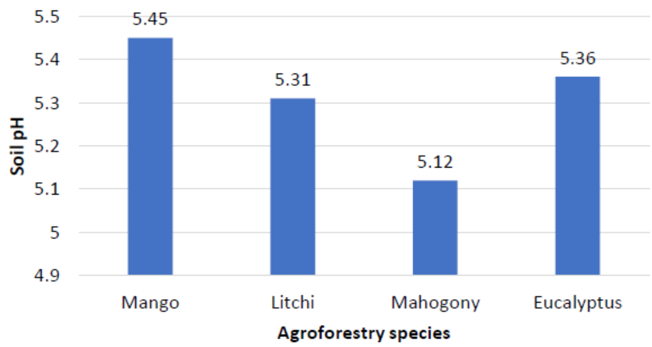

Figure 6 Effect of agroforestry species on the soil pH (CV for SOC and SOM are 18.16 and 11.86).

4. Conclusions and Recommendations

The soil has evolved into one of the world's most vulnerable resourcesdue to climate change, land degradation, and biodiversity loss. More carbon is stored in soil than in the atmosphere and terrestrial vegetation put together. The dynamics of SOC emphasize how crucial it is to measure global carbon flows to ensure that SOC has the greatest positive impacts on human welfare, food production, and water and climate management. The present study was carried out in three different locations in Dinajpur district, Bangladesh, to observe soil carbon sequestration in agroforestry systems as a mitigation strategy for climate change. At various locations within the study region, 108 composite soil samples were taken at 0 to 30 cm intervals. A total of 36 samples were taken from each of the three agroforestry systems (cropland, homestead, and orchard) to make up the total samples. From each agroforestry system, three neighboring soil samples were taken and combined to create composite soil samples.

The results of the current study suggest that the SOC and SOM alter as people age. The results also revealed that the systems differ significantly from one another. Based on the findings, homestead agroforestry systems have more SOC and SOM compared to cropland and orchard agroforestry systems; this may be because cropland and orchard undergo different soil disturbances, which led to soil carbon loss. The highest SOC was found in Eucalyptus woodlot-based agroforestry system, and the lowest SOC was found in the Mahogany woodlot-based agroforestry system. However, organic carbon and matter are deficient compared to the optimum level. Furthermore, in the case of soil pH, the highest value was recorded under the Mango tree, while the lowest value was recorded under the Mahogany tree.

The present study provides the following recommendations for soil carbon enrichment and environmental safety practices in agroforestry systems to mitigate climate change through soil carbon management:

- Plant and animal inputs should be increased by applying animal manure to fields, providing nutrient-rich fertilizer, and more extensive larger and more diverse soil microbe communities that break down organic matter and store it as soil carbon.
- Minimizing soil disturbances will increase soil stability by slowing the rate of organic matter decomposition, which will lower the amount of carbon lost back into the atmosphere.

- Microbes that consume and digest nutrients are necessary for soil carbon storage. Microbial variety is crucial because dead cells and microbial byproducts may contribute more to soil organic matter than actual plants do.
- Instead of leaving fields naked after harvest, the soil should have more living cover to lessen its susceptibility to carbon loss. A frequent technique is called "cover cropping," in which crops are planted but not meant to be harvested.
- An alternative source for mineralization should be focused.
- Afforestation programs should be undertaken close to mining areas.
- Climate-smart and sustainable agricultural technologies should be adopted in agroforestry systems, especially near the mineral and coal mining area.

Author Contributions

Abdirisak Jama Ali and Md Shoaibur Rahman conducted the research and prepared the draft manuscript. Asif Raihan finalized the manuscript and improved it based on the reviewers' comments.

Competing Interests

The authors have declared that no competing interests exist.

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