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Bamboo's Role in Climate Change Adaptation and Mitigation: An Analysis of Biomass, Carbon Stock, and Economic Potential in Tanzania

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

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ABSTRACT

Bamboo, a rapidly growing member of the grass family, thrives across diverse climates worldwide and offers vital ecosystem services essential for human well-being and economic development. Notably, bamboo releases 35% more oxygen than other trees and sequesters an average of 12 tons of carbon dioxide per hectare, highlighting its significant ecological benefits. This study analyses the contribution of bamboo to climate change adaptation and mitigation, focusing on Tanzania as a case study. Specifically, the study aims to determine the amount of biomass and carbon stock of bamboo in Tanzania, and estimate the financial benefits from including bamboo in carbon payment projects like REDD+. Utilizing adapted allometric models and data from the National Forest Resources Monitoring and Assessment (NAFORMA) of 2015, the study reveals that

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Tanzania possesses 4.04 billion tons of stored bamboo biomass and 1.9 billion tons of stored bamboo carbon, translating to an estimated 7.6 billion US dollars in unutilized conservation profit from carbon trading. The findings indicate that 51.4% of the stored bamboo biomass, carbon, and potential conservation profit are concentrated in the genus Bambusa, with nearly half of these resources located in the southern regions of Lindi and Mtwara. These results underscore the substantial ecological and economic benefits of bamboo ecosystem services, emphasizing the need for stakeholders to formulate strategies for the sustainable production, conservation, and management of bamboo in Tanzania. The study provides a benchmark for developing policies and plans that leverage bamboo's potential in climate change adaptation and mitigation, promoting environmental sustainability and economic growth.

Keywords: Bamboo; climate change adaptation and mitigation; biomass stock; carbon stock and carbon sequestration.

1. INTRODUCTION

With the mean concentration reaching 410 ppm in 2018, the highest in the previous 8,000 years, the unprecedently large increase in carbon dioxide (CO_2) concentration in the Earth's atmosphere has reached worrying levels [1]. According to Das et al. [2], carbon dioxide (CO_2) is a major greenhouse gas (GHG) that traps thermal energy and causes the greenhouse effect and global warming. The average worldwide temperature in January 2018 was 12.71°C, 0.71°C higher than that of the 20th century on both land and ocean surfaces [3]. One well-known method of mitigating climate change is to increase carbon sinks through biotic reservoirs [4,2]. Because soil and vegetation store carbon, an understanding of and approach to managing high carbon storage in terrestrial ecosystems can play a major role in regulating atmospheric CO_2 levels. Bamboo is one of these ecosystems that stands out for being a powerful but underrated carbon sink.

Bamboo is a fast-growing grass family member that is essential for both sustainable economic development and mitigating the effects of climate change, particularly in developing nations [5,3]. Bamboo is an important resource in afforestation/reforestation and avoided deforestation initiatives due to its quick growth rate, high biomass production, and potential for sequestering carbon [6,2]. Bamboo has a much shorter harvest cycle (3-5 years) than most timber species (10-50 years), which increases its potential for frequent absorption of carbon [1]. Bamboo is found in the tropics and subtropics of South America, Africa, and Asia. About 31.5 million hectares are covered by the about 1,250–1,500 bamboo species found in 75–107 taxa [7]. Despite being widely distributed and having at least 1,500 recognized uses worldwide, Tanzania and other underdeveloped nations tend to underuse bamboo's potential. Through its products and the forest ecosystem services it offers in tropical places, bamboo promotes livelihoods, contributes to the fight against poverty, and mitigates the effects of climate change.

Bamboo has the capacity to accumulate large amounts of carbon, on par with or more than that of rapidly expanding forest plantations. The AGC of tropical rainforests in Africa, especially in Tanzania, where AGC varies from 6.4 to 62 t C ha^{-1}, is comparable to or more than that of bamboo forests, which have an AGC ranging from 16 to 128 Mg C ha^{-1} [8,9]. But in Tanzania, bamboo receives little attention despite these advantages. The nation is home to four native bamboo species and six introduced varieties, however the full potential of bamboo cannot be fully realized due to a lack of political will, knowledge, technological advancements, and national regulatory frameworks. Due to this neglect, bamboo resources are used in an unsustainable manner. Bamboo integration into forest policy and management is urgently needed, especially within the UN-REDD program's Measurement, Reporting, and Verification (MRV) framework. To fully understand bamboo's role in sequestering carbon, allometric equations for estimating and tracking bamboo biomass and carbon must be developed. Although allometric formulas for calculating forest biomass have been created in Tanzania, they largely concentrate on large tree species and ignore the special qualities of bamboo.

Despite their significant ability to store carbon, bamboo forests are still underrepresented in models used to estimate carbon and biomass. Bamboo forests are likewise disregarded by the present Intergovernmental Panel on Climate Change (IPCC) recommendations, which do not include any particular guidelines for their inclusion in studies on greenhouse gas emissions. By creating and modifying multi-species allometric models for bamboo utilizing information from the 2015 National Forest Resources Monitoring and Assessment (NAFORMA), this work seeks to close this gap. The study will highlight bamboo's significance in carbon sequestration and sustainable development, assisting in its inclusion in national and international initiatives for mitigating climate change. The research will facilitate the incorporation of bamboo into climate change policies and forest management practices in Tanzania and other regions by offering an all-inclusive framework for the estimation and tracking of bamboo biomass and carbon.

2. MATERIALS AND METHODS

2.1 Materials

2.1.1 Description of the study area

Tanzania is an East African country that is located between latitudes 1° 00' S and 12° 00' S and longitudes 30° 00' E and 41° 00' E. Its elevation ranges from 358 meters above sea level (a.s.l.) to 5,950 meters above sea level, the highest point in Africa being reached at the peak of Mount Kilimanjaro. The nation, which has a land size of over 945,087 square kilometers, is renowned for its varied geography and climate.

Mainland Tanzania has a tropical climate that is divided into four distinct climatic zones: the semi-arid central plateau, the high-moist lake regions, the temperate highland parts, and the hot, humid coastal plain. The Indian Ocean coastal regions, which include large towns like Dar es Salaam and Tanga, are included in the hot, humid coastal plain zone. High humidity and temperatures between 25°C and 31°C are its defining characteristics. Because of the region's high annual rainfall which frequently exceeds 1,000 mm—it is ideal for a range of agricultural pursuits, including the growth of tropical crops. The central portion of Tanzania, which includes areas like Dodoma and Singida, is known as the semi-arid central plateau. Its average annual rainfall is between 500 and 800 mm, and its average temperature is between 20 and 30 °C. Agriculture faces difficulties due to the semi-arid climate, necessitating adaptable strategies for water conservation and sustainable farming methods. Regions near large lakes like Lake Victoria, Lake Tanganyika, and Lake Nyasa are classified as high-moist lake regions. Higher moisture content and heavy rainfall typically between 1,000 and 2,500 mm annually are characteristics of them. These areas have moderate temperatures (20°C to 28°C), which sustain a high level of agricultural activity and a rich biodiversity. The Southern Highlands, the Northern Highlands surrounding Mount Kilimanjaro, and the Usambara and Pare mountain ranges are examples of highland areas that fall within the category of temperate highland zones. These areas experience lower temperatures, typically between 10°C and 20°C, and heavy precipitation, frequently between 1,000 and 2,000 mm per year. Crops like tea, coffee, and other horticulture goods can be grown because of the moderate temperature.

The study primarily focuses on Tanzania's mainland forests, which are thought to span 48.1 million hectares. These forested regions are essential for their ecological services, which include preserving biodiversity, safeguarding water catchments, and regulating climate through the sequestration of carbon. The country's total forest cover and ecological balance are influenced by the diverse ecological zones that the woods are spread across. Tanzania's varied topography and climate create a favorable habitat for the growth of many kinds of bamboo. Bamboo grows best in areas with high moisture content in lakes and temperate highlands, where it may thrive in environments with moderate temperatures and regular rainfall. The study intended to investigate how bamboo in these areas may help with enhanced carbon sequestration and sustainable land management techniques, which could aid in climate change adaptation and mitigation.

2.1.2 Bamboo species distribution and coverage in Tanzania

According to Lyimo et al. [10], bamboo grows on about 1,025,033 hectares in Tanzania, demonstrating its importance and potential to support both economic growth and ecological sustainability. Approximately 62% of Tanzania's bamboo coverage, or 636,545 hectares, is found in the Southern Zone, which includes the areas of Lindi, Mtwara, and Ruvuma [11]. This significant concentration in the Southern zone highlights the region's ecological adaptability and ideal climate for the growth of bamboo.

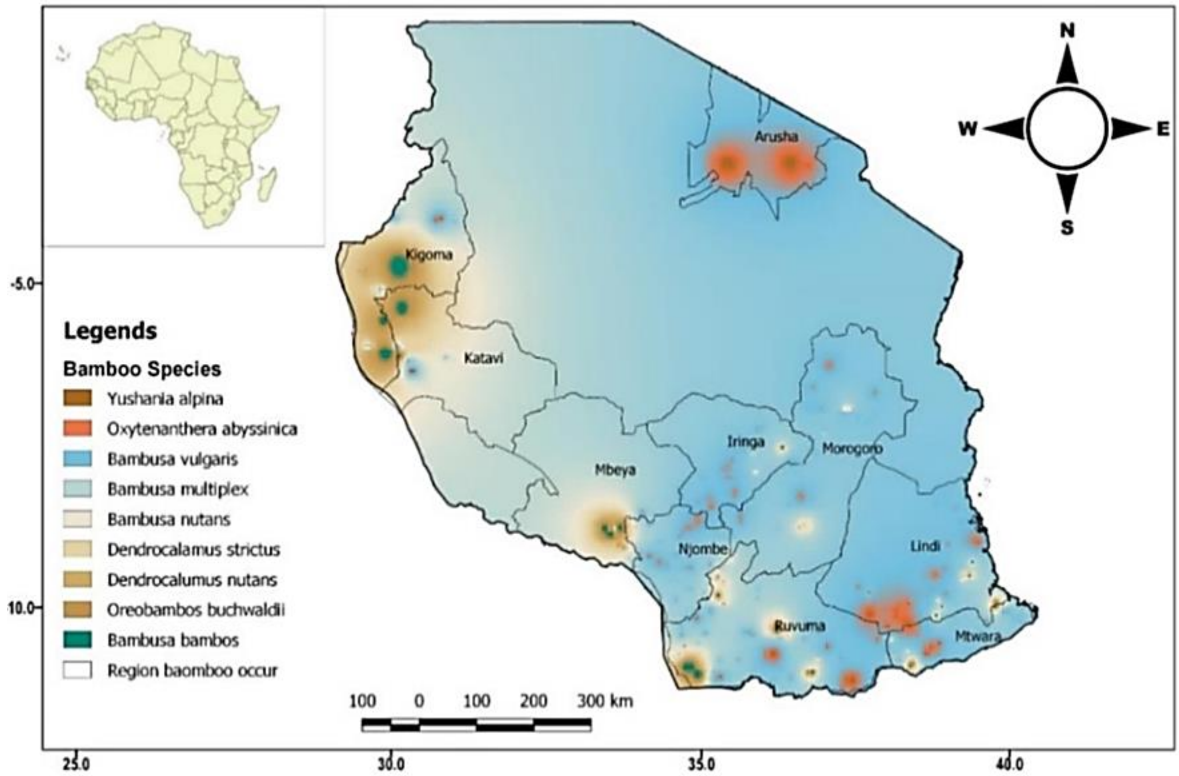

Fig. 1. A map of bamboo species distribution in Tanzania

Eleven Tanzanian administrative regions—Arusha, Tanga, Morogoro, Lindi, Mtwara, Ruvuma, Njombe, Iringa, Mbeya, Katavi, and Kigoma—are home to bamboo plantations. With 75.2% of the total bamboo coverage, the regions of Lindi, Ruvuma, Mtwara, Iringa, and Njombe are home to the majority of the bamboo populations [10]. The favorable climatic factors in the area, such as sufficient rainfall, appropriate soil types, and comfortable temperatures that encourage bamboo growth and proliferation, are responsible for this high concentration. Conversely, areas like Arusha, Mbeya, Katavi, and Tanga have comparatively less bamboo; they make up only 7.9% of the nation's overall bamboo population [11]. The lower distribution in these areas could be caused by a number of things, such as less ideal climate, human activities like agriculture and urbanization, and maybe a lack of attention to conservation and bamboo farming programs.

Tanzanian bamboo species are found mostly in low-lying areas as opposed to high-lying places. Bamboo prefers lower elevation habitats where conditions like temperature and moisture availability are ideal for their growth [12,5], as evidenced by the fact that 85.2% of the population is found below 1500 meters above sea level (m.a.s.l.) [11,3]. In Tanzania, bamboo is found in all sorts of land use, demonstrating its adaptability and versatility. It is extensively dispersed among wildlife-protected regions, production forests, and protection forests, which together make up public forests that account for over 65% of the world's bamboo distribution [11]. This broad presence in a variety of forest types highlights the significance of bamboo in preserving ecological balance and offering ecosystem services including soil erosion prevention, carbon sequestration, and wildlife habitat provision. Furthermore, Tanzania has a variety of plant types that are home to bamboo species. With forests making up 10%, cultivated lands accounting for 12%, and woodlands for 66%, these three areas have the largest proportion of bamboo occurrence. Bamboo is especially common in open woodlands that have 10–40% canopy cover [10]. This suggests that bamboo can adapt to different light conditions and plays a part in boosting the structural diversity of these ecosystems.

There is variance in species richness within each land use category, despite bamboo's extensive distribution across many vegetation types and land use categories. The majority of bamboo stems fall into the lower diameter breast height

(Dbh) class (<4 cm), and bamboo forests usually have an inverse J structure because there are a lot of small-diameter culms and not many large-diameter culms [11,13]. The distribution pattern of bamboo is indicative of its growth characteristics and regeneration dynamics, as younger, smaller culms predominate while older, larger culms are rare. Bamboo's broad range and abundance in Tanzania demonstrate its potential as a useful resource for mitigating and adapting to climate change. There are chances to exploit bamboo's ecological and economic benefits, promote sustainable land management, and improve the nation's carbon sequestration efforts due to the considerable coverage of bamboo, especially in the Southern zone and varied forest types.

2.2 Methods

2.2.1 Data sets for the study

To ensure accuracy and dependability, the study's data sets were carefully selected from databases that were already in existence. The National Forest Resources Monitoring and Assessment (NAFORMA) database, which is run by Tanzania's Sokoine University of Agriculture, is where the bamboo statistics were specifically taken from. This large dataset offered a solid basis for examining bamboo's potential to mitigate and adapt to climate change. The bamboo datasets (Table 1) came from the systematic extraction of data specific to bamboo from the NAFORMA database by Lyimo et al. [10]. The R software environment, a potent tool for statistical computing and data analysis, was used to import the complete NAFORMA dataset. Effective management and manipulation of massive amounts of data required taking this step. Using the sqldf package in R, Structured Query Language (SQL) queries were run in order to extract the bamboo data along with related cluster and plot details. With the help of this package, SQL queries may be seamlessly integrated into the R environment, making it easier to precisely extract pertinent data subsets from the broader NAFORMA dataset.

After being extracted, the data had to go through a rigorous validation and cleaning process. This step includes several processes, including as validation, data cleaning, and outlier analysis, to guarantee the accuracy and quality of the data. To ensure their accuracy, the retrieved data were cross-referenced with the original NAFORMA database entries. This required making sure that the data correctly matched the field observations entered into the NAFORMA database and verifying that measurements were consistent. The process of data cleaning involved eliminating data points that could potentially cause errors or inconsistencies in the analysis, often known as noisy data. To guarantee consistency throughout the dataset, data cleansing also entailed fixing any errors and standardizing the structure of the data entries. Outlier analysis was performed on the data to find and handle exceptional values that can distort the outcomes. Outliers were examined in the context of other data to see if they were true observations or mistakes. In order to maintain the integrity of the data, valid outliers were kept, while false outliers were either eliminated or corrected. Through the implementation of these rigorous data management procedures, the research guaranteed the high caliber and dependability of the bamboo data utilized, offering a solid foundation for the analysis that followed.

Accurate and significant research results depend on high-quality data, especially when it comes to studies on the adaptation and mitigation of climate change. The comprehensive validation and cleaning of the robust dataset from NAFORMA made it possible to conduct an accurate and thorough evaluation of bamboo's capacity to store carbon and support Tanzania's efforts to mitigate climate change.

2.2.2 Data analysis

Estimating the amount of stored bamboo biomass in Tanzania: To comprehend bamboo's significance in carbon sequestration and climate change mitigation, a precise calculation of its biomass is essential. To quantify bamboo biomass, the study used a multi-species allometric model that was modified from Xayalath et al. [14]. The model was specifically created to take into consideration the variations among bamboo species and the distribution of their biomass. Ten samples were gathered from each of the 11 bamboo species that were included in the multi-species allometric model employed in this investigation. One to three randomly selected culms per clump were included in each sample, representing a range of sizes from tiny to big species. The samples' diameter at breast height (DBH, or 1.3 cm) varied from 0.99 to 12.53 cm. The model was guaranteed to accurately depict Tanzania's richness of bamboo species because to this thorough sampling approach.

Table 1. Bamboo species coverage in Tanzania

Species name	Genera	Status	Area (ha)	Percentage (%)
Bamboo spp.	-	-	70,727.3	6.9
Bambusa bambos	Bambusa	Exotic and Naturalized	169,130.4	16.5
Bambusa multiplex	Bambusa	Exotic	16,400.5	1.6
Bambusa nutans	Bambusa	Exotic	17,425.6	1.7
Bambusa spp.	Bambusa	Exotic	111,728.6	10.9
Bambusa vulgaris	Bambusa	Exotic and Naturalized	212,181.8	20.7
Dendrocalamus nutans	Dendrocalamus	Exotic	27,675.9	2.7
Dendrocalamus strictus	Dendrocalamus	Exotic	19,475.6	1.9
Oreobambos buchwaldii	Oreobambos	Indigenous	11,275.4	1.1
Oxytenanthera abyssinica	Oxytenanthera	Indigenous	150,679.9	14.7
Yushania alpina	Arundinarieae	Indigenous	218,332.0	21.3
Total			**1,025,033.0**	**100**

Following harvesting, fresh weights of the culm, branches, and leaves were measured in the field, together with the DBH and culm length (H; m). Representative samples of each organ from each sample were oven-dried at 80ºC for 72 hours before being measured in the lab to ascertain the dry weight-to-fresh weight ratio. The biomass of the culm, branches, and leaves was added up to determine the aboveground biomass (AGB). The conventional allometric equation y=axb, where y is the culm length (H) or biomass of the culm, branches, leaves, and AGB (kg), x is DBH (cm) or DBH2H (cm^2 m), and a and b are coefficients derived by regression, was used to create species-specific allometric equations. These formulas made it possible to estimate biomass accurately using readily measured factors like culm length and DBH. The 11 bamboo species' combined data were used to create multi-species allometric equations for the research. Through a comparison of the allometric correlations with those generated from species-specific equations from prior worldwide research, the usefulness of these multi-species equations was evaluated. After log-transforming both variables, the standardized major axis (SMA) approach was used to accomplish this comparison [15,16,17].

Version 3.0.2 of the R software package was used for all statistical analyses [18]. Validation of the allometric equations and strong statistical modeling were made possible by the use of R. The 11 bamboo species found in mainland Tanzania could all have their biomass estimated using the multi-species allometric model, despite biochemical and geographic variations among the species. A trustworthy technique for determining the biomass of several bamboo species in Tanzania was made available by the multi-species allometric model. Understanding the capacity of bamboo forests for sequestering carbon is dependent on this calculation (Table 2). Bamboo has a major biomass accumulation capacity, especially in species with short harvest cycles that grow quickly. For this reason, bamboo is a crucial component of attempts to mitigate climate change. Through precise biomass estimation, the study adds significant information to the overall knowledge of bamboo's function in ecological and economic systems. This information is crucial for developing sustainable management practices that capitalize on bamboo's capacity for carbon sequestration and climate change adaptation, as well as for formulating policy.

Table 2. Bamboo biomass multi-species allometric model ($y = ax^b$)

Allometry	A	b	r^2	Allometry	a	b	r^2
DBH-H	3.4575	0.7845	0.8476				
DBH-Culm	0.0748	2.5356	0.9670	DBH^2H-Culm	0.0225	0.9256	0.9766
DBH-Branch	0.0389	2.0874	0.8814	DBH^2H-Branch	0.0145	0.7619	0.8781
DBH-Leaf	0.0410	1.5597	0.8024	DBH^2H-Leaf	0.0195	0.5693	0.7719
DBH-AGB	0.1794	2.2214	0.9668	DBH^2H-AGB	0.0625	0.8109	0.9671

r^2=Coefficient of Determination

Source: Xayalath et al. [17]

Estimating the amount of stored bamboo carbon in Tanzania: Taking into account bamboo's considerable potential for carbon sequestration, the study attempts to estimate the quantity of carbon stored in bamboo forests. Understanding bamboo's significance in mitigating climate change requires an estimation of the amount of carbon contained in its biomass. This estimation's approach adheres to accepted standards for figuring out carbon in terrestrial ecosystems.

The United Republic of Tanzania [19] states that the following formula can be used to calculate the carbon content in terrestrial ecosystems:

Carbon(tonnes/ha)=Biomass(tonnes/ha)×0.47

Based on the premise that 47% of the dry biomass of bamboo is carbon, this conversion factor of 0.47 has been calculated. For determining the carbon content of biomass, this is a generally recognized standard [20,21].

Estimating the amount of bamboo's conservation profit unutilized in Tanzania: Though underutilized, Tanzania stands to gain significantly from the protection of bamboo through carbon sequestration. Using the conventional carbon market price as a reference, this objective seeks to quantify the unrealized conservation profit from bamboo forests. This study illustrates the financial motivations for protecting and growing bamboo forests by analyzing these prospective profits. The study used the method of Jenkins [22] and Lobora et al. [23] to estimate the unutilized conservation profit. This method entails calculating the value of carbon stored by bamboo forests at the current market price for carbon credits. In this estimation, the standard carbon market price per ton of carbon is US$ 4.

Monetary value of carbon sequestered calculated as total carbon stored multiplied by the standard carbon market price to determine the potential revenue from carbon trading. The formula used is:

Conservation profit (US$) = Carbon stored (tonnes/ha) x Total area (ha) x US$ 4

3. RESULTS AND DISCUSSION

3.1 Amount of stored Bamboo Biomass in Tanzania

The study reveals significant findings regarding the distribution and potential of bamboo in Tanzania, particularly in the context of climate change adaptation and mitigation. The data presented in Table 3 indicates that 51.4% of the stored bamboo biomass, equivalent to approximately 2,075 million tons, is concentrated in the genera Bambusa. This substantial concentration highlights the importance of Bambusa species in contributing to Tanzania's overall bamboo biomass and underscores their potential role in carbon sequestration and climate mitigation efforts.

Furthermore, the findings detailed in Table 4 show that nearly 50% of the stored bamboo biomass is located in the Lindi and Mtwara regions. This geographic concentration suggests that the southern part of Tanzania holds significant potential for leveraging bamboo as a tool for climate change adaptation and mitigation. The southern regions' bamboo biomass not only adds to the ecological richness of the area but also complements the existing miombo woodlands, known for their biodiversity and carbon storage capabilities as discussed by Zella et al. [24]. The integration of bamboo conservation and management with the existing miombo woodlands in the southern regions offers a dual benefit. Miombo woodlands, characterized by their rich biodiversity and significant carbon storage, can be enhanced by the presence of bamboo. Bamboo can complement the ecological functions of miombo woodlands, providing additional carbon sequestration, habitat diversity, and sustainable livelihoods for local communities. This synergy can be leveraged to create comprehensive land management plans that maximize ecological and economic benefits.

Thereof, the findings of this study highlight the significant potential of bamboo in Tanzania for climate change adaptation and mitigation. The concentration of bamboo biomass in the southern regions, particularly within the genera Bambusa, offers a strategic advantage for leveraging bamboo's ecological and economic benefits. By integrating bamboo conservation with existing miombo woodlands and developing supportive policies and infrastructure, Tanzania can enhance its efforts to combat climate change and promote sustainable development.

3.2 Amount of stored bamboo carbon in Tanzania

The study provides a comprehensive analysis of the carbon storage potential of bamboo in Tanzania, with a particular focus on the southern regions. The data presented in Table 5 reveals that 51.4% of the stored bamboo carbon, equivalent to approximately 975.3 million tons, is concentrated in the genera Bambusa. This significant concentration underscores the pivotal role of Bambusa species in carbon sequestration efforts within Tanzania. The genera Bambusa is highlighted as a major contributor to Tanzania's carbon storage capacity. With over half of the country's bamboo carbon stored in these species, the importance of Bambusa cannot be overstated. Bamboo's rapid growth rate and extensive biomass accumulation make it an efficient carbon sink. The study's findings align with global observations that bamboo sequesters carbon more effectively than many other plant species, releasing 35% more oxygen and absorbing substantial amounts of carbon dioxide from the atmosphere.

Table 6 further illustrates that nearly 50% of the stored bamboo carbon is located in the Lindi and Mtwara regions. This regional concentration suggests that the southern part of Tanzania is particularly well-suited for initiatives aimed at climate change adaptation and mitigation using bamboo. The regions' favorable climatic and soil conditions likely contribute to the robust growth and carbon storage capabilities of bamboo in these areas. The substantial carbon storage in the southern regions of Tanzania indicates a high potential for using bamboo as a tool for climate change mitigation. By focusing conservation and cultivation efforts on bamboo in Lindi and Mtwara, Tanzania can enhance its carbon sequestration capacity. These efforts could be supported through international carbon trading mechanisms such as REDD+ (Reducing Emissions from Deforestation and Forest Degradation), which can provide financial incentives for preserving and expanding bamboo forests.

The rich biodiversity and carbon storage of miombo woodlands in southern Tanzania, as discussed by Zella et al. [24], complement the carbon sequestration potential of bamboo. Integrating bamboo conservation with miombo woodland management could create a synergistic effect, enhancing the overall ecological and economic benefits. Bamboo's fast growth and high biomass can augment the slower-growing miombo trees, providing a rapid increase in carbon storage and additional ecosystem services. Furthermore, the findings highlight the need for targeted policies and management practices to optimize the carbon sequestration potential of bamboo. Effective management practices should include sustainable harvesting, protection against over-exploitation, and restoration of degraded bamboo forests. Additionally, infrastructure development for bamboo processing and marketing can create economic opportunities for local communities, further incentivizing conservation efforts.

Thus, the findings from this study underscore the significant potential of bamboo, particularly the genera Bambusa, in contributing to Tanzania's climate change mitigation efforts. The high concentration of bamboo carbon in the southern regions, especially in Lindi and Mtwara, offers strategic opportunities for leveraging bamboo's ecological and economic benefits. By integrating bamboo conservation with existing miombo woodlands and developing supportive policies, Tanzania can enhance its efforts to combat climate change and promote sustainable development.

Table 3. Distribution of bamboo biomass among species in Tanzania

Species name	Biomass (Million tons)	Percentage (%)
Bamboo spp.	278.6	6.9
Bambusa bambos	666.1	16.5
Bambusa multiplex	64.6	1.6
Bambusa nutans	68.6	1.7
Bambusa spp.	440.0	10.9
Bambusa vulgaris	835.7	20.7
Dendrocalamus nutans	109.0	2.7
Dendrocalamus strictus	76.7	1.9
Oreobambos buchwaldii	44.4	1.1
Oxytenanthera abyssinica	593.5	14.7
Yushania alpina	859.9	21.3
Total	**4037.2**	**100**

Table 4. Distribution of bamboo biomass among regions in Tanzania

Species name	Biomass (Million tons)	Percentage (%)
Lindi	1181.6	29.3
Mtwara	787.7	19.5
Ruvuma	537.8	13.3
Njombe	393.9	9.8
Iringa	295.4	7.3
Other Regions	840.8	20.8
Total	**4037.2**	**100**

Table 5. Distribution of bamboo carbon among species in Tanzania

Species name	Biomass (Million tons)	Percentage (%)
Bamboo spp.	130.9	6.9
Bambusa bambos	313.1	16.5
Bambusa multiplex	30.4	1.6
Bambusa nutans	32.3	1.7
Bambusa spp.	206.8	10.9
Bambusa vulgaris	392.8	20.7
Dendrocalamus nutans	51.2	2.7
Dendrocalamus strictus	36.1	1.9
Oreobambos buchwaldii	20.9	1.1
Oxytenanthera abyssinica	278.9	14.7
Yushania alpina	404.2	21.3
Total	**1897.5**	**100**

Table 6. Distribution of carbon biomass among regions in Tanzania

Species name	Carbon (Million tons)	Percentage (%)
Lindi	555.3	29.3
Mtwara	370.2	19.5
Ruvuma	252.8	13.3
Njombe	185.1	9.8
Iringa	138.8	7.3
Other Regions	395.2	20.8
Total	1897.5	**100**

3.3 Amount of Bamboo's Conservation Profit Unutilized in Tanzania

The study sheds light on the untapped financial potential of bamboo conservation in Tanzania, particularly through the carbon market. The data presented in Table 7 reveals that 51.4% of the unutilized conservation profit from the carbon market, equivalent to approximately 3.9 billion US dollars, is concentrated in the genera Bambusa. This substantial figure underscores the significant economic value that could be harnessed through effective bamboo conservation and carbon trading mechanisms. The genera Bambusa stands out as a major contributor to the economic potential of bamboo conservation in Tanzania. With over half of the country's unutilized conservation profit from carbon markets derived from these species, Bambusa presents a lucrative opportunity for monetizing ecosystem services. The high carbon sequestration capacity of Bambusa, which aligns with its ecological benefits, translates directly into substantial economic gains when integrated into carbon trading schemes such as REDD+ (Reducing Emissions from Deforestation and Forest Degradation).

Table 8 further highlights that nearly 50% of the unutilized conservation profit from the carbon market is found in the Lindi and Mtwara regions. This regional concentration suggests that the southern part of Tanzania holds the greatest potential for leveraging bamboo for climate change adaptation and mitigation, as well as for economic development. The favorable conditions for bamboo growth in these regions, coupled with the substantial carbon storage, make them prime candidates for targeted conservation and carbon trading initiatives. The significant unutilized conservation profit in the southern regions of Tanzania indicates a dual potential for both climate change mitigation and economic development. By focusing conservation efforts on bamboo in Lindi and Mtwara, Tanzania can not only enhance its carbon sequestration capacity but also generate substantial financial returns. These funds could be reinvested into further conservation efforts, local community development, and other sustainable initiatives, creating a positive feedback loop.

The rich biodiversity and carbon storage of miombo woodlands in southern Tanzania, as discussed by Zella et al. [24], complement the economic and ecological potential of bamboo. Integrating bamboo conservation with miombo woodland management could amplify the benefits, enhancing both carbon sequestration and economic returns [25-27]. The rapid growth and high biomass of bamboo can augment the slower-growing miombo trees, providing a more immediate increase in carbon storage and additional ecosystem services. Moreover, the findings underscore the need for targeted policies and management practices to optimize the economic potential of bamboo conservation [28,29]. Effective management should include sustainable harvesting, protection against over-exploitation, and restoration of degraded bamboo forests. Additionally, developing infrastructure for bamboo processing and marketing can create economic opportunities for local communities, further incentivizing conservation efforts.

Thus, the findings from this study highlight the significant untapped economic potential of bamboo, particularly the genera Bambusa, in Tanzania. The high concentration of unutilized conservation profit from the carbon market in the southern regions, especially in Lindi and Mtwara, offers strategic opportunities for leveraging bamboo's ecological and economic benefits. By integrating bamboo conservation with existing miombo woodlands and developing supportive policies, Tanzania can enhance its efforts to combat climate change, promote sustainable development, and generate substantial economic returns.

Table 7. Distribution of bamboo's unutilized conservation profit among species in Tanzania

Species name	Unutilized profit (Billion US$)	Percentage (%)
Bamboo spp.	0.5	6.9
Bambusa bambos	1.3	16.5
Bambusa multiplex	0.1	1.6
Bambusa nutans	0.1	1.7
Bambusa spp.	0.8	10.9
Bambusa vulgaris	1.6	20.7
Dendrocalamus nutans	0.2	2.7
Dendrocalamus strictus	0.1	1.9
Oreobambos buchwaldii	0.1	1.1
Oxytenanthera abyssinica	1.1	14.7
Yushania alpina	1.6	21.3
Total	7.6	**100**

Table 8. Distribution of bamboo's conservation profit unutilized among regions in Tanzania

Species name	Unutilized profit (Billion US$)	Percentage (%)
Lindi	2.2	29.3
Mtwara	1.5	19.5
Ruvuma	1.0	13.3
Njombe	0.7	9.8
Iringa	0.6	7.3
Other Regions	1.6	20.8
Total	7.6	**100**

4. CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

This study has demonstrated the significant potential of bamboo in contributing to climate change adaptation and mitigation in Tanzania. Through the comprehensive analysis of biomass, carbon stock, and unutilized conservation profit, it is evident that bamboo represents a valuable ecological and economic resource. The findings indicate that Tanzania harbors approximately 4.04 billion tons of bamboo biomass and 1.9 billion tons of stored bamboo carbon, which translates to an estimated 7.6 billion US dollars in unutilized conservation profit from the carbon market.

Additionally, the study revealed that 51.4% of the bamboo biomass, equivalent to 2,075 million tons, is found within the genera Bambusa. This underscores the substantial carbon sequestration capability of these species. Also, nearly 50% of the bamboo biomass and carbon stock is concentrated in the Lindi and Mtwara regions, highlighting the southern part of Tanzania as a critical area for bamboo-based climate interventions. Furthermore, the economic valuation of unutilized conservation profit from carbon markets showed that 3.9 billion US dollars are tied to bamboo conservation, particularly within the genera Bambusa. The regions of Lindi and Mtwara again emerged as significant, with nearly 50% of this conservation profit potential located in these areas.

The ecological benefits of bamboo, including its rapid growth, high carbon sequestration rate, and ability to improve soil health, combined with its economic potential, make it a viable candidate for climate change mitigation strategies. Likewise, integrating bamboo conservation with the rich biodiversity of miombo woodlands can amplify both environmental and economic outcomes, creating a synergistic effect that enhances overall sustainability.

4.2 Recommendations

Based on the findings, seven recommendations (Table 9) are made to optimize the use of bamboo for climate change adaptation and mitigation in Tanzania.

Because of their significant biomass and carbon stock, the southern regions of Tanzania, especially Lindi and Mtwara, should be prioritized for bamboo-based interventions. By implementing these recommendations, Tanzania can leverage bamboo not only to combat climate change but also to achieve sustainable economic growth and environmental conservation. As such, bamboo represents a powerful tool in the fight against climate change, offering both ecological and economic benefits. With strategic planning and concerted efforts, Tanzania can position itself as a leader in bamboo conservation and utilization.

Table 9. Study recommendations

S/N	Recommendations	Explanation
1.	Policy development	Formulate and implement policies that promote the sustainable management and conservation of bamboo forests. This includes regulations that prevent over-exploitation and encourage reforestation and afforestation initiatives.
2.	Investment in bamboo industries	Encourage investment in bamboo processing industries to create value-added products. This can stimulate local economies, create job opportunities, and provide alternative livelihoods for communities dependent on forest resources.
3.	Carbon market integration	Develop mechanisms to integrate bamboo conservation into existing carbon trading schemes such as REDD+ (Reducing Emissions from Deforestation and Forest Degradation). This will help monetize the carbon sequestration potential of bamboo and generate funds for further conservation efforts.
4.	Research and Development	Support further research to refine allometric models for more accurate estimation of biomass and carbon stocks specific to Tanzanian bamboo species. Additionally, socio-economic studies should be conducted to understand the impacts of bamboo

S/N	Recommendations	Explanation
		cultivation on local communities.
5.	Community involvement	Engage local communities in bamboo conservation and management practices. Educating and empowering communities about the benefits of bamboo can enhance conservation efforts and ensure sustainable utilization of bamboo resources.
6.	Educational initiatives	Incorporate bamboo conservation and its benefits into educational curricula at various levels. Raising awareness about the ecological and economic advantages of bamboo can foster a culture of conservation among future generations
7.	Collaborative efforts	Foster collaborations between government agencies, non-governmental organizations, and international bodies to share knowledge, resources, and best practices in bamboo conservation and sustainable management.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

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COMPETING INTERESTS

Author has declared that no competing interests exist.

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