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Review

Bamboo as a Nature-Based Solution (NbS) for Climate Change Mitigation: Biomass, Products, and Carbon Credits

Chunyu Pan [1,2], Guomo Zhou [2], Anil Kumar Shrestha [1], Jialu Chen [1], Robert Kozak [1], Nuyun Li [3], Jinliang Li [3], Yeyun He [3], Chunguang Sheng [4] and Guangyu Wang [1,2,*]

1 Faculty of Forestry, University of British Columbia, 2424 Main Mall, Vancouver, BC V6T 1Z4, Canada; chunyu.pan@ubc.ca (C.P.)
2 State Key Laboratory of Subtropical Silviculture, Zhejiang A&F University, Hangzhou 311300, China
3 China Green Carbon Foundation, No. 18, Hepingli Dongjie, Beijing 100714, China
4 College of Economics and Management, Northeast Forestry University, Harbin 150040, China
* Correspondence: guangyu.wang@ubc.ca

Abstract: Bamboo, a rapidly growing woody grass prevalent in pan-tropical zones, holds promising potential as a nature-based solution (NbS) for climate change mitigation. In this systematic review of 91 research articles, we critically assess the scope and constraints of bamboo's role in mitigating climate change across three dimensions: as a carbon sink in biomass form, as carbon storage in bamboo products, and as a contributor to carbon project credits. Our analysis reveals that existing studies disproportionately focus on 36 limited species, such as *Phyllostachys pubescens* and *Bambusa vulgaris*, with geographic concentration in Asia (91%) and limited studies from Africa (7%) and South America (1%). While many studies emphasize the carbon-saving benefits of bamboo products compared with traditional goods, there is a noticeable gap in comprehensive evaluations of carbon pools from individual bamboo forests encompassing all product varieties. While bamboo forests offer significant carbon trading potential, their global role is restricted by the absence of internationally accepted methodologies and the presence of debates about classifying bamboo as a tree species. This extensive review highlights the multifaceted value of bamboo in climate change mitigation, thereby highlighting its significance as a critical component for informed policymaking and the development of sustainable practices in future climate strategies worldwide.

Keywords: forest carbon; bamboo forests; carbon sequestration; bamboo products; carbon offsets

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1. Introduction

Climate change has an adverse impact worldwide, creating conditions for widespread wildfires, droughts, and ecosystem deterioration [1]. Taking urgent action to combat climate change has been established as a Sustainable Development Goal (SDG) for the 2020s by the United Nations [2]. As a complement to emission reduction from carbon sources, nature-based solutions (NbSs) have gained growing attention from global researchers, scholars, and decision-makers for mitigating climate change [3]. By combining all ecosystem contributions, NbSs can reduce up to 11.7 $GtCO_2e$ annually by 2030 [4].

Bamboo is a fast-growing, woody grass with a high renewability [5], and it is widely distributed globally in tropical, subtropical, and temperate regions [6]. In China, bamboo forests constitute only 2.9% of the total forested area, yet they store 0.78 billion tC of carbon. This represents 9.2 billion tC, or an 8.48% contribution to China's total forest carbon storage [7,8]. Out of the 132 reporting countries in the Food and Agriculture Organization (FAO) Forest Assessment Report for 2020, 23 claimed bamboo resources, totaling 35 million ha in area. This area has increased by almost 50% from 1990 to 2020 [6] and is also projected to continue to expand its range under most climate change scenarios [9,10]. Bamboo's contribution to climate change mitigation, as an NbS, can be categorized into: (i) bamboo forest biomass acting as a carbon sink, (ii) carbon storage through bamboo products, and (iii) carbon credits from bamboo forest projects [11].

Firstly, compared with tree species from similar regions, bamboo forests present a higher ability and higher efficiency for carbon sequestration and biomass accumulation [12]. For instance, a well-managed Moso bamboo forest can sequester 24.31 tCO_2/ha annually; this compares favorably with other forest types in the same subtropical zones, as it sequesters about twice the amount sequestered by Chinese fir (11.48 $tCO_2/ha/yr$) in Hunan Province and around four times the amount sequestered by the Masson pine (6.49 $tCO_2/ha/yr$) in Guangdong Province, China [8]. Secondly, bamboo forests have short rotation times: the harvest cycle of mature-stand removal ranges from two to four years [12], making bamboo a highly renewable resource. Harvested bamboo culms are processed into various products, including bamboo flooring, panels, and furniture [13], which are suitable substitutes for more carbon-intensive productions. The life cycles of these products are carbon-negative when the emissions from transportation and production are minimized [14]. Thirdly, with forest-based management activities, such as afforestation, reforestation, improved forest management, and avoided deforestation, bamboo forests can sequester and store more carbon from the atmosphere than other baseline scenarios [5]. These activities can generate carbon offset credits for bamboo projects, incentivizing farmers to better manage their bamboo holdings in mitigating climate change [5].

Thoroughly understanding the importance and synthesizing the existing knowledge of bamboo forests in the climate change mitigation context is crucial for implementing relevant nature-based climate policy successfully. However, few researchers have comprehensively reviewed bamboo's climate change mitigation potential from all three perspectives: carbon sink in biomass, carbon storage in bamboo products, and carbon credits in bamboo projects. Recent reviews focused on more limited aspects: some studies reviewed the carbon sequestration ability of aboveground and belowground biomass and soil organic carbon [12,15]. Others focused on the mitigation effects of trading bamboo carbon credits as a means to support the livelihood of farmers [16,17]. And some other studies analyzed the carbon sequestered in bamboo biomass and stored in bamboo products [18,19]. Emamverdian et al. [20] broadly reviewed the social, economic, and environmental benefits of bamboo, but the scope of climate change mitigation was not extensively discussed. Therefore, successfully implementing relevant nature-based climate policies, such as fulfilling nationally determined contributions (NDCs) and developing voluntary carbon markets, will involve more thoroughly studying the potential of bamboo forests as climate change mitigators. Using a systematic literature review, we conducted a comprehensive knowledge synthesis of bamboo's contributions to climate change mitigation by providing a carbon sink in bamboo biomass, carbon storage in bamboo products, and carbon credits in bamboo projects. We also present the current challenges and gaps in bamboo forest research and propose some prospects for future research activities.

2. Materials and Methods

A systematic review was conducted to synthesize existing knowledge comprehensively and without bias [21]. The method was based on the "Five-Step Systematic Review" [22] (Table 1). This five-step systematic review process offers a structured and comprehensive methodology, ensuring clarity of research questions, thoroughness in identifying relevant work, rigorous quality assessment of studies, careful synthesis of evidence, and thoughtful interpretation of findings [22]. Step 1 was to unambiguously state the research question: what are the contributions of bamboo and bamboo products to climate change mitigation? In step 2, we identified 914 peer-reviewed research articles from 4 core databases: Web of Science (216), Scopus (288), EBSCO (166), and CAB Direct (244) following the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) framework. The search criteria used were consistent across the four databases. We searched for 'bamboo' in the title, and in the meantime, a series of abstract requirements were searched intersectant (using the Boolean operator 'AND') using a number of keywords, including bamboo forest, carbon sink, and carbon market (Figure 1).

Table 1. The five-step systematic review structure [22].

Step	Description of Each Step
I	Framing the Question
II	Identifying Relevant Publications
III	Assessing Study Quality
IV	Summarizing the Evidence
V	Interpreting the Findings

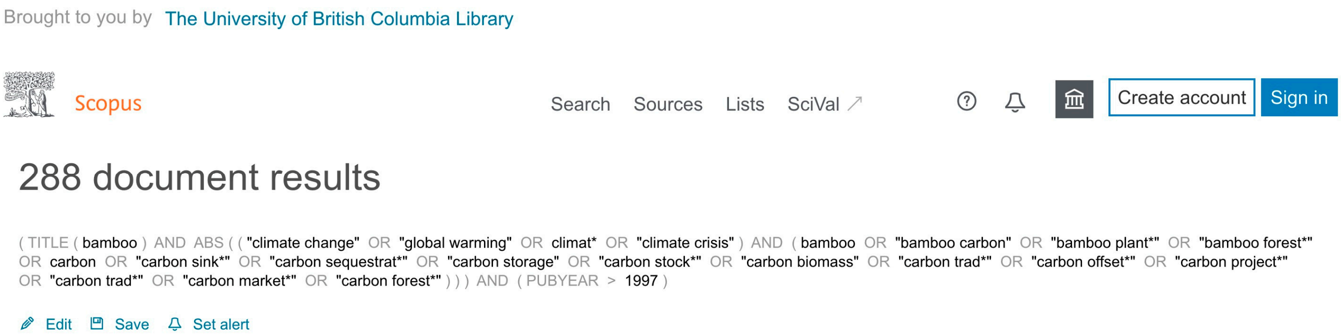


Figure 1. The Boolean structure in the Scopus Database (25 January 2022).

The year 1997 was set as the beginning of the timespan to reflect the time that the concept of carbon credits emerged through the Kyoto Protocol [23]. The search spanned until 25 January 2022. The Covidence platform was used to effectively assess the study quality in step 3, which is a professional platform explicitly designed for systematic reviews, enabling team members to collaborate seamlessly and synchronously [24]. The Covidence platform automatically removed 501 duplicates, resulting in 413 studies left for further screening. After first examining the titles and abstracts, 291 articles were excluded for falling outside our research scope. For instance, some studies focused on the soil contaminant uptake quantification of bamboo forests. Others emphasized the constructional strength of bamboo materials, and others researched the invasiveness of bamboo species. The remaining 122 studies were imported into the software NVivo for immersive reading [25].

After carefully reviewing the full text of the remaining 122 studies in NVivo, 31 articles were excluded. These papers were either unrelated to our research scope or technically challenging to interpret. For example, some were review papers focusing on different scopes; some studies were not in the scientific article structure, including magazines, prefaces, and perspective articles, and several papers were not publicly accessible online and remained unreachable after help from the University of British Columbia library staff. The complete PRISMA diagram shows the study quality assessment process (Figure 2).

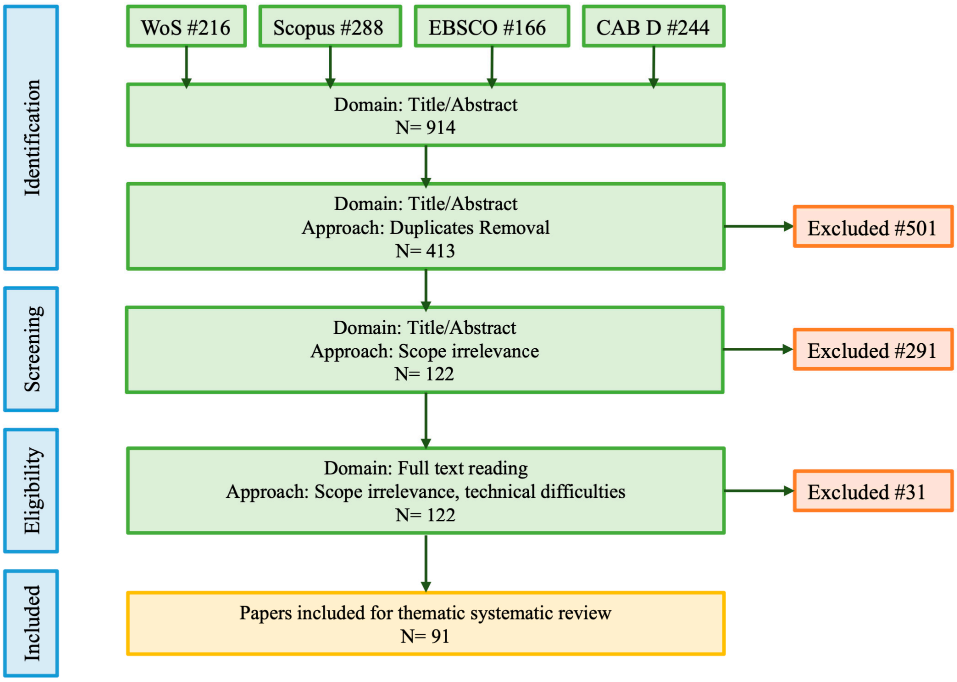


Figure 2. The PRISMA diagram for assessing the quality of the studies from Web of Science, Scopus, EBSCO, and CAB Direct.

We reviewed the remaining 91 studies in NVivo during step 4, summarizing the evidence based on a thematic analysis following the guidelines of Nowell et al. [26] (Figure 3). With the synthesis and analysis of the larger subject under many themes, this method enabled the generation of themes and the identification of patterns across the bulk of the research papers [27]. Our team thoroughly read most of the research papers and created a rough coding framework. Three broader themes emerged from this analysis, namely, carbon sinks in bamboo forest ecosystems, carbon storage in bamboo products, and carbon credits in bamboo projects. Additionally, several subthemes were defined under the three larger themes (Figure 4). We acknowledge that some papers studying other species might not have been included in our review, but the four databases represented a vast number of peer-reviewed bamboo forestry research articles. With a trustworthy thematic systematic review process established, we ensured that our results would present a general framework of how bamboo species are studied across the globe.

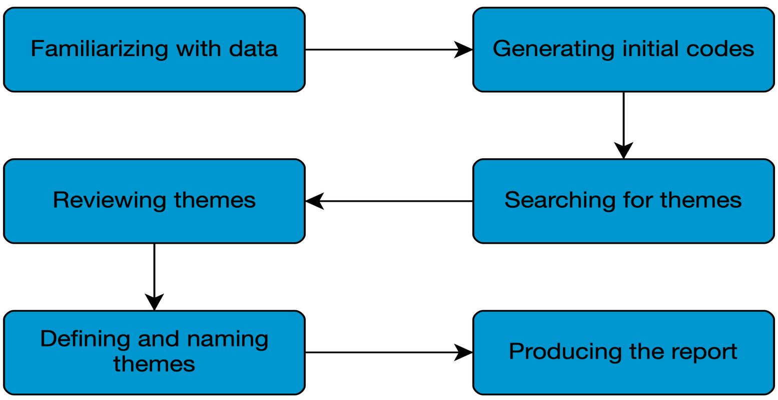
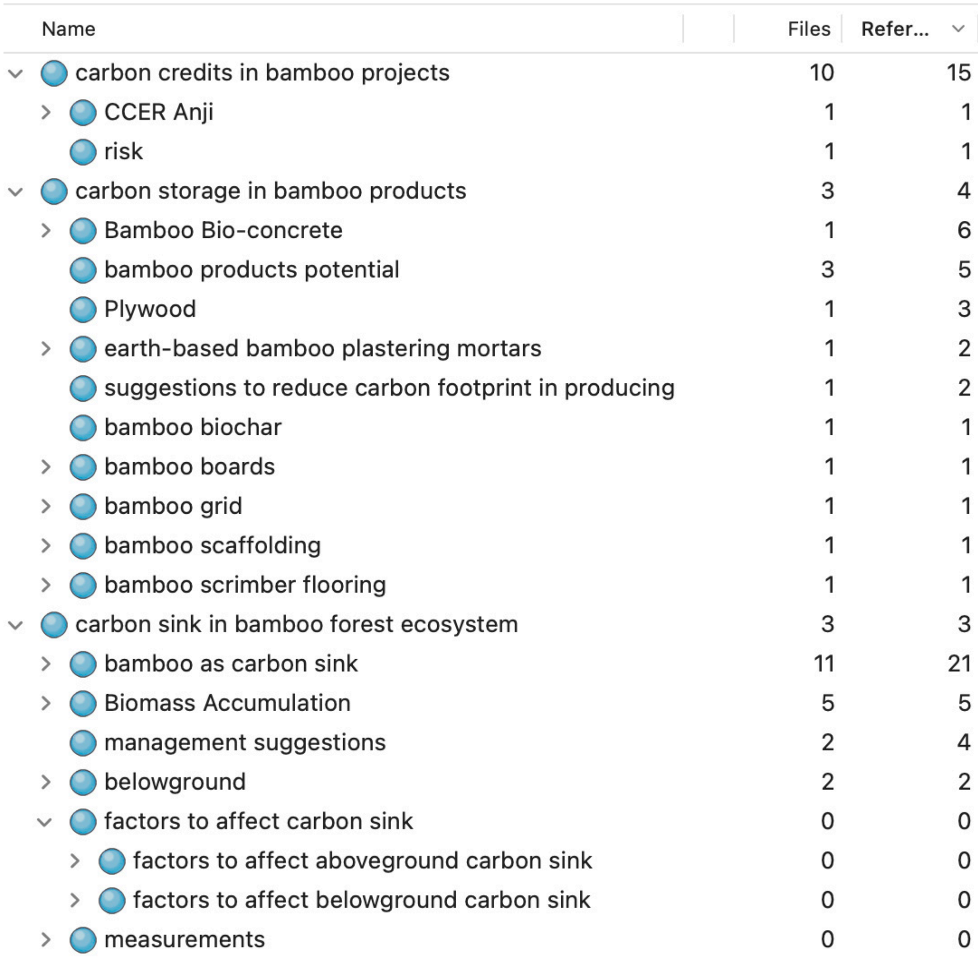


Figure 3. Steps toward the trustworthiness of a thematic analysis [26].



Name	Files	Refer...
carbon credits in bamboo projects	10	15
CCER Anji	1	1
risk	1	1
carbon storage in bamboo products	3	4
Bamboo Bio-concrete	1	6
bamboo products potential	3	5
Plywood	1	3
earth-based bamboo plastering mortars	1	2
suggestions to reduce carbon footprint in producing	1	2
bamboo biochar	1	1
bamboo boards	1	1
bamboo grid	1	1
bamboo scaffolding	1	1
bamboo scrimber flooring	1	1
carbon sink in bamboo forest ecosystem	3	3
bamboo as carbon sink	11	21
Biomass Accumulation	5	5
management suggestions	2	4
belowground	2	2
factors to affect carbon sink	0	0
factors to affect aboveground carbon sink	0	0
factors to affect belowground carbon sink	0	0
measurements	0	0

Figure 4. Coding framework created in NVivo software 12.

3. Results and Discussion

3.1. Carbon Sinks in Bamboo Forest Ecosystems

3.1.1. Bamboo as a Carbon Sink

Bamboo is a fast-growing species with high annual regrowth after harvesting. This unique nature of bamboo accounts for its strong biomass accumulating capacity: carbon dioxide in the atmosphere is transformed into biomass via photosynthesis, increasing the carbon sink capacity of the bamboo ecosystem, especially for bamboo during the early growth period [28,29]. A typical bamboo shoot grows into full culm height within two to four months at a maximum rate of 90–120 cm per day; after this time, branches emerge, and the culm diameter and height remain constant afterward [18]. In the following years, the bamboo culm continues to sequester carbon dioxide for up to seven years, and after harvest, the corresponding belowground biomass can survive and keep contributing to the carbon sink [18]. Additionally, the litter biomass, including leaf, sheath, and branch parts, together with the soil, can store a significant amount of carbon, increase soil fertility, prevent land degradation, and enhance bamboo productivity, resulting in sizable biomass accumulation in a positive feedback mechanism [30].

Most of the studies highlight that bamboo species generally act as carbon sinks rather than carbon sources, with different seasonal variations reported in the literature. Lei bamboo forest (*Phyllostachys violascens*) serves as a carbon sink throughout most of the year [31]; this pattern is quite different from temperate and boreal forests that are carbon sources during the nongrowing season [32]. From the perspective of diurnal variations, Lei bamboo and Moso bamboo forests serve as carbon sinks during most daytime periods [32]. In addition, the interval between each harvest activity is relatively short. Compared with most timber species that have a harvest interval of 10 to 50 years, the interval for bamboo is between three and five years [33]. Using a selective harvest approach, Moso bamboo can be harvested every two years [34], and bamboo in some village landscapes can be felled yearly [35]. Bamboo can be a unique carbon storage resource that exceeds many other woody crops as long as annual selective harvesting does not damage total carbon sequestration and the ecosystem [36].

Numerous studies have investigated the carbon fixation ability of various bamboo species worldwide by analyzing the carbon sequestration rate (CSR) (Table 2), net ecosystem production (NEP) (Table 3), bamboo forest biomass (Table 4), and bamboo forest carbon storage (Table 5). Although the numbers may differ across several orders of magnitude due to different forest conditions, management practices, study designs, and species productivity, they all illustrate that bamboo forest ecosystems have significant potential for mitigating climate change.

Table 2. Summary of research on the carbon sequestration rate (CSR) of bamboo forests.

Source	Species	Region	CSR (tCO_2/ha/yr)	Note
(Cao et al. [37])	*Phyllostachys pubescens*	Zhejiang, China	1.67	Lingfeng Bamboo Farm
	Phyllostachys pubescens	Zhejiang, China	1.48	Tianmu Mountain Natural Reserve
(Huang et al. [38])	*Phyllostachys violascens*	Zhejiang, China	0.29	Carbon occluded in phytolith (PhytOC)
(Y. Kuehl et al. [39])	*Phyllostachys pubescens*	China	18.69	60-year managed bamboo forest
(Nath et al. [40])	*Bambusa cacharensis*	Assam, India	4.77	Bamboo-based family forest
	Bambusa vulgaris	Assam, India	8.43	Bamboo-based family forest
	Bambusa balcooa	Assam, India	5.86	Bamboo-based family forest
(Tang et al. [41])	*Phyllostachys pubescens*	Hubei, China	41.38	Management with application of herbicide
(Teng et al. [42])	*Dendrocalamus latiflorus*	China	40.48	National-scale investigation
	Dendrocalamus membranaceus	China	34.91	National-scale investigation
	Bambusa textilis	China	38.43	National-scale investigation
	Dendrocalamopsis oldhami	China	57.09	National-scale investigation
	Bambusa burmanica	China	45.21	National-scale investigation
	Bambusa chungii	China	55.26	National-scale investigation
	Neosinocalamus affinis	China	51.08	National-scale investigation
	Dendrocalamus giganteus	China	70.11	National-scale investigation
(Yu et al. [43])	*Phyllostachys pubescens*	Zhejiang, China	1.86	Bamboo forest plantation (year 1–5)

Table 3. Summary of research on the net ecosystem production (NEP) of bamboo forests.

Source	Species	Region	NEP (Kg CO_2/m^2/yr)	Note
(Cai et al. [44])	*Phyllostachys pubescens*	Sichuan, China	1.94 ± 0.83	NEP (without nitrogen deposition)
(Y. Chen et al. [31])	*Phyllostachys violascens*	Zhejiang, China	0.13	NEP (high-efficiency management)
(L. Chen et al. [32])	*Phyllostachys pubescens*	Zhejiang, China	20.18	NEP (growing season)
	Phyllostachys violascens	Zhejiang, China	20.81	NEP (growing season)
(C. Li et al. [45])	*Phyllostachys pubescens*	Zhejiang, China	0.24	NEP (mid-fertilization and low-harvest)
(X. Li et al. [46])	Mix	Zhejiang, China	0.51 ± 0.31	All bamboo forests in Zhejiang (2001–2017)
(Liu et al. [47])	*Phyllostachys violascens*	Zhejiang, China	0.11 ± 0.02	Intensively managed forest
(Lu et al. [48])	*Phyllostachys violascens*	Zhejiang, China	1.50	Carbon flux measurement
(Mao et al. [49])	Mix	Zhejiang, China	0.41	All bamboo forests in Zhejiang (2015)
(Mazumder et al. [35])	Mix	Assam, India	0.20–0.74	Different species, ages, and village physiography
(Song et al. [50])	*Phyllostachys pubescens*	Zhejiang, China	0.6 ± 0.06	Mean value from 2011 to 2015
(Tang et al. [51])	*Phyllostachys pubescens*	Hubei, China	5.97	Management with application of herbicide
(M. Zhang et al. [52])	*Phyllostachys violascens*	Zhejiang, China	0.12	Intensively managed forest (triplex-flux model)

The CSR and NEP are similar indicators, measuring the amount of carbon dioxide sequestered in a bamboo forest ecosystem for the unit area and unit time. Teng et al. [42] investigated eight sympodial bamboo species in China on the national scale; by including carbon sequestration from the soil, litter, and vegetation, they found the CSR could be as high as 70.11 tCO_2/ha/yr (*Dendrocalamus giganteus*). Regarding the carbon stored in phytolith (PhytOC), specifically, Phyllostachys violascens can store only 0.29 tons of CO_2 per hectare annually; however, with intensive management techniques like mulching and fertilization, PhytOC storage can be significantly enhanced [38]. Interestingly, a Moso bamboo forest with regular harvesting activities and management for 60 years was projected to sequester 18.69 tCO_2/ha/yr [5]. Comparatively, during the first five years of plantation, another Moso bamboo forest could only sequester 1.86 tCO_2/ha/yr [43]. In Assam, India, Nath et al. [40] developed allometric scaling models and estimated the mean annual carbon accumulation rate of local bamboo family forests to be 4.77–8.43 $tCO_2/ha/yr$. Similarly, Sohel et al. [53] showed that the total carbon stock of a 5-year-old *B. vulgaris* forest was much higher (15.53 Mg ha^{-1} $year^{-1}$) compared with fast-growing tree species such as *Acacia auriculiformis* (recording 10.21 Mg ha^{-1} yr^{-1} after 11 years) and *Eucalyptus camaldulensis* (recording 10.12 Mg ha^{-1} yr^{-1} after 18 years) in Bangladesh.

Regarding NEP, the growing season of Moso bamboo and Lei bamboo have extraordinary capacity, reaching around 20 kg $CO_2/m^2/yr$ [32], which is in line with the fast-growing characteristic of bamboo forests. Li et al. [46], using the integrated terrestrial ecosystem carbon budget model, showed that all bamboo forests in Zhejiang Province sequestered 0.51 kg $CO_2/m^2/yr$ from 2001 to 2017. Similarly, Mao et al. [49] used the process-based model and found a comparable value of NEP, equal to 0.41 kg $CO_2/m^2/yr$, for all bamboo forests in Zhejiang in 2015. In Assam, India, the NEP for different species, ages, and village physiography ranged from 0.20 to 0.74 kg $CO_2/m^2/yr$ [53]. Other tools, including carbon flux measurements [48] and the triple-flux model [52], also demonstrated the great NEP potential of bamboo forests.

Table 4. Summary of research on bamboo biomass.

Source	Species	Region	Biomass (t/ha)	Note
(L. Cao et al. [28])	*Phyllostachys pubescens*	Jiangsu, China	173.47 ± 43.16	AGB; Intensive management
	Phyllostachys pubescens	Jiangsu, China	67.61 ± 13.10	AGB; Extensive management
(de Campos Gorgulho Padgurschi et al. [54])	*Merostachys neesii*	São Paulo, Brazil	12.10	AGB; Dominant species
(Isagi et al. [55])	*Phyllostachys pubescens*	Kyoto, Japan	182.50	AGB + BGB
(Kumar et al. [56])	*Dendrocalamus giganteus*	Terai, India	270.97	AGB + BGB; Natural forest
	Bambusa nutans	Terai, India	127.21	AGB + BGB; Natural forest
	Melocanna baccifera	Terai, India	16.31	AGB + BGB; Natural forest
(Leksungnoen [57])	*Thyrsostachys siamensis*	Nakhon Ratchasima, Thailand	34.80	ABG; Natural more than 10 years (same below)
	Mix	Nakhon Ratchasima, Thailand	43.60	*Dendrocalamus membranaceus* and *Thyrsostachys siamensis*
(Nigatu et al. [58])	*Yushania alpina*	West Amhara, Ethiopia	108.70 ± 1.80	AGB + BGB; Five dominant niches
(Teng et al. [42])	*Dendrocalamus latiflorus*	China	58.56	AGB + BGB; National scale
	Dendrocalamus membranaceus	China	49.91	AGB + BGB; National scale
	Bambusa textilis	China	57.18	AGB + BGB; National scale
	Dendrocalamopsis oldhami	China	82.67	AGB + BGB; National scale
	Bambusa burmanica	China	65.59	AGB + BGB; National scale
	Bambusa chungii	China	78.75	AGB + BGB; National scale
	Neosinocalamus affinis	China	74.03	AGB + BGB; National scale
	Dendrocalamus giganteus	China	103.60	AGB + BGB; National scale
(Xayalath et al. [59])	*Bambusa tulda*	Luang Prabang, Laos	25.85	AGB; Fallow forests dominated by bamboo
	Cephalostachyum vigatum	Luang Prabang, Laos	11.54	AGB; Fallow forests dominated by bamboo
	Dendrocalamus membranaceus	Luang Prabang, Laos	25.17	AGB; Fallow forests dominated by bamboo
	Gigantochloa sp.	Luang Prabang, Laos	21.21	AGB; Fallow forests dominated by bamboo
	Indosasa sinica	Luang Prabang, Laos	59.87	AGB; Fallow forests dominated by bamboo

The estimation of bamboo forest biomass carbon storage for a diverse grouping of regions and species worldwide was comprehensively studied. L. Cao et al. [28] used airborne LiDAR data and showed that the intensively managed Moso bamboo forest (173.47 t/ha) in Jiangsu, China, can accumulate much higher aboveground biomass than an extensively managed forest (67.61 t/ha). Similarly, a well-managed *Yushania alpina* forest, including harvest, fertilization, and prescribed flooding, in West Amhara, Ethiopia, can accumulate 92.20 to 118.60 tons of total biomass per hectare [58]. The fallow forests dominated by bamboo species in Luang Prabang, Laos, can reach 11.54 to 25.86 tons of aboveground biomass per hectare [59]. Additionally, a natural bamboo forest (*Dendrocalamus giganteus*) in Terei, India, can accumulate 270.97 t/ha in an aboveground biomass [56], while in Nakhon Ratchasima, Thailand, an afforested bamboo forest (*Thyrsostachys siamensis)*, naturally grown for more than ten years without human interventions, has about 34.80 t/ha in aboveground biomass [57]. Regarding carbon storage capacity, most global bamboo forests indicate great capacity. The riparian bamboo forest (*Dendrocalamus asper*) in Malang, Indonesia, demonstrates the most significant potential with 215.48 tC/ha [60]. Comparative capacities were found in several sympodial bamboo species in China, including *Dendrocalamus giganteus*, *Neosinocalamus affinis*, and *Dendrocalamopsis oldhami*, which can store up to 47.82 tC/ha [42]. Some bamboo forests present a lower capacity for carbon storage. For instance, the bamboo forest plantations with *Merostachys neesii* and *Dendrocalamus strictus* in the Atlantic Forest Protected Area (Brazil) are able to store 5.20 tC/ha [54], and the home garden management of mixed bamboo species in Assam, India, can store only 9.00 tC/ha [30]. These cases focus solely on bamboo's aboveground portions, underscoring gaps in research. It is evident that various study designs, methodologies, site conditions, species mixes, and climatic factors can greatly influence the outcomes

Table 5. Summary of research on bamboo biomass carbon storage.

Source	Species	Region	Carbon Storage (tC/ha)	Note
(de Campos Gorgulho Padgurschi et al. [54])	*Merostachys neesii*	São Paulo, Brazil	5.20	AGC; Dominant species
(Keren et al. [61])	*Dendrocalamus strictus*	Madhya Pradesh, India	5.02	AGC; Plantations in the Ladkui range of Sehore forest division
(Leksungnoen [57])	*Thyrsostachys siamensis*	Nakhon Ratchasima, Thailand	16.80	AGC; Natural more than 10 years (same below)
	Mix	Nakhon Ratchasima, Thailand	20.50	*Dendrocalamus membranaceus* and *Thyrsostachys siamensis*
(C. Li et al. [62])	*Phyllostachys pubescens*	Zhejiang, China	14.71	AGC; Transplanted in groups of three plants in excellent site conditions
(Liu et al. [63])	*Mix*	Zhejiang, China	13.1–17.13	AGC; All bamboo forests in Zhejiang
(Nath & Das [30])	*Mix*	Assam, India	9.00	AGC
(Nfornkah et al. [64])	*Oxytenanthera abyssinica*	Cameroon	13.13	AGC; Agro-ecological zones
	Phyllostachys aurea	Cameroon	67.78	AGC; Agro-ecological zones
	Bambusa vulgaris	Cameroon	29.62	AGC; Agro-ecological zones
(Prayogo et al. [60])	*Gigantochloa apus*	Malang, Indonesia	105.38	AGC; Bamboo riparian forest
	Dendrocalamus asper	Malang, Indonesia	189.84	AGC; Bamboo riparian forest
	Schizostachyum zollingeri	Malang, Indonesia	63.96	AGC; Bamboo riparian forest
	Gigantochloa atter	Malang, Indonesia	85.22	AGC; Bamboo riparian forest
(Singnar et al. [65])	*Pseudostachyum polymorphum*	Assam, India	29.00	AGC + BGC; Allometric modeling with R/S ratios
	Melocanna baccifera	Assam, India	60.50	AGC + BGC; Allometric modeling with R/S ratios
	Schizostachyum dullooa	Assam, India	69.70	AGC + BGC; Allometric modeling with R/S ratios
	Dendrocalamus hamiltonii	Assam, India	168.20	AGC + BGC; Allometric modeling with R/S ratios
(Sohel et al. [53])	*Bambusa vulgaris*	Moulvibazar, Bangladesh	52.96	AGC + BGC; Plantations in a degraded tropical forest
(Tang et al. [41])	*Phyllostachys pubescens*	Hubei, China	30.21	AGC; Management with the application of herbicide
(Teng et al. [42])	*Dendrocalamus latiflorus*	China	27.61	AGB + BGB; National scale
	Dendrocalamus membranaceus	China	23.81	AGB + BGB; National scale
	Bambusa textilis	China	26.20	AGB + BGB; National scale
	Dendrocalamopsis oldhami	China	38.93	AGB + BGB; National scale
	Bambusa burmanica	China	30.82	AGB + BGB; National scale
	Bambusa chungii	China	37.68	AGB + BGB; National scale
	Neosinocalamus affinis	China	34.88	AGB + BGB; National scale
	Dendrocalamus giganteus	China	47.82	AGB + BGB; National scale

We found only 36 bamboo species that were researched for carbon sink function; six monopodial species were studied in 22 papers, while 46 articles analyzed 30 sympodial species (Figure 5). However, there are more than 1600 bamboo species in 121 genera globally [66], and there is a significant lack of research on the remaining species. Moso bamboo (*Phyllostachys pubescens*) and Lei bamboo (*Phyllostachys violascens*) are the most studied monopodial species (green bars in Figure 5), and China, especially Zhejiang, is the region where the majority of research was conducted. However, the carbon sink capability of sympodial bamboo species in China remains an under-researched area. *Bambusa vulgaris* is the most studied sympodial bamboo species, followed by *Dendrocalamus membranaceus*, *Bambusa nutans*, *Bambusa balcooa*, and *Bambusa cacharensis*, with the research locations mostly in India. The majority of other sympodial bamboo species remain under-researched. The existing research includes countries in Asia that have large areas of bamboo, such as China (with research on *Phyllostachys edulis* and *Phyllostachys violascens*) and India (with research on *Bambusa cacharensis*, *Bambusa vulgaris*, and *Bambusa balcooa*) (Figure 6). A total of 35% of the selected studies focused on China, and another 35% focused on bamboo in India. The remaining studies included Laos (7%), Indonesia (7%), and Thailand (3%) in Southeast Asia; Cameroon (6%) and Ethiopia (1%) in Africa; and Brazil (1%) in South America.

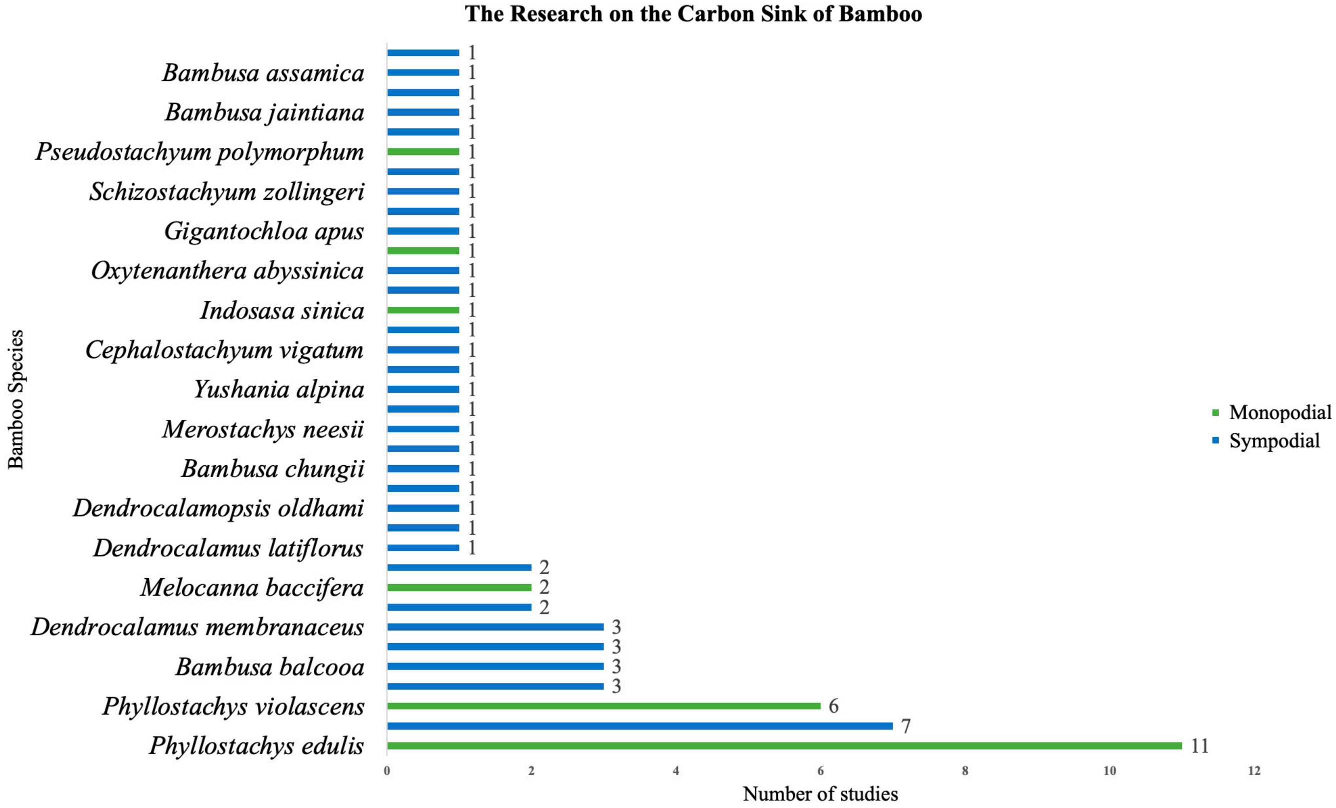


Figure 5. The relationship between monopodial and sympodial bamboo species and the number of studies.

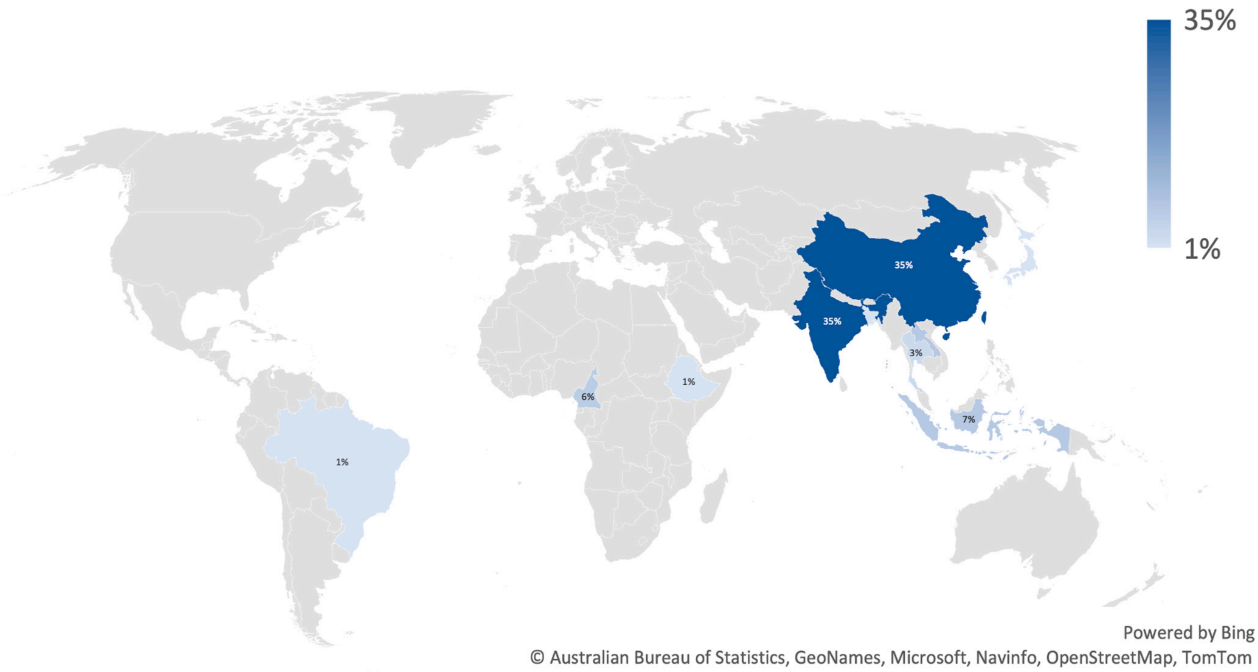


Figure 6. The intensity of research on bamboo carbon sink function by country (map created using Bing).

3.1.2. Factors Affecting the Bamboo Carbon Sinks

Abiotic Factors

Extreme climates, involving snow disasters, droughts, and floods, significantly affect bamboo plant growth, hence undermining their standing biomass and carbon sink function. For instance, following an extreme ice and snow event that occurred in 2008 and an extreme spring drought documented in 2011, carbon flux tower observations indicated that a local Moso bamboo forest's gross primary productivity (GPP) in the corresponding years was significantly reduced from the average level [67]. Mao et al. [49] further validated this drought effect on the net primary productivity (NPP) of the Moso bamboo forest in 2011 using a process-based ecosystem model. Similarly, Ge et al. [68] showed significant drops in shoot height, DBH (diameter at breast height), carbon sequestration capacity, soil carbon storage, and ecosystem carbon storage in throughfall exclusion Moso bamboo forest plots compared with the control groups that received regular rainfall. Using an eddy covariance data analysis, Liu et al. [47] argued that a summer drought was not a predominant factor in lowering GPP; however, ecosystem respiration could increase under drought conditions in a Lei bamboo forest. In Assam, India, bamboo forests in flood-unaffected villages have higher (about 1.5 times) standing biomass than flood-affected forests, indicating that flooding is a critical factor to consider in bamboo forest management [35]. As climate change worsens, more extreme weather events and climatic disasters could occur. Therefore, taking into account the climate factor is crucial for optimizing the carbon sequestration potential of future bamboo forests.

Sunlight, temperature, and rainfall are also the main climatic factors that influence the growth of bamboo species in different ways. Several researchers have reported a positive relationship between photosynthetically active radiation (PAR) and net ecosystem exchange (NEE). The absorbed PAR increases photosynthesis and drives more carbon sequestration and biomass accumulation. By measuring the CO_2 flux in the growing seasons of Moso and Lei bamboo forests in Zhejiang, China, L. Chen et al. [32] discovered a significantly positive correlation between PAR and NEE. However, Liu et al. [63] argued that considering all the bamboo forests in Zhejiang province, the correlation between annual irradiation and total carbon storage (0.32) was not as significant as other environmental factors, such as precipitation (0.86) and temperature (0.65). On the other hand, air temperature also impacts the carbon sequestration ability of bamboo forests. In different seasons, as the temperature changes, the carbon uptake of plants changes and tends to peak under certain appropriate temperatures. For instance, as the air temperature reaches its peak in July, around 25 °C, the carbon uptake of Moso bamboo in Zhejiang also peaks as the carbon sequestration of new leaves strengthens [32]. However, the situation differs for other species even in the same region. Lei bamboo's carbon sequestration ability in Zhejiang reaches a maximum value when the temperature reaches a suitable level (around 15 °C) in October [32]. On the national scale, the GPP and NPP of the bamboo forest ecosystem in China are negatively correlated with the minimum temperature (these findings apply mainly to Zhejiang, Guangdong, and Guangxi provinces; other provinces, like Hunan and Hubei, illustrated a positive correlation between GPP and NPP and minimum temperature) [69]. The temperature in spring, autumn, and winter is negatively correlated with the NEE of Lei bamboo forests; in contrast, in the summer, especially in dry conditions, temperature shows a positive correlation with the NEE, indicating that bamboo forests have different optimal temperatures for carbon sequestration depending on the season [46,70].

Precipitation increases the water availability for carbon sequestration in bamboo forests, directly influencing their productivity [32]. For example, by applying the integrated terrestrial ecosystem carbon-budget model, X. Li et al. [46] found that bamboo forests in Zhejiang had a significant positive correlation between precipitation and NPP. Liu et al. [63] also showed that precipitation was the most significant factor influencing the carbon stock of the bamboo forests in Zhejiang. Contrastingly, Shi et al. [71] applied structural equation modeling with the random forest algorithm on inventory data obtained in Zhejiang from 2004 to 2014. They concluded that the mean annual precipitation had adverse effects on

Moso bamboo carbon stock. This could be attributed to the exclusion of the soil carbon and atmospheric cycles in the modeling design.

Topographic factors, including slope position, slope gradient, aspect, and altitude, can also affect a bamboo ecosystem's carbon pool, especially at the soil level. In Zhejiang, the surface (0–30 cm) soil organic carbon (SOC) content showed a positive correlation with the altitude and slope gradient, while the correlation switched to negative for the deeper layer (60–100 cm) [72]. Comparing the SOC contents between the northern and southern aspects in all soil layers, Fang et al. [72] reported that the northern aspect contained a statistically in significant increase compared with the southern aspect.

Management Practices

The nature of management regimes for bamboo forests significantly affects their carbon sequestration potential. Most of the literature that covers management practices can be grouped into aboveground and belowground interventions. Soil is the primary substrate for bamboo growth, and suitable soil fertility conditions can lead to a larger soil organic carbon (SOC) pool and promote the aboveground plant carbon sink [60]. Thus, soil is a crucial part of bamboo management strategies. Fertilizer application is a common approach to boosting soil productivity; bamboo forests with a lower aboveground biomass standing are often observed in poor-quality sites with no fertilization [28]. L. Xu et al. [73] demonstrated that adding biomass charcoal significantly enhanced the total ecosystem carbon stock, including soil greenhouse gas emissions, SOC stocks, and vegetation carbon stocks of a Moso bamboo forest, but the effect varied when using medium (486.3% increase) and high (252.9% increase) application rates. Indeed, increasing the amount of fertilizer does not always result in an increase in biomass. Similarly, Li et al. [34] reported that a moderate fertilization (900 kg/ha biannually) treatment resulted in a higher increase in the average DBH of new Moso bamboo in Zhejiang compared with heavy fertilization (1800 kg/ha biannually) and no fertilization treatments. Still, a large amount of fertilization can boost the growth of bamboo shoots, increasing also the aboveground carbon sink with a simultaneous decrease in SOC content [34]. Also, intensive management of Moso bamboo in Zhejiang, combining high fertilization and high-intensity harvesting, diminishes the soil carbon storage in the 0–50 cm soil layer [34]. Fertilization applied in different seasons also affects bamboo carbon sequestration. In the winter, fertilization input causes a decrease in NEP in Zhejiang's Lei bamboo forests due to accelerated decomposition and respiration; in contrast, fertilization application in the autumn positively affects NEP due to the efficient nitrogen consumption during the carbon fixation process [48]. Also, Lu et al. [48] found that fertilization advances the starting date of the growing season by about a month, from April to March.

The other soil factor directly affecting bamboo carbon sink function is soil thickness. A high soil thickness can store enough nutrients and water, reflecting better performance in aboveground biomass accumulation [28]. SOC content decreases with decreasing soil thickness [72], and there is usually less SOC content in deeper soil because topsoil contains more organic matter [56]. Nitrogen, phosphorus, and potassium are all positively correlated with SOC since the amount of these three elements affects soil humus [56]. Winter mulching application, usually with rice straw and rice husks, aims to increase the soil temperature by 4–5 °C and preserve moisture, leading to enhanced bamboo shoot production in spring [74,75]. Huang et al. [38] measured the SOC storage, phytolith concentration, and PhytOC storage in a Lei bamboo forest in Zhejiang before and after mulch application. They found that the SOC storage in the 0–20 and 20–40 cm soil layers and the phytolith concentration and PhytOC storage in the 0–20 cm soil layer showed an apparent increasing trend after mulch application, but there was no evident change in the PhytOC storage and phytolith concentration in the 20–40 cm soil layer. Notably, the PhytOC accumulation rate (79 kg C/ha/yr) of 86% came from mulch application, significantly surpassing the global mean (24 kg C/ha/yr) [38].

Harvesting intensity and harvesting methods are critical for the bamboo ecosystem's function as a carbon sink. For instance, moderate harvesting and medium-density retention modes effectively promote an increase in aboveground carbon storage in new Moso bamboo in Zhejiang compared with intensive harvesting or no harvesting [34]. Also, intensive harvesting can induce significant soil disturbance, increasing greenhouse gas emissions and hence lowering long-term net carbon sinks [43,76]. Annual selective harvesting is an effective and unique method to store additional carbon (harvested bamboo products) without affecting the total carbon sink in a bamboo forest ecosystem [36]. Taking Moso bamboo as an example, biennial selective harvesting can contribute to a higher level of carbon sequestration than observed for other fast-growing species [39]. Additionally, the carbon stored in harvested bamboo can be transferred to durable harvest bamboo products (HBPs), implying that products with a longer lifespan can store the carbon for a longer time [39]. On the other hand, abandonment management (i.e., with no management activities) can also play a role in the SOC pool. Deng et al. [77] measured the SOC content in a Moso bamboo forest under different abandonment periods. They discovered that the SOC content increased in the topsoil (0–20 cm) with the extent of abandonment duration, but for the subsoil (20–40 cm), only a short abandonment duration (1–6 years) resulted in a noticeable increase in the SOC content compared with the control group (intensive management).

Furthermore, the bamboo forest standing structure, including the transplanting scheme and age, is also an essential factor influencing bamboo forest carbon sinks. Li et al. [78] reported that transplanting mother bamboo with rhizomes significantly facilitates carbon sequestration as the rhizome, especially in Moso bamboo, is a channel that absorbs nutrients in the early stage of reforested bamboo. The 3-PG transplanting approach (7.39 Mg C/ha), which means transplanting in groups of three plants, resulted in a larger amount of aboveground carbon accumulation than the individual-transplanting approach (3.98 Mg C/ha) in a ten-year Moso bamboo reforestation site [62]. Age also matters as different age structures within a forest may result in varying bamboo forest carbon stock levels. Lin et al. [79] assessed the carbon content factor (CCF) of four bamboo species in Taiwan: Moso, Ma, Makino, and thorny bamboo. They found that, except for thorny bamboo, the species presented a similar pattern: the CCF increased from 1 to 4 years with a slight decrease at 5 years. Also, the CCF of the four species showed a decreasing trend from the top to the bottom part of the bamboo culm [79]. Similarly, three bamboo species in India, Bambusa balcooa, Bambusa vulgaris, and Bambusa cacharensis, exhibited an increasing aboveground biomass pattern from one to three years but slowed down as the plants aged to four years, and the annual increment of aboveground biomass declined during the aging process [40]. This is partly because bamboo's photosynthetic function weakens as it ages, especially for Moso bamboo [67]. A recent study also explored the change in belowground bamboo biomass with the growth of culm in the sub-Himalayan region of eastern India. The study documented that the belowground carbon sink increased with the aging of culm via the increase in belowground biomass in two species: *Bambusa nutans* and *Dendrocalamus giganteus* [56].

Although the existing literature provides comprehensive insights into a variety of abiotic factors and management practices that influence a bamboo forest's carbon sequestration capabilities at various scales, the study of biotic factors, such as species interactions, mutualism, and ecological relationships, remains underrepresented. This gap in the literature partially stems from the absence of dedicated research that holistically considers both biotic and abiotic factors. For instance, C. Li et al. [34] only focused on how different fertilization rates and harvesting intensities affected the SOC pool, while Mao et al. [49] compared how different climate variables, including precipitation, temperature, and radiation, affected NPP. Also, whether abiotic factors or anthropogenic techniques have a more significant impact remains unknown. Although there is research at the national scale [42,69], the scope is limited to China, and future national-scale research in other bamboo-rich countries is needed.

3.2. Carbon Storage in Bamboo Products

While flowering is a natural phenomenon in bamboo forests, it often leads to the subsequent death of the plant in many bamboo species. In managed bamboo forests, it is ideal to maintain a regular harvesting cycle to not only prevent unpredictable large-scale flowering events but also to keep the bamboo robust and productive [18]. Bamboo needs a short harvesting cycle to keep it healthy, productive, and sustainable. This cycle allows forest managers to log bamboo every one to two years, leading to a significant yield for making products [80]. In this way, bamboo forests can be sustainably managed while constantly yielding bamboo culms for production. The annual yield of representative bamboo species, Moso bamboo and Guadua bamboo, is much higher than representative lumber species, including European oak, Scots pine, and Chinese fir [81]. Numerous studies in the literature have shown that bamboo woods can also be turned into a wide range of durable products and store a considerable amount of carbon, making them a sustainable substitute for wood and significantly depressurizing other timber resources [39,53,82]. In China, annual harvestable bamboo culms are about 1.8 billion, equating to more than 200 thousand m^3 of timber [8]. The avoided cutting of other arbor forests, since timber can be substituted with bamboo, can significantly contribute to forest conservation and biodiversity, water, and soil conservation [83]. Notably, while also storing carbon and leading to a carbon-negative life cycle, harvested bamboo products provide a stable income source for local rural communities, especially in the Global South [30,84]. For instance, in 2018, with 45 million people directly working in the bamboo industry, China's output value from the bamboo industry reached USD 35.4 billion [8].

Utilizing harvested bamboo in the building construction sector can significantly contribute to climate change mitigation. Bamboo, when used in construction, has the potential for causing the least climate impact and may even result in a net removal of carbon, largely due to its carbon storage capabilities, as highlighted in Table 6. Van der Lugt et al. [14] applied life cycle analysis (LCA) to flattened bamboo flooring boards, ply bamboo panels, and strand-woven bamboo made from Moso bamboo grown and processed in China and shipped to the European market. They concluded that all products have a negative carbon footprint. This conclusion was underpinned by their finding that credits from bio-energy production at the end of life (EoL) phase and carbon sequestration from land change substantially offset emissions associated with production and domestic transportation. Chang et al. [85] conducted an LCA that showed plybamboo's net negative carbon emission when compared with reinforced steel, concrete, and PVC, using a functional unit size of 2440 mm × 1220 mm × 20 mm and adjusting Ecoinvent data for Taiwan's conditions. This comprehensive methodology accounted for all life cycle stages, from harvesting to transportation, detailing the environmental impacts in comparison with other materials. Zea Escamilla et al. [86] found that bamboo-based constructions—including single-story houses, glue-laminated single-story houses, and multi-story glue-laminated houses—offer a carbon-negative advantage over traditional high-emission materials such as brick and concrete. Their assessment was rooted in a thorough LCA, factoring in biogenic carbon, consistent functional units, and system boundaries for a balanced comparison. Similarly, Laleicke et al. [87], using LCA, including plantation, harvest operation, conditioning, transportation, and use, clearly proved that bamboo scaffolding is far more carbon-negative than steel production, which is highly carbon-positive. It was suggested that producing each bamboo board in Colombia could reduce 117 kg of CO_2 emission per functional unit [88]. In the context of an LCA per functional unit, both industrialized and non-industrialized bamboo boards in Thailand showed 'net negative' carbon emissions, indicated by the values of -11.50 kg CO_2-eq. and -6.44 kg CO_2-eq., respectively; this means these bamboo boards effectively remove carbon from the atmosphere, in contrast with high-emission precast concrete cladding production, which emits 33.80 kg CO_2-eq [89]. Regarding producing bamboo scrimber flooring, Gu et al. [80] concluded, using LCA, that a negative 14.89 kg CO_2-eq could be achieved for every 1 m^3 produced in China, while in Vietnam, manufacturing strand-woven bamboo flooring can reach -0.26 kg CO_2-eq./kg [90]. In addition, kitchen countertop panels (−0.47 kg CO_2-eq./kg) and strand-woven mats (−0.70 kg CO_2-eq./kg) made from bamboo can also achieve a carbon-negative life cycle in Vietnam [90].

Table 6. Summary of research on LCA of bamboo products.

Source	Region	Product	Carbon Footprint (kg CO_2eq/m^3 Product)
(van der Lugt et al. [14])	China, Europe	Flattened bamboo flooring boards	−524.00
	China, Europe	Plybamboo panels	−148.00
	China, Europe	Strand-woven bamboo beams	−381.00
	China, Europe	Strand-woven bamboo decking	−23.00
(Chang et al. [85])	China	Plybamboo (bleached)	−990.00
(Estimated)	China	Plybamboo (heat treatment)	−700.00
	China	Plybamboo	−900.00
(Zea Escamilla et al. [86])	Colombia	Bamboo single-story house	−20.00
(Estimated)	Colombia	Glue-laminated bamboo single-story house	−10.00
	Colombia	Glue-laminated bamboo multi-story building	−5.00
(Laleicke et al. [87])	China	Bamboo scaffolding	−99.00
(Restrepo et al. [88])	Colombia	Bamboo board	−2456.00
(Bukoski & Gheewala [89])	Thailand	Industrialized bamboo board	−11.50
	Thailand	Non-industrialized bamboo board	−6.44
(Gu et al. [80])	China	Bamboo scrimber flooring	−14.90
(Caldas et al. [91])	Brazil	Bamboo bio-concrete-B (52.5%)/W (0.5)	−55.00
	Brazil	Bamboo bio-concrete-B (52.5%)/W (0.45)	−45.00
	Brazil	Bamboo bio-concrete-B (52.5%)/W (0.4)	−35.00
Source	**Region**	**Product**	**Carbon Footprint (kg CO_2eq/kg product)**
(Chang et al. [85])	China	Plybamboo (bleached)	−980.00
(Estimated)	China	Plybamboo (heat treatment)	−600.00
	China	Plybamboo	−1250.00
(Phuong & Xuan [90])	Vietnam	Strand-woven bamboo flooring	−0.26
	Vietnam	Bamboo kitchen countertop panel	−0.47
	Vietnam	Strand-woven bamboo mat	−0.70

However, while most studies demonstrated a net carbon-negative life cycle, some studies showed that bamboo products can be carbon-positive but still with significant climate change mitigation potential. For instance, bamboo particles, a waste material, can be synthesized into strong bamboo-based bio-concrete, acting as a sustainable alternative to conventional concrete and ceramic masonry [92]. Caldas et al. [92] assessed the climate change impact of bamboo bio-concrete and traditional concrete masonry in terms of production, replacement, operational energy use, and end-of-life. They found that bamboo bio-concrete presented the smallest carbon dioxide emissions regardless of whether the IPCC method (static life cycle impact assessment) or Levasseur et al. [93] method (dynamic life cycle impact assessment) was used. This emission reduction is primarily attributed to bamboo's inherent carbon sequestration during its growth phase and the enhanced time-dependent carbonation in bamboo bio-concrete, rather than an assumption of zero net GHG contribution. Caldas et al. [92] further showed that both wood bio-concrete and bamboo bio-concrete, using a LCA, could achieve a carbon-negative status if considered as a replacement for Portland cement for SCMs (supplementary cementitious materials). Similarly, adding bamboo particles to plastering mortars can significantly reduce greenhouse gas (GHG) emissions, as the carbonation, carbon sequestration, and storage processes of bamboo, although still slightly carbon-positive, are low enough to considerably contribute to GHG reduction [94]. Paiva et al. [94] further reported that mortar made with a greater portion of bamboo particles presented a greater potential for GHG reduction and better thermal performance due to a lowered thermal conductivity in the bamboo end product.

Various studies have demonstrated the carbon storage potential of bamboo products; however, there are research gaps in how much carbon a bamboo forest can store because it is difficult to trace all product types, as bamboo timber from one forest can produce various types of products. Different types of bamboo products may have different shares in a particular bamboo forest, so future research should focus on the amount of carbon stored in all types of products each year using a LCA. An accurate calculation of the product carbon pool can help future bamboo carbon project development. At present, it is still unclear how much wood timber is saved and, hence, how much carbon is stored in a bamboo forest based on the number of bamboo culms harvested annually or biennially.

3.3. Carbon Credits in Bamboo Projects

Bamboo is extensively distributed in tropical, subtropical, and mild-temperate global zones with around 1662 species and 121 genera [66]. Bamboo forest carbon projects have considerable potential for trading in the form of afforestation, reforestation, and reducing emissions from deforestation and forest degradation (REDD) under the clean development mechanism (CDM) and many other national and international schemes [53,82]. For instance, the Moso bamboo forest can sequester around 22% more carbon than the fast-growing Chinese fir forest per 60-year cycle [11]. In addition to carbon sequestration and its potential for carbon offset projects, bamboo forests also play an essential role in rural poverty alleviation and diverse ecosystem functions, including soil erosion prevention and maintaining the atmospheric oxygen–carbon balance [36]. However, there are limitations to including bamboo in REDD projects, as the core management strategy of selectively cutting bamboo forests is considered unsustainable for REDD projects [82]. Additionally, REDD projects require trees, while bamboo belongs to the Poaceae family, causing a fuzzy definition of whether or not to include bamboo in forest ecosystems [82]. Nath et al. [82] proposed that forthcoming REDD initiatives should consider bamboo due to its sustainable harvesting practices, and the 2013 Warsaw Framework for REDD empowers nations to individually define their forests.

Bamboo carbon project methodologies refer to methodological accounting rules and standards for measuring, reporting, and verifying bamboo-related carbon activities. Although the Chinese market is already equipped with bamboo methodologies, the National Development and Reform Commission of China (NRDC) halted the China Certified Emission Reduction (CCER) market because of issues, including the small transaction volume of CCER and insufficient standardization of individual projects [95]. As a result, there is only one registered bamboo CCER project on the market (Table 7), the bamboo afforestation project in Tongshan County, Hubei Province (Tongshan). The Tongshan Project is a 20-year afforestation project covering about 700 ha, accounting for aboveground, belowground, and product carbon pools; it removes about 6556 tons of carbon annually [96]. Cheng et al. [97] used the net present value method to analyze input–output data from the Tongshan project considering three aspects: bamboo timber, carbon credits, and bamboo shoots. They found that the project's expected earnings were RMB 28,488 per hectare, and the net present value was RMB 10,750 per hectare, demonstrating great economic benefits. Although the Shunchang County State-owned Forest Farm Bamboo Forest Management Carbon Project (Shunchang) is listed under the Fujian Forestry Carbon Emission Reductions (FFCER), it also complies with CCER bamboo methodologies. The Shunchang Project is a 30-year forest management project with 2278 ha and extensive tending measures, including adjustments in stand structure and density, fertilization, and shoot retention. The project can reach 8639 tons of annual emission reductions [98]. Zhao et al. (2020) [99] applied the CCER methodology for bamboo forest management to systematically measure the carbon credits generated by the Shunchang Project over the first six years. They found that the average annual emission reduction was 25,563 t CO_2-e, suggesting that the carbon credit potential is greater in the early years. On the other hand, the French Development Agency (AFD) developed a large forest management project with 100,100 ha of bamboo rehabilitation and 60,600 ha of tree plantation. The annual emission reduction capacity was 129,000 tons, but the detailed methodology was not reported [100]. However, the stagnation of CCER prevented a significant number of CCER bamboo projects from entering the market. All relevant industry participants expect the relaunch of CCER as the remaining valid CCER in stock is running out.

Table 7. The current bamboo forest carbon projects worldwide [96,98,100,101].

Name	Platform	Status	Country	Estimated Annual Emission Reduction (tCO_2e)	Crediting Period Start Date	Crediting Period End Date
Bamboo Plantations by Farmers and Community in the Country	VCS	Under development	India	61,126	09-07-2019	08-07-2049
Reforestation Project in Meghalaya by Shillong Bamboo	VCS	Under development	India	100,000	01-07-2017	30-06-2037
Bisignano and Mesoraca Project of Afforestation of the Agricultural Company Gaia SRL Bamboo Plants	VCS	Under development	Italy	315,494	01-07-2022	30-06-2050
Reforestation Project of the Agricultural Company Gaia SRL Bamboo Plant	VCS	Under validation	Italy	2,430,904	17-09-2019	16-09-2051
Eastern Cape Bamboo Forestry Project, South Africa	VCS	Under validation	South Africa	460,404	N/A	N/A
Eastern Cape Restoration Project, South Africa—Somerset East	VCS	Under validation	South Africa	211,721	01-10-2022	30-09-2062
Eastern Cape Restoration Project, South Africa—Makhanda	VCS	Under validation	South Africa	135,772	01-10-2022	30-09-2062
Lanao del Sur Bamboo Reforestation Project	VCS	Under validation	Philippines	297,917	01-06-2022	31-05-2042
North Bandai Bamboo Reforestation Project	VCS	Under validation	Ghana	105,106	01-06-202	31-05-2041
Bandai Hills Bamboo Reforestation Project	VCS	Under validation	Ghana	157,858	01-06-2022	31-05-2032
Rwanda Riparian Restoration Project	VCS	Under validation	Rwanda	45,841	01-10-2022	30-09-2032
Peri-urban Bamboo Planting around South African Townships	VCS	Registered	South Africa	16,000	01-03-2011	28-02-2031
EcoPlanet Bamboo Central America—Reforestation Project	VCS	Registered	Nicaragua	40,815	01-06-2011	31-05-2031
Bamboo Afforestation Carbon Project in Tongshan County, Hubei Province	CCER	Registered	China	6556	01-01-2015	31-12-2034
Shunchang County State-owned Forest Farm Bamboo Forest Management Carbon Project	FFCER	Registered	China	8639	15-01-2010	14-01-2040
Fostering Sustainable Forest Management in Hunan Province	AFD	Completed	China	129,000	19-12-2012	31-10-2018
Bamboo Forest Carbon Project in Xishuangbanna, Yunnan	Panda	Withdrawn	China	18,200	01-11-2010	31-10-2030

Regarding the international aspect, the Ecoplanet Bamboo Group developed the first-accredited bamboo reforestation project under the Verified Carbon Standard (VCS) in Nicaragua with 3199 ha of area (EcoPlanet Bamboo Central America—Reforestation Project Nicaragua) [102]. This project has five additional bamboo reforestation projects in the VCS pipeline [103]. Another registered VCS bamboo project is the Peri-urban Bamboo Planting around South African Townships (South Africa) project, developed by the Food and Trees for Africa (FTFA) and Renewable Energy Solutions (RES) [104]. All the VCS bamboo projects (Table 7) are based on traditional CDM methodologies, and they present higher emission reduction ability than Tongshan and Shunchang projects, especially the Nicaragua project. Apart from the significant difference in total area (Nicaragua, 3199 ha vs. Tongshan, 700 ha), the Nicaragua project included carbon pools from shrubs, dead wood, forest litter, and soil organic matter [105]; however, due to conservative principles, the projects based on CCER bamboo methodologies ignored all these carbon pools [96,98].

As in China, the development of carbon projects for bamboo forests in other bamboo-rich global locations is currently very under-exploited. Acquiring data from the Verra registry database [101], the number of bamboo projects (13) is insignificant when compared to the large number of all forestry projects (520) (Table 8). Similarly, comparing the annual emission reduction amount, bamboo projects account for only 0.34% of all forestry projects in VCS. These bamboo projects were developed based on arbor forest methodologies rather than bamboo-specific methodologies, potentially blocking the convenience and accessibility of developing bamboo projects. Bamboo is different from tree species regarding its biological mechanisms. For instance, a bamboo forest afforestation project typically has two natural periods: growth and stable periods [106]. Bamboo grows rapidly when new shoots come out and can reach maturity within 4–5 years, much quicker than common tree species; after reaching maturity, an afforested bamboo forest can be sustainably managed. Thus, the calculations of net aboveground carbon stock changes in these two periods are different from the existing tree-based afforestation methodologies. An internationally recognized bamboo methodology may motivate the development of under-exploited bamboo projects. Other underlying reasons that limit their development, including geographic locations, costs and benefits, public awareness, etc., need further research.

Table 8. The bamboo forest carbon project status at VCS [101].

	Number	Annual Emission Reductions (tCO_2e)
Bamboo Projects	13	4,378,958
Forestry Projects	520	1,283,575,126
Bamboo's Proportion	2.50%	0.34%

Managing bamboo forest projects also presents challenges. Although gregarious flowering can be overcome using short rotation and stand replacement, bamboo forests are vulnerable to insects and disease [18], influencing project permanence. The offset standard's credibility is crucial. For example, before the completion of afforestation, the Bamboo Forest Carbon Project in Xishuangbanna, Yunnan Province (Table 7), was withdrawn after the Panda Standard exited the carbon market due to the standardization of the national carbon offset market. A farmer's commitment to managing a project is essential to effective emission reduction; however, Wang et al. [107] found that project-related income and persistence in and perception of a project can largely influence a farmer's overall commitment to a bamboo project. Although Pan et al. [108] broadly reviewed critical challenges in forestry carbon projects, there is minimal research on comprehensively analyzing the barriers and issues of developing bamboo projects and the potential solutions.

Nevertheless, numerous studies have assessed the great potential of future bamboo carbon projects. For instance, Kumar et al. [56] demonstrated that three bamboo species in the Indian Eastern Himalaya, *Bambusa nutans*, *Dendrocalamus giganteus*, and *Melocanna baccifera*, have huge ecosystem carbon stocks (44.46–163.28 t/ha), indicating the considerable potential for developing CDM and REDD+ projects. Similarly, in Northeast India, village bamboo in the traditional home garden scheme showed a total carbon storage of 50.1 t ha^{-1}, providing the local small-hold farmers the opportunity to earn carbon credits under CDM [30]. Recently, new forms of bamboo carbon credits trading have emerged. For example, the government-led Liangshan Cooperative in Anji County, Zhejiang Province, has gained increasing public attention in China. The forest rights of farmers are transferred to the professional village cooperatives for unified management; after verification, a carbon project package is formed, and the transactions are carried out through the Liangshan Cooperative [109]. In addition, 80% of the net income from the bamboo project transaction are returned to the village collectives and townships [109]. The future global potential of bamboo forests in developing carbon projects regarding the area and emission reduction amount remains unclear, especially for undeveloped bamboo forests, which could turn into projects in all kinds of platforms, including compliance markets, voluntary markets, cooperatives, and banks.

4. Conclusions

We presented a comprehensive synthesis of the role of bamboo in mitigating climate change as a nature-based solution (NbS), contributing in three major ways as bamboo biomass carbon sinks, bamboo product carbon storage, and bamboo project carbon credits. Bamboo forests, being fast-growing species with high annual regrowth after harvesting, have a considerable capacity for carbon sequestration and storage. However, most of the studies focused on Asia, namely, China (*Phyllostachys pubescens* and Phyllostachys *violascens*) and India (*Bambusa vulgaris*), with only 36 species compared with over 1600 species globally. In China, particularly, the carbon sink function from plentiful sympodial bamboo resources, especially those with large diameters, still needs to be researched. Given China's emerging emphasis on sustainable development and its commitment to the Paris Agreement, the potential of bamboo as a carbon sink becomes even more crucial. While our review predominantly encompasses studies from Asian countries with abundant bamboo resources, we recognize the need to expand research to other bamboo-rich regions such as South America and Africa. This would ensure a more comprehensive understanding of the carbon sink function of bamboo forests, considering their unique abiotic factors across different continents. Different abiotic factors along with under-researched biotic interactions and management strategies positively or negatively affect the carbon sequestration capacity of bamboo forests. For optimal bamboo forest management, although with great difficulty, future research should combine all factors influencing carbon sinks and analyze their importance. Current national-scale research is limited to China, and future analysis of other countries' national-scale research on how different factors affect bamboo carbon stock is needed.

Harvested bamboo can be made into durable products, which further store carbon for the long term. Most bamboo products exhibit net-negative carbon emissions, thus contributing to long-term carbon sequestration. However, the research scope is limited to the LCA of products rather than how much carbon can be reduced based on the scale of a bamboo forest, as the whole forest can yield bamboo timbers for all types of products. Future research on product carbon pools at the bamboo forest scale is needed for optimal forest management and to enhance the product carbon pool calculation in bamboo carbon projects. This paper also documented bamboo forest potential for trading in the carbon offset market; however, the number is not comparable to other forestry projects, partially owing to the lack of appropriate bamboo methodologies. A notable challenge in REDD projects is the contention around bamboo's inclusion due to its categorization in the *Poaceae* family and its perceived unsustainable harvesting. This paper also highlighted limited critical studies related to the challenges of existing bamboo carbon projects. Future studies should comprehensively analyze the best practices and lessons learned from existing bamboo carbon projects to address the value and limits of bamboo as an NbS to climate change. Moreover, we call for research on the future global potential and challenges of bamboo carbon project development from all possible platforms, such as compliance markets, voluntary markets, cooperatives, and banks, considering bamboo's role in climate change adaptation and mitigation. Scholars can refer to this review as a guide for future research, and decision-makers can refer to it so as to better formulate future climate policies.

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