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Research article

Integrating bamboo forests into the carbon markets: Insights from China

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ABSTRACT

In the course of fighting climate change, bamboo forests are increasingly recognized as a modern nature-based solution. Developing bamboo-based carbon projects can bring triple-bottom-line benefits to livelihood, climate, and industry, but they can also face various barriers. Based on a qualitative research framework, this paper discusses the key challenges and lessons learned from China. It then describes some of the innovative approaches that have been adopted to overcome these challenges. We identified four overarching challenges: economic, market, technical, and social. First, the rising labor costs and declining market demand for bamboo products are critical economic challenges, leading to high upfront project development costs and increasingly lower financial viability of bamboo-based investments. Second, the low transaction demand and the shifts in the national offset market have contributed to the market challenges. Moreover, many bamboo-rich regions face technical difficulties, such as lacking forestry infrastructure and skilled bamboo-specific carbon experts. Fourth, social challenges exist regarding the information asymmetry between farmers and project developers and the difficulties encountered when managing forest land-use rights in China. Inspired by several recent innovations, this paper recommends a green financing model integrating large-scale, professional forest management and the essential downstream bamboo industry development via strategies such as concessional loans and carbon-linked subsidies. There is a need for internationally standardized methodologies for bamboo forest management that incorporate advanced carbon accounting for selective harvesting and product carbon pools, enhancing credibility and scalability in compliance and voluntary markets. Such developments are needed if global policymakers, especially from some of the bamboo-based economies of the Global South, are to transform bamboo resources effectively for climate change mitigation, environmental protection, and local livelihood enhancement.

1. Introduction

The climate change crisis has been intensifying, bringing adverse impacts to every region worldwide (Lee et al., 2023). Global warming has climbed in the decade of the 2010s to 1.1 °C above pre-industrial levels (Lee et al., 2023) and recently exceeded 2 °C in November 2023 (European Union's Copernicus Climate Change Service, 2023). 2024 was the hottest year ever, with an average of 1.6 °C above pre-industrial levels, the first time that the Paris 1.5 °C target was surpassed for a calendar year (Copernicus Climate Change Service, 2024). Under current global commitments, the temperature rise is expected to reach 2.6–3.1 °C in the 21st century, requiring much more ambitious pledges and actions (United Nations Environment Programme, 2024). While emission reductions are always the top priority in addressing climate change, carbon offsetting has emerged as a critical mechanism that allows more flexibility in fulfilling climate targets (United Nations, 2023). There is increasing interest in nature-based solutions (NbS) involving agriculture and forestry activities because of their evident co-benefits to

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local livelihoods, biodiversity, and the environment (World Bank, 2023). In 2022, 54 % of new project registrations, in both regulatory and voluntary markets, were sourced from forest-related activities, suggesting a promising future expansion (World Bank, 2023). Despite the anticipated prospects for forest carbon offsets, carbon finance in the bamboo realm remains significantly under-explored (Pan et al., 2023).

Bamboo, widely distributed in tropical, subtropical, and temperate regions, now occupies 35 million hectares globally (Food and Agriculture Organization, 2020). The majority (~92 %) of the species (ca. 1358/1482) are woody (Liese and Köhl, 2015a), and some species can grow up to 35 cm in diameter and 40 m in height (Liese and Köhl, 2015b; Lobovikov et al., 2009), forming tree-like forests that are accredited by many authoritative sources such as the Food and Agriculture Organization (FAO) and the Intergovernmental Panel on Climate Change (IPCC) (Lobovikov et al., 2012). Woody bamboo forests are renowned for their carbon sequestration, rapid growth, and regenerative ability, ensuring an enormous and sustainable carbon sink with stocks of up to 392 Mg C per hectare (Yuen et al., 2017). For example, Moso bamboo (*Phyllostachys edulis*), naturally distributed in East Asia, the most economically valuable monopodial bamboo species worldwide (Liese and Köhl, 2015c), can grow 12.5 m in 50 days while sequestering 1.82 kg carbon, surpassing the carbon sequestration capacity of another widely distributed species in similar regions, Chinese fir (*Cunninghamia lanceolata*), 1.4 fold (Zhou and Shi, 2017). Once these bamboo forests mature, regular selective harvesting (annually or biennially) is practiced to ensure its sustainability (Katayama et al., 2015; Kuehl et al., 2013), yielding substantial quantities of harvested bamboo that can be made into various durable products, often replacing less sustainable products such as plastics (Gan et al., 2022; Wang et al., 2025). In addition, bamboo shoots are a nutrient-rich, low-fat, high-fiber food product with well-known health benefits, including anticancer and antioxidant properties (Chongtham et al., 2011). There are also potential carbon benefits from sustainable treatments in processing (Weng et al., 2024).

Studies worldwide have investigated the carbon sinks of bamboo forests and prospected their roles in the carbon markets. Many of these studies have focused on sympodial bamboo species, which are dominant in tropical and subtropical regions and characterized by clumping rhizomes. For instance, the significant carbon stock in the three prominent bamboo species in North East India (*Bambusa cacharensis, B. vulgaris*, and *B. balcooa*) suggest that bamboo can be a potential climate solution not only for its carbon benefits (120.75 t C ha^{-1}) but also for local livelihoods and the economy (Nath et al., 2009). In a later study, Nath et al. (2018) developed biomass models for these species and indicated that properly managing these sympodial bamboo forests can provide significant opportunities for the carbon market. In Africa, bamboo forests have received attention for their role in landscape restoration and their foreseeable opportunities for carbon offsetting schemes (Masisi et al., 2022; Nigatu et al., 2020). Similarly, the total ecosystem carbon stock for typical Guadua bamboo forests (*Guadua angustifolia*) in Colombia and the Andean region of South America can reach 330.9 Mg C ha^{-1} (Camargo García et al., 2023), demonstrating their enormous potential for carbon farming. Although Europe has no native species, bamboo has gained popularity in gardening (Zhou and Shi, 2017). Vadalà et al. (2022) confirmed Moso bamboo is a suitable species to introduce to Italy for afforestation, and these forests can potentially offset 26,888 t CO_2 per hectare in a hypothetical 100-year project period (Marchi et al., 2023). Despite being increasingly recognized for their potential in carbon markets, these exploratory studies have limited scope in connecting real-life bamboo carbon projects.

Bamboo is widely distributed and abundant in China, and its utilization is more diverse than anywhere else (Zhou and Shi, 2017). There have been numerous studies of bamboo carbon sinks, providing a comprehensive basis for bamboo project financing and implementation, both for plantations and forest management projects (Ao et al., 2021). For instance, a 10-year field monitoring study demonstrated that transplanting in groups of three plants accumulated significantly higher carbon than individually in a reforestation context, reaching 14.71 Mg C ha^{-1} (Li et al., 2021a). Another study highlighted the positive correlations between the number and biomass of culms (individual bamboo stems) with various rhizome parameters, suggesting a closely linked growth and resource allocation strategy between the aboveground and belowground parts of the bamboo (Li et al., 2021b). The age group of bamboo forests in China is usually classified according to the following pattern: age group 1 (age 0–1), age group 2 (age 2–3), age group 3 (age 4–5), age group 4 (age 6–7), and so on in a similar fashion. Optimal aboveground carbon stocks rely on an appropriate culm age structure (age ratio 3:3:3:1) and harvesting strategies to develop a productive stand structure with the optimal diameter at breast height (DBH), culm density, and age (Xu et al., 2022). Further studies have reported that management combining medium fertilization and low harvesting will lead to a healthy bamboo forest ecosystem and yield optimal carbon benefits (64.72 t C ha^{-1}) (Li et al., 2017, 2018). An economic study revealed that the annual net present values (NPV) for real-life bamboo forest management projects in China were about US$ 500 per hectare, implying poverty alleviation and livelihood improvements (Gu et al., 2019).

There are two published methodologies for developing bamboo-related carbon projects: one for bamboo afforestation (China National Development and Reform Commission, 2013) and one for improving bamboo forest management (China National Development and Reform Commission, 2015). Most existing officially registered bamboo carbon offset projects in China primarily serve regulatory purposes: Chinese Certified Emission Reduction (CCER) for the China National Emission Trading System (ETS) and other Pilot ETS markets and Fujian Forestry Certified Emission Reduction (FFCER) for the Fujian Pilot ETS. A few bamboo projects are also involved in provincial/municipal voluntary programs, such as in Zhejiang Province and Chishui City of Guizhou Province. The summary of the current development status of the seven main bamboo-related carbon projects in China is listed in compliance markets (Table 1). Apart from the afforestation project in Hubei Province, all projects are related to forest management for carbon enhancement, i.e., improved forest management (IFM) activities. This landscape significantly differs from bamboo carbon projects outside China, mainly developed by Ecoplanet Bamboo (Ecoplanet Bamboo, 2024). Among their eight (six registered and two registration requested) ARR-type projects (afforestation, reforestation, and restoration) across Asia, Africa, and Central America, four relate to reforestation, and four target restoration (Verra, 2024). This difference is primarily due to a lack of an international IFM bamboo methodology that can be applied to regions outside China.

Bamboo forest plantation projects usually have a shorter period (20 years) than forest management projects, thanks to bamboo's fast growth and strong adaptability to new ecological conditions. The annual credits per unit area for afforestation projects are typically higher as the additionality is from the conversion of non-forest land to forests. Despite the availability of bamboo methodologies in the Chinese market, in 2017, the National Development and Reform Commission of China (NDRC) suspended CCER due to concerns such as low transaction volumes and a lack of standardization in individual projects and started revision processes (National Development and Reform Commission of China, 2017). The pause in the CCER stopped the five projects undergoing validation. Seven projects in China are distributed in three southern provinces, Zhejiang, Hubei, and Fujian (Fig. 1). Out of the 7.56 million ha of bamboo forests in China, these provinces possess more than 30 % (2.32 million ha) (Feng and Li, 2023). Zhejiang has the most projects because of its abundant bamboo resources (0.88 million ha) (Feng and Li, 2023), and more than half of the core researchers in bamboo forest carbon sink enhancement are affiliated with Zhejiang institutions (Ao et al., 2021). However, many bamboo-rich provinces, such as Jiangxi (1.23 million ha) and Hunan (1.22 million ha) (Feng and Li, 2023), have yet to develop a bamboo carbon project, demonstrating the immense future potential.

Table 1
Current status of bamboo carbon offset projects in China's compliance carbon markets.

Project Name	Market	Status	Annual Credits (tCO_2e)	Project Area (ha)	Unit Amount (tCO_2e/ha)	Project Period (year)
Bamboo Forest Management Carbon Project in Shunchang County, Fujian Province	FFCER	Registered	8639	2278.5	3.8	30
Bamboo Afforestation Carbon Project in Tongshan County, Hubei Province	CCER	Registered	6556	700.94	9.4	20
Bamboo Forest Management Carbon Project in Tongshan County, Hubei Province	CCER	Under Validation	132,853	25,202.54	5.3	30
Bamboo Forest Management Carbon Project in Anji County, Zhejiang Province	CCER	Under Validation	8322	1426.27	5.8	30
Bamboo Forest Management Carbon Project in Jingning County, Zhejiang Province	CCER	Under Validation	32,389	5513	5.9	30
Bamboo Forest Management Carbon Project in Zhuji City, Zhejiang Province	CCER	Under Validation	41,176	6179.24	6.7	30
Bamboo Forest Management Carbon Project in Suichang County, Zhejiang Province	CCER	Under Validation	61,852	8636	7.2	30

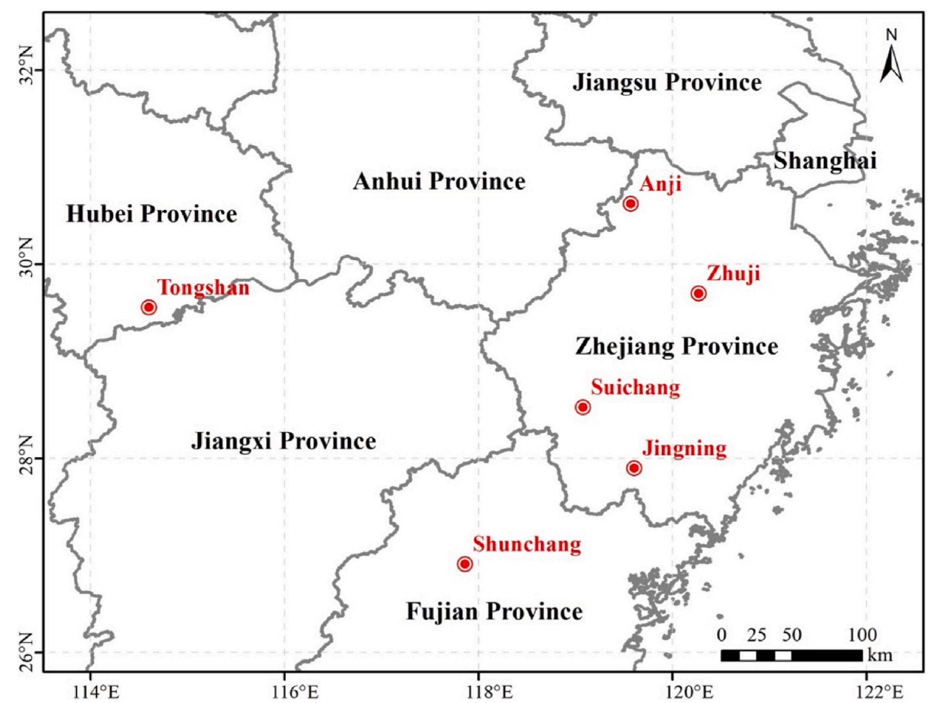

Fig. 1. The locations of seven bamboo carbon projects in China's compliance markets.

However, developing forestry-based carbon projects remains challenging and uncertain due to a combination of methodological barriers—including additionality, permanence, and leakage—socio-economic issues such as transaction and opportunity costs, and implementation difficulties related to MRV (Pan et al., 2022), as well as systemic baseline inflation that results in substantial over-crediting in existing offset programs (Badgley et al., 2022), and deep ecological and institutional uncertainties that undermine the long-term reliability of forest carbon accounting (Wells et al., 2023). Thus, successful case studies can be valuable. Over the past decade, a series of bamboo projects in compliance with voluntary markets, including plantation and management types, have been developed and implemented in China (Li et al., 2022a,b; Pan et al., 2023; Xu, 2024). Also, detailed investigations of the successes and lessons learned in China are notably lacking. This study addresses the following questions: What are the prominent challenges in integrating bamboo forests into the carbon offset markets, and what effective approaches to address them for optimal climate, economic, and social benefits? By qualitatively synthesizing and analyzing the perspectives from interviewing experts and practitioners in China, this paper provides an in-depth understanding of the challenges and opportunities in developing bamboo carbon projects. These experts included project developers, government officials, enterprise leaders, and leading scholars closely engaged with the bamboo sector. The insights from these semi-structured interviews were analyzed through a thematic analysis approach. Given that bamboo forest carbon offset projects often involve rural communities, insights from this research could inform community-based projects aimed at supporting sustainable livelihoods and achieving broader sustainable development goals (SDGs) (Zhao et al., 2022). Also, this study could stimulate further innovation and investment in the bamboo industry.

2. Methods

The underlying methodology of this research was to inductively seek understanding, theory, or patterns of meanings and implications by deciphering information inside the human community (Creswell and Creswell, 2023). Aligning with this perspective, we employed a descriptive method, namely thematic analysis, guided by Braun and Clarke (2006). We acknowledge the strengths of other qualitative analytic methods, but they are more constrained by their specific theoretical lens and may not align with the objectives of our study. The thematic analysis offers great flexibility where researchers are not confined to a rigid analytic framework but are rather immersed in the data while systematically identifying, analyzing, and reporting patterns (themes) within it (Braun and Clarke, 2006; Creswell and Creswell, 2023). This strategy is appropriate for investigating the complex experiences of stakeholders in the bamboo carbon sector, providing rich insights and understanding into the interactions between environmental objectives and socio-economic factors. The methodological protocol was approved by the Behavioural Research Ethics Board at the University of British Columbia, Canada (certificate number: H22-01237).

Semi-structured interviews (SSIs) were employed as the primary method for thematic analysis. SSIs offer flexibility in the interview process, enabling researchers to adapt and explore emerging themes while maintaining the focus (Adams, 2015). This approach allowed for follow-up questions, in-depth discussion, and expansion of specific areas of interest. Interviews were conducted with experts directly involved in bamboo carbon projects to capture their insights and experiences. A multi-stage purposive sampling strategy, specifically the funnel approach (Palinkas et al., 2015), was utilized to select participants. This method ensured the inclusion of individuals with significant expertise and involvement in bamboo carbon projects. A total of 28 participants were selected, representing diverse stakeholder groups: government officials (GO, 11), academic researchers (AR, 10), and project specialists (PS, 7). The selection criteria emphasized participants' experience, active engagement in bamboo carbon initiatives, and their potential to provide meaningful contributions to the study. Various benchmarks have been proposed to indicate data saturation. Creswell and Creswell (2023) suggest a minimum of 20 interviewees to achieve saturation, while Hennink and Kaiser (2022) found that saturation is typically reached within 9–17 interviews. Our sample size of 28 participants demonstrated sufficient breadth, encompassing diverse stakeholder perspectives and geographic coverage. It ensured the robustness and reliability of the research findings, aligning with established methodological standards.

Before each interview, participants were provided with details about the study's context, including the interview questions and a consent form. The interview contained approximately 20 questions covering a variety of aspects related to bamboo carbon projects: (1) the existing challenges, issues, and potential improvement areas in the development of bamboo forest carbon projects; (2) the significance and impact of products derived from harvested bamboo, particularly concerning accounting for the carbon pool; and (3) the effective management practices and strategies used in bamboo forests for climate change mitigation efforts. Depending on the interviewees' preferences, interviews were either audio-recorded or notes were taken. The average duration was 45–60 min, a recommended length for semi-structured interviews that ensures the collection of sufficient data while minimizing fatigue (Adams, 2015).

Audio transcriptions and notes were anonymized by numerical labels and imported to NVivo 14 for subsequent thematic analysis (Woolf and Silver, 2017). We followed the six-phase thematic analysis framework proposed by Braun and Clarke (2006): "(1) familiarizing yourself with your data; (2) generating initial codes; (3) searching for themes; (4) reviewing themes; (5) defining and naming themes; (6) producing the report." Throughout the analysis, we employed multiple validity strategies and trustworthiness-enhancing measures suggested by Creswell and Creswell (2023) and Nowell et al. (2017), including prolonged engagement with data, peer debriefing, and researcher triangulation. First, several peer debriefings helped ensure the initial codes and themes were accurately defined. We continuously triangulated data types to build coherent evidence for themes, including research articles, reports, and documents. These are discussed in the following sections. Additionally, we conducted the coding process intermittently and spent prolonged time in the field during the gaps to gain an in-depth understanding of the context. For instance, we visited bamboo carbon project sites in Zhejiang, Fujian, and Hubei provinces and gained substantial onsite insights and experience essential in validating the study.

Thematically analyzing the interview data led to the generation of numerous initial codes. These were grouped into themes that effectively presented the critical experience and lessons learned from China. When reviewing the themes, we conducted several additional rounds of peer debriefings to review, define, and accurately name the themes. For example, we decided to change 'lack of infrastructure' to 'lack of capacity,' merge the 'issues in bamboo timber' to 'challenges in bamboo industry,' merge 'low transaction' with 'low carbon price,' and merge the 'high cost of forest tending' with 'high labor cost.' The final coding framework was confirmed in a discussion session with our senior investigators and several participants.

3. Results

Through the thematic analysis of expert interviews, we identified four broad themes related to the key challenges in developing bamboo forest carbon projects: 1) economic challenges, 2) market challenges, 3) technical challenges, and 4) social challenges (Table 2). Notably, 45 % of node frequency, the frequency of each individual challenge discussed by experts, were related to economic challenges, indicating that they were the highest concern among interviewees. Within this category, two specific challenges related to the declining profitability of the bamboo industry (31 %) and high transaction costs (14 %) were primarily discussed by all expert groups but more frequently by government officials (26 and 15 response frequencies, respectively). Respondents emphasized that rising labor costs, coupled with decreasing bamboo timber and shoot prices, have significantly impacted project viability. Also, high transaction costs, mostly arising from third-party validation and monitoring expenses, were reported as a disproportionate burden on smallholder farmers, limiting their ability to engage in carbon projects. The second critical category of market challenges (25 %) includes those related to low transaction volumes (14 %) and the suspension of the Chinese Certified Emission Reduction (CCER) market (11 %). Respondents, mostly government officials, highlighted the oversupply of allowances in China's compliance markets, which demotivated the demand for carbon offsets, including bamboo-related credits. The pause of the CCER market further exacerbated these challenges, creating uncertainty for project developers and stalling many bamboo carbon projects in the validation phase. Project specialists more frequently highlighted the CCER market suspension than government officials and academic researchers, reflecting its direct impact on their work.

Table 2
The frequency of response (node frequency) and the corresponding relative frequency (RF) of broader thematic category and individual challenges out of the total node frequency. The response frequency from academic researchers (AR), government officials (GO), and project specialists (PS) for each individual challenge is shown respectively.

Challenge Category	Frequency (RF %)	AR	GO	PS	Total
Economic Challenges	**77 (45 %)**	**23**	**41**	**13**	**77**
Bamboo Industry	53 (31 %)	16	26	11	53
Transaction Cost	24 (14 %)	7	15	2	24
Market Challenges	**44 (25 %)**	**11**	**18**	**15**	**44**
Low Transaction	25 (14 %)	6	12	7	25
CCER	19 (11 %)	5	6	8	19
Technical Challenges	**32 (18 %)**	**12**	**10**	**10**	**32**
Lack of Capacity	12 (7 %)	4	5	3	12
Lack of Integrity	12 (7 %)	6	1	5	12
Weather and Climate	8 (4 %)	2	4	2	8
Social Challenges	**20 (12 %)**	**10**	**4**	**6**	**20**
Public Awareness	13 (8 %)	6	2	5	13
Tenures and Ownership	7 (4 %)	4	2	1	7
Total	173 (100 %)				

Technical challenges emerged as the third thematic category (18 %) from the expert interviews, including lacking capacity (7 %), integrity concerns (7 %), and challenges posed by the weather and climate (4 %). Experts, especially government officials, emphasized that the lack of infrastructure, such as forest roads and mechanization, and the capacity of trained bamboo carbon experts can be critical barriers to effective forest management and project implementation. Concerns about the integrity of carbon accounting methods for bamboo projects were also raised, mostly by academic researchers and project specialists, particularly in accurately quantifying carbon pools during bamboo's unique growth and harvesting cycles. Furthermore, government officials emphasized that climate variability, especially more frequent and intensive drought and extreme weather events under climate change, can result in less permanent and reliable projects. The fourth category (12 %) falls into social challenges, which were discussed more frequently by academic researchers, with the subthemes of low public awareness (8 %) and issues in tenure and ownership (4 %). Several respondents reported that knowledge of carbon markets and offset project benefits was particularly lacking among bamboo farmers as they often lacked access to reliable information; this information asymmetry can reduce trust and engagement in project activities. Additionally, the unique bamboo forest ownership in China – land fragmentation requires unanimous consent from all stakeholders for project implementation – creates delays and logistical challenges.

4. Discussion

Although this study specifically focused on bamboo forests, the highlight of economic viability aligns with recent research based on traditional forest-based offsets. According to another interview-based survey of forest projects in British Columbia, Canada, limited economic benefits were reported by 19 of 26 respondents as one of the top decisive barriers (Peterson St-Laurent et al., 2017), indicating the critical role of economic feasibility. The primary cause of this barrier is the low adoption incentives arising from the high transaction and production costs against the prevailing carbon prices (Cacho et al., 2013; Galik et al., 2012). A broad systematic review regarding the challenges of forest carbon offsets also showed that the socio-economic challenges (35 % of the included paper in the review) emerged as a critical thematic category involving transaction cost, social cost, opportunity cost, and carbon price, but falling behind the methodological challenges (46 %) (Pan et al., 2022). Traditional forest carbon offset projects emphasize methodological challenges such as additionality, permanence, and leakage largely because there is already a substantial number of these projects in operation, and addressing these challenges is essential to ensure their effectiveness and credibility. These elements were reported less by the experts in our study, primarily due to the relatively limited number of projects at this stage, and plenty of tougher challenges exist, such as economic challenges. This section includes a discussion of the results from the thematic analysis along with the existing literature.

4.1. Economic challenges

A critical difference between bamboo and trees is that the former needs regular selective harvesting to sustain and often optimize its productivity once reaching maturity. For instance, when a Moso bamboo (*Phyllostachys edulis*) plantation reaches its steady state (about 15 years), roughly 30 % can be sustainably harvested biennially, making it significantly more productive than a no-harvest scenario (5.10 t C/ha compared to 1.65 t C/ha in annual carbon increment) (Kuehl et al., 2013). Regular selective harvesting is one of the key project activities listed in the bamboo carbon offset project methodologies under the China Certified Emission Reduction (CCER) scheme, regardless of whether it is a bamboo plantation or a bamboo forest management project, and the carbon pool for the durable bamboo product is included, especially in the IFM activities to enhance the bamboo forest productivity (Zhou and Shi, 2017). This means that in a carbon project scenario, bamboo can be a sustainable raw material, and the accompanying bamboo industry is a crucial component in the chain of bamboo carbon projects.

However, a number of respondents pointed out that the bamboo industry has recently experienced critical issues, posing fundamental financial barriers to ongoing and potential new projects. For example, if a bamboo offset project is located in a region experiencing challenges in the bamboo industry, the financial viability and incentives of the project development may be severely compromised. Respondents were not optimistic about the situation, even with the additional income from carbon credits. In this case, project proponents may seek additional funding opportunities to compensate for the gap and unexpected costs, but with the ongoing pessimistic situation in the bamboo industry overall, this would deter most of the potential project developers, as indicated by respondent (PS5): *"So essentially, when we talk about doing these carbon projects, according to our calculations, there isn't much money involved. It's about 4.5 tonnes* per *hectare. You start with CNY30. It's CNY135* per *hectare. It's not even CNY135; cutting one culm costs around ten to twenty. Honestly, the investment might not even cover it if you were to implement these management measures and those management strategies."*

The once-flourishing bamboo industry in China started to decline in 2014 (Wei et al., 2023), laying the foundation for the current depressed industry landscape. For example, in Anji County, one of the top bamboo hometowns in China, the number of bamboo enterprises dropped from 1035 in 2019 to 678 in 2022 (Xu et al., 2024). Respondents reported two key reasons behind the industry decline: 1) escalating labor costs and 2) declining bamboo prices, which would ultimately affect the project's feasibility.

At the moment, the entire bamboo industry is still labor-intensive, including forest tending, harvesting, transportation, and processing, and the labor price in China has risen dramatically in the recent decade, consistent with economic development. The rising labor cost is also compounded by the decline in available labor in forestry (halving from 14 million in 1998 to 7 million in 2019) (Zhang and Jiang, 2023), as most bamboo farmers have been attracted by off-farm employment in cities (Wei et al., 2023; Xie et al., 2022). In Hubei, *"the labor cost for bamboo harvests was CNY200-220* per *tonne back in 2015, but now it is about CNY300-360, and this provides little incentive for farmers to manage the forests when the bamboo price went down from CNY800-860 to CNY480-500* per *tonne" (GO2)*. With little room in earnings, large areas of natural bamboo forests that are distant from forestry roads have been left unmanaged. Similarly, *"in 2015, the bamboo price peaked at CNY1, 000* per *tonne in Zhejiang, but now the number dropped to CNY420; correspondingly, harvesting one tonne of bamboo cost as low as CNY100 in labor back in time but now nobody is willing to do even you pay CNY300" (PS4)*. The recent national forestry reforms have further complicated the situation. The land, management, and timber rights in forests, which used to be state-owned before the 1980s, have gradually been decentralized to farmers (Hyde, 2019). As a result of years of land fragmentation, most bamboo farmers today are smallholders, further disincentivizing farmers' willingness to manage bamboo.

The decreasing demand for bamboo timber, mainly arising from better alternatives, directly impacts the price. For example, bamboo scaffold boards (a buffer for falling debris) were once in high demand and widely used in the construction sector, *"but now, under government restrictions, it has been completely replaced by nets for safety purposes"* (GO2). Similarly, bamboo scaffolding was once widely used in construction but has now been largely replaced by steel and wood (Wei et al., 2023). From the consumer's point of view, the vulnerability of bamboo products to mold, pests, and cracking may limit its market (Zhang et al., 2021). In line with this, respondent AR7 added, *"Producing bamboo products may require adhesives, which involves environmental issues. Bamboo products have specific requirements for the ambient environment; they will crack and mold if the temperature or humidity is too high."* Additionally, the large-scale nationwide environmental governance started in 2011 has gradually shrunk the sector (Wei et al., 2023; Xie et al., 2022). According to respondents, Zhejiang, for instance, a leading province in the bamboo industry, has introduced strict environmental regulations regarding sewage discharge from factories, forcing companies to invest immense capital. Counties were greatly influenced as *"more than half of the factories, especially those responsible for pre-processing, could not withstand the high costs of upgrading to environmentally friendly facilities and have to shut down. Thus, the demand for local raw bamboo dropped dramatically" (GO11)*. This means that in an industry chain, the bridge between primary processing and product manufacture is disconnected, with the latter seeking pre-processed materials elsewhere.

Another critical challenge identified from the interviews is the high upfront transaction cost, a universal challenge in the forestry carbon industry (Cacho et al., 2013; Milne, 1999). An early study indicated that transaction costs of forest carbon projects range from 6 to 45 % of the total cost (Milne, 1999), while a more recent analysis showed that it is generally less than 25 % of implementation costs in the United States (Galik et al., 2012). In the case of bamboo, numerous respondents reported that the required transaction costs range from at least CNY 200, 000 to 300,000, which involves third-party costs mainly for monitoring, reporting, and verification (MRV), vastly reducing the incentive for project development. After these lengthy steps, the carbon credits are issued ex-post, a system that further disincentivizes project owners as they must invest at least five years ahead. These fixed high costs, required for any project type, can *"reduce the actual benefits for the forest farmers, who are the major contributors to carbon projects, yet they receive only a relatively small portion of the payback"* (AR3). Also, respondents emphasized that developing a bamboo-based carbon project is complicated, particularly in relation to measuring biomass. For instance, *"I've always struggled to understand how to calculate the amount from the adjustment period in the beginning. I want to know how much it increases each year, but I couldn't figure it out without consultation"* (GO1). As noted earlier, bamboo management requires ongoing selective harvests every one or two years, making the aboveground, belowground, and subsequent harvested product carbon pools difficult to model. In the context of improved forest management (IFM) bamboo project, there is typically a stand adjustment period, usually from an age-group structure of 1:2:3 = 1:1:1 to 1:2:3:4 = 1:1:1:1.

4.2. Market challenges

The majority of respondents reported that carbon offset transactions in China are passive, mainly due to the mismatched allowance allocation in the compliance carbon markets, which ultimately led to excess CCER stock and a lowered carbon price. *"The biggest challenge for the market is that the allowances are too lenient, which leads to insufficient market demand, and as of now, the trading is more symbolic"* (GO5). This is reflected in the China National Emissions Trading System (CNETS), where the allowance allocation method is based on the benchmarking free allocation without the presence of an auctioning (ICAP, 2024). Additionally, the cap-setting is based on the actual production level of covered entities in a bottom-up manner, meaning it is not a continuously decreasing cap. For instance, the cap for CNETS in 2019 and 2020 was 4500 $MtCO_2$, while it climbed to 5000 $MtCO_2$ in 2021 and 2022 (ICAP, 2024). Although adopting a flexible cap setting may reflect regional development differences, these market characteristics potentially disincentivized the use of offset credits despite the 5 % being allowed. In local pilot markets like the Hubei Pilot Emission Trading System, the offset credits also include green electricity certificates, certifying that a certain amount of electricity was renewably sourced, such as wind, solar, or hydro (ICAP, 2024). The use of green electricity certificates adds an additional layer to the already marginalized forest credits market demand. As a result, the carbon price may shrink. If the carbon price is unattractive, the smallholder forest farmers are usually resistant to switching business-as-usual practices to project activities (Zhu et al., 2017).

Bamboo carbon offset credits face an even worse situation in the less normative voluntary markets, where the projects are usually based on the protocols or methodologies only approved at the city or county level. These credits are not eligible for trading in the compliance carbon markets, but the demand outside these markets is nearly zero, especially when the economy is in a challenging period, such as during COVID-19. According to respondent GO8, the bamboo forest management project in the Chishui city-level platform in Guizhou province has been issued credits worth one million tonnes, but due to the sluggish regulatory demand, only about 11,000 tonnes were transacted for judicial compliance and carbon-neutral events. Reflected by the demand situation, forest credits are usually not reasonably priced compared to the already considerable management and transaction costs. If the carbon price cannot surpass the costs, the project may be ineffective, as the expected annual carbon credits are around 5.85 tCO_2/ha in the case of improved bamboo forest management (Yan and Tong, 2022). *"When developing a project, 1 ha generates about five to six tons, with each ton worth CNY 30, which is equivalent to adding only about 30 bamboo culms* per *hectare. Economically, it doesn't add much value"* (AR7). This is consistent with the work by Zhang et al. (2023) that the average carbon price for CCER ranged between CNY 20–30 per ton, dropping to CNY 10 in some regions.

Since 2017, advances in the forest carbon industry have halted. With ongoing criticisms of the quality and integrity of forestry offsets (Greenfield, 2023; West et al., 2023), China has temporarily slowed its development of the methodologies related to forest management and conservation while focusing on improving the afforestation methodology. In late 2023, China published the first batch of revised methodologies for afforestation, mangroves, solar thermal power, and offshore wind power generation (Reklev, 2023) and subsequently reopened the CCER market in January 2024 (Kuo, 2024). In the revisions, the carbon pool for harvested wood products has been removed, a non-permanence risk deduction has been added, and biodiversity protection has been considered (Ministry of Ecology and Environment, 2023). Although the CCER market is back online, the fate of bamboo IFM-related projects remains to be determined. In many bamboo-producing provinces, the quality of at least one-third of bamboo forests is deteriorating (Wei et al., 2023), with declining productivity and carbon sequestration. There is a pressing need to include bamboo IFM methodologies in the newly reopened CCER markets to optimize the opportunities for bamboo to mitigate climate change.

4.3. Technical challenges

Capacity is deficient in the following aspects: the infrastructure for harvesting and transportation, skilled carbon experts, and academic research. Access to forest roads is integral to optimal forest productivity and labor intensity, providing a nexus among primary, secondary, and tertiary sectors (Li et al., 2022a,b). For intensive tending activities in bamboo forest carbon projects, the experts stressed that the existing infrastructure is significantly less advanced than in traditional forestry, where forestry roads are well-designed and constructed. Partly due to historic land-tenure reforms (Hyde, 2019), bamboo forests are owned mainly by smallholders and collectives, and *"it would be hard for them to reach an agreement to build the roads covering the full mountains" (AR1)*. In Anji County of Zhejiang, the funds to build these roads were raised by the local farmers, and they often face challenges with their maintenance as the capital chain frequently breaks. Also, 95 % of existing roads are built under an elevation of 400 m, and only 15 % are hardened (Li et al., 2022a,b). Bamboo forest tending activities are still done mainly by hand, using machetes to conduct thinning, weeding, and harvesting. Owing to the high labor cost and distance from roads, more than 8000 ha of bamboo forest at high altitudes have been abandoned in the county. In many parts of China, mechanized operations have been attempted, but they are not fully compatible with the bamboo situation: *"We have tried* *many mechanized methods, but it is indeed quite challenging to implement them in bamboo forests. For instance, we even started experimenting with drones to harvest Moso bamboo. Despite our extensive efforts, it has proven difficult mainly due to the high costs involved. Additionally, it is very challenging for the machines to operate in mountainous areas"* (GO11).

Skilled experts, especially for bamboo forest carbon project development, are required in the whole chain of project development. Similar to the development of conventional forestry projects, bamboo projects also need to go through lengthy yet complex processes, including project design document drafting, implementation, monitoring, reporting, and verification (MRV), and many more. However, due to bamboo's unique properties, the project design may be further complicated. Problems include the carbon accounting of the aboveground carbon pool under continuous selective harvests, the harvested wood product (HWP) carbon pool under the variety of bamboo products, and the belowground carbon pool of bamboo rhizomes especially after the corresponding culms have been harvested. The project developers often face these challenges, as reflected by respondents (PS1): *"We are also in the process of exploring and figuring things out, such as how to set up monitoring plots and how to transmit data. Of course, we are not capable of handling advanced mathematical calculations, and we are not familiar with the methods or computational models. Therefore, we definitely need to collaborate with agricultural and forestry universities, as well as cooperate with government departments, enterprises, and local state-owned companies. This is the standard approach."*

Bamboo forest carbon offset is an emerging field, and most related research comes from only a handful of organizations, such as Zhejiang A&F University, Nanjing Forestry University, and the International Centre for Bamboo and Rattan (Ao et al., 2021). On top of that, existing research mainly focuses on the monopodial Moso bamboo carbon additionality from both afforestation (Li et al., 2021a) and improved forest management (Li et al., 2017, 2018) perspectives. However, the distribution of sympodial bamboo species is extensive in southwest China and many parts of the world. For instance, respondent AR5 reported that *"some surveys have been conducted on the existing carbon stocks of sympodial bamboo species, including total vegetation carbon stocks and soil carbon stocks. However, there has been relatively little scientific experimentation on their potential for increasing carbon sequestration through management practices."* This is consistent with the review by Pan et al. (2023), which concluded that current sympodial research primarily focuses on the standing biomass and carbon storage of the existing forests, while the gap is on how to enhance the carbon sink of these species, thus translating the knowledge to the bamboo forest carbon projects.

The additionality of bamboo forest plantation projects can be easily observed, but this does not apply to IFM. Another technical issue relates to the quality and integrity of bamboo IFM. First, many respondents pointed out ongoing doubts in the Chinese research communities and government sectors regarding whether standing forests can generate real and additional carbon benefits through management. Bamboo, as one of the forest categories in China, naturally receives similar counterviews. *"They believe that forest management-related projects are intangible and hard to grasp"* (PS2). This could explain why CCER has slowed its revision of forest management methodologies. On the other hand, the advances in bamboo IFM have also stagnated. For instance, the proposal '*Methodology for Improved Forest Management through Adjusting Bamboo Forest Stand Structure*' under the Verified Carbon Standard (VCS) was rejected due to reasons such as unclear climate mitigation potential and additionality (Verra, 2023). Experts stressed the pressing need for research clarifying the additionality and climate benefits of IFM bamboo activities, especially under the ongoing bamboo forest abandonment and deterioration.

Under current climate change, drought has been listed as a significant climate-driven risk impacting forest carbon cycling via productivity declines and mortality (Anderegg et al., 2020). Similarly, droughts can significantly suppress bamboo's carbon sequestration capacity (58.1 %), bamboo shoots (64.6 %), and new culms (70.8 %) (Ge et al., 2018). In prolonged and persistent droughts, the situation could be worse, as *"bamboo forests can die off in large patches"* (PS5). Indeed, a portion of the 2015 bamboo afforestation project in Hubei did not survive through a two-year drought: *"Due to consecutive years of drought in 2019 and 2020, Hubei experienced extremely severe drought conditions for two years in a row. Many tens of thousands of hectares of forests, which were already established, died on their own, let alone the newly planted seedlings"* (GO2). Irrigation techniques, such as sprinkling and dripping, have been proposed for the bamboo projects, but these add another cost to the project implementation.

4.4. Social challenges

The majority of respondents focussed on the information asymmetries between the general public, bamboo farmers, and project developers. First, some public lectures by so-called carbon experts have spread incorrect information, which risks increasing rapidly and undermining genuine knowledge in the way that 'bad money drives out good.' For instance, *"It is a significant misconception that all carbon prices in the European Union are prices for carbon offsets. The EU does not have carbon offsets, so this misunderstanding has raised the expectations of leaders. As a result, developers involved in carbon projects are profiting not from the projects themselves but from manipulation. They engage in fraudulent activities and financial speculation to make money, and some definitely profit from this"* (PS2). Additionally, some experts claim that there are also inaccurate journal articles and books, further disrupting the already complicated public perception. In some forest projects, such as an afforestation project in Guangdong province, the awareness of carbon forests among participating farmers was deficient (27 %), and these farmers remained passively involved in the decision-making and benefit-sharing negotiations (Zhou et al., 2017). When it comes to bamboo farmers, especially since their awareness of carbon offsets remains low, many will lose their deserved benefits from participating in the project activities. *"In market negotiations, farmers are always the disadvantaged group, as they have limited access to information and resources. Everyone is trying to gain more benefits during these negotiations. Farmers want to earn a bit more, while developers aim to maximize their profits"* (AR7).

The second aspect of the social challenges, yet relatively technical, lies within the bamboo forest tenures of forest land, management, and timber rights. This complex tenure structure, shaped by smallholder, collective, and state-owned ownership (Hyde, 2019), has posed critical challenges for bamboo farmers to participate in and benefit from the project activities. Regarding the land tenures of a forest project, CCER requires (CCER, 2023): *"The project land must have clear ownership, with property ownership certificates, land contracting, or transfer contracts; or it has land certificates or forest rights certificates issued and approved by the relevant government authorities or competent departments with approval authority"*. The procedures are more straightforward for state-owned bamboo farms. Still, those owned by smallholder farmers and collectives would require all individuals under their households to consent and sign the management right transfer contracts. For instance, some farmers wish to participate, but members of their households may not be present for various reasons, such as off-farm employment. Also, with the uncertain benefits, many farmers have hesitated regarding this complex transfer. A similar situation happened in Fujian province: *"One of the issues is the chaos in property rights. The ownership of forest land and trees belongs to the village collective, while individuals hold the management rights (or usage rights). We tried to mobilize the village officials to seek cooperation, but some people were not at home and could not sign the agreements"* (GO9). Also, this signing requires all individuals under one forest ownership certificate to be present in person, meaning a tremendous capacity is already needed at this very first phase in the project development.

4.5. Applications and recommendations

Corresponding to the challenges listed above, the respondents suggested potential approaches. They stressed that available and accessible carbon finance in various forms, including direct grants and concessional loans, would lay a foundation for successful project implementation. Most importantly, developing innovative models incorporating these finances and other features like large-scale and professional management are the essential vehicles to realize the optimal potential of bamboo projects to mitigate climate change along with the co-benefits of environmental protection, biodiversity conservation, and livelihood enhancement. Building on the economic, market, technical, and social challenges uncovered in the thematic analysis, this section examines how integrated strategies might improve the viability of bamboo carbon projects.

Several experts indicated that bamboo forestry could gain insights from the innovative practices of traditional forestry. Like the bamboo industry, traditional forest farmers in China have also encountered the modern dilemma of land fragmentation and low management profits resulting from the series of forestry reforms. Smallholders now face the challenges of optimal investments in their forests to reach sustainable forestry while dealing with unknown risks, especially those forests that need a long-term rotation (Huang et al., 2020). In 2018, an initial attempt to finance these forest resources started in Shunchang County of Fujian Province, China: the Forest Ecological Bank (FEB). FEB is a state-owned enterprise that provides the platform for individual farmers to transfer the management and timber rights voluntarily, and FEB will manage the forest professionally on a large scale and return the annual rental and dividends from thinning/clear-cuts back to farmers (Huang et al., 2020). In this way, the smallholder farmers can securely receive higher profits than managing individually and without the concerns of related risks. An analysis demonstrated that with FEB's operation, Shunchang could potentially increase its production value, both provisioning and ecosystem services, collectively by USD 25.92 million (Xu et al., 2023). Shunchang's FEB has shown practical experience in effectively resolving the modern challenges in Chinese forestry, primarily the economic challenges arising from land fragmentation and decreasing labor availability. Similarly, in the U.S., the Family Forest Carbon Program (FFCP) empowers family forest owners to participate in carbon projects, overcoming high initial costs and technical complexities by offering financial incentives and professional guidance. This program has successfully enrolled over 86,000 acres, with payments amounting to USD 20 million and an estimated additional sequestration of 1.2 million tonnes of CO_2 (American Forest Foundation, 2024; Family Forest Carbon Program, 2024). Lessons from the FEB and FFCP could be highly applicable to bamboo carbon projects.

An innovative green finance model for bamboo could effectively address the economic, technical, and social barriers, especially for smallholders. As the product carbon pool is a vital part of carbon accounting, incorporating downstream bamboo industry development is also important for a successful project and for local livelihoods. A prosperous bamboo industry will mutually reinforce the advances made by the bamboo carbon industry.

Anji County in Zhejiang Province, China, has launched the '*Bamboo Industry Transformation and Upgrading and Carbon Sequestration Capacity Enhancement Program*' to tackle significant challenges in bamboo carbon offsets amid a downturn and the abandonment of 12,000 ha of bamboo (20 % of county total) (Yan and Tong, 2022). With funding from green finance, Anji created a comprehensive model that spans the primary, secondary, and tertiary sectors of the bamboo industry (Pan et al., 2025). The program allows smallholders to voluntarily transfer management and timber rights to village cooperatives, where forest professionals implement large-scale standardized management. A digital platform supports efficient resource management, streamlining the transfer process and enables farmers to visualize projected benefits (Chai et al., 2023). Beyond enhancing carbon sequestration, the program has improved infrastructure by building 2000 km of forest roads, railways, and cableways for timber transport and irrigation systems to mitigate drought impacts, reducing management costs by 50 % (Anji Forestry Bureau, 2022). To enhance product quality and transportation efficiency, Anji established 119 pre-processing sites near bamboo forests and invested in advanced processing technologies, aiming to upgrade the competitiveness of bamboo products. These efforts have led to a 10 % increase in bamboo timber prices, and additional tourism developments such as eco-tourism have emerged, generating new income sources for locals (Yuan, 2023). Farmers representing 55,000 ha have enrolled in the project (Wu et al., 2022), with annual payments now 3–4 times higher than before (Yuan, 2023). Anji's model demonstrates the potential synergy between carbon finance and industry development in addressing both climate change and rural economic growth.

Internationally, Ecoplanet Bamboo (EB) has pioneered bamboo reforestation projects outside China under the Verified Carbon Standard (VCS) since 2011, starting with 3199 ha in Nicaragua and five projects across Asia, Africa, and Central America. Collectively, these projects aim to mitigate 12 million tonnes of carbon over 20 years while also investing in local bamboo processing facilities (Ecoplanet Bamboo, 2024). Their overarching strategy is similar to Anji: besides the climate benefits of generating carbon credits, EB focuses on the downstream bamboo industry development. EB has established strategic onsite properties, including toxin-free processing and manufacturing facilities for pulp and paper and their operating offices, leveraging the funds raised from carbon credits and global investors (Ecoplanet Bamboo, 2024). This comprehensive strategy has benefited local livelihoods by providing increased employment and by aiding the development of local bamboo industries.

Inspired by several recent innovations, it is apparent that comprehensive green carbon financing models could address most of the challenges listed above (Fig. 2). This model should first obtain a large amount of green finance, such as the Green Climate Fund (GCF), to lay a foundation for the project initiation. The proposed elements include large-scale forest management, professional team establishment, digital platform management, infrastructure construction, and supportive measures for the bamboo industry. Large-scale unified management of the decentralized land will reach cost-effectiveness (economy of scale) by employing a professional team to cope with the increasing labor price and decreasing availability of labor. In addition, the high upfront transaction cost could be vastly reduced. The skilled teams can address the need for more experts, avoid the information asymmetry issue, manage the bamboo scientifically according to the methodology requirements to realize authentic additionality, and professionally develop the carbon project through the lengthy procedures of MRV. A digital platform, such as the one designed by the Anji government, can help monitor and visualize forest health conditions, management progress, and project additionality. Importantly, it is user-friendly for the farmers when signing and managing contracts.

Another element is the development of bamboo forest infrastructure: 1) Building facilities such as forest roads and railways or cableways is critical for reducing transportation costs and optimizing the management structure. 2) Irrigation systems could reduce the impacts of prolonged droughts. Last but not least, incorporating measures to enhance the local bamboo industry is the enabler of the project's success. Investing in near-site facilities for raw timber pre-processing will significantly reduce the emissions to the environment, help standardize the quality, and enhance the competitiveness of these timbers. The upgraded processing and manufacturing technologies can further improve product quality. These measures will level up the value and competitiveness of the bamboo industry and play a vital role in local livelihood enhancement. Lastly, the model should design an annual payment back to farmers to ensure they are properly compensated.

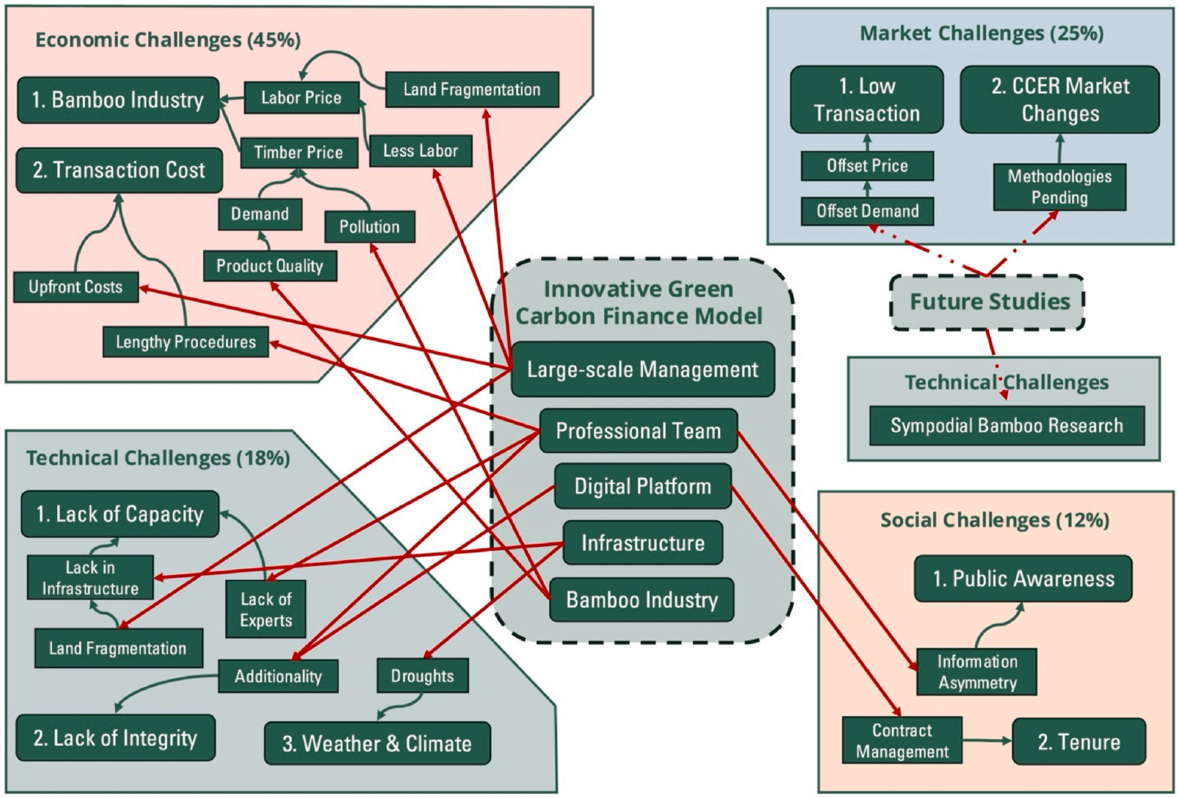

Fig. 2. Summary of the key challenges identified, the proposed approaches, and the research areas prospected for advancing bamboo carbon offset projects.

5. Prospects

Most challenges discussed in this study could be addressed by combining the above-mentioned innovations. Fundamentally, green climate finance could be the driving engine for project initiation, enabling management and timber rights transfer for a large-scale project or enabling land purchases. After the United Nations Climate Change Conference (COP28) in December 2023, 33 countries and one region committed to the second round of the Green Climate Fund (GCF) replenishment to a record level of USD 12.8 billion for 2024–2027 (Green Climate Fund, 2024). Also, COP29 concluded with an increased climate finance pledge from 100 to 300 billion USD per year. These global efforts provide immense potential for the world, especially the Global South, where most bamboo naturally grows, to obtain essential green carbon finance. Second, the innovative models must incorporate large-scale and professional management and support for upstream infrastructure and downstream bamboo processing for synergistic development through primary production of carbon sequestration to the secondary bamboo industry.

However, the crucial part of market challenges remains intangible at this stage (Fig. 2). To address the passive transactions of carbon offsets, especially in China, future research needs to investigate the strategic mechanisms that will ensure both rigorous carbon reductions and the appropriate and efficient use of offset projects. For instance, China's national carbon market may need to set thorough and decreasing caps over time, slowly reduce the free allowance, and introduce allowance auctions. In August 2024, following "The Work Plan for Accelerating the Establishment of a Dual Control System for Carbon Emissions" issued by the General Office of the State Council, China announced the plan for the total quantity control for carbon emissions covering all levels from national and local, to industry, enterprises, projects, and products (Tang, 2024), indicating the positive signals for future decreasing caps in the carbon markets. On the other hand, the sustainability limits of using offsets regarding land-use capacity and biodiversity impacts need to be considered (Deprez et al., 2024). Also, the overreliance on carbon dioxide removal offsets may also contravene the legal liabilities for emission reduction under the Paris targets, and such legal limits should also be thoroughly considered (Stuart-Smith et al., 2023).

Although the methodology for bamboo afforestation/reforestation projects is available both for China (CCER) and the world (VCS), the one for bamboo IFM is pending updates in China and is stagnant in VCS. There is a need for the development of new bamboo forest management methodologies, such as converting low-productivity to high-productivity bamboo forests, that also specifically account for the unique properties of bamboo: the dynamics between aboveground, belowground, and bamboo product carbon pools. As more future bamboo-based carbon projects are in place, prominent challenges pertaining to traditional forestry projects, such as additionality, permanence, and leakage, should be further explored in the context of bamboo forests. Future studies should also focus on the carbon sink enhancement technology for global sympodial bamboo species to better fit the international context — for example, through baseline biomass estimation and quantification of additional carbon sequestration outcomes. These efforts should also take into account the ecological feasibility of such projects—including soil conditions, temperature suitability, and water availability—in order to inform policy and investment decisions tailored to local biophysical constraints. More research needs to be conducted on the solutions to address the market challenges, including the intricate mechanisms to balance carbon emission reductions and the rational use of carbon dioxide removal credits and the internationally recognized bamboo IFM methodologies.

CRediT authorship contribution statement

Chunyu Pan: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Anil Shrestha:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Conceptualization. **Chong**

Li: Writing – review & editing, Validation, Resources, Methodology, Investigation, Conceptualization. **Mengjia Ying:** Software, Investigation, Formal analysis. **Jie Duan:** Writing – review & editing, Validation, Resources. **Mei He:** Writing – review & editing, Resources, Project administration, Funding acquisition. **Weirong Zhu:** Writing – review & editing, Validation, Resources. **Qinghui Chai:** Writing – review & editing, Validation, Resources. **John L. Innes:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization. **Robert Kozak:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization. **Guomo Zhou:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Guangyu Wang:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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