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The Bamboo City: Nature-Based Development Model for a Regenerative City Through Bamboo

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ABSTRACT

"At COP27, Bamboo was declared as one of the top five solutions to mitigate global warming, by replacing traditional housing materials such as carbon and steel with Bamboo helps reduce carbon emissions caused by the global housing sector." (Washington Post 2022) **Cities, as engines of growth,** consume substantial amounts of energy and emit greenhouse gases (GHGs) with the building sector contributing 40% of all global emissions (IEA 2019). The adverse effects of an unsustainable built environment have put a strain on the environment, affecting humanity. In this scenario**, Bamboo stands as an ideal nature-based solution** capable of achieving soil and moisture conservation, providing water security, preventing soil erosion, repairing degraded lands, improving air quality, and providing eco-friendly buildings because of its manifold uses and industrial applications rendered possible by recent advancements. **The 2030 Climate and Energy Framework** states that 27% of energy should be sourced from sustainable energy sources to meet the target for 2030. (EU 2021). This paper is part of her C40 Women4Climate project by the author. It examines the current state of environmental impacts of air and water pollution in cities like Bangalore and intercedes through nature-based interventions with Bamboo as a mainstream material in construction, phytoremediation, and air pollution mitigation by collating available data, engaging with stakeholders, and identifying points of action consistent with national and international climate action and sustainability commitments among governments. **The Bamboo City** project will be a plug-in to the main Climate Action Plan with a roadmap for lowering GHG emissions and building community climate resilience to achieve carbon neutrality by 2030 and regenerative status thereafter. Using Bamboo for sustainable development in the city will not only cut greenhouse gas emissions but also provide income opportunities, ensuring the triple bottom line of environmental, economic, and social growth thus fulfilling the SDGs.

1. Introduction

Rapid urbanization and widespread sprawl have led to adverse climate change impacts leading to depleted green cover and increased communities' vulnerability to climate change. The urban population in India grew from 17.9 % in 1960 to 35.8 % in 2022 indicating a rise in rapid urbanization (World Bank, 2022). Urban expansion comes at the cost of natural resources, including open spaces, causing the depletion of ecosystems. Cities were the first to experience climate change impacts. Adverse climate change, such as deterioration in air quality, water shortages, urban floods, and heat islands, is worsening living conditions and causing economic losses along with social insecurity (Nadja Kabisch, 2017).

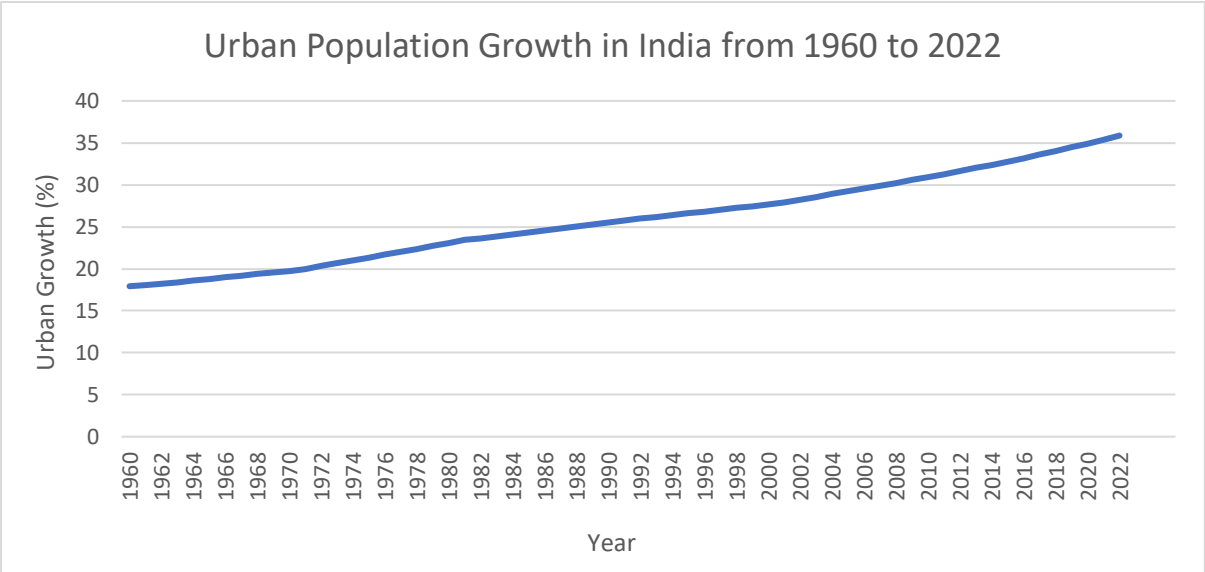

Figure 1.Urban Population Growth in India from 1960 to 2022, Source: United Nations

Cities, as engines of growth, consume a substantial amount of energy and emit significant amounts of greenhouse gases (GHGs). The building and infrastructure sectors contribute over 40% of CO_2 emissions globally (Fig1 & 2) (IEA 2019). The exponential production and release of CO_2 have led to severe consequences and repercussions, contributing to life-threatening issues in urban areas. In this scenario, Bamboo stands as an ideal nature-based solution capable of achieving soil and moisture conservation, providing water security, preventing soil erosion, repairing degraded lands, improving air quality, providing livelihood options, and providing economic security because of its manifold uses, including industrial applications rendered possible by advancements in technology. The project proposes to use Bamboo, a sustainable resource for development, housing, and infrastructure in the city, to cut greenhouse gas emissions while providing income opportunities, ensuring the triple bottom line of integrated sustainable development encompassing environmental, economic, and social growth.

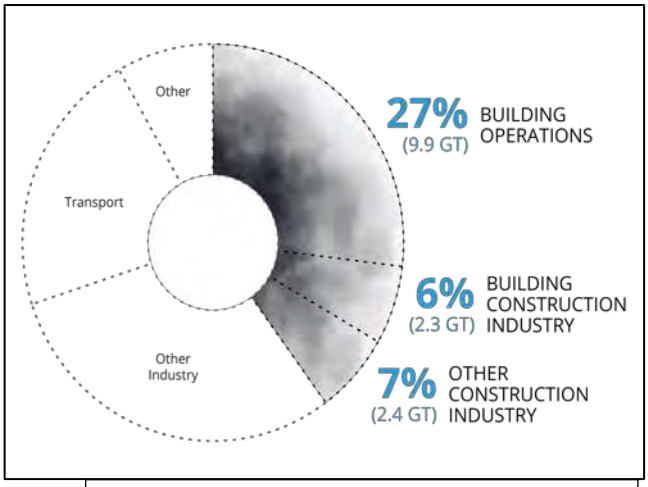

Figure 2 Annual Global CO2 Emissions (Source: IEA 2022)

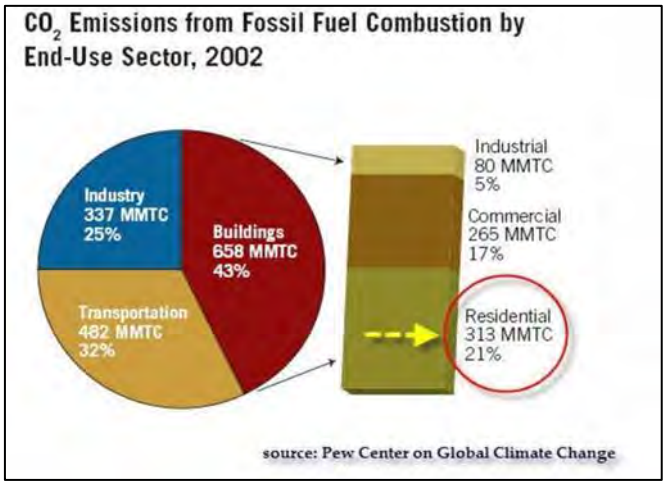

Figure 3 CO2 Emissions from fossil fuel combustion by end-use sector (Source: Pew Center on Global Climate Change)

1.1 Aims and Objectives

The primary aim of this development model is to lay out an action plan for making a city carbon-neutral by 2030. This involves working out a systemic strategy with evidence based data and stakeholder mapping for reforestation of degraded lands along water bodies, parks, densely populated areas of the city, and suburbs, and integrating Bamboo into buildings and infrastructure. This will result in many advantages, as listed below.

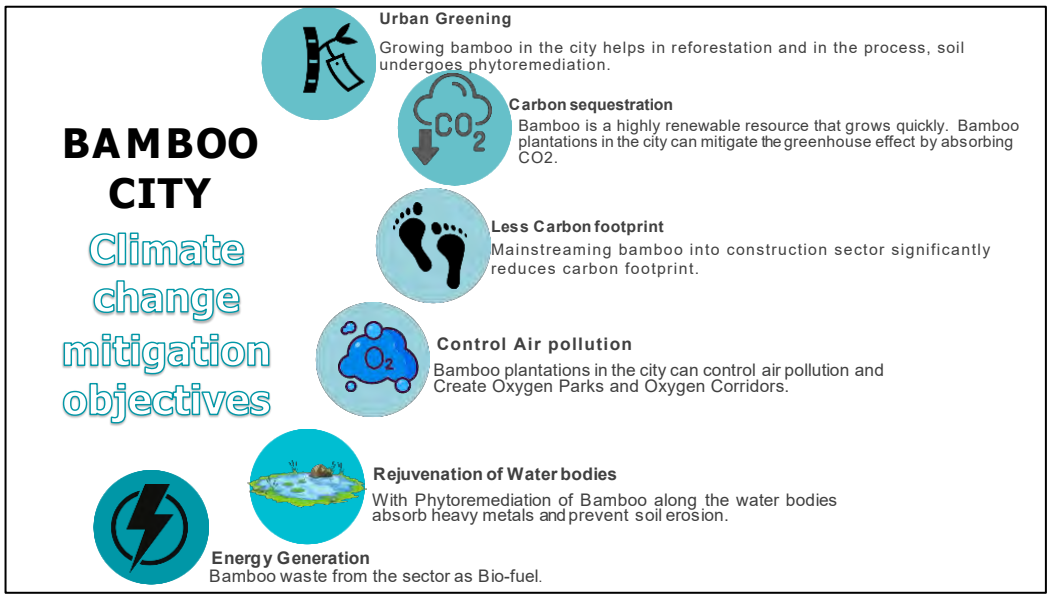

Figure 4 The Bamboo City Climate Change Mitigation Objectives (Source: Author)

The vision of the project is to prepare a Bamboo-based plug-in action plan to transform cities into sustainable and resilient urban environments by harnessing the potential of Bamboo for ecology and development and making cities carbon neutral by 2030 and regenerative thereafter.

1.2 Background and Justification

Traditionally, urban and regional planners have relied on conventional engineering to mitigate climate change impacts, which are neither cost-effective nor sustainable and thus have worsened the problem. We require nature-based solutions (NBS) to mitigate climate change impacts. NBS uses natural solutions to achieve social and environmental goals.

Bamboo is the most effective NBS to achieve carbon neutral status in the short term. It absorbs greenhouse gases faster than any other tree, releases 35% more oxygen than traditional trees (Lindsey Schueman, 2023), and has low embodied energy, which also controls GHG emissions from the buildings and construction sector. Growing Bamboo and using it as a sustainable resource for development in the city can not only cut greenhouse gas emissions but also provide income opportunities, ensuring integrated sustainable development.

2. Bamboo City Project: An Overview

Table 1 Project at a glance, Source: Author

Project Title	The Bamboo City – Nature Based Development Model for a Regenerative City through Bamboo
Author	Ar. Prof Neelam Manjunath
Initiative	CGBMT , pitched @C40 cities-Women4Climate
Pilot City (Area, Elevation)	Bengaluru (4474 sq. km, 920m)
Coordinates	Latitude: 12°58′18″ N Longitude: 77°35′37″ E
Population	15 million(present)
GDP	US$300 billion
Project Timeline	2023-2030
Climate Risks addressed	 Urban Heat Urban Flooding Air Pollution Water Pollution Water Scarcity
Stakeholders involved	WBO, INBAR, Individual researchers, NGOs, Private Institutions, Citizens, Construction Professionals and others
Proposed to be involved	BBMP, BMRDA, BIAPPA, BDA, Bamboo Industry and other organizations

Important sectors addressed	

2.1 Mission of the Bamboo City Project and Action points

A. Bamboo Plantation Initiative: According to NASA, one person on average needs 0.84 kg of oxygen per day. Bamboo produces approximately 0.82 kg of oxygen per day, which is equivalent to the oxygen needed by one person per day. **The project proposes one Bamboo plant per citizen in the city to provide lifelong oxygen to the citizens.** The pilot initiative focuses on setting up Bamboo plantations across Bengaluru, in vacant lands, degraded areas, public parks, water bodies, under high-tension lines, in schools and institutions, housing developments, by roadsides etc to achieve urban greening and environmental conservation.

B. Integration of Bamboo in Construction and Energy sector: From Figure 2, it is observed that the construction sector is a major contributor to GHG emissions. Using 30% Bamboo for all development, and specifically the infrastructure and construction sectors, can reduce more than 50% of emissions. Therefore, an increase in the usage of Bamboo for the purposes of development is proposed. This component aims to promote the use of Bamboo as a sustainable building material in the construction sector through capacity building, training programs for architects, engineers, and builders, policy interventions, and development of building codes and regulations. In addition to the above, this component includes waste management and energy generation strategies leveraging Bamboo biomass to promote circular economy principles and reduce environmental impacts.

2.2 Limitations and implications

Developing a Bamboo City within an existing urban setting can be a sustainable and viable option with innovative concepts, but it does have the following limitations and implications:
a. Monoculture: Planting large areas with Bamboo within the city can have negative effects on local ecosystems, reducing biodiversity. To combat this, Bamboo plantations should only account for one-third of the green areas alongside other plantations in order to preserve existing biodiversity.
b. Compatibility: Integrating a Bamboo city within the existing infrastructure may require modifications and revitalization of older and existing dense urban areas, which can be difficult.
c. Building Codes and Regulations: Existing building codes may not specifically address Bamboo construction, creating a need for additional codes to ensure safety. This can be a complex process.

d. Perception and Acceptance: While many citizens are aware of the benefits of Bamboo, adopting Bamboo structures over traditional concrete and steel buildings requires a shift in thinking. Over time, exposure to more Bamboo buildings will lead to widespread acceptance.

2.3 Sustainable Development Goals to be Achieved through this Project

The SDGs cover a broad range of social and economic development issues also known as "Transforming Our World: the 2030 Agenda for Sustainable Development (2030 Agenda)". The Bamboo City project can play a major role in achieving several of the SDGs:

Figure 5 Sustainable Development Goals achieved through this project,

3. Bamboo as a Sustainable Material

The author has been working with Bamboo for over 25 years, and her personal field research and observations have also been used as a resource in the paper.

Bamboo grows in tropical, subtropical, and sub-temperate zones around the world, and its distribution is closely related to population density. It is widely available and has been traditionally used as a natural solution for many uses in these parts of the world since time immemorial and even today. Globally, Bamboo forests cover 30,538.35 million hectares, with Asia boasting the largest at 17,370.75 million hectares, constituting 56.88% of the world's Bamboo forests. China and India emerge as the leading contributors to Asia's Bamboo cover, with 6,285.23 million hectares and 5,591.40 million hectares, respectively.

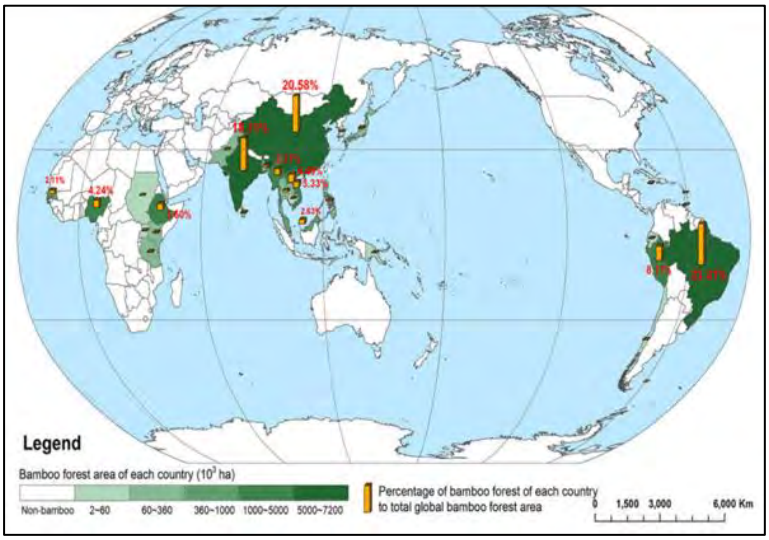

Figure 6 Distribution of Bamboo around the world, Source: Huaqiang Du, 2018

Table 2 Bamboo Supply and Civilization in Different Continents

Continents	**Population (projected for 2050) (Million)**	**Bamboo Supply**	**Bamboo civilization**
Asia	5268	High	Well Developed
Africa	1766	Medium	Average Development
South America	809	Less	Under Development
Europe	628	Less	Recently introduced Bamboo houses
Northern America	392	Less	Under Development
Australia and Antarctica	46	Nil	Not Developed

3.1 Properties of Bamboo

a. Bamboo, characterized as a rapidly growing woody grass, demonstrates remarkable growth rates, reportedly exceeding 100 cm per day (Li et al., 2020). This exceptional growth rate positions Bamboo as a highly resource-efficient material, offering cost-effective solutions across various applications. Widely accessible across the globe, except for Europe, where recent introductions have expanded its presence, Bamboo offers opportunities to conserve energy by minimizing transport, particularly in tropical regions where it proliferates abundantly.

b. Despite the formidable strength and hardness of Bamboo culm walls, the material yields easily to processing, even with rudimentary tools such as a stone axe, necessitating minimal labour and equipment for utilization.

c. Bamboo's lightweight and hollow structure, reinforced by its nodes, provide exceptional flexibility. This inherent property enables the construction of dynamically balanced buildings that can withstand natural forces with greater efficiency.

d. With superior tensile and compressive strength compared to conventional wood or timber, Bamboo fibre within a vascular bundle exhibits tensile strengths of up to 12,000 kg/sq. cm (Lopez, 2003). For equivalent applications, this attribute translates to significant material savings by weight.

e. Bamboo's extensive root system plays a pivotal role in soil conservation by compacting soil structure and mitigating erosion risks posed by rainfall, wind, and human activities, while simultaneously enhancing soil quality. Its roots can retain a lot of water and, hence, can be used along water bodies to enhance water retention. Leveraging Bamboo for phytoremediation purposes proves beneficial in absorbing harmful metals, contributing to environmental remediation efforts.

f. Embracing a circular economy ethos, Bamboo emerges as a sustainable resource with versatile applications ranging from construction to textiles. Its inherent recyclability and adaptability enable multiple uses throughout its lifecycle, thereby minimizing waste and maximizing utility in resource management strategies.

The Bamboo regenerative cycle is a fascinating aspect of Bamboo's natural life cycle, involving rapid growth, propagation, and renewal. This cycle is a fundamental characteristic that distinguishes Bamboo from many other plant species and contributes to its sustainability and ecological importance.

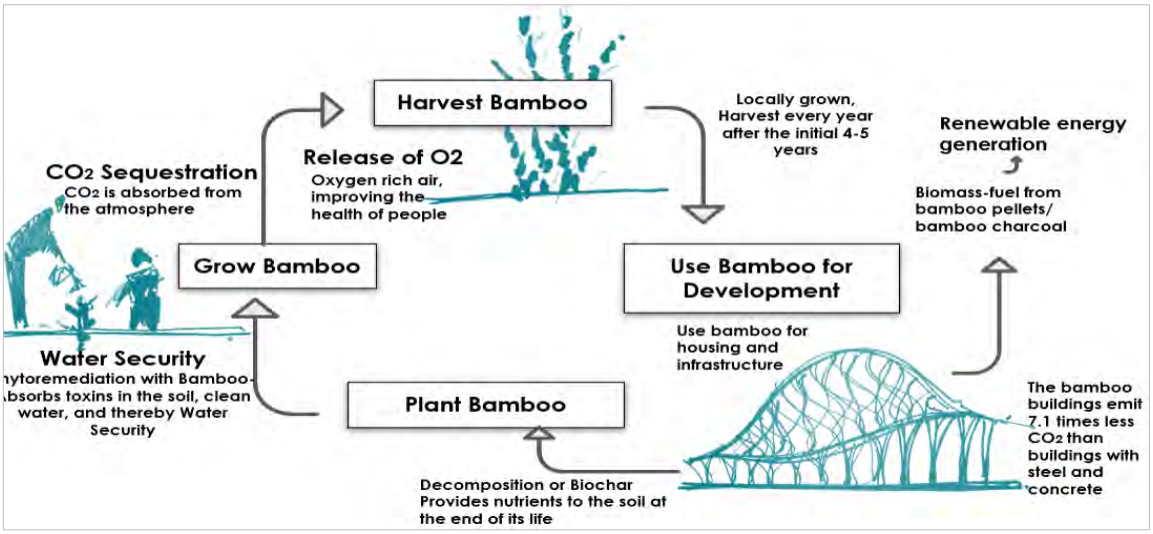

Figure 7 Regenerative Cycle of Bamboo, Source: Author

Table 3 Comparison of Traditional Tree and Bamboo, Source: Author

Parameter	**Traditional Tree (average values)**	**Bamboo (average values)**
Oxygen release	The lungs of the planet A tree produces oxygen by absorbing carbon dioxide	Produces **35%** more Oxygen than traditional trees (NRDC, 2011)
CO2 absorption	All trees will absorb carbon dioxide,	Absorbs carbon dioxide 5 Times more than traditional tree (NRDC, 2011)
Harvest Cycle (years)	Mature for lumber in 30-40 years (approx.)	Mature for harvest in 3-5 years
After harvest	The tree dies when it gets cut down	New Culms emerge from the Clump after every harvest
Growth rate	Very slow	Very fast
Equipment and labor to cut	Thick trunks require chainsaws and heavy machinery	As hard as Oak, lightweight, hollow, and easily cut with a hand saw

3.2 Bamboo as a Building Material

The table provided illustrates the embodied energy (EE) of different building materials, which encompasses the entirety of energy expended throughout the production process of a material, incorporating all upstream activities, including raw material extraction and transportation. Notably, Bamboo stands out with remarkably low embodied energy, positioning it as an exceptionally sustainable option for building construction, and emphasizing its minimal environmental impact.

Table 4 Embodied Energy of Different Building Materials, Source: Laiyee, 2011

Material	Extraction MJ/kg	Processing MJ/kg	Transportation km	Energy use MJ/kg	Carbon emission CO_2/kg
Bamboo	0.044	1.71	300	2.58	0.13
Wood	0.047	7.01	800	7.22	0.41
Laminated bamboo board	0.52	9.32	200	9.98	0.53
Laminated wood board	0.20	12.76	200	13.22	0.74
Steel (10 per cent recycled content)	1.40	27.15	1000	28.65	2.21
Cement	0.03	4.62	500	5.27	1.05
Concrete (C40)	1.27	2 kWh/m3	10	1.12	0.20
Cement mortar (1:2.5)	2.70	2 kWh/m3	10	1.64	0.31
Expanded perlite concrete	4.66	2 kWh/m3	10	9.39	0.61
Brick	0.044	1.57	50	1.75	0.14
VIPs	38.25	5.4 kWh/m3	800	36.97	2.16
Aluminum	-	-	-	155.0	8.24
Polystyrene	-	-	-	86.6	2.50
Plaster board	-	-	-	6.75	0.38

3.3 Energy Generation from Bamboo

Bamboo is a sustainable energy source, producing 1 kWh of electricity from 1.2 kg of Bamboo. This is similar to the biomass requirements for wood products, but it outperforms other types of biomass sources such as hemp, bagasse, or rice husk. Bamboo can produce an enormous amount of biomass in a relatively short period of time and can be processed into various energy products such as charcoal, pellets, and briquettes. Bamboo pellets can also serve as eco-friendly alternatives for heating or cooking applications, characterized by their clean combustion process devoid of smoke emissions.

Table 5 Energy Generation from Different Tree Biomasses, Source: Guadua Bamboo

Biomass	LHV MJ/Kg	HHV MJ/Kg
Bagasse	17,7	19,4
Bamboo	**19,0**	**19,8**
Birch	18,7	20,1
Cherry	17,9	19,1
Coconut	16,6	17,8
Cypress	21,5	23,0
Douglas	19,7	21,0
Elm	19,0	20,5
Eucalyptus	18,3	19,6
Hemp	16,5	17,6
Larch	18,7	20,1
Maple	18,7	20,0
Miscanthus	17,8	19,1
Oak	17,4	18,8
Pine	19,5	20,8

3.4 Bamboo for ecology

Bamboo's potential for carbon sequestration: Bamboo, being a sustainable resource, is effective in reducing air pollution as it can absorb greater amounts of CO2 due to its rapid growth. It also emits a significantly higher amount of oxygen per acre compared to traditional trees. (Lin et al. 2017; Yiping et al. 2010)

Revitalization of water bodies: Bamboo's phytoremediation properties make it useful in removing toxins from soil and its widespread root system holds soil firmly thus reducing soil erosion. Bamboo planting can also aid in groundwater absorption and increase groundwater capacity, resulting in lake rejuvenation. (Bian et al. 2017; Nkeshita et al. 2020).

4.0 Methodological Approach for Bamboo City Project

To ensure the success of the project, a methodology has been developed not only to gather, analyse, and interpret data but also to make informed decisions in a timely and dynamic manner. Unlike other projects, this is an action-plan based research project that has to result in implementation. Hence, a carefully designed project plan is necessary to achieve the desired milestones on time.

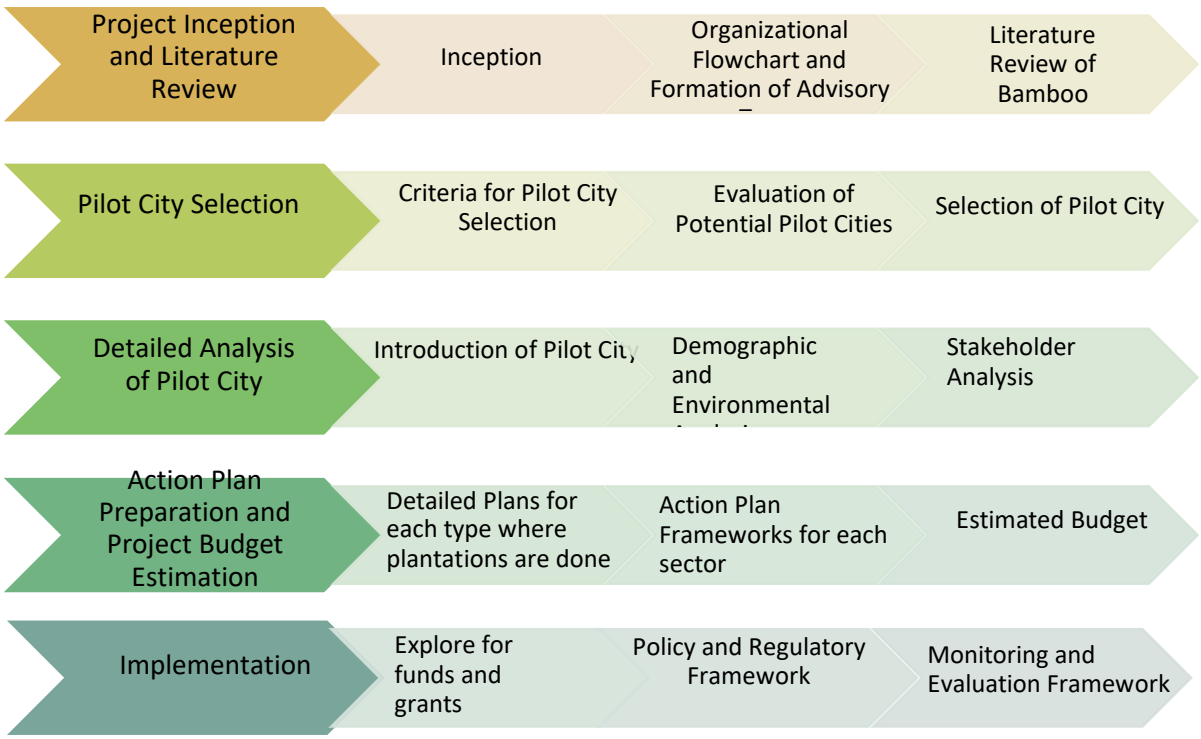

Figure 8 Project Milestones

4.1 Data Collection

a. Surveys, questionnaires, and interviews shall be used to gather information directly from residents, businesses, and other stakeholders regarding demographics, preferences, or opinions.

b. Geospatial data shall include information about the physical geography of the area, such as terrain, land use, and natural features. It can be collected through satellite imagery and aerial photography.

c. Demographic data shall include the population of the area, including age, gender, income levels, education, and employment status. This data will be obtained from national census records, surveys, or government databases.

d. Environmental data shall include environmental conditions of the area, including air quality, water quality, and air pollution levels. It will be collected through monitoring station data online.

e. Secondary Data Sources: Existing datasets, reports, and academic literature will be researched for the project.

4.2 Project Inception and Preparation

When C40 Cities launched the Women4Climate Initiative in Bengaluru in December 2022, the author saw this as an opportunity to propose her project under the Women4Climate Cohort Program for Bengaluru as a plug-in to BCAP (Bangalore Climate Action Plan) aimed at combating climate change. Having experience in the field of sustainability for over 36 years and having the intent to mainstream Bamboo in the construction industry due to its natural properties and its ability to mitigate climate change, the author envisaged that C40 provided a suitable platform for scaling up the project to the city level for grassroots action in the global south.

CGBMT, the Centre for Green Building Materials and Technology, Bengaluru, has formed an advisory team comprising of local, national, and international scientists, advisors and researchers to work on this project with the author as the project lead.

Initial work started with collecting and reviewing available literature and data on the usage of Bamboo for ecology and as a building material.

4.3 Identification of Stakeholders

The criteria for selecting the stakeholders for our survey was based on the potential of Bamboo for ecological, economic and social development of the city for the basic needs of its citizens like clean air, clean water, healthy food, affordable safe housing and energy.

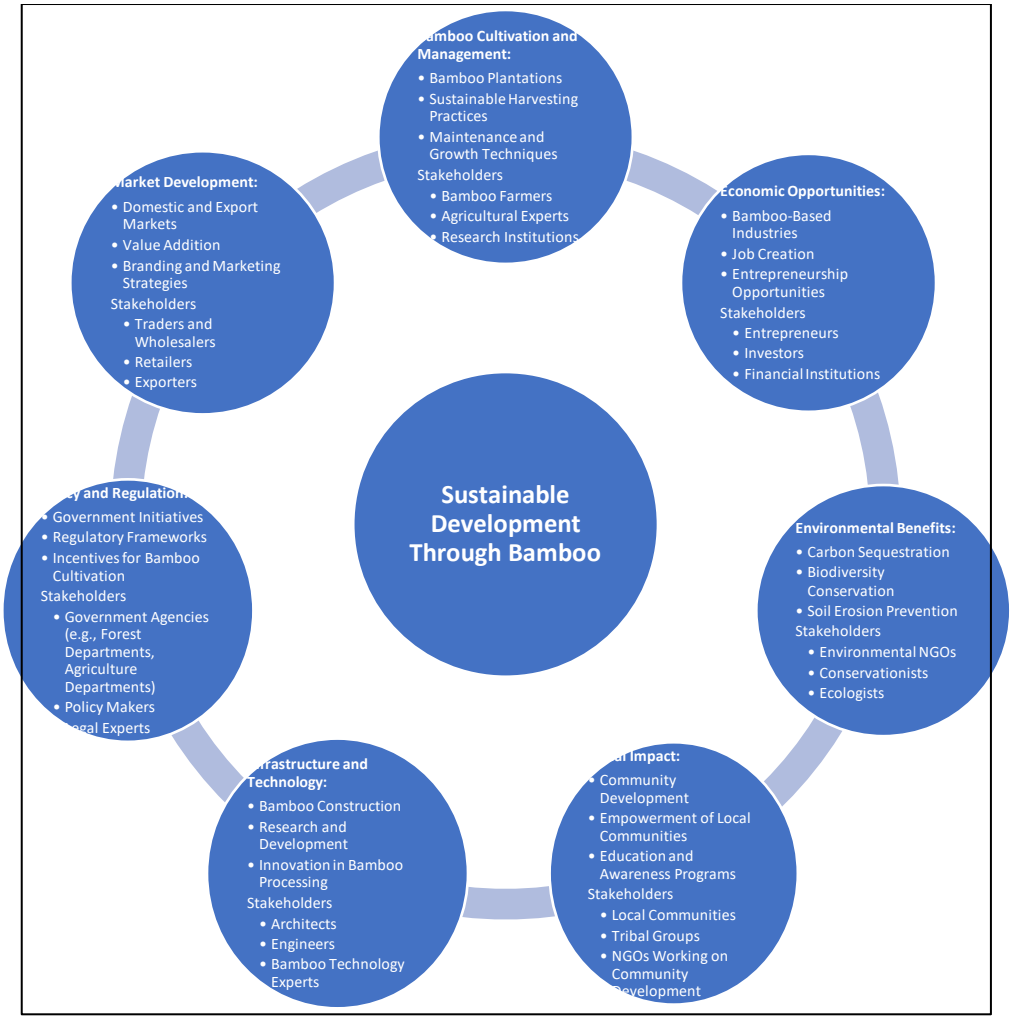

Fig 9 Sustainable development through Bamboo

4.4 Pilot City Selection

To achieve a proof of concept for the Bamboo City project before advocating it for other cities, some key criteria were formulated for the pilot project.

a. Urban Challenges and Climate Vulnerabilities:

It was required that cities that are facing significant urban challenges such as pollution, deforestation, climate change impacts (e.g., extreme weather events, urban flooding), and a lack of green spaces should be selected. Cities where the implementation of nature-based solutions like Bamboo can directly address these challenges and enhance resilience should be prioritized.

b. Population Density and Demographics:

Cities with a sizable population to be selected to ensure maximum impact and engagement. Demographics such as income levels, education, and social vulnerability should be considered ensure inclusivity and equitable distribution of benefits.

c. Available Land and Suitable Climate:

The availability of land suitable for Bamboo plantations within city limits or in nearby areas and the climatic conditions required for Bamboo growth should be assessed.

d. Policy and Governance Support:

The city's existing policies, regulations, and governance structures related to environmental conservation, urban planning, and sustainable development shall be evaluated.

e. Community Engagement and Stakeholder Support: The level of community engagement and stakeholder support within the city, including local residents, civil society organizations, businesses, academic institutions, and government agencies shall be assessed as it is extremely important for effective execution of the action plan.

f. Infrastructure and Resources:
The availability of infrastructure such as nurseries, transportation networks, and waste management facilities that are essential for Bamboo plantation, construction, and maintenance activities, as well as the financial resources and technical expertise required for project implementation shall be considered.

g. Economic Opportunities and Development:
Prioritize Cities where the integration of Bamboo-based solutions aligns with economic development priorities, job creation, and poverty alleviation efforts should be prioritized.

h. Environmental Impact and Sustainability:
Cities where the project aligns with sustainability goals and contributes to long-term environmental benefits to be prioritized.

i. Track Record and Success Stories:
Cities that have demonstrated a commitment to sustainability and innovation, with a track record of implementing successful nature-based solutions or similar projects to be considered.

j. Scalability and Replicability:
City where the Bamboo-based action plan can serve as a model for scalability and replicability in other urban areas regionally, nationally, and globally shall be chosen.

5. Bangalore a Potential City for Bamboo City project

A comprehensive evaluation of potential pilot cities based on the established criteria was done. This evaluation involved data analysis, stakeholder consultations, and site visits to assess the feasibility and readiness of candidate cities for the Bamboo-based action plan. Collection and analysis of relevant data on environmental and climatic challenges faced in Bengaluru city was done by engaging with government agencies, community groups, academic institutions, and other stakeholders through surveys to gather input and insights on opinions on people's mindset towards Bamboo. Site visits were conducted to assess the suitability of cities first-hand, to assess whether the city is suitable for Bamboo plantations, has areas for plantations, and is familiar with Bamboo.

Bengaluru, one of the most populous cities with a diverse demographic, faces various urban challenges, including rapid urbanization, traffic congestion, air and water pollution, and the loss of green spaces. Climate vulnerabilities, such as heatwaves and erratic rainfall patterns, also affect the city. The city has space available for plantations and a tropical savanna climate, which is conducive to Bamboo growth.

Bengaluru has shown commitment to sustainability through several government initiatives, such as green building regulations and promoting Bamboo cultivation and utilization. The city has active community groups, environmental organizations, and government agencies engaged in sustainable development efforts.

Bengaluru has implemented various sustainability initiatives, including urban forestry projects and waste management programs. The city has good infrastructure, technical expertise, and financial resources for Bamboo plantations and construction activities. Scaling up Bamboo-based solutions can contribute to sustainable urban development efforts beyond Bengaluru.

Considering these criteria, Bengaluru emerges as a suitable candidate for implementing the Bamboo City project. With its urban challenges, supportive policies, engaged stakeholders, and available resources, Bengaluru has the potential to harness the benefits of Bamboo for promoting sustainability, mitigating climate change, and improving the quality of life for its residents.

5.1 Analysis of Pilot City-Bengaluru

Bengaluru, previously called Bangalore, is the capital city of the Indian state of Karnataka. It is the third-most populous city and fifth-most populous urban agglomeration in India, with a population of over ten million (Govt of Karnataka, 2022). It is known as the "Silicon Valley of India" because of its role as the nation's leading exporter of Information Technology (IT) (Govt of Karnataka, 2022). Indian technological organizations such as the Indian Space Research Organisation (ISRO), Hindustan Aeronautics Limited (HAL), Infosys, and Wipro are headquartered in Bengaluru (Govt of Karnataka, 2022).

The city's temperature has been steadily rising over the years with a recorded increase of 0.9 degrees Celsius between 1978 and 2018 (Indian Institute of Science, 2018). This temperature rise can be attributed to various factors, including the heat island effect caused by concrete structures and reduced green cover in the city (Ramachandra, T. V., & Bharath, S, 2016).

Moreover, Bengaluru has been experiencing erratic rainfall patterns, leading to water scarcity issues in the region. The city's annual average rainfall has been decreasing with a 16% decline recorded over the past few decades (Government of Karnataka, 2020).

Additionally, air pollution levels in Bengaluru have been on the rise, posing a serious threat to public health. The city has been ranked as one of the most polluted cities in India, with high levels of particulate matter and vehicular emissions contributing to poor air quality (Central Pollution Control Board, 2019).

To address these climatic challenges, policymakers and urban planners need to prioritize sustainable development practices. By taking proactive measures to mitigate the impact of climate change, Bengaluru can work towards creating a more resilient and sustainable future for its residents.

Figure 10 Urban Flooding, Source: Scroll Staff, 2022

Figure 11 Polluted Lake, Source: Sanjana Alex, 2021

Figure 12 Air Pollution, Source: Mayur Channagere, 2016

Figure 13 Water Scarcity, Source: The Hindu, 2019

5.2 Bengaluru and Bamboo

a. Skill and Commerce: Bamboo has a rich history in Bengaluru, with numerous Bamboo markets scattered throughout the city. The tradition of Bamboo craftsmanship dates back hundreds of years in these markets, featuring an array of Bamboo products such as ladders, baskets, Bamboo jalis, mats, fences, blinds, furniture, hand fans, hanging lamps, and more. Raw materials are typically procured from Maharashtra and other parts of Karnataka, with recent procurement from the nearby town of Nelamangala. Many skilled artisans depend on these markets for their livelihood.

Figure 14 Bamboo Bazaars in Bengaluru, Source: Ar. prof. Neelam Manjunath, 2023

b. Indigeneous plant: There are several patches of Bamboo plantations in the city, such as the Hennur Bamboo Forest, a part of the Karnataka Reserve Forest. In addition to the flora, these forests have also seen a spurt in wild life and bird sightings of different varieties thereby enhancing the biodiversity of the city.

Figure 15 Hennur Bamboo Forest, Source: Sargun, 2023

c. Technical knowhow: Bengaluru is home to several prestigious institutions and organisations that have been extensively researching the utilization of Bamboo in the ecology, products. and construction industries for a significant period of time. The Indian Plywood Industries Research & Training Institute (IPIRTI) and the Indian Wood Science Institute (IWST), both located in Bengaluru, have been at the forefront of developing value-based Bamboo products such as ply, boards, and roofing sheets. These institutes are leading cutting-edge research while also assisting in the establishment of industries and technology transfer across the country. CGBMT is an NGO working on taking the research results from lab to land in addition to doing R & D in their own projects.

Figure 16 Research Institutes in Bengaluru, Source: IWST

d. Proof of concept: Kempe Gowda International Airport's Terminal 2 is known as a Bamboo paradise. Majority of its interiors is done with bamboo symbolising Bengaluru as the Garden City. The project architects at SOM, New York consulted the author as a Bamboo expert for material selection and design vetting.

Figure 17 Bamboo usage in Terminal-2, Bengaluru Airport, Source: BIAL, 2023

*e. Tree Survey:*According to a survey conducted by the Indian Institute of Science, Bengaluru now has one tree for every fifteen people. Such a ratio underscores the importance of urban forestry and environmental conservation efforts in densely populated areas like Bengaluru.

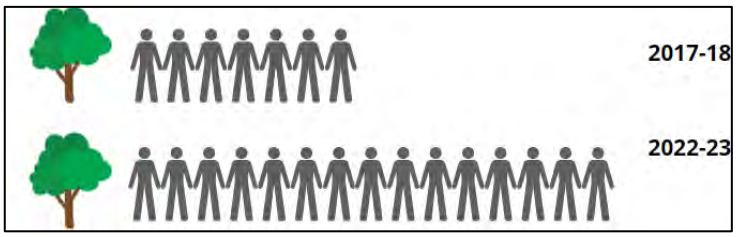

Figure 18 Number of trees per person in Bengaluru, Source: IISC

5.3 Stakeholder Survey Analysis

Following are the briefs of some of the key results of the stakeholders' surveys conducted for the project:

5.3.1 Citizen's Survey

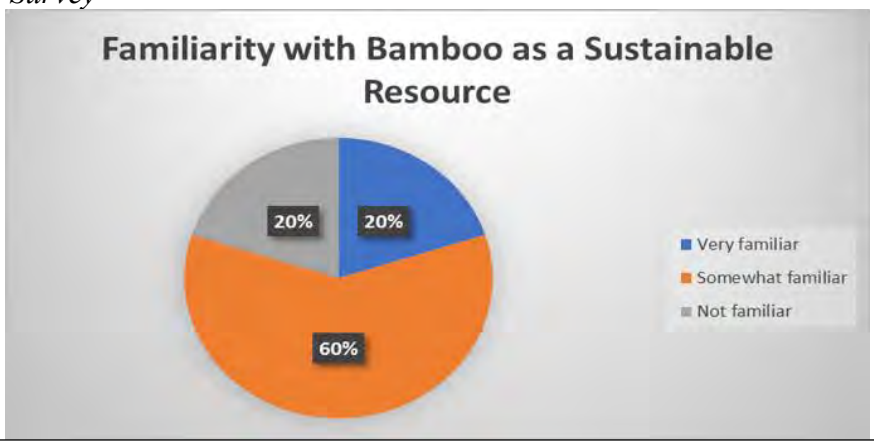

Figure 19 Familiarity with Bamboo as a sustainable resource, Source: Author

The pie chart illustrates people's familiarity with Bamboo as a sustainable resource. Almost **80%** of the respondents are **familiar or somewhat familiar, and only 20% are not familiar** with Bamboo's sustainability aspects.

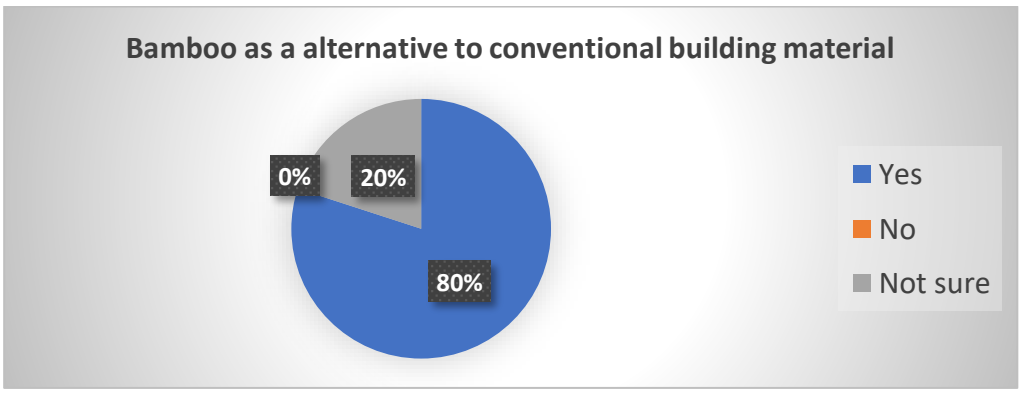

Figure 20 Bamboo as an alternative to conventional building material, Source: Author

80% of Bengaluru citizens feel that Bamboo can be an alternative to conventional building materials. The remaining 20% are not sure, but they have not said no to it.

5.3.2 Construction Industry Professionals Survey

a. Architects

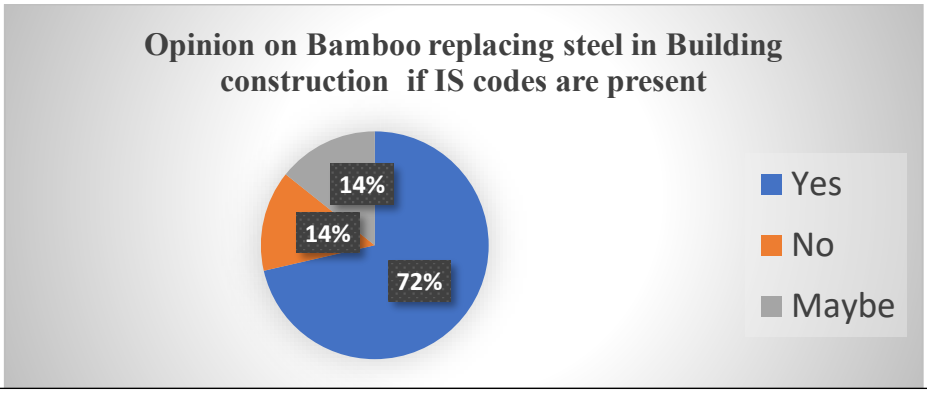

Figure 21 Opinion on Bamboo replacing steel in building construction if IS codes are present, Source: Author

The pie chart represents architects' opinions on whether Bamboo can replace steel in building construction if IS codes are present. Yes (72%): A significant majority, represented by the large blue segment, agree that Bamboo can replace steel in building construction if IS codes are present.

b. Civil Engineers

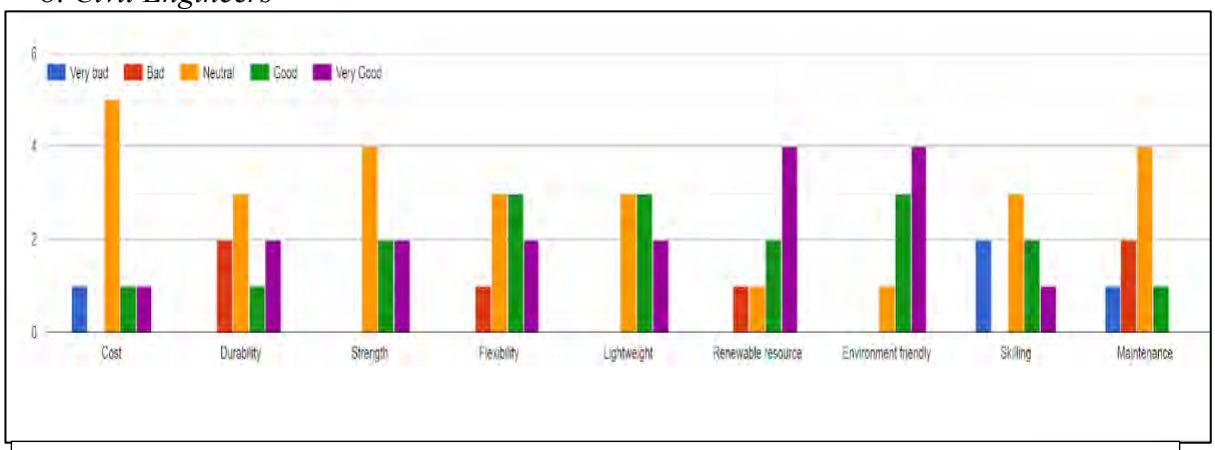

Figure 22 Ratings for various attributes of Bamboo by Civil Engineers, Source: Author

The bar graph represents the evaluation of various attributes like cost, durability, strength, flexibility, lightweight, renewable resource, environment friendliness, skilling, and maintenance of Bamboo. Each attribute is rated on a scale from "Very Bad" to "Very Good."

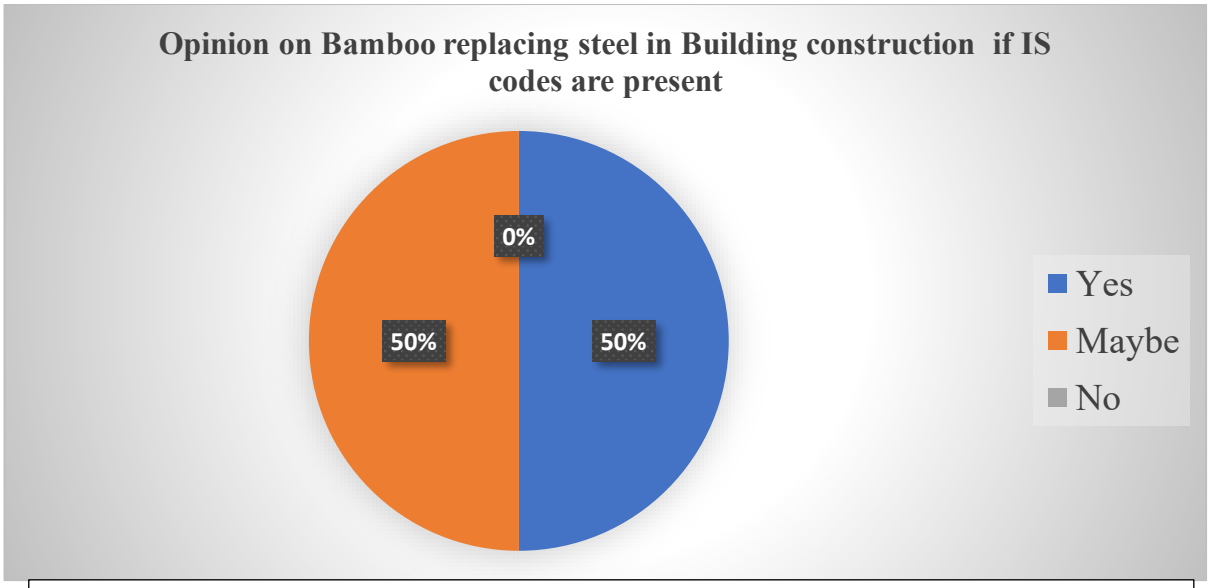

Figure 23 Civil Engineer's opinion in Bamboo replacing steel if IS codes are present, Source: Author

The pie chart indicates civil engineers' opinions on Bamboo as a replacement for steel. The chart is divided into two equal parts, each representing 50%. Notably, no one selected "No" in this survey. This suggests that there is a general openness to the idea of Bamboo replacing steel in building construction, provided that appropriate IS codes are present.

5.3.3 Students Survey

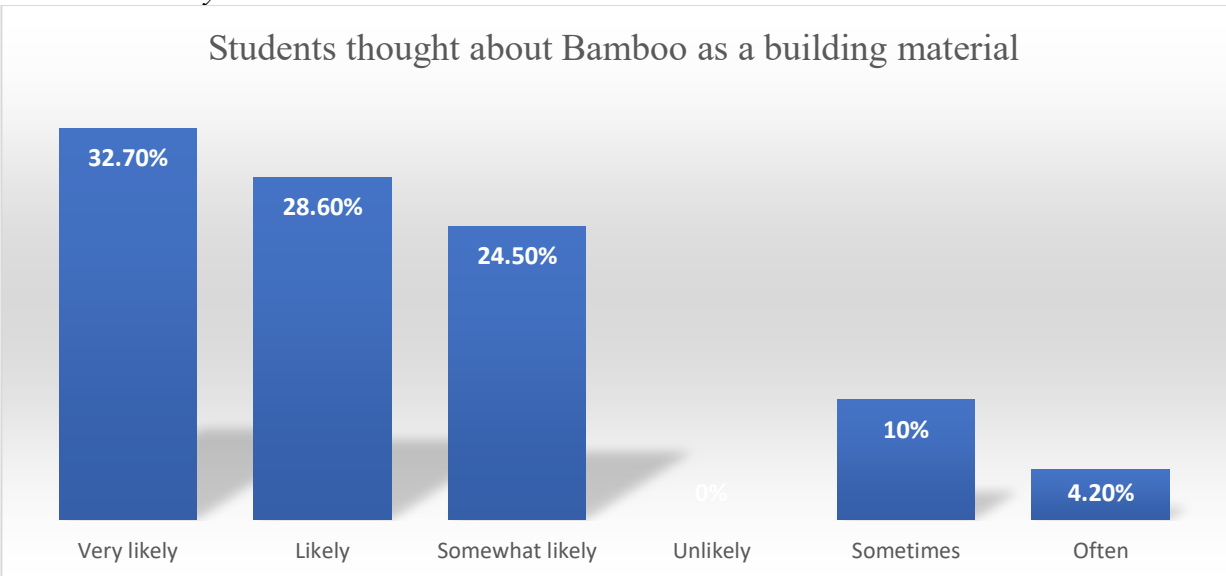

Figure 24 Students thought about Bamboo as a building material, Source: Author

The bar graph represents students' opinions on the use of Bamboo as a building material. It suggests that most students are open to or are actively considering the use of Bamboo as a building material.

5.4 Feasibility Studies
5.4.1 Identified Bamboo Species that can grow in Bengaluru

Table 6 Species that can be grown in Bengaluru, Source: Author

Group	Bamboo species	Properties	Area suitable to grow	Uses/ Applications
1.	Thyrsostachys Oliveri	• Dense clumping • 2-inch dia Bamboo semi-solid • Straight growth • Good looking	• House front • Roadside • Live fencing • Parks and spaces • Degraded barren land	• structural members • garden aesthetics • poles • lathi • furniture
2.	Bambusa Bamboo (avoid in urban settings)	• Strongest Bamboo • Tall variety • Giant Bamboo • High biomass • Bush variety	• Rajakaluves • Lake periphery • Barren and degraded land • High dense areas	• Construction • Ladder • Utensils • Handicraft • Biomass • Paper pulp • timber
	Dentrocalamus Strictus,	• 2-inch dia Bamboo • High biomass • Strongest Bamboo • Bush variety		
	B Balcooa,	• High biomass • Strongest Bamboo		
3.	B Tulda,	• 3-inch dia Bamboo • Lightweight	• Lake periphery • Barren and degraded land • High dense areas	• poles • structural members • Construction • scaffolding
	Dentrocalamus Stocksii	• 2-inch dia Bamboo • High biomass • Strongest Bamboo	• Lake periphery • Barren and degraded land • High dense areas	• structural members • garden aesthetics • poles • lathi • furniture
4.	D. Brandisii	• Tall variety • Giant Bamboo • High biomass	• Rajakaluves • Lake periphery • Parks and spaces • Dense plantation	• poles • structural members • Construction

5.4.2 Land availability for Bamboo plantations in Bengaluru

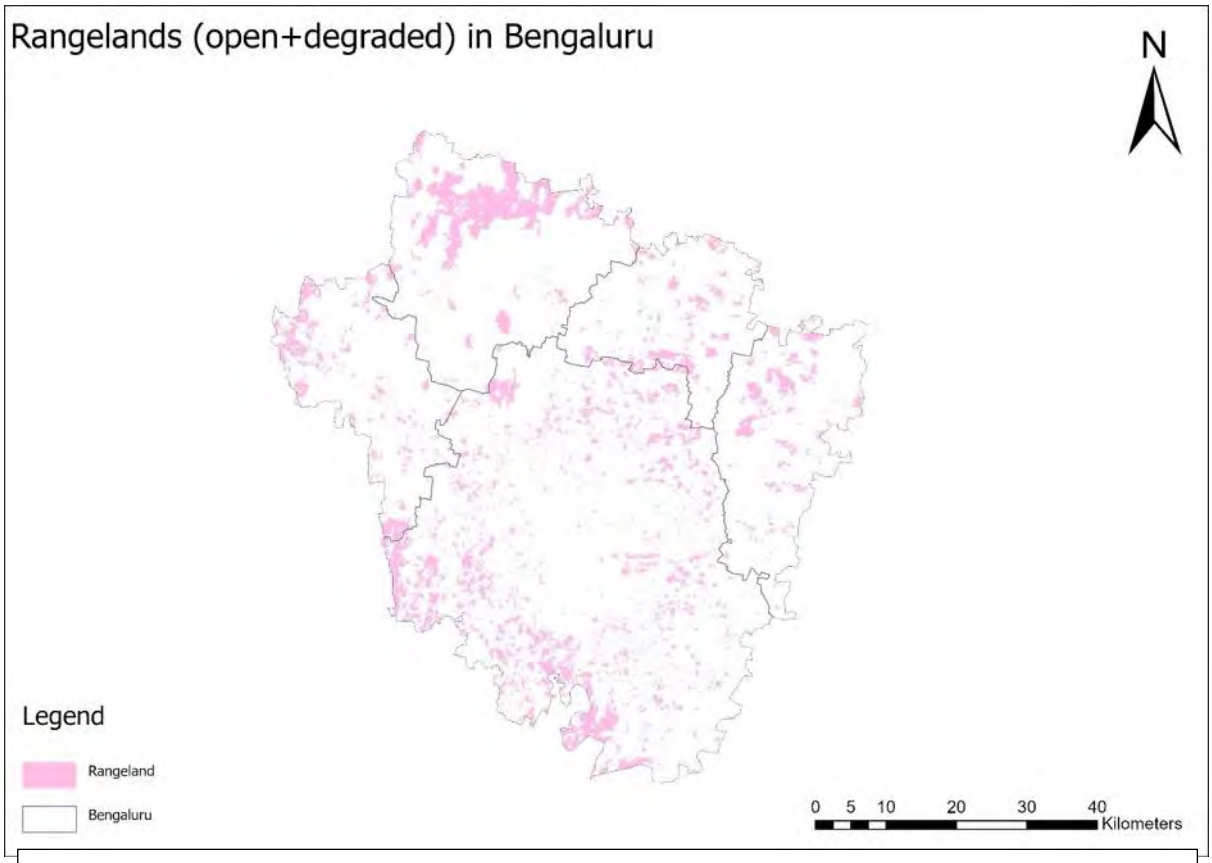

Figure 25 Rangelands (open+ degraded) in Bengaluru, Source: Author

In the bustling metropolis of Bengaluru, often dubbed the Concrete Jungle, the prospect of accommodating 15 million plants might seem like a daunting challenge. However, meticulous planning and innovative approaches suggest that the land needed for such a green initiative is indeed within reach. By employing low, medium, and high-density planting techniques, it is estimated that approximately 100 square kilometres of land would be required to host these plants, primarily. Fortunately, Bengaluru boasts ample degraded land across its urban and rural landscapes, totalling well over 200 square kilometres.

5.4.3 Building codes for usage of Bamboo in buildings

Bamboo was integrated in the National Building code in the year 2005.Though the code is not very comprehensive, but it does have guidelines that are helpful in selection, treatment and design for usage of Bamboo in buildings.

6. Action Plan Preparation

6.1 Oxygen Corridors

To establish Bamboo plantations along roads, railways, parks, water bodies, wastelands, etc in Bengaluru, here are guidelines formulated along with descriptions:

Table 7 Detailed steps to plant Bamboo along roads and railways, Source: Author

Aspect	**Description**	**Responsible Stakeholders**
Selection of Bamboo Species	Choose suitable Bamboo species known for resilience and deep root systems.	Local botanists or horticulturists
Site Selection and Preparation	Identify appropriate locations with sunlight and water access, away from utility lines	Local environmental authorities, urban planners
Spacing and Planting	Maintain 3 to 5 meters spacing between plants.	Community volunteers, gardening clubs
Maintenance and Care	Monitor for pests, diseases, or nutrient deficiency, Water during dry periods	Local gardeners, community maintenance teams
Integration with Infrastructure	Coordinate with relevant authorities to ensure no interference	Bengaluru Metro Rail Corporation Limited (BMRCL), Bruhat Bengaluru Mahanagara Palike (BBMP), BDA, BMRDA, Lake Development Authority, Horticulture Department, Forest Department
Community Engagement	Involve local communities in planning and maintenance. Organize events and workshops	Community leaders, neighbourhood associations
Long-Term Management	Develop a management plan including maintenance, rejuvenation, and sustainable harvesting. Explore value-added products for additional income.	Environmental NGOs, local government agencies

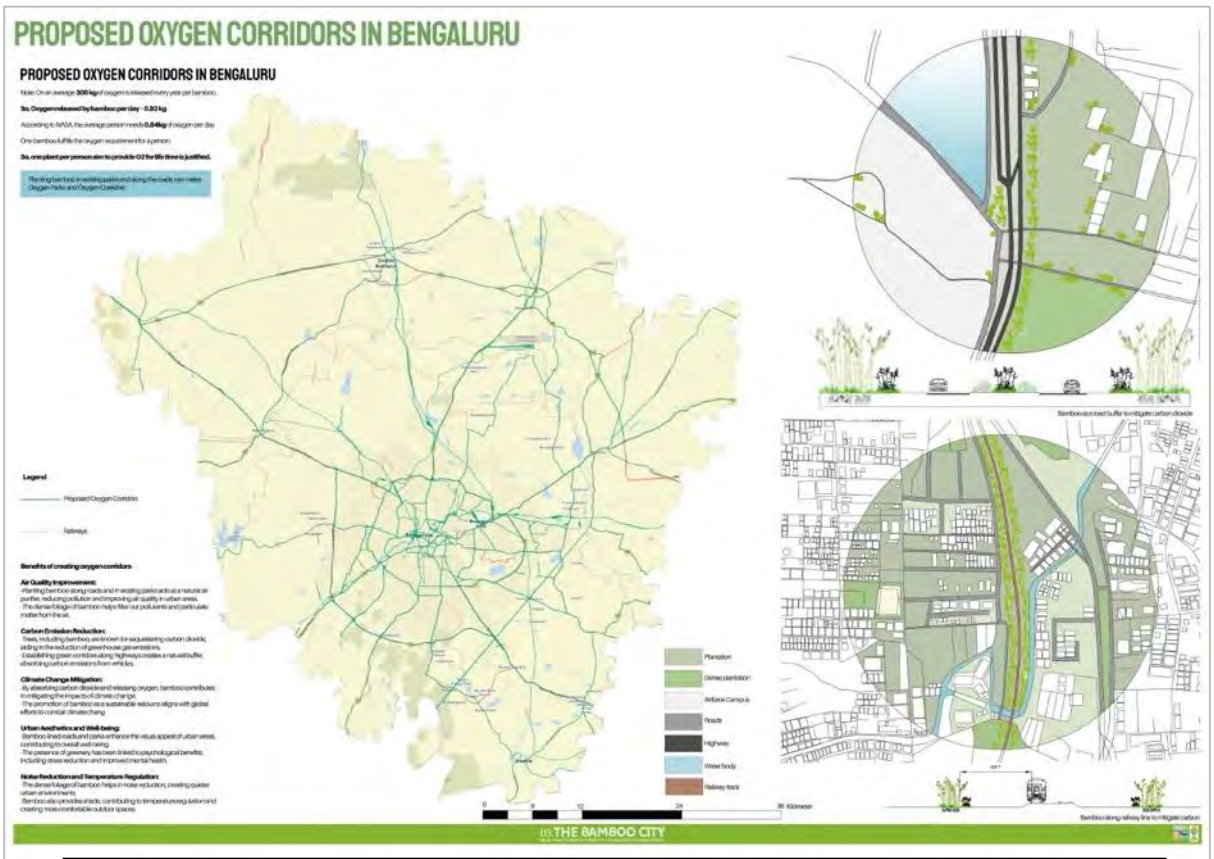

Figure 26 Proposed Oxygen Corridors in Bengaluru

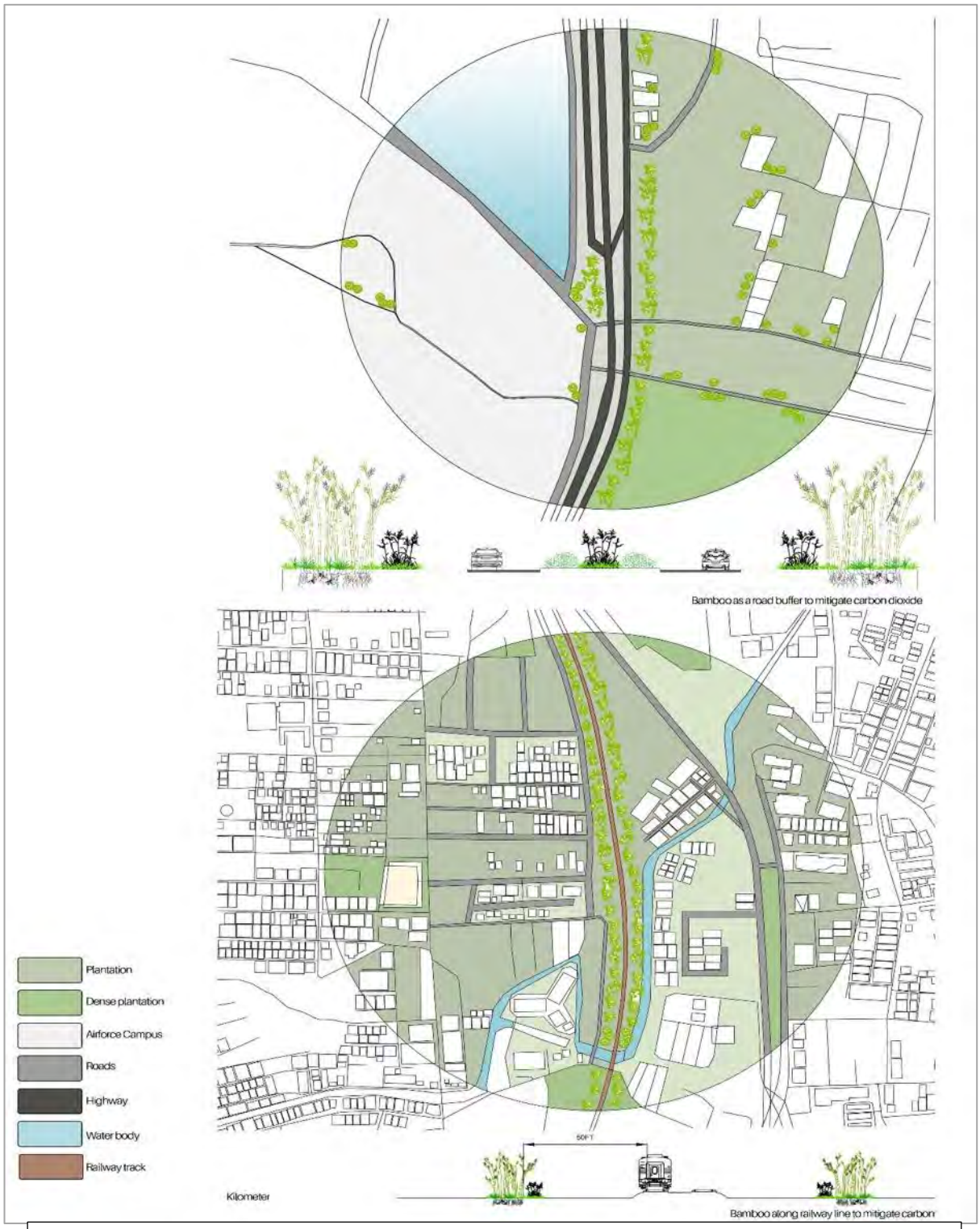

Figure 27 Detailed section plan for planting Bamboo along Roadways and Railways, Source: Author

6.2 Water Body Management

Our approach involves targeted afforestation along the peripheries of the lakes in these valleys and within check dams. By strategically planting vegetation, we aim to enhance water quality by mitigating pollutants through natural filtration processes.

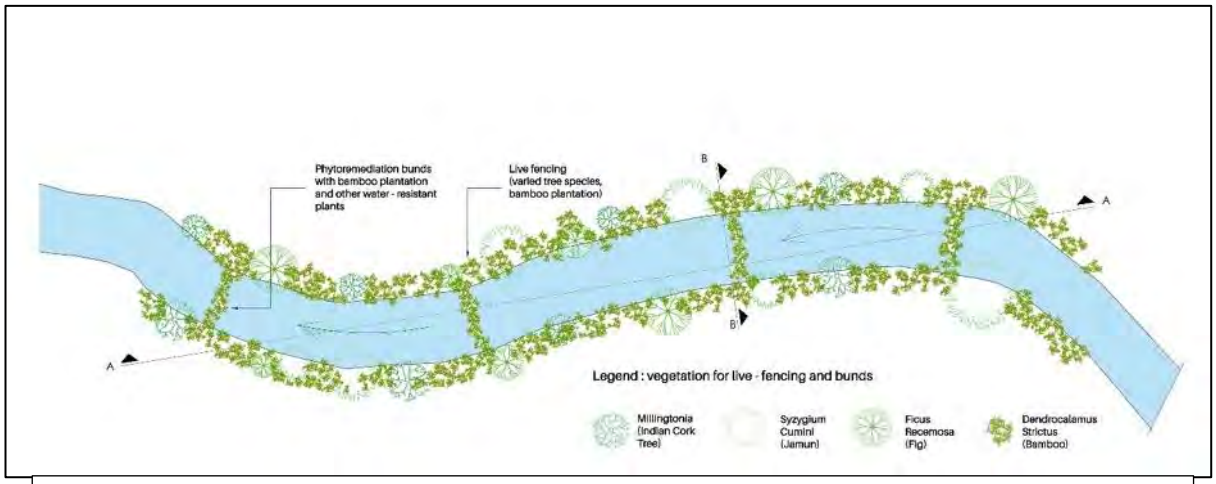

Figure 28 Detailed plan of planting Bamboo along water bodies along Subramanyapura Lake, Source: Author

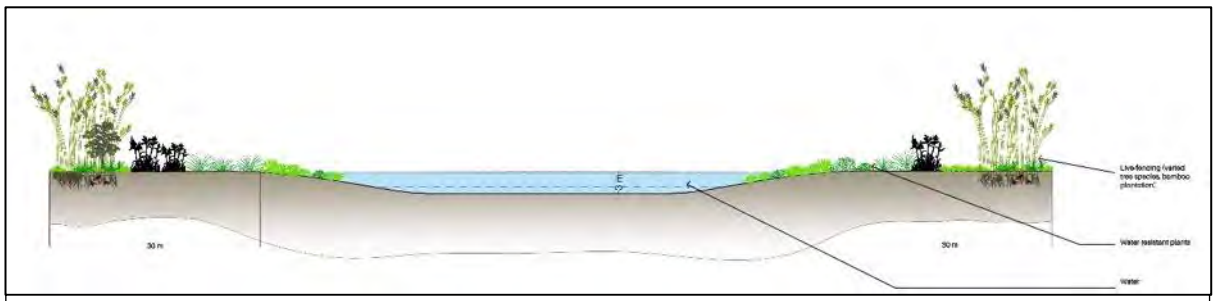

Figure 29 Sectional view of the lake, Source: Author

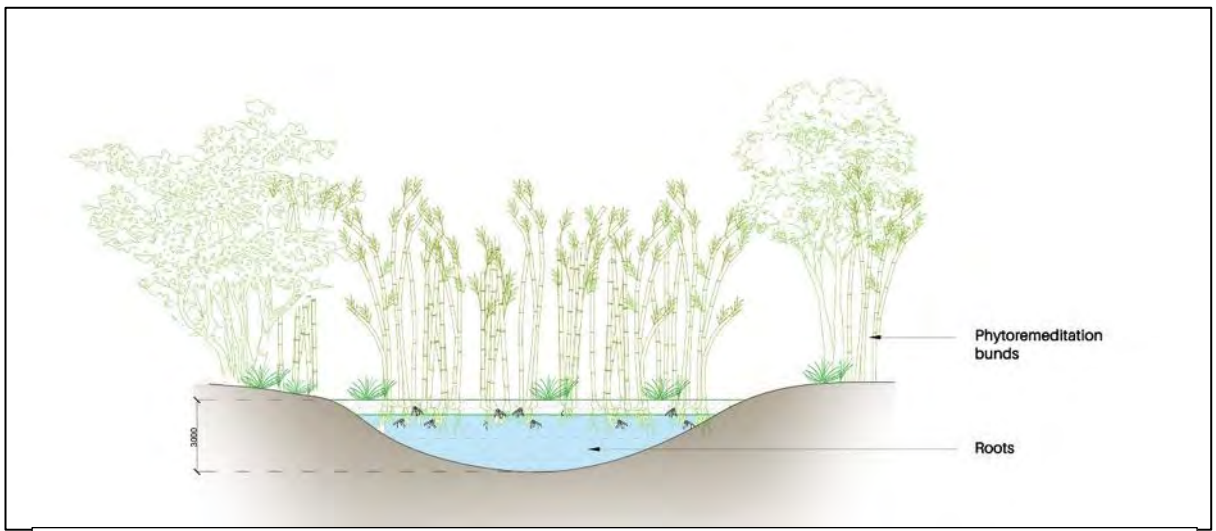

Figure 30 Planned Phytoremediation Bunds on the lake, Source: Author

6.3 Parks Detailed Plan

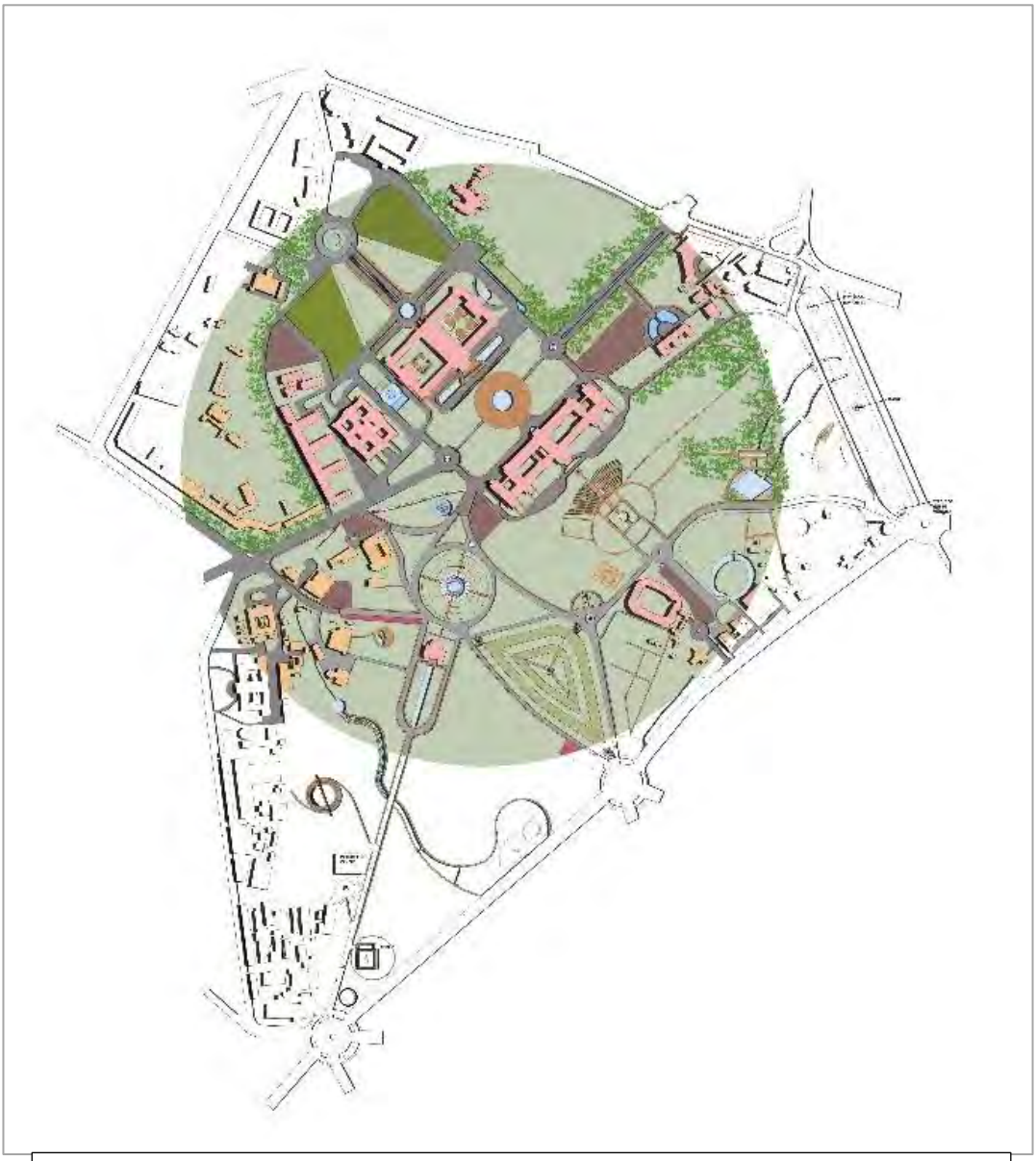

Figure 31 Detailed plan to plant Bamboo in Cubbon Park, Source: Author

6.4 Degraded Lands Detailed Plan

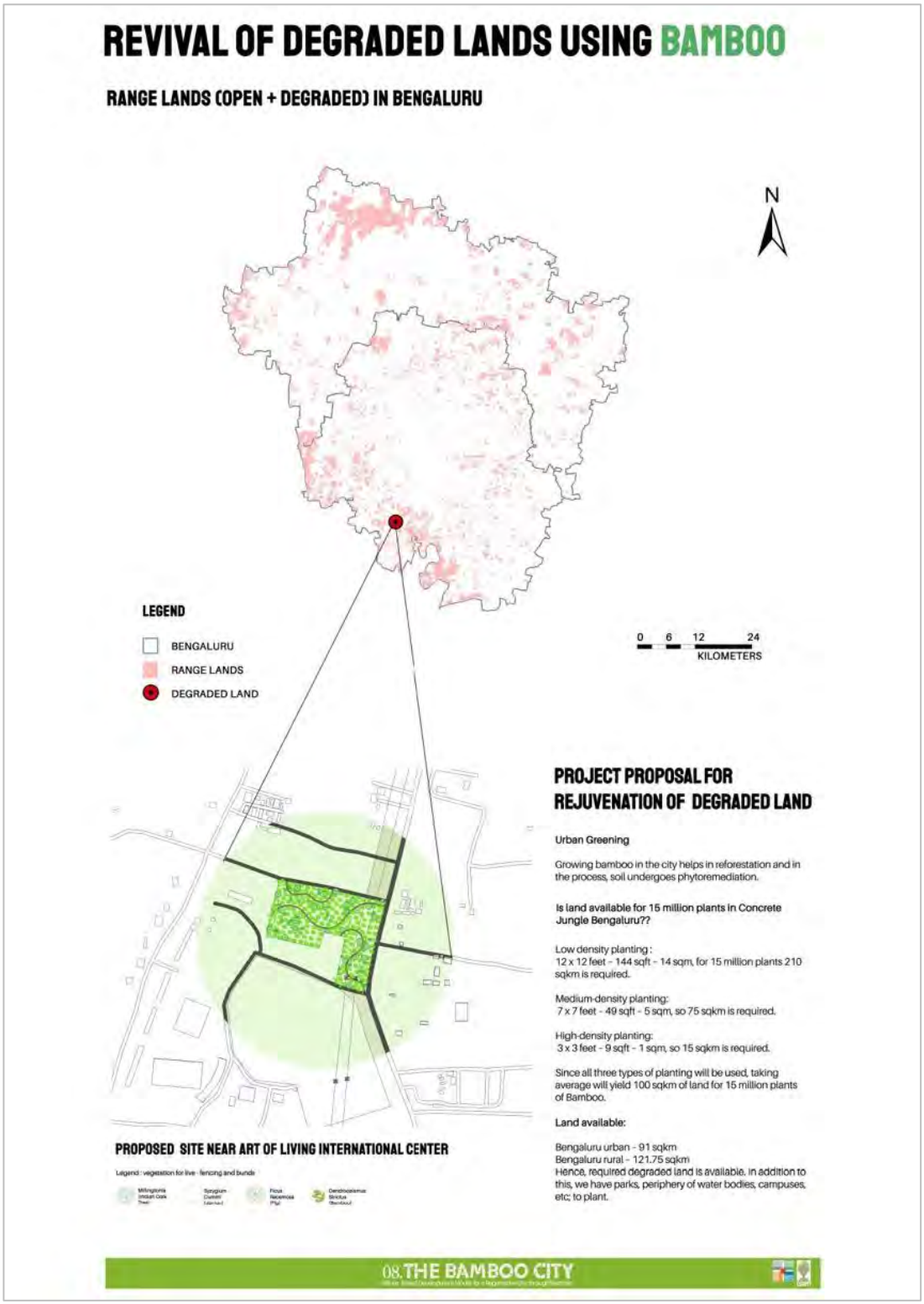

Figure 32 Detailed plan to plant Bamboo in Degraded Land near Art of Living Centre, Source: Author

7. Action Plan Frameworks for each Sector

7.1 Housing and Infrastructure

Table 8 Detailed action plan for Housing and Infrastructure Sector, Source: Author

Activity	**Action Description**	**Government Bodies to be Contacted**
Policy Support	Advocate for policy reforms, introduce incentives such as tax breaks or subsidies, establish building codes and standards;	1. Urban Development Department, Government of Karnataka 2. Bengaluru Development Authority (BDA) 3. Karnataka State Pollution Control Board (KSPCB)
Research and Development	Invest in research to improve the quality, durability, and fire resistance of Bamboo-based construction materials; Collaborate with academic institutions and research organizations;	1. Department of Science and Technology (DST), 2. Karnataka Council for Technological Upgradation (KCTU)
Capacity Building and Training	Provide training programs and workshops for architects, engineers, and construction workers on Bamboo construction techniques and best practices, Establish vocational training centres and partner with industry experts;	1. Department of Skill Development, Entrepreneurship and Livelihood, Government of Karnataka. 2. Bengaluru Mahanagara Palike (BBMP)
Community Engagement	Raise awareness among homeowners, developers, and the general public about the environmental benefits of Bamboo construction.	1.Department of Information and Public Relations (DIPR), Government of Karnataka. 2. Bengaluru Urban District Administration
Public-Private Partnerships	Foster partnerships between government agencies, private sector companies, NGOs, and community organizations to implement Bamboo-based construction projects, Encourage collaboration with Bamboo growers and suppliers;	1. Department of Industries and Commerce, Government of Karnataka. 2. Karnataka Industrial Areas Development Board (KIADB).
Monitoring and Evaluation	Implement a monitoring and evaluation framework to track the adoption of Bamboo-based construction practices and their impact on carbon emissions, Use feedback from stakeholders and for future implementation;	1. Karnataka State Remote Sensing Applications Centre (KSRSAC). 2. Department of Economics and Statistics, Government of Karnataka.

7.2 Air Pollution:

Bamboo can help reduce air pollution in Bengaluru through a comprehensive framework that includes planting, policy, technology, and community involvement. Here's a structured framework:

Table 9 Detailed action plan for Air Sector, Source: Author

Activity	**Action Description**	**Government Bodies to be Contacted**
Assessment and Planning	Conduct a comprehensive assessment of air quality in different parts of Bengaluru to identify areas with high pollution levels, Develop a strategic plan with clear goals and targets using Bamboo;	1. Karnataka State Pollution Control Board (KSPCB) 2. Urban Development Department, Government of Karnataka
Bamboo Plantation and Urban Greening	Identify suitable areas for Bamboo plantation within Bengaluru, such as parks, roadside strips, vacant lands, and along water bodies;	1. Karnataka Forest Department. 2. Bruhat Bengaluru Mahanagara Palike (BBMP)
Bamboo-Based Air Purification Technologies	Explore and develop innovative technologies that utilize Bamboo for air purification;	1. Department of Science and Technology (DST), Government of Karnataka. 2. Ministry of Environment, Forest and Climate Change (MoEFCC), Government of India
Policy and Regulation	Advocate for policy changes to promote Bamboo cultivation and utilization for air pollution mitigation;	1. Karnataka State Government. 2. Department of Industries and Commerce, Government of Karnataka. 3. Ministry of Environment, Forest and Climate Change (MoEFCC), Government of India
Awareness and Education	Conduct awareness campaigns to educate the public about the benefits of Bamboo in air pollution reduction, engage schools and universities in environmental education programs, encourage community participation;	1. Department of Education, Government of Karnataka. 2. Department of Information and Public Relations, Government of Karnataka. 3. Karnataka State Council for Science and Technology (KSCST)
Monitoring and Evaluation	Establish monitoring systems to track the progress of Bamboo plantations and its impact on air quality;	1. Karnataka State Pollution Control Board (KSPCB). 2. Urban Local Bodies (ULBs)
Collaboration and Partnerships	Foster collaboration between government agencies, research institutions, private sector entities, and civil society organizations to implement the Bamboo-based air pollution reduction framework;	1. Karnataka Biodiversity Board. 2. Ministry of Environment, Forest and Climate Change (MoEFCC), Government of India

7.3 Water Management Framework

Rejuvenating water bodies in Bengaluru through Bamboo can be achieved through a comprehensive framework that involves multiple steps and stakeholders as follows:

Table 10 Detailed action plan for Water Sector, Source: Author

Activity	**Action Description**	**Government Bodies to be Contacted**
Assessment and Identification	Conduct a thorough assessment of the current state of water bodies in Bengaluru, including their size, depth, water quality, surrounding vegetation, and biodiversity;	1. Bruhat Bengaluru Mahanagara Palike (BBMP). 2. Karnataka State Pollution Control Board (KSPCB)
Community Engagement	Engage with local communities living around the identified water bodies, encourage active participation;	1. BBMP 2. Karnataka Forest Department
Bamboo Plantation and Restoration	Select suitable species of Bamboo that thrive in wetland ecosystems and are native to the region;	1. Karnataka Forest Department. 2. BBMP
Eco-friendly Infrastructure	Construct eco-friendly infrastructure using Bamboo, such as floating platforms, walkways, and fencing, to facilitate access for maintenance and recreational activities without disturbing the ecosystem;	1. BBMP 2. Karnataka Urban Infrastructure Development and Finance Corporation (KUIDFC)
Wetland Restoration and Conservation	Restore wetland habitats within and around the water bodies by creating channels, ponds, and marshy areas using Bamboo structures;	1. Karnataka State Wetlands Authority 2. BBMP
Monitoring and Maintenance	Implement a monitoring system to regularly assess the progress of rejuvenation efforts, including water quality parameters, vegetation growth, and biodiversity;	1. BBMP 2. Karnataka State Remote Sensing Applications Centre (KSRSAC)
Policy Support and Funding	Advocate for supportive policies at the local government level to incentivize and facilitate, Seek funding and resources from government grants and CSR;	1. Department of Ecology and Environment, Government of Karnataka. 2. Urban Development Department, Government of Karnataka
Education and Outreach	Conduct educational programs and workshops to raise awareness about the importance of water conservation, wetland ecosystems, and the role of Bamboo in rejuvenating water bodies;	1. BBMP 2. Karnataka State Council for Science and Technology (KSCST)

7.4 Energy and Waste Management

Table 11 Detailed action plan for Energy and Waste Management, Sector, Source: Author

Activity	**Action Description**	**Government Bodies to be Contacted**
Policy and Regulation	Formulate policies and regulations supporting the cultivation, processing, and use of Bamboo for energy and waste management;	1. Department of Industries and Commerce, Government of Karnataka
Bamboo Processing and Conversion	Establish Bamboo processing facilities equipped with appropriate technology for energy and waste conversion;	Karnataka State Industrial Infrastructure Development Corporation (KSIIDC)
Energy Generation	Implement Bamboo-based energy generation systems like biomass power plants or biogas digesters, Offer financial incentives and subsidies;	Karnataka Renewable Energy Development Limited (KREDL)
Waste Management	Utilize Bamboo-derived products for waste management, such as biochar for organic waste composting or activated carbon for water purification.	Bruhat Bengaluru Mahanagara Palike (BBMP)
Community Engagement and Awareness	Conduct educational programs and workshops to raise awareness about the benefits of Bamboo-based energy and waste management;	Department of Urban Development, Government of Karnataka
Monitoring and Evaluation	Implement a monitoring and evaluation system to track the progress and effectiveness of Bamboo-based energy and waste management initiatives, collect data, conduct regular audits, provide technical assistance;	Karnataka State Pollution Control Board (KSPCB)
Scaling and Replication	Share best practices and lessons learned to facilitate the replication of the framework in other regions, collaborate and support	Department of Rural Development and Panchayat Raj, Government of Karnataka
Research and Innovation	Invest in research and development to explore new applications and technologies related to Bamboo utilization, support pilot projects, promote knowledge sharing and collaboration;	Karnataka State Bamboo Development Corporation (KSBDC)

7.5 Implementation and Timelines

On the ground, the project implementation was soft-launched with plantations on September 18, 2023 on World Bamboo Day at the CGBMT Headquarters site in Bengaluru, India. We are in the process of collaborating with various stakeholders for the preparation of a DPR. with all the costs involved. Once a DPR is prepared, funds and grants will be raised from government, international organizations, CSR, philanthropists, and other sources working in the climate action sector. With the available funds and collaborations in place, implementation work will be carried out in phases.

Phases of Bamboo City Project

Production Phase	Post-harvest Phase	Industrial Phase
Creating bamboo awareness (Webinars, bamboo plantation drives). Educating on bamboo application (Courses through bamboo school of studies). Bamboo plantations (Establishing and accrediting nurseries). Standardization of harvesting techniques.	Establishing primary and secondary processing units in production areas. Setting up of demand-driven treatment facilities & CFCs near bamboo bazaars. Creation of storage & marketing infrastructure. Skill development of artisans, designers, architects, etc.	Encourage bamboo in construction. Bamboo based energy, biofuel generation and activated charcoal/biochar. Establishment of industries for manufacturing PEBB, bamboo-based composites. Setting up of Bamboo economic zones.

Figure 33 Timeline to implement the Bamboo City Project, Source: Author

Legend to understand implementation matrix

In this action points implementation matrix:

1. Short term: 2023-26
2. Mid term: 2026-30
3. Long term: 2030 and beyond

1. ₹ : indicates that an action can be completed with minimal financial investments (e.g., through current staff capacity or minimal financial costs, typically less than 10 lakhs).

2. ₹₹ : indicates that an action can be completed with moderate financial investments (e.g., will require some additional staff capacity or moderate financial costs, typically between 10 lakhs and 50 lakhs.

3. ₹₹₹ : indicates that an action can be completed with significant financial investments (e.g., will require multiple new staff members or significant financial costs, typically over 50 lakhs.

Benefit type	Description	Symbol
GHG Emissions Reduction	Potential Action could have high GHG reduction potential because this action targets a large source of emissions	
Public Health	Action could have a positive impact on public health in the community	
Economic Growth	Action could have a positive impact on the economic growth of the community	
Equity	Action either addresses inequities or could have a positive impact on equity in the community.	
Affordability	Action could be more cost-effective for the city and/or funding is already available	
Resilience	Action could have a positive impact on community resilience to climate change	

Figure 34 Legend to implementation matrix

7.6 Policy Interventions:

To execute such a complex project on the ground with several stakeholders, some key policy interventions will be required to enable effective implementation of the project:

a. Integration in Urban Planning Policies: Zoning Regulations and Land Use Planning: Integrate Bamboo plantations into citywide zoning regulations and land use plans

b. Government Incentives: Public Procurement Policies to prioritize the use of sustainable materials, including bamboo, Research and Development Funding

c. *Building Codes and Regulations* to include Bamboo comprehensively

d. *Green Infrastructure Standards:* Develop green infrastructure standards and guidelines that incorporate Bamboo as a key element in urban green infrastructure planning and design.

e. *Community Land Rights and Tenure Security:* Ensure community land rights and tenure security for Bamboo growers and traditional forest dwellers to promote sustainable Bamboo cultivation and livelihood development.

f. *Capacity Building and Training Programs*

g. *Promotion and Awareness Campaigns*: Launch public awareness campaigns and promotional initiatives to highlight the benefits of Bamboo-based solutions for sustainable urban development, climate change mitigation, and poverty alleviation, utilizing various communication channels.

7.7 Evaluation and Monitoring:

What we measure, we control. Documentation, monitoring, and evaluation are major components that we have. Inclusion, as it is, is very important for dynamic adjustment to get the desired results. This data will also assist in recommending policy interventions.

a. Documentation: Keeping records of the number and type of species planted as well as their growth process will be helpful in further planning.

b. Monitoring: assessing the impact of the plantation on the air quality and water quality regularly and recording the same for future initiatives.

c. Calculation of CO2 emissions from Bamboo-based buildings and assessment of the circularity index;

d. Structural, durability, safety, and economic evaluation of Bamboo as a building material to establish results.

8. Conclusions

8.1 Oxygen requirement calculation

On average, Bamboo releases approximately 300 kg of oxygen annually (TNAU, 2019), equating to approximately 0.82 kg per day. NASA estimates that the average person requires 0.84 kg of oxygen daily. As a result, one Bamboo plant's oxygen output effectively meets an individual's oxygen needs for an assumed life span of 60 years which is also the average life of a bamboo plant. This correlation suggests that adopting a one-plant-per-person approach could feasibly fulfil their lifetime oxygen requirements. Such a strategy underscores the significance of Bamboo as a sustainable source of oxygen, supporting the notion of incorporating Bamboo planting initiatives for environmental and human health benefits.

8.2 CO2 reduction by Plantations

The population of Bengaluru in 2030 will be approximately 20 million and according to the objective 20 million Bamboo plants will be implemented. CO2 Emissions per year in Bengaluru will be approximately 21 million tons by 2030.

Total CO2 Absorbed by the proposed Bamboo Plantations, Agroforestry, and existing Trees would be approximately 4.7 million tons.

8.3 CO2 Emissions reduction through 30% usage of Bamboo in construction

Embodied carbon factor of concrete – 0.103
Embodied carbon factor of steel – 1.99
Embodied carbon factor of Bamboo – 0.017

Figure 35 Comparison of embodied factor of materials

By using Bamboo in new constructions, we can reduce approximately 10 million tons of CO2 emissions in Bengaluru.

A total of 14.7 million tons of CO2 can be sequestered through Bamboo plantations, agroforestry, and using 30% Bamboo in new constructions. Hence, a total of 70% of carbon will be sequestered through the proposed bamboo plantations and using 30% Bamboo in the construction sector, and the remaining 30% can be sequestered by existing other trees, other plantations and other sustainable city development strategies such as products, eco-friendly public transport systems, and the usage of Bamboo and biowaste for energy generation etc.

Nature has an innate ability to regenerate, forming the foundation of the intricate web of life and essential ecosystem services that sustain human livelihoods. As cities rely on nature, a model for regenerative cities must prioritize nature as a fundamental stakeholder when developing an action plan to address urban environmental, economic, and social issues. The Bamboo City project presents an opportunity to absorb and store carbon, mitigate greenhouse gas emissions, provide a renewable resource for housing and infrastructure, remediate degraded lands, rejuvenate lakes, and reverse air pollution. These efforts will foster inclusive, equitable, resilient, and safe urban spaces while providing clean water, clean air, and local livelihood opportunities, especially for marginalized populations.

Therefore, Bamboo Cities can serve as a nature-based solution to curb global warming and achieve net-zero carbon goals by 2030, ultimately leading to regenerative cities. The limitation of this Bamboo City framework is that it is general in nature developed for cities where bamboo has been growing naturally. Some of the action points derived in this paper are based on results and analysis by applying city specific data to the framework for Bengaluru city as a pilot case. For adopting the framework to any other city, city specific data will have to collected and applied to prepare the action plan for the city.

Acknowledgements
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