CHAPTER 70

Feasibility Study on the Use of Industrial Waste for Sustainable Construction

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ABSTRACT

There are many types of waste generated during various mining and industrial operations. Among them the fly ash and crushed fine aggregate are on highest generated waste in the thermal power plants and mining of stones respectively. The project aims to promote sustainable construction by repurposing plastic waste and industrial byproducts into eco-friendly outdoor sitting bench, reducing environmental waste and offering a cost-effective, durable alternative. This research explores a sustainable construction method utilizing recycled materials such as plastic bottles, fly ash, crushed sand and bamboo to create environmentally responsible sitting chairs. By repurposing plastic waste and leveraging renewable materials, this approach reduces landfill waste and carbon emissions while promoting resource efficiency. The study demonstrates the feasibility of integrating recycled materials into construction as a scalable and economical solution, aligning with international sustainability standards and supporting the circular economy. The finding highlights waste utilization, reduce carbon emissions, and material costs, setting a precedent for future green construction initiatives.

Keywords: Cement; Flyash; Construction; Cost; Sustainability.

1.0 Introduction

1.1 Sustainability and waste management within the construction industry

The construction sector is among the biggest industries in the world economy, with a key role to play in development, urbanization, and infrastructure development. The sector works with intricate supply chains and utilizes huge amounts of resources to respond to increasing demands of development.

Engineering and construction (E&C) firms are increasingly being subjected to pressure to resolve sustainability issues while ensuring economic feasibility in a rapidly competitive environment. Its influence stretches beyond direct construction activity to encompass longer-term operational factors, and as such, the built environment is an essential priority for sustainable development initiatives (Deloitte, 2024).

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1.2 Importance of sustainability in construction

Sustainability is necessary in construction because it has a major impact on the environment, with 39% of global operational and embodied carbon emissions coming from the built environment (Deloitte, 2024). More than 90% of US construction companies have reported increasing client pressure to lower embodied carbon, reflecting the movement toward sustainable operations. With rapid urbanization, the environmental footprint of construction increases, and conserving resources and reducing pollution becomes essential for sustainable development (Aranca, 2024).

1.3 Waste generation in construction sector

Construction produces heterogeneous waste streams, which differ according to project type and local operations. Typical wastes such as concrete, wood, metal, bricks, and plastics typically find their way into landfills with associated environmental impacts (Aranca, 2024). It was revealed in one study conducted in Malaysia that the Conventional Construction Method (CCM) resulted in the greatest waste at 197.657 tons (0.046 tons/m²), while the Industrialized Building System (IBS) generated much lower at 77.188 tons (0.018 tons/m²) (ETASR, 2018). This calls attention to how construction activities affect the production of waste, with a focus on choosing effective methods to reduce waste.

Figure 1: Anatomy of the Wall

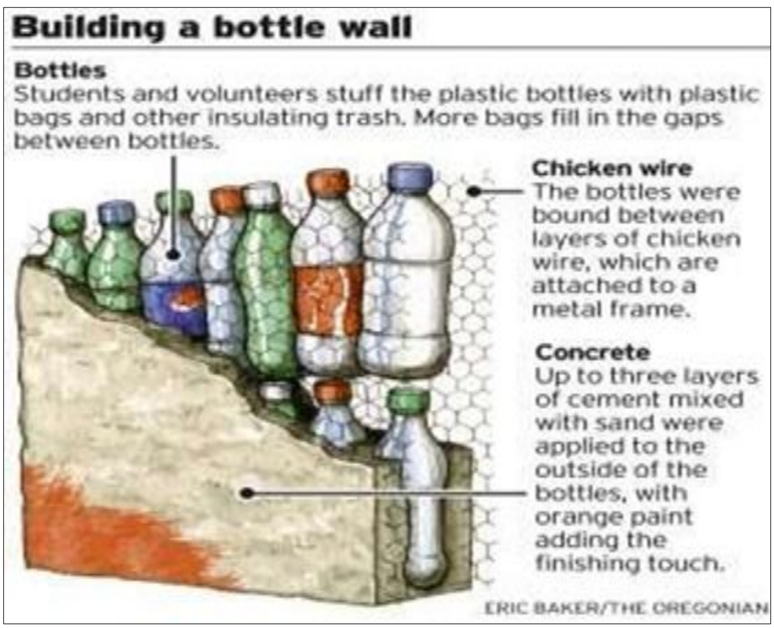

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Figure 2: Placement of Bottles in the Wall

Figure 3: Finished Wall Bottle School in Guatemala

Source: Bright Vibes

2.0 Literature Review

2.1 Plastic waste incorporation in concrete

The global plastic waste crisis has led scientists to explore new applications for such materials beyond conventional recycling streams. Polyethylene terephthalate (PET), the polymer in beverage bottles and packaging for foods, represents an abundant waste stream with physical characteristics of potential application in construction materials. Recent studies have

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investigated the effect of chemical pre-treatment on PET waste before application in concrete mixes. When plastic waste is mixed into concrete, chemical treatment has been demonstrated by scientists to significantly improve compatibility with cementitious materials. Hydrogen peroxide and calcium hypochlorite solutions treat plastic aggregates to produce a rough surface on plastic aggregates and enhance the mechanical bond with the concrete paste around them. This modification overcomes one of the principal problems in plastic-concrete composites: the low quality of the interfacial transition zone between plastic particles and the paste of the cement. Testing between percentages of replacement between 10% and 30% demonstrates treated plastic aggregates enhance compressive strength and concurrently reduce concrete permeability and porosity compared to their non-treated counterparts (Lee *et al.*, 2019).

2.2 Fly ash as a sustainable cement substitute

Portland cement manufacturing is a major source of global carbon emissions and as such there exists interest in supplementary cementitious materials with the potential to reduce environmental impact at no loss of performance. Fly ash, the finely divided residue of coal combustion in power plants, has been an extremely successful partial substitute for cement. It is siliceous and aluminous in character and when properly activated in concrete mixes develops strength over the longer term by pozzolanic reaction.

Environmental studies indicate that the utilization of fly ash in concrete mixtures offers considerable sustainability benefits. Environmental impact assessments demonstrate that incorporating fly ash into concrete mixtures delivers substantial sustainability benefits. Research indicates that replacing 25% of cement with fly ash reduces the global warming potential of concrete by 22-30.6%, while 50% replacement levels achieve reductions of 44-51.4%. These environmental advantages stem primarily from avoiding the carbon-intensive cement production process, with each unit of fly ash substitution preventing approximately equivalent CO_2 emissions. Beyond climate impacts, fly ash utilization provides additional environmental benefits including reduced energy consumption and conservation of landfill capacity that would otherwise be required for ash disposal (Green Education Foundation, 2023).

2.3 Recycled aggregates as natural material alternatives

The construction and demolition sector generates substantial waste volumes annually, much of which holds potential value as secondary materials. Recycled concrete aggregates, produced by processing demolition waste, offer a promising alternative to natural aggregates in new concrete production. This approach simultaneously addresses waste management challenges and reduces demand for virgin material extraction. Performance analysis of recycled aggregate concrete indicates that strength development depends on multiple factors including the quality of source materials, processing methods, and mixture proportions. Water absorption characteristics of recycled aggregates differ significantly from natural materials, requiring adjustments to mixture designs to maintain workability and performance. As the replacement

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percentage of recycled aggregates increases, modifications to sand ratios become necessary to optimize mechanical properties. Research suggests that incorporating supplementary cementitious materials like fly ash alongside recycled aggregates can help address strength development challenges, though early-age performance may be affected differently than long-term properties (Darpan International Research Analysis, 2024).

2.4 Alternative waste materials in construction

Beyond plastic and fly ash, researchers have investigated numerous other waste streams for potential concrete applications. Bamboo fiber, derived from a rapidly renewable plant resource, has shown promise as a reinforcement material in concrete mixtures. These natural fibers, comprising primarily cellulose, hemicellulose, and lignin, provide tensile reinforcement that can help control cracking and enhance concrete durability.

Experimental studies incorporating bamboo fibers into concrete mixtures demonstrate improvements in several performance characteristics. Research indicates that optimal fiber content levels (approximately 0.75%) help limit concrete shrinkage, reduce crack propagation, and positively influence tensile properties. However, fiber content must be carefully controlled, as excessive amounts can negatively impact concrete workability. When combined with other supplementary materials such as waste marble powder and waste glass powder at replacement levels around 10%, bamboo fiber-reinforced concrete exhibits enhanced mechanical properties including improved compressive strength, shear resistance, and bond characteristics (Ramos-Fernández *et al.*, 2021).

From the above literature review it is observed that the conventional construction material environmental impact requires embracing sustainable alternatives. This study is focused on the development of an environmentally friendly bench using waste materials like plastic bottles, bamboo, fly ash, and waste crushed sand to make it durable and sustainable while limiting environmental effects. PET bottles are to be converted into structural parts with chemical modification to improve the bonding with cementitious materials. Bamboo, with its high tensile strength and renewability, will be utilized as reinforcement to enhance load-carrying capacity and resistance to cracks.

Fly ash will be employed as a partial cement replacement to reduce carbon emissions while aiding in long-term strength development through pozzolanic reactions. Waste crushed sand will also replace natural fine aggregates, maximizing the use of resources and reducing reliance on natural sand. This research will analyze the mechanical properties, durability, and sustainability advantages of the suggested material mixtures in terms of compressive strength, permeability, and structural stability. By incorporating waste materials into functional products such as urban furniture, this research seeks to advance circular economy principles and sustainable building practices. The results will help create effective, low carbon building solutions, showcasing the potential of substitute materials in contemporary infrastructure while tackling global sustainability issues.

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3.0 Key Waste Materials for construction Applications

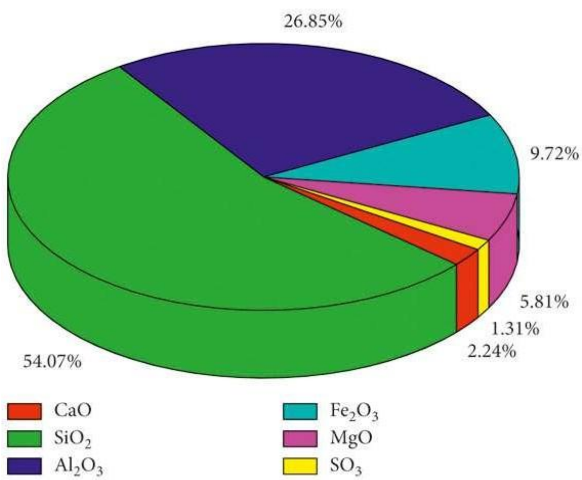
3.1 Plastic waste utilization

Plastic waste, particularly polyethylene terephthalate (PET) bottles, poses a global disposal challenge. Their high tensile strength, chemical resistance, and strength-to-weight ratio make them suitable for modular construction (Modification of Waste Aggregate PET, 2019). Additionally, recycled aggregates from construction and demolition waste, along with industrial by-products like coal bottom ash, offer sustainable alternatives to natural aggregates, supporting a circular economy by reducing landfill waste and conserving resources (Evaluating Recycled Concrete Aggregate, 2024).

Figure 4: Polyethylene Terephthalate (PET) Bottle

Source: Plastics for change

Figure 5: Main Chemical Composition of Fly Ash



Source: Zhiyu Tang, Nianchun Deng Research gate

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3.2 Fly ash as a cementitious material

For external bonding among bottles, the paste is normally designed with 10-15% Portland cement content to facilitate rapid development of strength and weather resistance. Optimum proportioning of water content (water-to-solid ratios of 0.28-0.35) achieves satisfactory workability without compromise in strength development. Prototype bench structural testing has demonstrated compliance with relevant standards for public seating, including ISO 7173:1989 (Furniture — Chairs and stools — Determination of strength and durability). The structure is able to withstand concentrated loads of 1.2-1.8 kN and distributed loads of 3-5 kN/m² and experiences gradual deformation rather than catastrophic failure under overloading—a critical safety consideration for public installations.

3.3 Crushed sand

Crushed sand (M-sand) is a sustainable alternative to natural sand, addressing resource scarcity and environmental concerns from riverbed mining. Research shows that up to 40% replacement of natural sand in concrete maintains compressive strength, while 60-70% substitution enhances tensile strength (International Journal of Engineering Research and Technology, 2022). It also improves flexural strength at 28 days and is cost-effective due to lower transport costs (Singh, 2021). Studies confirm its viability in pavement construction and full replacement in M20 concrete with proper mix adjustments (Darpan International Research Analysis, 2024; Green Education Foundation, 2023). Additionally, its shape properties influence elasticity and shrinkage, supporting its use as a fine aggregate (Ramos-Fernández *et al.*, 2021).

Figure 6: Fly Ash Sample

Source: Indiamart

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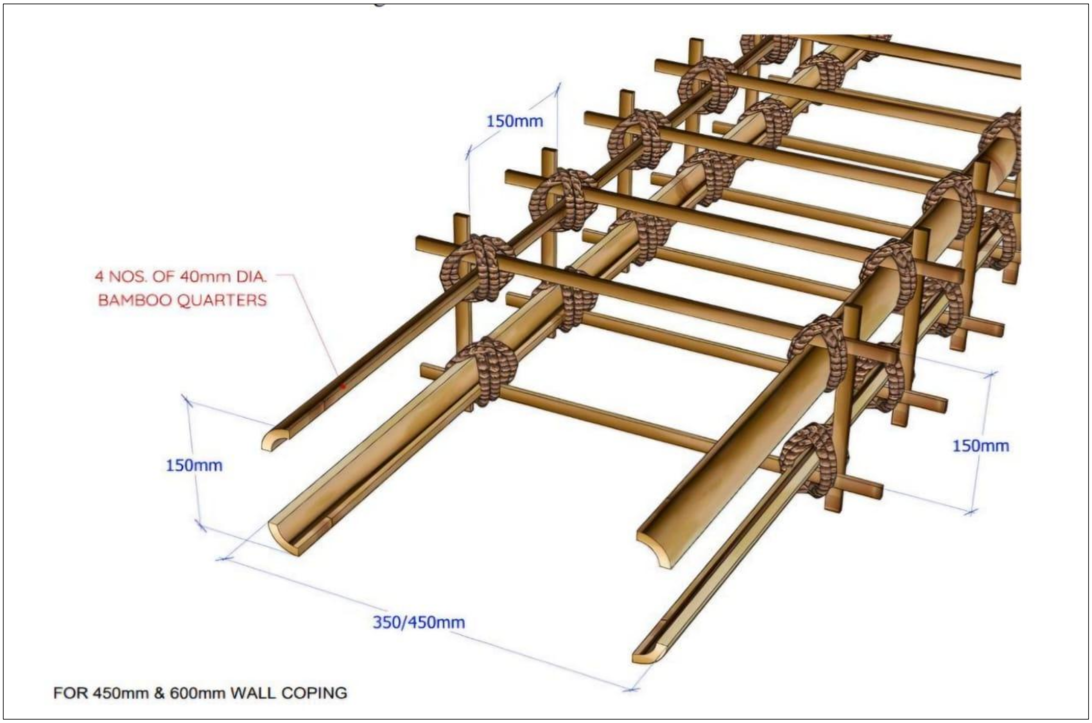
Figure 7: Bamboo as a Reinforcement in Green Carbon Building



3.4 Bamboo for sustainable construction

Bamboo is emerging as a sustainable alternative in construction due to its rapid growth, high tensile strength comparable to steel, and natural resistance to decay and moisture (Revista Electronica De Veterinaria, 2021). Its flexibility allows it to absorb seismic loads, making it ideal for earthquake-resistant structures (UN-Habitat, 2022). Bamboo also sequesters large amounts of CO_2, reducing carbon emissions compared to steel and concrete (Green Building Council, 2023). Economically, bamboo construction is 20-30% cheaper than conventional materials, making it viable for low-cost housing and disaster-resistant structures (World Economic Forum, 2023; Disaster Resilience Journal, 2024). Additionally, its full utilization could generate over $1.2 billion annually, supporting sustainable economic growth (International Bamboo and Rattan Organisation, 2024).

4.0 Methodology Adopted

To develop the sustainable bench for that purpose following methodology has been developed. The procedure starts with material preparation by combining fly ash and crushed

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sand in the proportion of 1:6 with a water-fly ash ratio of 0.25 to achieve desirable consistency. The fly ash and crushed sand mixture is properly mixed without any segregation and bleeding, with proper storage to prevent contamination. Then, plastic bottles are washed and filled with the prepared mortar in three layers with each layer compacted 25 times with a tamping rod to eliminate air pockets. The bottles are sealed with their original caps once full and left aside for curing. In structural construction, bottles are laid in a header bond fashion, toe-to-toe, in four layers, like bricks. There are proper leveling and alignment checks, and pointing is done using a 1:6 cement-fly ash-crushed sand mortar mix with a water-to-cement ratio of 0.40 to provide stability. Bamboo supports are fitted at the back for strengthening, with 28 vertical and 4 horizontal members fixed securely with nails. The bamboo is treated to be durable, not to decay or absorb moisture. This green approach guarantees a robust, sustainable, and affordable option for the production of outdoor bench.

Figure 8: Flow Chart of Methodology

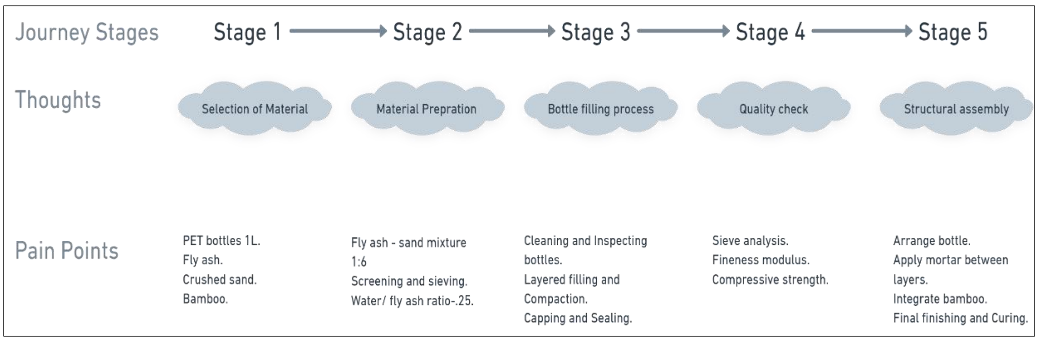

Figure 9: Fly ash and Crushed Sand Mix

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Figure 10: Bottle Filling

Figure 11: Mortar with Fly Ash

Figure 12: Curing of Chair

Figure 13: Sustainable Chair

Table 1: Typical Sieve Analysis Results for Crushed Sand (as per IS 383:2016)

SIEVE SIZE	RETAINED WEIGHT(g)	CUMULATIVE RETAINED WEIGHT(g)	% RETAINED	%PASSING
4.75	0	0	0%	100%
2.36	50	50	5%	95%
1.18	200	250	25%	75%
0.6	300	550	30%	45%
0.3	250	800	25%	20%
0.15	150	950	15%	5%
0.075	40	990	4%	1%
PAN	10	1000	1%	0%

Interpretation: Zone II Fine Aggregate as per IS 383.

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5.0 Tests and Calculations

5.1 Sieve analysis of crushed sand

Sieve analysis assesses the particle size distribution of crushed sand, verifying its compliance with construction standards.

5.2 Fineness modulus

Fineness Modulus (FM) = 3.59

Interpretation: Since the FM is between 2.3 and 3.6, the crushed sand qualifies as fine aggregate as IS 383:2016. This FM indicates moderately coarse sand, suitable for concrete and masonry work.

Table 2: % Cumulative Retained (as per IS 383:2016)

Sieve Size	Cumulative % Retained
4.75	0
2.36	5
1.18	25
0.6	55
0.3	80
0.15	95
0.075	99

5.3 Compressive strength of bottle

Assessing load and strength is essential to evaluate the structural performance and safety of the bench constructed using plastic bottles filled with fly ash and sand. Various testing methods, including compression tests, finite element modeling, and long-term performance evaluations, are used to verify compliance with safety and durability standards.

5.3.1 Compressive strength of filled bottles

Laboratory tests confirm that the compressive strength of a single filled bottle, measured using a Compression Testing Machine (CTM), is approximately 100 kN. This indicates the bottle's ability to withstand significant compressive forces before failure. While empty PET bottles have limited load-bearing capacity, the densely packed fly ash and sand mixture significantly enhances their structural stability.

5.3.2 Structural load capacity

Finite element modeling and experimental tests confirm that the bench structure can support distributed loads ranging from 3-5 kN/m², making it suitable for public seating applications. Additionally, the bench design withstands concentrated loads of 1.2-1.8 kN,

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meeting ISO 7173:1989 standards for public furniture. Since the bottles are arranged in a staggered pattern and embedded in a binding mortar mix, compressive forces are evenly distributed throughout the structure. The interaction between the bottles, mortar, and bamboo reinforcements ensures that the bench remains structurally sound under prolonged use. Bamboo components provide additional tensile reinforcement, preventing deformation under stress. High-tensile cross-filament tape further enhances stability by securing the bottle layers and minimizing lateral displacement.

5.3.4 Impact resistance and safety

Testing through dynamic impacts indicates the bench's ability to take sudden loads very fast and safely for everyday use. Reinforcement of joints with bamboo and external cladding increases its durability in high traffic areas. The bench is structurally sound and suitable for sustainable construction with the tested compressive strength of 100 kN per bottle.

6.0 Cost Analysis

6.1 Economic considerations for implementation

The economic feasibility of construction from waste depends on material purchase costs, processing costs, and methods of implementation. For the proposed bench structure, plastic bottles are an inexpensive material when purchased from recycling programs or garbage collectors at approximately ₹2.90 per bottle. Fly ash pricing varies significantly based on proximity to thermal power plants, ranging from ₹2,697 to ₹7,865 per ton, though partnerships with power producers can potentially reduce these costs as they seek waste management solutions. Supporting materials include sand (approximately ₹2,282 per ton), bamboo (₹166.5 per linear meter), and cross-filament tape (₹103.75 per meter).

Table 3: Quantity and Rate Analysis

S. No.	Items	Unit	Rate (Rs)	Quantity	Amount
1.	Plastic Bottles	Kg	50	3	150
2.	Fly Ash	Kg	3	100	300
3.	Sand	Kg	2.6	600	1,560
4.	Bamboo	No.	45	17	765
5.	Cross Filament Tape	No.	188	6	1,128

Processing costs primarily involve labor for bottle preparation, material mixing, and assembly, with bamboo processing representing the most skill-intensive component. Engaging local community groups and artisans for these processes can create employment opportunities while reducing overall production costs. The circular economy approach to waste management not only addresses environmental challenges but offers economic advantages as well. A recent

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UN report suggests that maintaining current waste management practices would cost more than $417 billion annually by 2050, while circular approaches emphasizing waste reduction and recycling could reduce costs to less than $255 billion annually while delivering superior environmental outcomes.

6.2 Total material and processing costs (INR)

The total material and processing costs for a standard 1.5-meter bench ranges approx. ₹4972, representing approximately 30-50% of the cost of conventional concrete bench alternatives.

6.3 Carbon analysis

When compared to traditional options, the suggested bench design's lifecycle assessment (LCA) shows notable environmental benefits. Bench production results in greenhouse gas emissions of about 25–35 kg CO_2-equivalent per standard unit, which is 65-75% lower than concrete benches of similar size (80–120 kg CO_2-equivalent) and 50–60% lower than steel- framed alternatives (60–80 kg CO_2-equivalent). The use of waste materials instead of virgin resources and the low processing energy requirements are the main causes of this advantageous carbon profile (Siddique, 2010; Zhang *et al.*, 2008). Because fly ash's cementitious qualities enable it to reduce or eliminate Portland cement, which normally produces 800-900 kg CO_2 per ton produced, it delivers especially large climate advantages. In a similar vein, recycling plastic bottles cuts down on emissions from landfilling or incineration of waste as well as emissions from the creation of virgin plastic (about 2.5 kg CO_2 per kg of PET) (Yousuf & Ahmed, 2019; Medina *et al.*, 2015).

The production process uses only a small amount of water, about 15 to 25 liters per bench unit, compared to 80 to 120 liters for similar concrete alternatives. The production process is completely free of hazardous chemicals, which eliminates the possibility of soil or water contamination, and the physical containment of fly ash in sealed bottles prevents the leaching of trace elements that could otherwise cause environmental problems (Pacheco-Torgal *et al.*, 2012; Malhotra & Mehta, 2005). The bamboo components are the most environmentally sensitive material input, requiring responsible harvesting practices to prevent habitat destruction and ensure regeneration. Bamboo is a carbon-negative material that sequesters about 5-8 kg CO_2 per bench unit when it comes from stands that are correctly managed, which further improves the design's favorable climate profile.

7.0 Conclusion

Our evaluation of benches manufactured from plastic bottles filled with sand and fly ash, bound with bamboo and cross-filament tape, reveals promising results across multiple dimensions. The design successfully repurposes problematic waste materials while creating

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functional outdoor furniture suitable for public spaces. Testing confirms these benches can withstand normal usage scenarios, with load-bearing capacity meeting requirements for public seating applications when properly constructed. However, maintaining consistent quality during scaled production represents a significant challenge that must be addressed through standardized processes and quality control measures. From an economic perspective, this design shows favorable production costs compared to conventional alternatives. Material procurement and manufacturing expenses remain substantially lower than traditional concrete or metal benches, creating potential for competitive market positioning based on cost advantages alone.

The environmental benefits represent perhaps the most compelling aspect of this design. Lifecycle assessment demonstrates a 65-75% reduction in carbon footprint compared to concrete equivalents. Additionally, the visible reuse of waste materials provides educational value beyond immediate environmental impacts, showcasing practical circular economic principles in everyday settings.

The social sustainability advantages further enhance the value proposition of these benches. Local communities can participate in production processes, creating income opportunities while developing practical skills. This aspect proves particularly valuable in contexts where combined social and environmental outcomes are prioritized.

Despite these advantages, several obstacles must be overcome before widespread implementation becomes feasible. Market perception represents a significant barrier, as potential buyers may question durability and quality compared to traditional products. Weather resistance in various climate conditions requires further testing and possible modifications to treatment methods. Regulatory hurdles related to building codes and safety standards must be navigated, while ensuring consistent quality across production batches remains challenging.

To address these issues, we recommend developing standardized production protocols with clear quality benchmarks. Selectively mechanizing repetitive processes could improve consistency while maintaining opportunities for manual labor where appropriate. Engagement with policy stakeholders would help develop supportive regulatory frameworks, while strategic marketing should emphasize performance characteristics alongside sustainability benefits.

When these factors are addressed, the bottle-bamboo bench design offers a compelling alternative to conventional products, particularly in contexts where environmental impact and social benefits carry significant weight in purchasing decisions. The successful implementation of this approach could serve as a model for other construction applications seeking to incorporate waste materials, contributing to broader adoption of circular economic principles in the built environment.

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