DESIGNING BIO-INSPIRED CLAY BRICKS FOR SUSTAINABLE CONSTRUCTION: HARNESSING NATURE'S DESIGN FOR REDUCED ENVIRONMENTAL IMPACT AND ENHANCED PERFORMANCE

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ABSTRACT

The construction industry in India is rapidly expanding, placing significant pressure on its limited natural resources. One of the primary materials used in construction is fired clay bricks, which contribute to high levels of greenhouse gas emissions. To address this environmental concern, this research focuses on exploring alternative materials that can be tailored to meet the needs of the Indian construction sector. One such material is bio-brick, derived from agro-waste, which shows promise as a sustainable and cost-effective solution. Bio-bricks offer several advantages over traditional fired clay bricks. They serve as effective heat and sound insulators while also boasting a negative carbon footprint, making them environmentally friendly. Additionally, the use of bio-bricks can help mitigate air pollution caused by stubble burning, a prevalent issue in northern India. Furthermore, their low density reduces the dead load in high-rise structures, leading to cost savings in reinforced concrete construction.

The research also delves into the various applications of bio-bricks within a building structure, highlighting their versatility and potential benefits. By showcasing the efficacy of bio-bricks, the study aims to inspire architects, designers, researchers, and builders to embrace and promote the development of sustainable and eco-sensitive materials in the construction industry. Overall, this research underscores the importance of adopting environmentally sustainable practices in construction to mitigate the industry's impact on the environment. By exploring alternative materials like bio-bricks and advocating for their widespread adoption, the construction sector can move towards more sustainable and environmentally responsible practices, contributing to a greener and healthier future for India.

Keyword: *Sustainable Construction, Bio-Bricks, Agro-Waste, Building Materials, Carbon Footprint*

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1. Introduction

The construction industry in India, second only to agriculture, faces increasing demand due to rapid urbanization and population growth. However, this surge in demand exacerbates the shortage of conventional building materials, leading to resource depletion and environmental pollution from their production. To address these challenges, there's a critical need for sustainable alternatives. Concurrently, the accumulation of agricultural solid waste poses a significant environmental threat, particularly in developing countries like India. The research outlined in this paper aims to tackle both issues simultaneously by exploring the conversion of agricultural waste, such as straw stubbles and leftover wood, into viable building materials, specifically bio-bricks. By utilizing agro-waste as a raw material for construction, the study aims to mitigate resource depletion, reduce energy consumption, and alleviate air pollution caused by agricultural burning. Additionally, this approach presents an opportunity to generate additional income for farmers by incentivizing the sale of leftover stubbles instead of burning them, thereby contributing to environmental sustainability and socio-economic development.

The research paper delineates a two-part approach to achieving its objectives. The first section examines the burgeoning construction and agriculture sectors in developing nations like India, emphasizing their adverse environmental impacts. It underscores the urgent need for sustainable solutions to alleviate resource strain and environmental degradation. The second part delves into the process of producing bio-bricks from agro-waste, detailing its manufacturing process, advantages, potential applications in the construction industry, and environmental benefits. By employing up-cycling techniques to transform agro-waste into functional bricks through the combination of lime, stone dust, and water, the study aims to demonstrate the feasibility and efficacy of this approach. Ultimately, the research seeks to promote the widespread adoption of bio-bricks in the construction industry, offering a sustainable alternative that addresses both environmental concerns and the growing demand for building materials. Through this comprehensive exploration, the paper aims to catalyze discussions and initiatives aimed at leveraging agricultural waste for sustainable construction practices, thereby fostering environmental stewardship and socio-economic development in India and beyond.

1.1Construction industry

The construction industry in India has undergone rapid growth, fueled by substantial investments and government initiatives such as the 'Smart City' project and 'Housing for All by 2022.' This growth trajectory is evident from the industry's expansion by 20-30% in 2015, with expectations of doubling by 2018. Projections indicate a staggering investment of $650 billion over the next two decades, highlighting the sector's pivotal role in India's economic development. However, this remarkable growth also poses significant challenges. The escalating demand for conventional building materials like sand, clay bricks, cement, and steel has led to their scarcity and increased costs. Consequently, there has been a surge in illegal mining activities, exacerbating environmental degradation. The unchecked exploitation of natural resources poses a threat to ecosystems and biodiversity, necessitating urgent action to adopt sustainable practices in the construction sector. To address these challenges, there is a pressing need to explore alternative, eco-friendly building materials that minimize the industry's environmental footprint. Bio-bricks, made from agro-waste materials like straw stubbles and leftover wood, present a promising solution. By upcycling agricultural waste into viable construction materials, bio-bricks not only reduce reliance on conventional resources but also mitigate air pollution caused by stubble burning, particularly prevalent in northern India. Additionally, the use of bio-bricks can contribute to the economic well-being of farmers by providing an additional source of income through the sale of agricultural waste. In conclusion, while the growth of the construction industry in India offers significant economic opportunities, it also underscores the urgent need for sustainable practices. Embracing innovative solutions like bio-bricks can help mitigate environmental impacts, reduce resource depletion, and foster inclusive growth in the construction sector while meeting the demands of a burgeoning population and urbanization.

1.2 Demand of raw material

The escalating demand for raw materials in India's construction industry, driven by rapid urbanization, poses significant environmental and social challenges. By 2030, it is projected that approximately 590 million people will reside in urban areas, necessitating substantial investments in housing infrastructure. This surge in urbanization is expected to require around 15 billion tonnes of raw materials by 2030 and a staggering 25 billion tonnes by 2050. Unfortunately, many of these resources are situated in ecologically sensitive zones, such as river basins, exacerbating environmental concerns. River sand, in particular, is highly sought after in construction due to its inert, hard, and durable properties. However, the rampant extraction of river sand has led to the degradation of river systems, with unregulated activities proliferating due to the allure of high profits. Reports indicate that illegal sand extraction generated around INR 10 billion (USD 150 million) in revenue in India in 2011 alone. The magnitude of sand extraction in India is alarming, with extraction rates per area significantly surpassing global averages. India's extraction rate stands at approximately 1579 tonnes per square kilometer, compared to the worldwide average of 454 tonnes per square kilometer. This excessive extraction not only depletes natural resources but also contributes to environmental degradation and habitat destruction. Given that material costs constitute a significant portion of construction expenses, addressing the unsustainable extraction of raw materials is crucial for fostering sustainable development and mitigating adverse environmental impacts.

2. Pollution and destruction of nature

The brick kiln industry in India is a significant contributor to environmental pollution and degradation. With approximately 140,000 brick kilns operating in the country, they collectively produce an estimated 66 million tonnes of CO_2 emissions annually, along with harmful pollutants like carbon monoxide (CO), sulphur dioxide (SO_2), nitrous oxides (NO_x), and particulate matter. These emissions account for about 9% of India's total greenhouse gas emissions, exacerbating air pollution and contributing to climate change.

In addition to emissions, brick production also entails extensive extraction of topsoil and clay, totaling around 350 million tons annually. This extraction leads to soil erosion and degradation, posing significant environmental risks and potentially triggering large-scale disasters. Moreover, the expansion of mining activities further accelerates ecological degradation, heightening conflicts over land use and resource exploitation. The cumulative impact of brick kiln operations and mineral extraction not only exacerbates environmental degradation but also undermines India's efforts to fulfill international climate change commitments. Increased carbon emissions from these activities pose significant challenges to achieving climate targets and mitigating global warming. Thus, addressing the environmental consequences of brick production and mining activities is imperative for India to effectively combat climate change and preserve its natural ecosystems for future generations.

2.1 Agriculture Waste

India faces a significant challenge in managing its agricultural waste, with large quantities of paddy straw and cane bagasse being produced annually. Despite half of the paddy straw being utilized as fodder, the remaining portion, along with the entire quantity of cane bagasse, often ends up as waste, contributing to environmental concerns. Table 1 illustrates the state-wise distribution of agricultural waste in India, highlighting the diverse agricultural practices across the country, which collectively generate over 500 million tons of agricultural waste annually. The surplus agricultural waste, estimated between 84 to 141 million tons, is typically disposed of through burning, particularly in states like Punjab. This practice of stubble burning not only leads to massive air pollution but also poses significant health hazards. In Punjab alone, studies indicate that substantial quantities of paddy and wheat stubble are burnt annually, with around 85% of paddy stubble and 11% of wheat stubble being subjected to open-field burning. Even burning a smaller percentage of this stubble can result in substantial environmental damage, underscoring the urgency of finding sustainable solutions to manage agricultural waste and mitigate its adverse effects on the environment and public health.

3. Sustainable Development

Sustainability, as defined by the United Nations in 1987, emphasizes a balanced approach to development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs. It encompasses economic growth, environmental protection, and social well-being, aiming to address the negative impacts of industrialization and population growth while promoting long-term viability. Buildings play a significant role in global resource consumption and environmental impact, consuming 40% of the world's energy, 25% of water, and 40% of material resources in construction, while also contributing to one-third of greenhouse gas emissions. This underscores the importance of pursuing sustainable materials and construction technologies to mitigate environmental stress.

Research indicates that brick and concrete, common building materials, have a significant carbon footprint compared to other materials. The manufacturing process for bricks, for example, results in an average carbon footprint of 195g CO_2/kg, considering factors such as fuel usage and transportation. By reducing reliance on materials with high carbon footprints and adopting sustainable alternatives, such as bio-bricks or agro-waste-based materials, the construction industry can significantly reduce its environmental impact. This shift towards sustainable materials not only directly reduces emissions and resource consumption but also indirectly contributes to broader environmental conservation efforts. Therefore, investing in sustainable construction practices is crucial for achieving environmental sustainability and mitigating the adverse effects of construction activities on the planet.

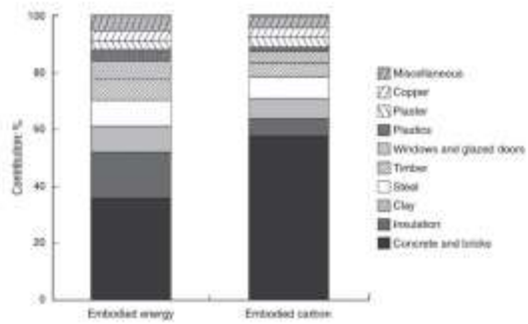

Figure 1. Constituent raw materials for building

Figure 2. Constituent raw materials

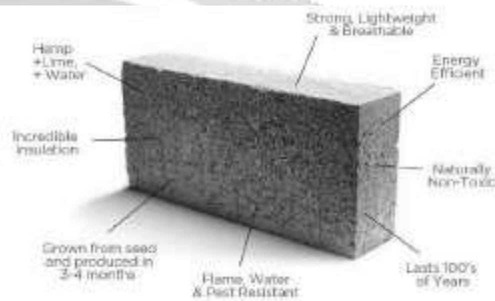

Figure 3. Benefits of hempcrete

Various sustainable alternatives are being employed in the construction industry to mitigate environmental impact. These include fly ash, recycled concrete, foam concrete, agro-based panel boards, recycled materials boards, silica fumes, and recycled tires, among others. One particularly promising alternative is hempcrete, a bio-based material made from the residue of the hemp plant. Hempcrete consists of a mixture of lime binder, water, and the non-fibrous part of hemp, known as "shiv." Over time, this composition hardens to form durable bricks or construction blocks. Hempcrete's manufacturing technology can be adapted to utilize agro-waste generated in India effectively. The use of hempcrete offers several advantages, as illustrated in Figure 3, including its low environmental impact, excellent thermal insulation properties, and carbon sequestration potential. By exploring and implementing sustainable alternatives like hempcrete, the construction industry can reduce its reliance on traditional materials with high environmental costs and move towards more eco-friendly construction practices. Bio-bricks represent a novel construction material with significant environmental benefits, such as carbon sequestration due to the retention of absorbed carbon dioxide. However, the end-of-life management and disposal of bio-bricks remain largely unexplored. Unlike conventional materials, bio-bricks do not decompose, meaning that the absorbed carbon dioxide remains locked within them. To address this issue sustainably, we propose a solution whereby bio-bricks can be pulverized at the end of their lifecycle and mixed with new biomass to create new bio-bricks. This approach not only prevents bio-bricks from ending up in landfills but also facilitates the continuation of their carbon sequestration function. By recycling bio-bricks in this manner, we can promote a closed-loop system that minimizes waste generation and maximizes the utilization of renewable resources. Further research and development are needed to evaluate the feasibility and efficiency of this disposal method, as well as its potential environmental benefits and economic viability.

Hempcrete demonstrates a remarkable capacity to contribute positively to the environment by acting as a carbon sink. Through two main mechanisms, hempcrete blocks exhibit a negative carbon footprint, making them highly sustainable building materials. Initially, during the growth of hemp plants, biogenic CO2 uptake occurs as carbon dioxide is absorbed from the atmosphere and stored within the plant cellulose. Subsequently, during the process of carbonation, the calcium hydroxide present in hempcrete absorbs additional carbon dioxide from the atmosphere, forming stable compounds such as calcium bicarbonate or calcium carbonate. As depicted in Figure 4, this dual process results in the retention of more carbon dioxide within the hempcrete blocks than is emitted during their production, effectively making them carbon-negative building materials. Furthermore, hempcrete offers excellent heat insulation and sound absorption qualities, enhancing its appeal as a sustainable construction material. By harnessing the potential of hempcrete, not only can we mitigate pollution caused by burning agricultural waste, but we can also address the escalating demand for environmentally friendly construction materials, contributing to a more sustainable future.

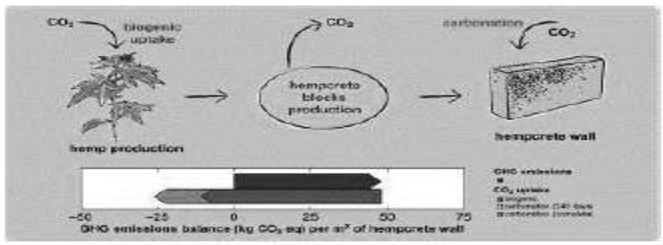

Figure 4. Negative carbon foot print of hempcrete

4. Design and Development

The research conducted by Jain et al. (2014) revealed the significant generation of residual agro-waste in India, leading to air pollution due to its disposal through burning, compounded by the soaring demand for raw materials in the construction sector. This paper proposes a solution by repurposing agro-waste into valuable bio-bricks for construction, establishing a symbiotic economic model. Inspired by the manufacturing process of hempcrete, the method involves careful selection and chopping of dry agro-waste, followed by the preparation of a lime-based slurry with added binder and stone dust. The agro-waste is then mixed into the slurry, poured into moulds, compacted, and left to air dry for around fifteen to twenty days. This sustainable approach eschews controlled or machine drying, reducing the carbon footprint while maintaining production efficiency comparable to fired clay bricks. After the drying period, the bio-bricks develop a rigid skin primarily composed of carbonate lime through calcination, enhancing their overall strength. Despite having lower compressive strength than traditional bricks or concrete blocks, bio-bricks are remarkably lightweight, approximately 1/8 of fired clay bricks and 1/10 of concrete blocks of similar volume. This characteristic makes them ideal for non-load bearing walls in framed structures, offering excellent heat and sound insulation while imposing minimal dead load on the structure. By repurposing agro-waste into bio-bricks, this approach not only addresses environmental concerns associated with waste burning and resource depletion but also offers a sustainable solution for the construction industry, aligning with principles of ecological balance and economic viability.

In addition to their environmental benefits, bio-bricks also present economic advantages by utilizing agro-waste, a previously discarded resource, thereby reducing waste disposal costs for farmers and potentially generating additional income. Moreover, the manufacturing process of bio-bricks requires minimal energy input, further contributing to cost savings and sustainability. By promoting the adoption of bio-bricks in construction projects, this research fosters a circular economy model wherein agricultural residues are repurposed into valuable building materials, aligning with the principles of sustainable development. Furthermore, the lightweight nature of bio-bricks facilitates easier handling and transportation, reducing logistical complexities and costs associated with construction projects. Their versatility in construction applications, coupled with their thermal and acoustic insulation properties, makes bio-bricks a viable alternative to conventional building materials, offering architects and builders a sustainable choice without compromising on structural integrity or performance. Overall, the development and utilization of bio-bricks represent a significant step towards achieving a more sustainable and environmentally conscious construction industry in India and beyond, contributing to the global efforts to mitigate climate change and promote responsible resource management.

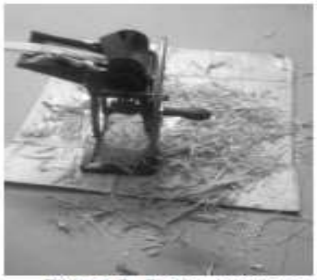

Figure 5. Dry sugarcane bagasse was chopped into fine pieces

Figure 6. Basic tools used along with lime, stone dust and water

Figure 7. Chopped bagasse, lime, water and stone dust were mixed properly

Figure 8. The mixture is properly compacted into the mould

Figure 9. The bio-brick was allowed to dry in air for a month

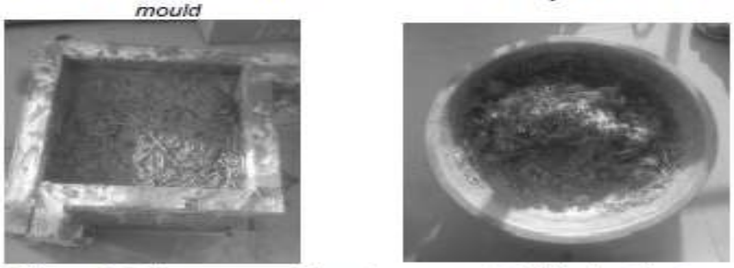

Figure 10. The same experiment was repeated with wheat husk

5. Prototyping – with sugar cane bagasse and wheat husk

Figures 5 to 9 depict various laboratory experiments and the step-by-step process involved in manufacturing bio-bricks. These figures likely illustrate stages such as the selection and preparation of agricultural waste, the mixing of lime slurry with the waste material, the molding and compaction of the mixture, and the subsequent drying and curing processes. Each step is crucial in determining the quality and properties of the bio-bricks produced. Additionally, these figures may showcase the equipment and apparatus used in the experimental setup, along with any measurements or analyses conducted to assess the performance and characteristics of the bio-bricks. In Figure 10, a bio-brick made from wheat husk is presented, highlighting the practical application of the manufacturing process outlined in the preceding figures. Wheat husk, being a common agricultural waste in India, exemplifies the potential of bio-bricks to utilize diverse types of agricultural residues effectively. However, achieving the optimal composition and properties of bio-bricks from different agricultural wastes requires careful calibration of the lime slurry ratio. This calibration process involves experimentation and testing to determine the ideal proportions of lime slurry and waste material that result in bio-bricks with desirable attributes such as strength, durability, and insulating properties. By customizing the composition of bio-bricks to suit the specific characteristics of various agricultural wastes prevalent in India, the manufacturing process can be optimized for maximum efficiency and sustainability.

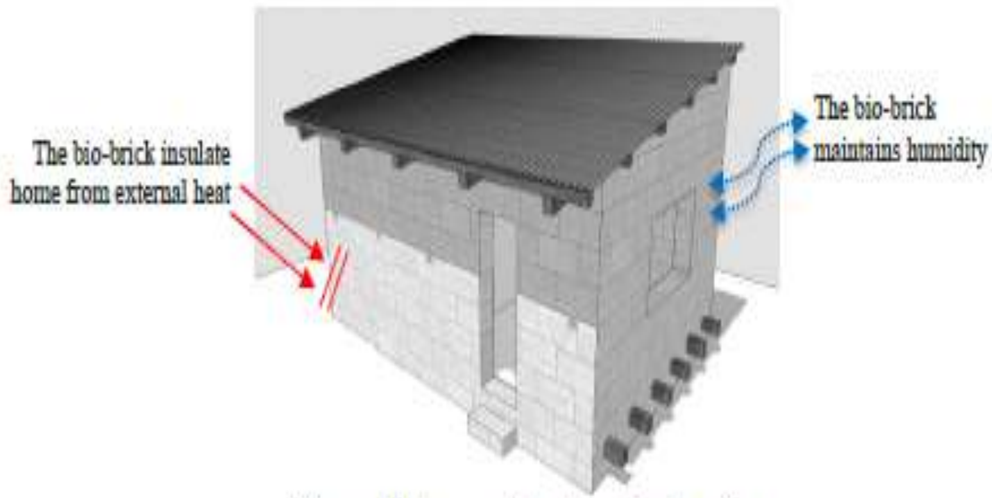

Figure 11. Low cost load bearing housing

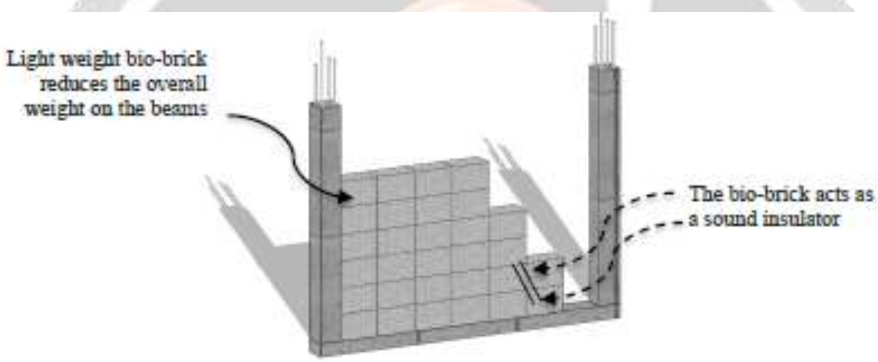

Figure 12. Filler wall material for column beam structure

Bio-bricks offer a sustainable alternative to burnt clay bricks, acting as a carbon sink by sequestering more carbon dioxide than they emit during their lifecycle. For example, a bio-brick made from sugarcane bagasse can store approximately 639 grams of carbon dioxide, offsetting the 710 grams emitted by burning 1 kilogram of the same material. Additionally, the process of carbonation further fixes atmospheric carbon dioxide, resulting in a net greenhouse gas emission of around -1.015 kilograms of carbon dioxide per bio-brick block. This negative value indicates a positive environmental impact, making bio-bricks an eco-friendly choice for construction.

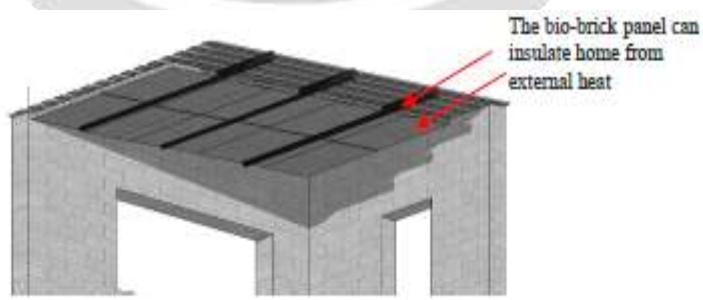

Figure 13. Used as an insulation material for corrugated sheet roofing

While bio-bricks may not be suitable for load-bearing structures, they excel in low-cost housing with wooden or metal frames. With a low thermal conductivity of approximately 0.27 W/mK, bio-bricks provide effective insulation against heat and sound, making them ideal for walls in hot and humid climates like India. Moreover, their porosity and low density help regulate humidity, enhancing comfort in living spaces. With an average density of 423.7 kg/m³, bio-bricks are a viable replacement for burnt clay bricks and concrete blocks in partition walls of column-beam structures. Their lightweight properties reduce the overall load on the frame structure, enabling the design of lighter and more cost-effective constructions. Additionally, bio-bricks can be utilized as panel or insulation boards, expanding their applications in creating sustainable and comfortable living environments. As designers continue to explore the potential of this eco-friendly material, its versatility and positive environmental impact make it a promising choice for future construction projects.

6. Conclusion

India's abundant agricultural sector generates vast quantities of agro-waste, ranking among the world's top three producers of agricultural waste. This surplus presents a pressing need for disposal. Concurrently, the construction industry's demand for raw materials, particularly bricks, is incessantly rising. The bio-bricks derived from common agro-waste offer a significantly improved net carbon footprint compared to conventional building materials, while remaining cost-effective and simple to produce. While bio-bricks may not be suitable for heavy loads, they hold immense potential for applications in low-load bearing wall construction, sound reduction, and insulation, particularly in the low-cost housing sector, which constitutes a significant market segment in India. Thus, the conversion of agro-waste into bio-bricks could effectively address the dual challenges of raw material demand in the construction industry and the surplus agro-waste generated in the agricultural sector. To ensure the successful development of this new material, government support and public awareness campaigns are essential. Initiatives such as government incentives and awareness programs targeting grassroots masons and builders are crucial. Additionally, campaigns aimed at educating farmers on the benefits of converting waste into bricks are necessary. By demonstrating the potential impact of bio-bricks on improving the sustainability of the Indian construction industry, these efforts can garner widespread support. Further research and development efforts are also needed to optimize bio-brick production for pan-India application. This includes exploring methods to enhance the load-bearing capacity of bio-bricks and optimizing manufacturing processes for large-scale, cost-effective production. Ultimately, with the right support and innovation, bio-bricks have the potential to revolutionize the construction industry in India while addressing environmental concerns associated with agricultural waste disposal.

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