

INNOVATIVE MATERIALS FOR A DECARBONIZED FUTURE: STRATEGIES FOR THE DEVELOPING REGIONS

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Abstract. *In the pursuit of a low-carbon future, the construction industry faces urgent challenges and opportunities to mitigate its substantial CO₂ emissions. This paper examines innovative materials and strategies poised to redefine sustainable construction practices, with a focus on Brazil's unique socio-economic and environmental context. The study explores four key areas: cementitious materials, free-clinker cement alternatives, lignocellulosic fibers, and bamboo. Cementitious materials are highlighted for their potential to reduce carbon footprints through supplementary cementitious materials (SCMs), including industrial and agricultural by-products. Free-clinker alternatives, such as alkali-activated materials and CSA cements, offer transformative solutions leveraging Brazil's abundant resources. Lignocellulosic fibers, from renewable sources like sisal, enhance material performance and support local economies, though durability challenges remain. Bamboo, with its exceptional mechanical properties and ecological benefits, stands out as a structural and non-structural material. The paper underscores the need for interdisciplinary collaboration and policy innovation to overcome technical barriers. By integrating global sustainability trends with local resource use, Brazil can lead in advancing low-carbon construction technologies.*

Keywords: Sustainable materials, low-carbon construction, cementitious innovations, lignocellulosic fibers, bamboo applications, SCMs, CCS technologies.

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Introduction

In the global pursuit of a low-carbon future, sustainable materials and construction methods have become pivotal to environmental progress. The construction sector, a major contributor to worldwide CO₂ emissions, must navigate significant challenges to adopt greener practices. Researchers and industry leaders worldwide are investigating innovative materials that harmonize ecological benefits with economic feasibility and social impact. Brazil occupies a strategic position in this movement. As a leading economy with vast natural resources, Brazil is well-positioned to pioneer sustainable construction solutions. This paper examines four key material innovations—alternative cementitious binders (including magnesium-based cements), clinker-free cement substitutes, lignocellulosic fibers,

and bamboo—that align with global sustainability trends while addressing Brazil’s unique socio-economic and environmental needs.

Among these, magnesium oxide (MgO)-based cements and carbon capture, utilization, and storage (CCUS) technologies stand out for their potential to drastically cut emissions. Unlike traditional Portland cement, magnesian cements absorb CO₂ during curing, turning a waste product into a structural component. When combined with CCS-enhanced production methods, these materials could revolutionize low-carbon construction. Alongside these advancements, Brazil’s abundant biomass resources, such as lignocellulosic fibers and bamboo, offer additional pathways to sustainability by promoting carbon sequestration and regional economic growth.

By integrating global innovation with local opportunities, this work underscores how these materials can drive sustainable construction, both worldwide and within Brazil’s dynamic context, reducing emissions, leveraging natural assets, and fostering eco-conscious development.

Cementitious materials

Cementitious materials, especially Portland cement, serve as the backbone of modern construction yet account for a substantial portion of global CO₂ emissions. In the Brazilian context, the construction industry significantly impacts the national carbon footprint, as highlighted by Reis *et al.* [1], underscoring the urgent need for low-carbon alternatives. Mitigating emissions from cement production is indispensable for achieving key Sustainable Development Goals (SDGs)—particularly SDG 9 (industry innovation), SDG 11 (sustainable cities), SDG 12 (responsible consumption), and SDG 13 (climate action) [2].

Reducing Portland Cement Content through Supplementary Cementitious Materials (SCMs)

One of the most promising strategies for mitigating the environmental impact of cementitious materials involves partially replacing Portland cement with supplementary cementitious materials (SCMs) such as fly ash, slag, and silica fume. These materials not only reduce CO₂ emissions but also enhance the mechanical properties and durability of concrete through pozzolanic reactions that form additional C-S-H gel, improving long-term performance. Research has demonstrated that optimized SCM blends can maintain or even exceed the strength and durability of conventional Portland cement mixtures while significantly lowering their carbon footprint.

Brazil is uniquely positioned to capitalize on this approach due to its abundant natural and industrial resources. The country’s vast deposits of kaolinitic clay enable the production of limestone-calcined clay cement (LC3), a low-carbon alternative capable of reducing clinker content by up to 50%. Additionally, industrial by-products like fly ash from power plants and slag from steel production offer high-volume SCM sources, transforming waste into valuable construction materials. However, the availability of both fly ash and slag in Brazil and worldwide is steadily declining due to the country’s shift toward renewable energy and changes in industrial processes, underscoring the urgency of diversifying SCM sources. Agricultural residues, particularly sugarcane bagasse ash from Brazil’s thriving bioenergy sector, further contribute to the pool of sustainable alternatives, though their full potential remains underexplored and requires further research to optimize processing and application.

Despite these advantages, current cement standards in Brazil and internationally often restrict SCM use to around 30% to preserve mechanical performance. Overcoming this limitation will require innovative solutions such as advanced SCM formulations with optimized particle size distribution, chemical activation, or hybrid systems combining multiple supplementary materials. Carbonation curing techniques, especially for magnesium-based SCMs, could further enhance sustainability by sequestering CO₂ during the curing process.

The integration of SCMs into Brazil’s construction industry not only addresses environmental concerns but also creates economic opportunities by valorizing industrial and agricultural waste. However, broader adoption depends on overcoming technical and regulatory barriers, including the standardization of alternative materials and the development of policies that incentivize higher SCM utilization. By leveraging its natural resources and industrial by-products, Brazil can lead the transition toward low-carbon cement while setting a precedent for sustainable construction practices worldwide.

Lignocellulosic Fibers: Sustainable Reinforcement for Brazil's Construction Sector

Brazil’s rich biodiversity and agricultural capacity position it as a global leader in the development and application of lignocellulosic fibers for construction. Derived from renewable sources such as coconut coir, sisal, jute, and curauá, these natural fibers offer a compelling alternative to conventional reinforcement materials, combining environmental sustainability with enhanced mechanical performance in cementitious composites.

The integration of lignocellulosic fibers into construction materials addresses multiple industrial challenges. These fibers significantly improve tensile strength, crack resistance, and toughness in cement matrices, enabling the

production of lighter, more resilient structures. Particularly noteworthy is their role in replacing hazardous asbestos fibers (associated with public health risks) and energy-intensive synthetic fibers. Sisal fibers, for instance, have demonstrated exceptional energy dissipation properties, making them suitable for seismic-resistant applications [8].

Brazil dominates global sisal (*Agave sisalana*) production, with an output of approximately 139,700 tons in 2004 - 87% originating from Bahia and 7.4% from Paraíba [9]. Production in the state of Bahia is mainly in the North Center and Northeast regions, as presented in Figure 1. While traditionally used in cordage and textiles, sisal fibers are now gaining traction in advanced applications, including reinforcement for cementitious and polymeric materials. This shift not only adds value to agricultural production but also supports circular economy principles by utilizing byproducts that would otherwise go to waste.

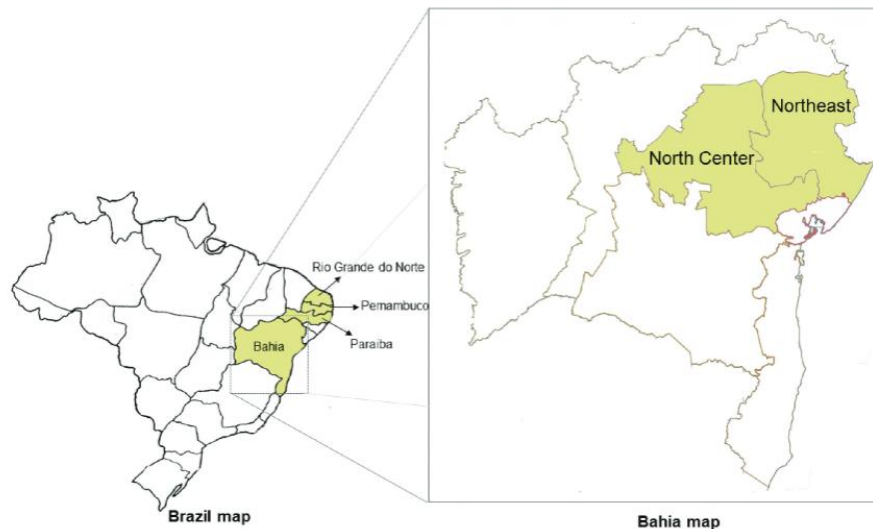


Figure 1: Location of the state of Bahia in Brazil.

Source: Ferraz-Almeida, R., & Ribeiro Ferreira da Silva [9].

However, several technical challenges must be addressed to fully realize the potential of lignocellulosic fibers in construction [10]. The fibers' high-water absorption, susceptibility to biodegradation, weak interfacial bonding with some cement matrices, and overall durability concerns, particularly in Brazil's tropical climate, which accelerates degradation. Current research focuses on overcoming these limitations through:

- Chemical treatments (alkali, silane, or acetylation) to improve fiber-matrix adhesion and moisture resistance;
- Hybrid reinforcement systems combining natural and synthetic fibers;
- Innovative coating technologies to enhance durability while maintaining environmental benefits.

The successful large-scale implementation of lignocellulosic fibers in the construction sector will require coordinated efforts across multiple fronts. Targeted research should focus on optimizing treatment methods and developing standardized performance criteria. Simultaneously, policy support and incentives could stimulate market adoption, while partnerships between agricultural producers and construction firms could ensure a stable supply chain.

By leveraging its natural resources and technical expertise, Brazil has the opportunity to establish a global benchmark for sustainable construction materials. The development of high-performance, fiber-reinforced composites could not only reduce the environmental impact of the construction sector but also create new economic opportunities for rural communities, aligning with broader sustainable development goals.

Carbon Capture and Storage (CCS) Technologies in Cementitious Materials: Brazil's Path to Carbon-Neutral Construction

The development of carbon capture and storage technologies for cementitious materials has gained significant attention as a pathway to decarbonize the construction sector [11]. Among emerging solutions, magnesium oxide (MgO)-based cement systems demonstrate remarkable potential for enhanced CO₂ sequestration through optimized curing processes.

These materials leverage the natural carbonation properties of magnesium compounds, which actively react with atmospheric CO₂ during curing to form stable carbonate minerals. Brazil stands at the forefront of this technological innovation due to its substantial magnesium mineral reserves and growing expertise in sustainable construction materials. Ongoing research into specialized curing methods further strengthens Brazil's capacity to develop MgO-based cement systems, maximizing CO₂ uptake. As illustrated in Figure 2, precise control of curing parameters during the manufacturing of fiber-reinforced cement composites can significantly increase the rate of carbonation and mineralization. This approach not only improves the material's carbon capture capacity but also enhances its mechanical performance, resulting in construction materials with a substantially reduced carbon footprint.

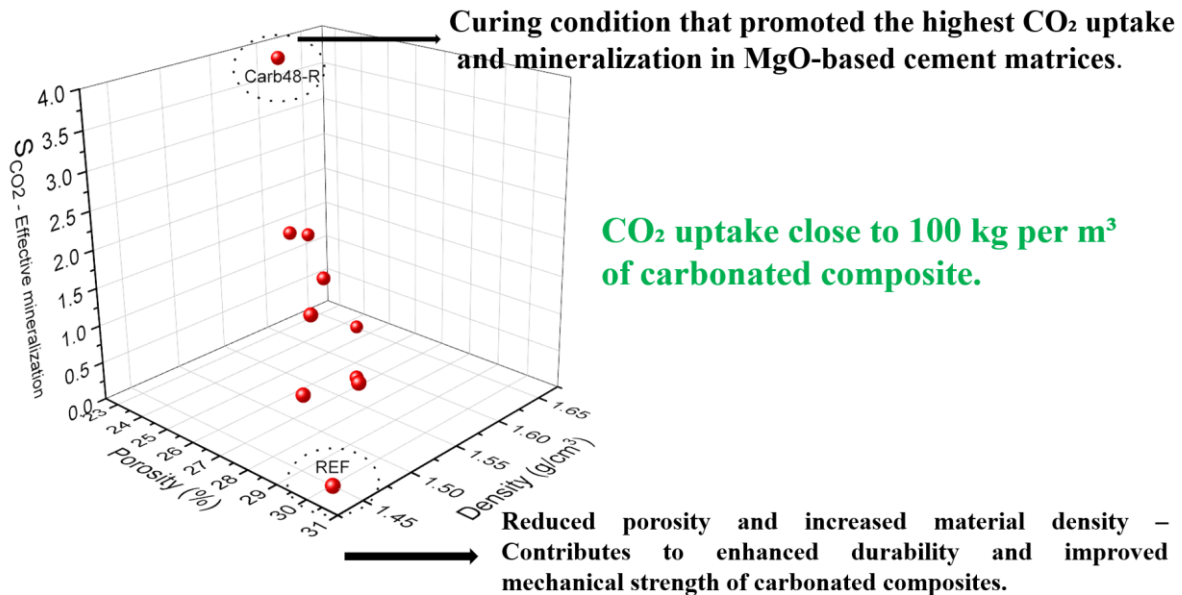


Figure 2: Relationship between controlled curing parameters in fiber-cement manufacturing and enhanced CO₂ capture rates, highlighting how process optimization can yield materials with a significantly lower embodied carbon footprint.

Source: Azevedo & Savastano (2024)[12].

The carbonation curing process for MgO-based systems involves careful regulation of temperature, humidity, and CO₂ concentration to optimize the reaction kinetics. When applied to fiber-cement products, this method promotes deeper CO₂ penetration and more complete conversion of Mg(OH)₂ to carbonates throughout the material matrix. The resulting composites benefit from increased density and reduced porosity, leading to improved durability while permanently sequestering CO₂. Furthermore, the integration of industrial byproducts and mineral residues as supplementary components can create synergistic effects, enhancing both the environmental and economic viability of these materials. The use of magnesium-rich mining tailings, for instance, provides dual benefits of waste valorization and increased carbon storage capacity.

Despite these promising developments, scaling up carbonation-cured MgO cement systems requires addressing several technical challenges. These include standardizing curing protocols for different product formats, ensuring consistent quality control in industrial settings, and developing appropriate testing methods to verify long-term performance. Continued research is particularly needed to optimize the balance between carbonation depth, reaction rates, and final material properties across various applications.

The progressive implementation of these technologies in Brazil's construction sector could establish new benchmarks for low-carbon building materials globally. By combining the nation's mineral resources with advanced curing methodologies, MgO-based cement systems may soon offer a commercially viable pathway to carbon-neutral construction while maintaining competitive material performance. This transition would position Brazil as a leader in sustainable cement technologies and contribute meaningfully to global climate change mitigation efforts.

Decarbonizing Construction with Clinker-Free Cement Alternatives

The global construction industry stands at the precipice of a materials revolution, with clinker-free cement alternatives emerging as transformative solutions that combine environmental benefits with technical performance.

These innovative binders – particularly alkali-activated materials, calcium sulfoaluminate (CSA) cements, and magnesium-based systems – present Brazil with a unique opportunity to redefine sustainable construction while leveraging its natural resources and industrial byproducts.

Alkali-activated materials

Alkali-activated materials represent a particularly promising avenue for Brazil's construction sector. By utilizing the country's abundant kaolinitic clays and industrial residues from mining and steel production, these materials can deliver performance characteristics that often surpass traditional Portland cement, including enhanced durability against chemical attack and superior high-temperature resistance. The compatibility of alkali-activated binders with natural fiber reinforcements further increases their appeal for developing sustainable composite materials [13]. However, a major challenge lies in the dependence on commercial alkaline solutions, which are typically derived from synthetic silicates and hydroxides produced through energy-intensive and environmentally harmful chemical processes. This reliance undermines the environmental advantages of alkali-activated systems and limits their scalability, especially in regions without access to these costly inputs [14].

In this context, Brazil's agroindustry emerges as a strategic source of alternative inputs. A growing body of research, currently representing around 6% of national studies on alkali-activated materials (Figure 3), highlights the potential of biomass residues such as ashes [15] and biochar [16], which often contain elevated levels of silica (SiO_2) and potassium oxide (K_2O). These components enable them to play a dual role: contributing to the aluminosilicate matrix and serving as alternative alkaline sources. This dual function offers a path toward reducing dependence on commercial activators while fostering circular economy practices and enhancing regional value chains.

Notably, approximately 4% of Brazilian studies now investigate the use of sludge ash—a by-product of water and wastewater treatment processes. Although less common than biomass ashes, sludge ash is gaining attention for its potential reactivity and availability, particularly in urban areas [17]. Its composition, which can include amorphous silica, alumina, and alkaline elements, makes it a viable complementary precursor in alkali-activated formulations. Unlocking the full potential of these unconventional materials will require further development in processing technologies, standardization protocols, and performance optimization to handle their inherent variability and ensure consistent, scalable applications.

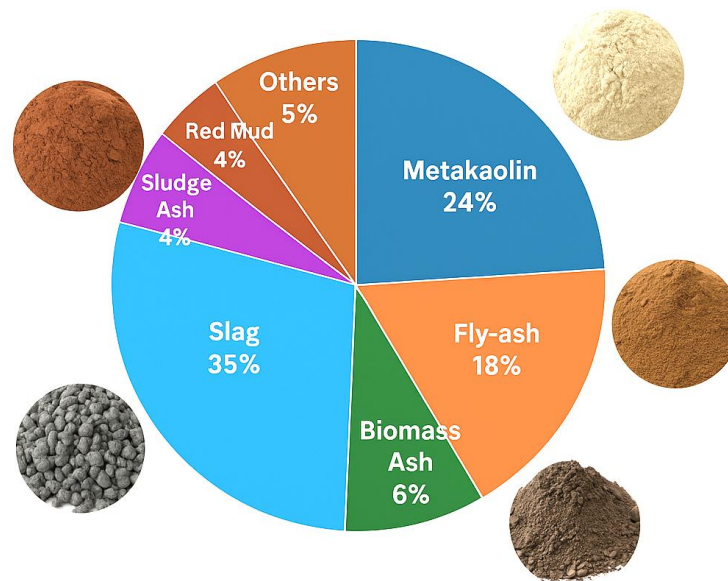


Figure 3: Distribution of aluminosilicate precursors employed in studies on alkali-activated materials published in Brazil since the early 2000s. Data retrieved from the Elsevier Scopus database (June 2025).
Source: Authors.

MgO-Based cement

Magnesium-based cement systems stand out as one of the most promising solutions for Brazil's transition to low-carbon construction. These innovative binders offer a dual environmental advantage: they not only generate significantly lower process emissions during manufacturing compared to Portland cement but also actively sequester CO₂ during the curing process through carbonation reactions [18].

Brazil is particularly well-positioned to lead in this technology, thanks to its extensive magnesite and dolomite reserves. When combined with agricultural byproducts such as sugarcane bagasse ash, these cement systems can achieve an even more sustainable profile. Recent breakthroughs in accelerated carbonation curing have shown remarkable results, with some formulations demonstrating up to 50% greater CO₂ uptake, potentially enabling the production of carbon-negative building materials.

A key advantage of magnesium-based binders is their compatibility with lignocellulosic fiber reinforcement. Unlike traditional Portland cement, which creates a highly alkaline environment (pH > 12.5) that degrades natural fibers, magnesium cement systems maintain a more moderate pH level (10-11) after hardening, as shown in Figure 4. This characteristic makes them ideal for creating durable, fiber-reinforced composites that leverage Brazil's abundant natural fibers like eucalyptus, sisal, and coconut [19].

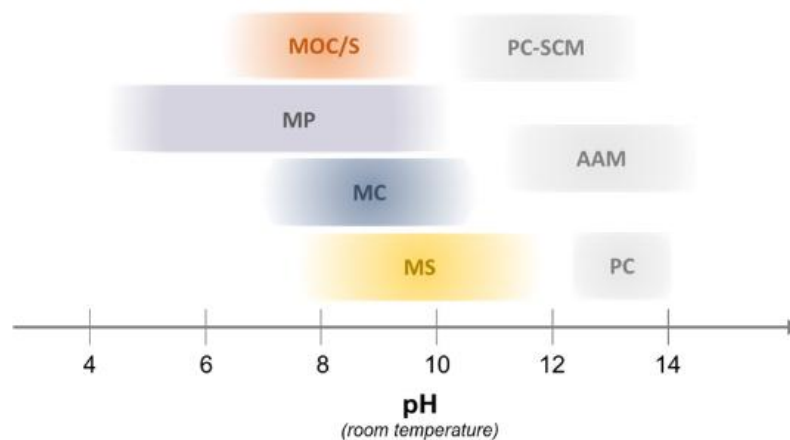


Figure 4: Approximate pH range associated with the stability of different MgO-based cement systems. MOC/S = Mg-oxysulfate/Mg-oxychloride cements, MC = Mg-carbonate cements, MP = Mg-phosphate cements, MS = Magnesium silicate cements, PC-SCM = blended Portland cements, AAM = Alkali activated materials, PC = Portland cement.

Source: Bernard et al. (2023) [20].

Bamboo: A Strategic Resource for Sustainable Construction in Brazil

Bamboo stands out as a renewable powerhouse for Brazil's construction sector, combining rapid growth (3-5 years to maturity) with exceptional carbon sequestration capacity and mechanical properties superior to many traditional materials. With 5.26 million hectares of native bamboo forests encompassing over 300 species, Brazil possesses unmatched potential to lead in bamboo-based construction solutions, from structural elements to innovative composites (Fig. 2) [21-22]. The material's high tensile strength and flexibility make it ideal for diverse applications, including affordable housing and engineered building components.

Key challenges must be addressed to unlock bamboo's full potential, particularly regarding standardized treatment methods for durability in tropical climates and the development of specific design codes. Recent advances in thermal modification and eco-friendly preservation techniques show promise for enhancing performance. Simultaneously, integrating bamboo with other sustainable materials like earth-based mortars or magnesium cements could create novel hybrid systems with enhanced properties.

Strategic investment in Brazil's bamboo value chain could simultaneously drive rural development, ecosystem restoration, and carbon-neutral construction. Figure 5 illustrates the segmentation and geographic distribution of bamboo-related activities in Brazil, emphasizing the nation's significant resources and potential for industrial leadership. Success requires coordinated policies supporting research, quality standards, and market development, positioning bamboo as a cornerstone of the country's sustainable construction future while meeting growing global demand for green building materials.

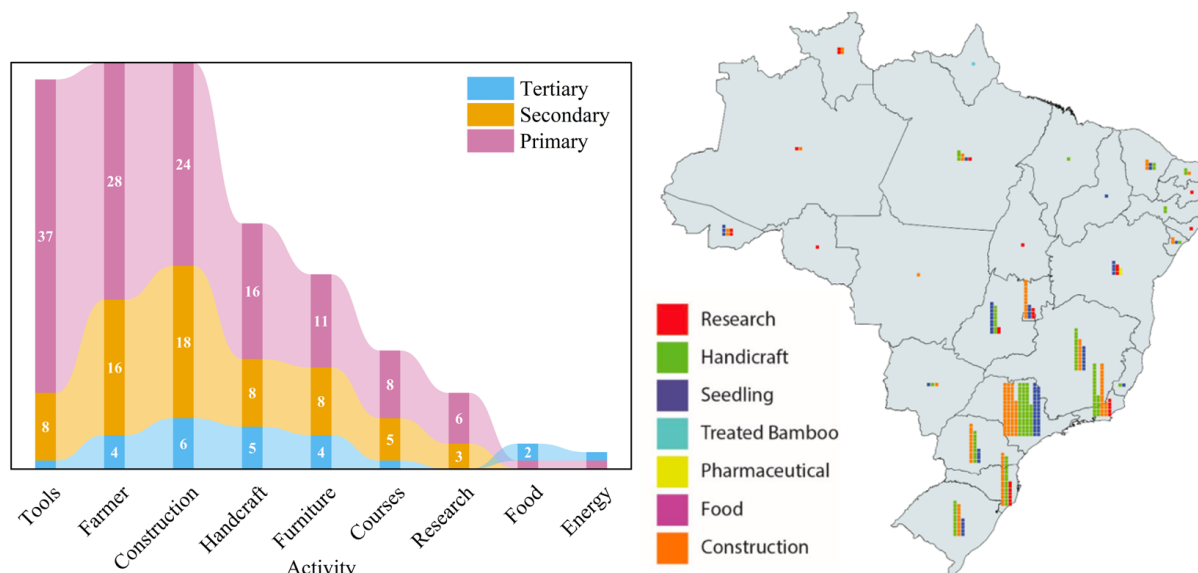


Figure 5: Segmentation and Geographic Distribution of Bamboo-Related Activities in Brazil
Source: Kadivar et al. (2024) [21].

Conclusion

Brazil stands at the forefront of a construction revolution, where innovative materials as low-carbon cements, lignocellulosic fibers, and bamboo can transform the industry's environmental impact. The country's unique advantages - abundant mineral reserves, agricultural resources, and industrial byproducts - position it to develop cutting-edge solutions such as magnesium-based cements that actively sequester CO₂, durable natural fiber composites, and high-performance bamboo structural elements. These materials not only address climate challenges but also create opportunities for circular economies and inclusive growth.

While the potential is substantial, realizing this sustainable future requires overcoming critical technical and regulatory hurdles. Standardizing alternative binders, optimizing material processing, and developing localized construction methods remain key challenges. Success depends on strengthened collaboration between researchers, industry leaders, and policymakers to bridge the gap between laboratory innovations and large-scale implementation. By strategically investing in these sustainable material technologies, Brazil can achieve dual objectives: establishing global leadership in green construction while addressing local socioeconomic needs. The transition to low-carbon building materials represents more than an environmental imperative - it's an opportunity to redefine construction practices, create green jobs, and build a more sustainable and equitable future for Brazil's built environment. Continued innovation and policy support will be essential to fully guarantee these materials' transformative potential.

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