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NEW CHALLENGES FOR A LOW-CARBON FUTURE: A MATERIALS PERSPECTIVE

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ABSTRACT

Materials engineering plays a pivotal role in addressing the urgent need for low-carbon solutions to mitigate CO_2 emissions. This study explores innovative material strategies tailored to the socio-economic and environmental contexts of developing regions. It highlights four key areas: cementitious materials, clinker-free binders, lignocellulosic fibers, and bamboo. Supplementary cementitious materials (SCMs), such as fly ash and sugarcane bagasse ash, reduce carbon footprints, while alkali-activated and calcium sulfoaluminate cements leverage regional mineral resources. Renewable lignocellulosic fibers, including sisal (Agave sisalana), improve performance and support local economies, despite challenges in bonding and durability. Bamboo, with its exceptional mechanical properties, offers sustainable solutions for various applications. This paper underscores the need for interdisciplinary collaboration, advanced material research, and supportive policies to overcome technical barriers. By aligning global sustainability trends with local resource utilization, materials engineering can drive low-carbon technologies, foster regional development, and contribute to global climate goals.

Keywords: sustainable materials, low-carbon construction, cementitious innovations, lignocellulosic fibers, bamboo applications

1. INTRODUCTION

In the global quest for a low-carbon future, the development of sustainable materials and construction practices is a cornerstone of environmental innovation. Developing countries face unique challenges and opportunities in this transition, as they work to balance rapid urbanization, economic growth, and environmental sustainability. Around the world, researchers are investigating materials that combine ecological benefits with economic feasibility and social relevance. This paper focuses on four material-based innovations—cementitious binders, clinker-free alternatives, lignocellulosic fibers, and bamboo—that align with international sustainability trends while addressing the distinct needs of developing countries. These materials not only reduce carbon emissions but also utilize abundant local resources, stimulate regional economies, and promote sustainable practices. By adopting a global perspective, this work underscores how materials engineering can foster sustainability in diverse socio-economic and environmental contexts, offering pathways for developing nations to lead in the advancement of low-carbon technologies.

2. METHODOLOGY

This study employs a multidisciplinary approach to analyze the potential of sustainable materials in developing countries. The materials discussed were chosen based on their carbon emission reduction potential, availability in developing regions, and socio-economic impact. Priority was given to innovations that leverage local resources and address environmental challenges. Information was gathered through an extensive literature review, case studies, and analysis of industrial and academic research data. Metrics such as CO_2 emissions, cost-effectiveness, mechanical properties, and regional availability were considered. Examples from Brazil, India, Egypt, and South Africa were analyzed to identify best practices and lessons for scaling sustainable materials.

3. CEMENTITIOUS MATERIALS: REDUCING CARBON FOOTPRINT

Cementitious materials, particularly Portland cement, are fundamental to modern construction but are accounted as a major source of global CO_2 emissions. In developing countries like Brazil, India, Indonesia, Turkey, Egypt, and South Africa, the construction sector contributes notably to national carbon footprints, as discussed by Reis *et al.* [1], necessitating a shift toward more sustainable alternatives. Reducing emissions from cement production is critical for meeting the Sustainable Development Goals (especially SDG 9, SDG 11, SDG 12 and SDG 13) [2].

3.1. Reducing Portland Cement Content

A promising strategy to mitigate the carbon impact of cementitious composites is the partial replacement of Portland cement with supplementary cementitious materials (SCMs). SCMs, including fly ash, slag, and silica fume, have proven effective in reducing emissions while enhancing mechanical and durability properties through pozzolanic reactions, forming additional calcium silicate hydrates (C-S-H) [3,4]. Brazil, due to its vast natural resources, demonstrates significant potential in this area. Its abundant reserves of kaolinitic clays are ideal for producing limestone-calcined clay cement (LC_3) [5], and industrial by-products such as fly ash and slag offer further opportunities for sustainable SCM production [6]. Agricultural residues, such as sugarcane bagasse ash, generate 6 million tons of ash annually, representing a valuable clinker substitute to reduce emissions and waste [7,8]. Similarly, mining by-products like tailings present an opportunity to develop innovative SCM formulations while addressing environmental risks from waste disposal.

Other developing countries are also exploring similar strategies. India has effectively utilized fly ash and slag from its thermal power and steel industries to produce blended cements. South Africa integrates slag and waste from its mining operations into cement production. Egypt, rich in agricultural by-products such as rice husk ash and palm ash, holds promise for advancing SCM research, while Indonesia capitalizes on volcanic ash for similar applications [9]. Despite these opportunities, limitations in cement standards globally restrict the use of SCMs to approximately 30% to preserve mechanical properties. Advancing innovative binder formulations and employing high-performance admixtures are crucial for increasing SCM utilization without compromising material performance. Developing countries, with their unique waste streams and environmental challenges, have the potential to drive the adoption of SCM technologies and play a leading role in global efforts to achieve low-carbon construction.

3.2. Lignocellulosic Fibers

Lignocellulosic fibers—derived from renewable sources such as coconut coir (*Cocos nucifera*), sisal (*Agave sisalana*), jute (*Corchorus capsularis*), and curauá (*Ananas comosus var. erectifolius*)—offer significant environmental and socio-economic benefits.

Additionally, fibers extracted from palm trees, like date palm (*Phoenix dactylifera*), are of particular interest to regions such as Egypt, where date cultivation is prominent. These fibers hold promise for sustainable construction applications, leveraging their strength and availability. By integrating these fibers, countries like Brazil and Egypt can foster sustainable practices while supporting local agricultural economies and innovation in material development.

The incorporation of lignocellulosic fibers into cementitious matrices can potentially enhance tensile strength, crack resistance, and toughness, offering potential for lighter, more resilient construction, being a replacement to the asbestos fibers (public health concerns) and synthetic ones (high cost and energy consumption). Sisal fibers, for example, have demonstrated energy dissipation capabilities, making them suitable for seismic or high-stress applications [10].

Figure 1 highlights the production stages of sisal (*Agave sisalana*) fibers, which are derived from Agave plant leaves and produced in regions like South America, Africa and Mexico. Brazil, the world's largest producer, generated approximately 139700 tonnes in 2004, with most production concentrated in Bahia (87%) and Paraíba (7.4%). Beyond traditional uses, sisal fibers are being increasingly utilized in innovative applications such as the pulp and paper industry and as reinforcements in cementitious and polymeric materials [11].

However, significant challenges remain in utilizing these fibers, especially in terms of high-water absorption, biodegradation, and poor bonding with cement matrices. Regions with tropical climates exacerbate these issues by accelerating fiber degradation.

***Figure 1**: Production stages in the sisal cordage industry, highlighting the generation of sisal residues as potential resources for innovative applications in construction and material development [11].*

Solutions such as chemical treatments (e.g., alkali or silane modifications) and hybrid systems combining natural and synthetic fibers are being explored to improve durability and performance. Scaling up the use of lignocellulosic fibers in developing countries requires targeted research, local innovation, and policy support to overcome technical barriers and ensure performance standards are met.

3.3. Carbon Capture and Storage (CCS) Technologies

The integration of carbon capture and storage (CCS) technologies into cementitious materials marks a transformative leap toward reducing CO_2 emissions in the global construction industry. Concrete's natural carbonation process enables it to act as a carbon sink, absorbing CO_2 from the atmosphere during its curing phase. This intrinsic property can be strategically enhanced to offset emissions produced during cement manufacturing.

In Brazil, the abundant reserves of magnesium-based minerals position the country as a leader in adopting magnesium-based cements, which can capture CO_2 during curing operations [12]. These cements, when combined with CCS technologies, provide a dual advantage: reducing emissions during production and sequestering CO_2 during curing. Similarly, the use of carbonation curing in precast concrete elements offers the potential to improve material properties, such as strength and durability, while actively sequestering carbon. Moreover, Brazil's vast reserves of underutilized mining residues could serve as aggregates, boosting the carbon sequestration capacity of concrete [13]. CO_2 mineralization in these natural aggregates could significantly mitigate the environmental footprint of mining activities, transforming waste into valuable construction materials.

The promise of CCS technologies extends beyond Brazil, offering transformative potential for other developing countries as well. Nations such as India, Indonesia, and South Africa face similar challenges with high CO_2 emissions from cement production. These countries, rich in natural resources and industrial by-products, could leverage CCS in locally adapted ways. For instance, India's abundant fly ash and slag could serve as supplementary cementitious materials with enhanced carbonation potential. Similarly, Indonesia and South Africa could utilize their mining waste to create aggregates with carbon sequestration capabilities.

Despite its immense potential, the adoption of CCS technologies in developing nations is hindered by several barriers, including high initial costs, technical complexities, and inadequate regulatory frameworks. Addressing these challenges requires tailored approaches that account for local economic and environmental contexts.

4. CLINKER-FREE REVOLUTIONIZING BINDERS

Clinker-free cement alternatives present transformative solutions that could revolutionize the construction and materials industry. These alternatives—especially alkali-activated materials, Calcium Sulfoaluminate (CSA) cements, and magnesium-based cements—offer unique opportunities to address both environmental and economic challenges while positioning itself as a global leader in low-carbon construction.

4.1. Alkali-Activated Materials

Alkali-activated materials are an attractive alternative to traditional Portland cement. These materials, made from kaolinitic clays or industrial by-products such as fly ash and slag, exhibit comparable or superior properties, including resistance to chemical attacks and high temperatures, along with great compatibility with natural reinforcements [14].

Developing countries' vast mining and steel industries generate large quantities of industrial by-products that could serve as raw materials for geopolymer production, offering an opportunity for large-scale implementation [15]. However, challenges such as material consistency, quality control, and developing cost-effective activation systems must be addressed to make geopolymer technology commercially viable.

4.2. Calcium Sulfoaluminate (CSA) Cements

CSA cements, which require lower kiln temperatures and emit significantly less CO_2 than Portland cement, are another promising clinker-free alternative. These cements, which feature rapid setting and high early strength, are particularly suited for precast elements and repair mortars [16]. While CSA cements have not yet been widely adopted, the availability of bauxite and gypsum in developing countries—key raw materials for CSA production—presents a significant opportunity to develop this technology locally.

4.3. Magnesium-Based Cements

Magnesium-based cements provide a sustainable alternative to traditional binders, combining low production emissions with the ability to sequester CO_2 during curing [10]. Brazil, with its abundant magnesite and dolomite reserves, is well-positioned to harness this technology, particularly by integrating agricultural residues like sugarcane bagasse ash to enhance sustainability [17]. Similarly, other developing countries, such as Egypt, with significant dolomite resources, can leverage magnesium-based cements to address local construction challenges while promoting sustainable development. The use of agricultural by-products like rice husk ash or date palm residue further supports waste reduction and the circular economy, aligning with global efforts to lower the carbon footprint of the construction sector.

For widespread adoption, technical challenges must be addressed, including optimizing mix designs for mechanical performance and ensuring compatibility with regional construction practices. In arid climates, such as those in Egypt and the Middle East, magnesium-based binders need to demonstrate durability under harsh conditions like high salinity. Cost-effective production and supply chain strategies are also crucial for scaling their use in resource-constrained regions. By fostering innovation and investing in local industries, countries like Brazil and Egypt can position themselves as leaders in sustainable construction, reducing environmental impact and driving socio-economic benefits through low-carbon building materials.

5. BAMBOO: A SUSTAINABLE MATERIAL FOR TROPICAL REGIONS

Bamboo represents a transformative solution for sustainable construction, not only in Brazil but across other tropical regions globally. As one of the fastest-growing plants on Earth, bamboo holds immense potential to contribute to ecological balance, reduce carbon footprints, and support climate change mitigation efforts [18,19,20]. In addition to its rapid biomass production, bamboo plays a critical role in carbon sequestration, making it a key player in sustainable development, particularly within the construction sector, which is a major emitter of greenhouse gases. Bamboo is particularly well-suited to tropical regions, where its growth and proliferation align with the climate and soil conditions. Brazil, with its vast and varied biomes, is home to a rich diversity of bamboo species, as shown in Figures 2 and 3.

The country boasts approximately 5.26 million hectares of bamboo resources, making it a global leader in terms of bamboo potential. Over 300 species are found throughout Brazil's tropical forests, including the Amazon, Cerrado, and Atlantic Forest, each offering unique mechanical properties such as high tensile strength, flexibility, and resilience. These characteristics make bamboo an ideal material for a wide range of applications, from structural components like beams and columns to non-structural elements like flooring, furniture, and composites.

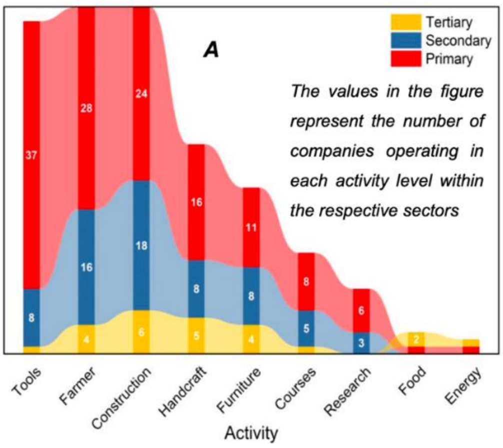

Figure 2: *Segmentation of Bamboo-related Activities in Brazil [18].*

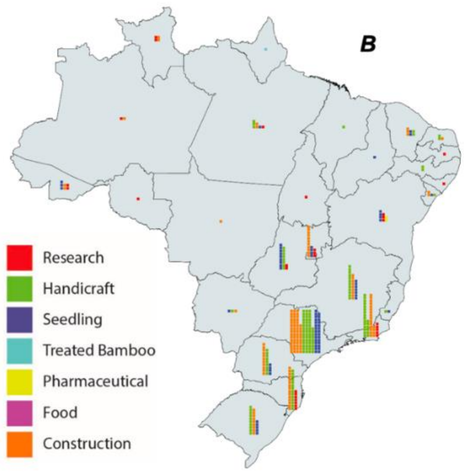

Figure 3: *Geographic Distribution of Bamboo-Related Activities in Brazil [18].*

The potential for bamboo in tropical regions extends beyond Brazil. Countries like Indonesia, India, Thailand, and the Philippines also have abundant bamboo resources and are exploring its role in sustainable construction. In Southeast Asia, bamboo has long been used in traditional building practices, but there is growing interest in developing engineered bamboo products that can compete with more conventional materials, such as steel and concrete. This shift is driven by a combination of environmental concerns and the desire to support local economies by leveraging indigenous resources.

To maximize bamboo's potential, however, several challenges need to be addressed. Key issues include developing effective treatment methods to enhance its durability, establishing standardized design codes for its use in construction, and integrating bamboo with other sustainable materials. There is also a need for better understanding and documentation of bamboo's properties, to ensure that its full potential is realized in diverse construction applications.

Research and innovation are critical to overcoming these hurdles. In Brazil, increasing investments in bamboo-related industries are leading to advances in areas such as biomass-based energy solutions, biofuels, and engineered bamboo products, including laminated panels and advanced composites. These innovations could revolutionize the material's role in construction, opening the door for bamboo to become a staple in sustainable building practices.

Expanding bamboo's use can also offer profound social and economic benefits. In rural areas, where bamboo is often abundant and plays a part in local culture, initiatives to promote bamboo-based construction could drive sustainable development. Community engagement, local training programs, and supportive policies are crucial to ensuring that the benefits of bamboo are widely distributed. The creation of a value chain that supports both local farmers and the broader construction industry can foster economic growth, job creation, and increased social well-being.

6. CONCLUSIONS

Achieving a low-carbon future requires a paradigm shift in materials engineering, particularly in developing countries, where unique challenges and abundant local resources converge. This study underscores the importance of advancing sustainable materials, such as clinker-free binders, supplementary cementitious materials, and renewable lignocellulosic fibers, to meet global climate goals. Technologies like carbon capture and storage (CCS) and innovative uses of bamboo and agricultural by-products highlight the potential to align economic growth with environmental responsibility.

Realizing these advancements requires interdisciplinary collaboration, targeted research, and supportive policies. Implementing incentives for low-carbon materials, prioritizing research on locally abundant resources, and fostering public-private partnerships are critical to advancing sustainable construction practices. Capacity building and community engagement should be emphasized, equipping stakeholders with the expertise to adopt sustainable technologies and practices. Robust monitoring frameworks are essential to measure environmental and economic impacts and ensure scalability and replication of innovations across regions. Furthermore, global collaboration to share best practices and technologies can accelerate progress while respecting regional differences.

By leveraging local resources and fostering innovation, developing regions can lead the way in transforming the construction industry into a model for sustainable development. This collective effort will not only reduce emissions but also create resilient, eco-friendly infrastructures that enhance societal well-being while protecting the planet. A long-term vision that integrates sustainability into every stage of material development is essential to align construction practices with global climate goals.

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8. Author contributions

Conceptualization: Trindade and Savastano Junior; **Methodology:** Trindade, Azevedo and Amaral; **Data Analysis:** Trindade and Amaral; **Writing – Draft Preparation:** Trindade, Azevedo and Amaral; **Review, Editing and Supervision:** Savastano Junior.

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