Unizik Journal of Metallurgy and Engineering Materials
journal homepage: https://journals.unizik.edu.ng/index.php/ujmem/about

Recent Advances towards Green Ceramics in Developing Countries

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Abstract

The ceramics industry is a critical sector for economic development in developing countries, yet it remains one of the most energy-intensive and environmentally burdensome manufacturing domains globally. This review examines recent advances (2020–2025) in green ceramics research and practice specifically relevant to developing nations across Africa, Asia, and Latin America. Key thematic areas include the incorporation of agricultural and industrial waste materials—such as rice husk ash, fly ash, sugarcane bagasse ash, and ceramic production waste—as sustainable substitutes for virgin raw materials in ceramic formulations. The paper evaluates innovations in low-energy processing technologies, including geopolymer-based ceramics and alkali-activated materials that eliminate or significantly reduce high-temperature firing requirements. Life cycle assessment studies from countries such as India, Brazil, Sri Lanka, and Nigeria are synthesised to quantify the environmental benefits of these approaches, including reductions in CO2 emissions, energy consumption, and landfill waste. Policy frameworks, economic barriers, and technology transfer challenges that shape the adoption of green ceramics in resource-constrained settings are also critically assessed. The review concludes that developing countries possess unique advantages—abundant agricultural residues, growing construction demand, and opportunities for technological leapfrogging—that position them to lead a global transition toward sustainable ceramic manufacturing, provided that supportive institutional mechanisms and international collaboration are strengthened.

ARTICLE INFO

Keywords:
Green ceramics; sustainable manufacturing; developing countries; waste valorisation; geopolymers

Corresponding author: **oo.taiwo@unizik.edu.ng**
Received: 9 March 2026 Received in revised form: 12 April 2026 Accepted: 13 May 2026 Published online: 28 May 2026
Publisher: Department of Metallurgical and Materials Engineering, Unizik

1. Introduction

Ceramics constitute one of the oldest and most ubiquitous classes of engineered materials, with applications spanning construction, sanitary ware, tableware, and advanced technological components. The global ceramics market was valued at approximately USD 124.75 billion in 2024 and is projected to reach USD 150.37 billion by 2028, growing at a compound annual growth rate of 4.8 percent (The Business Research Company, 2026). A substantial proportion of this growth is concentrated in developing regions, where rapid urbanisation and infrastructure expansion are driving unprecedented demand for ceramic products, particularly tiles, bricks, and sanitary ware (Custom Market Insights, 2026). However, the environmental footprint of conventional ceramic manufacturing is considerable. Furszyfer Del Rio et al. (2022) documented that the manufacture of ceramics in the European Union alone generates approximately 19 million tonnes of CO2 annually, while brick production accounts for 2.7 percent of global carbon emissions. The global annual energy consumption for firing ceramics through natural gas is estimated at 182 terawatt-hours, and in India, approximately 272 million metric tonnes of fertile soil are consumed daily for brick manufacturing (Furszyfer Del Rio et al., 2022; United Nations Industrial Development Organization [UNIDO], 2022). These environmental costs are disproportionately borne by developing countries, where energy-inefficient kilns, reliance on fossil fuels, and limited regulatory enforcement compound the ecological damage. The concept of "green ceramics" encompasses a broad range of strategies aimed at reducing the environmental impact of ceramic products throughout their lifecycle. These include the substitution of natural raw materials with industrial and agricultural wastes, the adoption of energy-efficient firing and processing technologies, the development of geopolymer and alkali-activated alternatives to conventional ceramics, and the implementation of circular economy principles in ceramic production and waste management (Hasan et al., 2021; Rambaldi et al., 2023). For developing countries, these strategies hold particular promise because they simultaneously address environmental sustainability, waste management challenges, and economic competitiveness. This review systematically examines recent advances in green ceramics that are specifically relevant to developing countries. It synthesises findings from peer-reviewed literature published between 2020 and 2025, with a focus on practical innovations in waste-derived ceramic materials, low-energy processing routes, life cycle assessment evidence, and policy and institutional considerations. The review is organised into five thematic sections covering waste material utilisation, geopolymer technologies, energy efficiency innovations, life cycle and environmental assessment, and challenges and future directions.

2. Waste Material Utilisation in Green Ceramic Production

2.1. Agricultural waste residues

Because of their abundance and the fact that they generally have low costs, agricultural waste streams can potentially become one of the best feed stocks for green ceramics in developing countries. Many agricultural by-products have also been shown to have interesting chemical compositions for this purpose. Examples of agricultural residues that have been studied in detail include rice husk ash (RHA), sugar cane bagasse ash (SBA), fly ash from biomass combustion and coconut shell ash, all of which also have a large proportion of either amorphous or semi-amorphous silica and alumina that are able to partially or completely replace typical ceramic raw materials such as quartz, feldspar and clay (Hasan et al. 2021). Particularly because of their high silica content (generally 85–95 percent), rice husk ash has received growing attention for their use in ceramic applications, as they exhibit pozzolanic reactivity and thus, can be utilized both in ceramics and in cementitious applications. In India, approximately 31.40 million metric tons of rice husk are produced each year. However, much of this waste is discarded either in landfills or burned in open fields. This creates a not only a significant waste management issue, but also an air quality problem (Kumar et al. 2024). Phonphuak and Chindaprasirt (2021) and Tippayasam et al. (2021) have recently conducted experimental work that has demonstrated that RHA and recovered glass cullet can be used to successfully create virtually no-burn ceramic tiles with acceptable levels of mechanical strength and water absorption without having to go through the energy-intensive process of firing ceramics to develop their properties. These findings are particularly significant for countries in Southeast Asia and sub-Saharan Africa where rice cultivation is extensive and construction material costs are prohibitive. As the largest producer of sugarcane in the world, Brazil processes an estimated 654 million tonnes of sugarcane annually. As a result, sugarcane bagasse ash has been considered a possible ceramic additive. In a recent study, Viana et al. (2025) showed that incorporating agricultural waste ash into environmentally friendly ceramic tiles can lead to lowered firing temperatures, with their technical performance being acceptable. It was shown that the formation of mullite and anorthite phases during lower temperature sintering can be attributed to the fluxing action of alkali and alkaline earth metal oxides contained in the agricultural ashes used. Between 2014 and 2024, an extensive review was performed on eight separate agricultural waste materials (sugarcane bagasse, rice husks, wheat straw, corn cobs, coconut shells, coffee husks, palm kernel shells, and peanut shells) confirming that all of these agricultural residues can be used in combination to provide filler materials and partially replace raw materials in manufacturing ceramic tiles (Awoyera et al., 2024).

2.2. Industrial waste and by-products

Beyond agricultural residues, a diverse array of industrial by-products has been investigated for incorporation into green ceramic formulations. Fly ash from coal-fired thermal power plants is among the most extensively studied, particularly in India, where coal-based generation accounts for nearly 79 percent of total domestic electricity supply. Satpathy et al. (2025) developed fly ash-based ceramic tiles with up to 60 percent fly ash content fired at 1,250°C, achieving water absorption of 0.98 percent, apparent porosity of 2.2 percent, and diametral tensile strength of 27.47 MPa—values meeting international standards for floor tile applications. The waste created from the production of ceramics accounts for a large and expanding amount of waste in general. Approximately 8-12 percent of the raw materials used in making tile will be produced as waste during the forming, cutting, glazing and polishing processes. That results in many manufacturers having thousands of tonnes of fired ceramic products rejected each year (Earth Tatva 2025). Khater et al. (2025) provided evidence to demonstrate the feasibility of producing low-cost kiln roller waste, ceramic sludge and limestone into refractory ceramics that consist of the 3 crystalline materials found in the CaO-MgO-Al2O3-SiO2 system, using industrially produced ceramic production wastes. The outcome of this process will create solutions for operators to reduce waste disposal as well as reduce operational reliance on new minerals. There is also a high level of research associated with utilising the wastes generated by the manufacture of ceramics for the production of concrete. Jwaida et al. (2024), conducted a systematic review of the literature and confirmed that ceramic waste powder can serve as a substitute to a portion of the cement used in producing concrete and can provide substantial savings related to environmental impact through a Life Cycle Analysis conducted by researchers. Increased durability, reduced porosity and increased resistance to chemical attack are important features of infrastructure in developing tropical countries where there are harsh conditions of exposure to the elements.

3. Geopolymer and Alkali-Activated Ceramic Technologies

Geopolymer and alkali-activated materials (AAMs) represent a paradigm shift in sustainable ceramics, as they can be synthesised at ambient or near-ambient temperatures through the chemical activation of aluminosilicate precursors, thereby eliminating the energy-intensive firing step that constitutes the primary source of carbon emissions in conventional ceramic production. The global geopolymer market was valued at USD 9.7 billion in 2023 and is projected to reach USD 62.5 billion by 2033, growing at a compound annual growth rate of 20.5 percent (Allied Market Research, 2024). Alkali-activated materials and geopolymers present an opportunity to help mitigate climate change, according to Kriven et al. (2024), who published a perspective article in the Journal of the American Ceramic Society. The authors established that geopolymers can be transformed through heating to approximately 1,000°C to become polycrystalline stoichiometric ceramic compounds, allowing for the low-energy synthesis of both normal and ultra-high-temperature ceramics such as silicon carbide, silicon nitride, and mullite. The dual capability of geopolymers to act both as construction materials at ambient temperature and as precursors providing advanced ceramic capabilities, makes geopolymer technology particularly attractive for developing nations wishing to build manufacturing capacity without a significant capital investment in high-temperature manufacturing equipment. Wang et al. (2024) expanded on this work by demonstrating a geopolymer-binder-integrated additive manufacturing process capable of producing ceramic composite structures with a greenhouse gas emission value of only 0.79 kg of CO2 equivalent per kg—representing a reduction of 1,000 times compared to typical binder-jetting additive processes for ceramics. While conventional additive manufacturing has very high capital costs and therefore is not practical for many developing countries, the principle of using geopolymer binders for low carbon consolidation processes can be applied to traditional ceramic forming methods. In Pakistan, a study conducted by researchers at Sarhad University produced geopolymer concrete using Class F fly ash and ground granulated blast furnace slag as base materials from local sources. The use of sodium hydroxide and sodium silicate as the activators at a concentration of 16M yielded a geopolyer with mechanical properties comparable to Portland cement systems, and a cost reduction of about 15 to 20 percent when using local waste materials (Adnan and Anas 2025). In Morocco, Allaoui et al. (2024) demonstrated the valorisation of ceramic sanitary waste into phosphoric acid-based geopolymers with thermal stability, good mechanical properties and microstructure integrity that met the requirements for sustainable construction applications. Despite advances in geopolymer research, there are several barriers to the widespread adoption of geopolymer ceramics in developing countries. These include the inconsistent availability and quality of precursor materials (e.g. fly ash, metakaolin), the relatively high cost of alkaline activators in areas without domestic chemical production facilities, and the lack of internationally accepted standards and building codes for geopolymer products (Dos Santos et al., 2025). The innovative solutions to these barriers will require collaborative efforts among researchers, industry and policy makers.

4. Energy Efficiency and Decarbonisation Innovations

Energy consumption remains the dominant cost factor and environmental determinant in ceramic manufacturing, with energy costs accounting for approximately 30 percent of production costs across the global industry (UNIDO, 2022). Lourenco Alves et al. (2025), in a comprehensive review published in the International Journal of Applied Ceramic Technology, documented that the ceramic tile industry has a global warming potential of 14.4 kg CO2 equivalent per square metre, with CO2 emissions comprising 92.1 percent of its environmental impact. The industry collectively emits approximately 19 million tonnes of CO2 annually. Several promising energy efficiency technologies have been identified for adoption in developing country contexts. Hybrid kilns that reuse exhaust gases to drive heat pumps can deliver up to 65 percent in energy savings, while microwave-assisted drying and firing can achieve up to a 99 percent reduction in energy use compared to conventional thermal processes (UNIDO, 2022). However, the practical implementation of these technologies in developing countries is constrained by high capital costs, limited access to financing, and the long operational lifespan of existing kilns (typically exceeding 40 years), which creates path dependency in energy technology choices. Brazil has emerged as a leader among developing countries in pursuing biofuel-based decarbonisation of ceramic manufacturing. As the third-largest global producer and consumer of ceramic tiles, Brazil benefits from its position as a world leader in biofuel production and use. Lourenco Alves et al. (2025) demonstrated through flowsheet simulations that optimising raw material composition—specifically through the incorporation of talc as a flux—can simultaneously lower firing temperatures, reduce total production costs, and decrease CO2 emissions in both Brazilian and Spanish production scenarios. The simulation methodology enables manufacturers to evaluate optimal compositions before committing to costly raw material acquisitions or process modifications. In China, Zhang et al. (2023) conducted one of the first comprehensive assessments of decarbonisation routes available to the ceramic industry, examining 14 green technologies across four categories: energy substitution, energy efficiency improvement, material consumption reduction, and process improvement. Their analysis of Huida Group Co. Ltd., a world-leading ceramic manufacturer, found that replacing coke oven gas with natural gas or green hydrogen produced the most significant carbon reductions. When economic feasibility was considered, energy efficiency improvement technologies, lightweight product design, and waste recycling emerged as the most effective strategies, reducing total emissions by 4.31, 2.58, and 1.8 percent respectively, while simultaneously increasing profits. These findings have direct relevance for developing countries that are currently investing in new ceramic manufacturing capacity and can therefore avoid the technology lock-in that characterises established production facilities in industrialised nations.

5. Life Cycle Assessment and Environmental Performance

In Yarahmadi and Asadi (2025), the authors were involved in a multi-dimensional sustainability evaluation where the comparison between the ceramic tile and natural stone industry was evaluated in seven countries, which included some developing countries (Brazil, Iran, China). Countries were categorised into three structural categories (sustainable industrial economies, semi-sustainable states and high-risk developing economies) by using principal component analysis, k-means clustering and SHAP (SHapley Additive exPlanations). According to their analysis, CO2 emissions were the most significant driver of structural pressures for all three categories and demonstrated its importance to future climate-related policy for ceramics. Additionally, their analysis of life cycle costs showed that, although natural stone has a higher initial cost to install, it has a lower total cost than ceramic tile over the long term; this finding will have a significant impact on developing countries, where initial cost is often the main consideration when evaluating life cycle economics. Moreover, environmental assessments of how ceramics utilise waste in concrete have provided additional support for the agenda of green ceramics. Dehghani et al. (2024) showed through LCA that the use of ceramic waste powder as a partial replacement for cement provides a large reduction in many different types of adverse environmental impacts, such as global warming potential, acidification and resource depletion. These reductions stem from the avoidance of both virgin mineral extraction and the high-temperature calcination process required for cement production, offering dual environmental benefits when ceramic production waste is diverted from landfills to concrete applications.

6. Challenges and Future Directions

6.1. Technical and economic barriers

Though many studies indicate their technical for manufacturing, there are many barriers to their large-scale use in developing nations. A primary barrier to the use of waste as ceramic raw material is the large degree of variability in quality of waste materials—specifically in the case of C and D and mixed industrial waste—as the variability makes it challenging for ceramic manufacturers, who typically use a small number of standardised, naturally occurring raw materials, to create a consistent product (Rambaldi et al., 2023). As a result, the variability of the chemical and mineral components in the waste stream creates inconsistent product characteristics and requires the implementation of characterisation methods and material formulation approaches that many small- and medium-sized enterprises do not have the expertise to execute in developing countries. The economic viability of producing green ceramics in many cases also is a barrier to their acceptance. Although the raw materials (waste) that can be used for production of green ceramics are often inexpensive or free, the costs associated with collecting, transporting, processing and providing quality assurance typically exceed the savings resulting from using waste-derived materials. In addition to low-quality waste materials, producing geopolymer ceramics requires the use of alkaline activators (for example, sodium hydroxide and sodium silicate); therefore, the use of these activators can present a major cost impact in areas where there is no domestic chemical production, given their high cost and limited availability. In addition, some fly-ash-based geopolymers require elevated temperature curing, which increases energy cost, especially in the absence of cheap, reliable energy sources (Dos Santos et al., 2025). Lourenco Alves et al. (2025) noted that switching kiln fuel types requires significant financial investment, and given that kilns have operational lifespans exceeding 40 years, decisions about energy sources must be carefully considered in terms of long-term fuel supply security and affordability.

6.1.1 Policy and institutional considerations

The regulatory and institutional environment plays a critical role in either facilitating or hindering the adoption of green ceramics. In many developing countries, environmental regulations for the ceramics sector are either non-existent or inadequately enforced, removing a key market driver for sustainable production. Conversely, where regulations are stringent, small-scale producers may lack the financial and technical resources to comply, potentially leading to market consolidation that displaces artisanal and community-based ceramic production (Furszyfer Del Rio et al., 2022). The absence of internationally harmonised standards for waste-derived and geopolymer ceramic products represents a significant market barrier. While progress has been made in developed countries—notably the Australian Technical Specification 199:2023 for geopolymer concrete design (Kriven et al., 2024)—comparable standards are largely absent in developing regions. Miranda et al. (2021), in their review of green technology practices across BRICS countries, highlighted that the high cost of technology transfer remains a major impediment, and that overcoming this challenge requires efficient allocation of resources, dedicated research and innovation programmes, and mechanisms for South–South knowledge exchange.

6.2. Emerging opportunities

Several emerging trends create favourable conditions for accelerating green ceramic adoption in developing countries. The growing global emphasis on green building certification systems—such as LEED, BREEAM, and locally adapted equivalents—is creating market demand for sustainably produced construction materials, including ceramics. Ceramic tiles have emerged as the leading flooring material in LEED Platinum buildings in Southeast Asia, and energy-saving and anti-skid variants are increasingly mandated in public infrastructure projects under programmes such as India's Smart Cities Mission and Indonesia's National Urban Housing Plan (Future Market Insights, 2025). The rapid expansion of digital manufacturing technologies, including computational simulation of ceramic formulations and processes, offers developing countries the opportunity to accelerate innovation cycles while minimising costly experimental trial-and-error. Lourenco Alves et al. (2025) demonstrated that flowsheet simulation enables manufacturers to evaluate the optimal raw material composition that minimises both production costs and emissions before committing to physical process modifications—a capability that could democratise access to process optimisation across the global ceramics industry. Finally, the circular economy paradigm is gaining traction across developing countries, supported by international frameworks

Table 1: Challenges and Future Directions in Green Ceramic Production

Category	Challenges	Future Directions
Technical Barriers	• Variability in quality of waste materials (e.g., C and D and mixed industrial waste) making it hard to produce consistent products. • Lack of expertise in characterisation methods and material formulation, especially in small- and medium-sized enterprises in developing countries.	• Development of efficient material formulation and characterisation methods for consistent product quality. • Improved technical expertise and knowledge transfer to small enterprises.
Economic Barriers	• Costs of collection, transportation, processing, and quality assurance often exceed savings from using waste-derived materials. • High costs of alkaline activators (e.g., sodium hydroxide) and energy costs related to curing processes. • Financial investment required for switching kiln fuel types.	• Explore economic models that reduce processing costs, such as improved waste collection methods or domestic production of alkaline activators. • Consider long-term fuel supply investments for cost-effective energy use in ceramic manufacturing.
Policy and Regulatory Barriers	• Lack of strict environmental regulations or enforcement in many developing countries, limiting the market for green ceramics. • Small producers may struggle with compliance in regions with stringent regulations. • Absence of internationally harmonised standards for waste-derived and geopolymer ceramics.	• Create and implement clear and enforceable regulations that promote sustainable production. • Development of internationally accepted standards for waste-derived ceramics. • Efficient resource allocation and South–South knowledge exchange for technology transfer.
Emerging Opportunities	• Barriers to adopting green ceramics due to lack of awareness or technical capacity. • Slow adoption of green technologies due to financial constraints.	• Integration of green ceramics into global green building certification systems (e.g., LEED, BREEAM). • Use of digital manufacturing technologies to accelerate innovation and reduce trial-and-error costs. • Strengthening circular economy practices, focusing on ceramic waste recycling.

such as the United Nations Sustainable Development Goal 12 (Responsible Consumption and Production). The integration of ceramic waste recycling into broader industrial ecology networks—where the waste stream from one process becomes the feedstock for another—holds particular promise for densely industrialised regions in India, China, Brazil, and Nigeria where ceramic production clusters generate concentrated waste streams amenable to efficient collection and reprocessing.

7. Conclusion

This review has demonstrated that significant advances have been made in recent years toward the realisation of green ceramics in developing countries. The incorporation of agricultural waste residues such as rice husk ash and sugarcane bagasse ash, the utilisation of industrial by-products including fly ash and ceramic production waste, and the development of geopolymer and alkali-activated alternatives to conventional fired ceramics collectively offer viable pathways for reducing the environmental footprint of ceramic manufacturing while simultaneously addressing waste management challenges and reducing production costs. Life cycle assessment evidence from countries across Asia, Latin America, and Africa confirms that these approaches can deliver measurable reductions in greenhouse gas emissions, energy consumption, resource depletion, and landfill waste. However, the transition from laboratory-scale demonstrations to industrial-scale implementation remains incomplete, constrained by technical barriers related to waste feedstock heterogeneity, economic challenges associated with activator costs and technology investment, and institutional gaps in standards, regulations, and technology transfer mechanisms. Developing countries possess unique structural advantages for leading the global transition to green ceramics: abundant agricultural and industrial waste streams that can serve as low-cost ceramic precursors, rapidly growing construction demand that creates large and expanding markets for sustainable building materials, and the opportunity for technological leapfrogging—adopting state-of-the-art green technologies in new manufacturing facilities rather than retrofitting existing ones. Realising this potential will require sustained investment in applied research, the development of contextually appropriate standards and quality assurance frameworks, supportive policy environments that incentivise green production, and strengthened mechanisms for international technology transfer and South–South cooperation. The convergence of environmental necessity, economic opportunity, and technological maturity suggests that the coming decade will be decisive for establishing green ceramics as the normative standard for ceramic production in developing countries worldwide.

Conflict of interest

The authors declare there is no conflict of interest

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