Discover Materials

Review

Banana leaf ash as sustainable alternative raw material for the production of concrete: a review

Bamidele Charles Olaiya[1] · Mustapha Muhammad Lawan[1] · Kolawole Adisa Olonade[1] · Sani Aliyu Abubakar[1]

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Abstract
The construction industry is under increasing pressure to adopt sustainable materials that minimize environmental impact. Agricultural waste, such as banana leaf ash (BLA), has shown potential as an eco-friendly alternative in concrete production. This review examines the viability of BLA as a partial replacement for cement, highlighting its effects on mechanical properties, durability, and sustainability. Improper disposal of agricultural waste contributes to pollution, greenhouse gas emissions, and resource depletion. Utilizing BLA in concrete reduces landfill waste and lowers carbon emissions by decreasing cement consumption, potentially reducing CO_2 emissions by up to 30% per ton of cement replaced. The results of this review indicate that BLA exhibits pozzolanic activity, with studies reporting compressive strengths ranging from 20 to 32 MPa at replacement levels of 5–15%. Water absorption rates have remained within acceptable construction limits, typically below 10% at optimal mix designs. The findings suggest that moderate cement replacement with BLA can yield concrete with sufficient compressive strength, workability, and durability in line with industry standards such as BS EN 206 and ASTM C618. Despite its advantages, challenges such as quality control, mix design optimization, and lack of standardization must be addressed for widespread adoption. Further research is essential to enhance performance consistency and encourage market acceptance. This review underscores the potential of BLA as a sustainable construction material, contributing to a greener and more resource-efficient built environment.

Keywords Banana leaf ash · Alkali-activated materials · Supplementary cementitious materials (SCMs) · Sustainability · Eco-friendly

1 Introduction

The construction industry is one of the largest consumers of natural resources and a significant contributor to environmental degradation and greenhouse gas emissions [1]. Among its key components, conventional concrete, widely used for infrastructure, housing, and urban development poses substantial environmental challenges due to its high energy consumption and CO_2 emissions, primarily stemming from cement production. In 2022, more than 4.4 billion tons of cement were produced globally, accounting for over 8% of the total carbon dioxide (CO_2) emissions produced by humans [2]. Finding sustainable substitutes for conventional cement-based products is becoming more popular in light of these environmental effects.

This demand is especially pronounced in developing and underdeveloped regions, where the high cost of imported or industrial construction materials remains a barrier to affordable housing and infrastructure [3–6]. In these settings, the

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✉ Bamidele Charles Olaiya, bmolaiya@kiu.ac.ug | [1]Department of Civil Engineering, School of Engineering and Applied Sciences (SEAS), Kampala International University, Western Campus, Ishaka, Uganda.

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use of locally available agricultural waste as supplementary cementitious materials (SCMs) provides a viable and sustainable alternative [5]. One such material is banana leaf ash (BLA), a by-product derived from the controlled combustion of banana leaves, which are typically discarded in tropical and subtropical regions. Rich in amorphous silica, BLA exhibits promising pozzolanic activity, improving the performance of concrete when used as a partial cement replacement [7]. Moreover, Life Cycle Assessment (LCA) studies have demonstrated that substituting cement with agricultural wastes like BLA can reduce embodied energy and CO_2 emissions by 20–30%, depending on the replacement ratios and processing methods [8].

Although several experimental studies have explored the incorporation of BLA into concrete, most have focused on specific performance metrics such as compressive strength or chemical durability [9–13]. Existing research tends to be fragmented, addressing individual aspects such as sulphate resistance, self-compacting properties, or mechanical strength at isolated replacement levels. Few studies offer an integrated, critical synthesis of BLA's properties, environmental benefits, and engineering potential. Moreover, prior reviews lack quantitative evaluations of environmental impact or detailed discussions on practical implementation, policy considerations, and region-specific standardization needs.

This review bridges these gaps by providing a holistic and interdisciplinary assessment of banana leaf ash as a sustainable raw material for concrete production. It systematically evaluates BLA's physical, chemical, and engineering properties and its applicability in conventional and alkali-activated systems. It also critically compares BLA to other SCMs, identifies barriers to scale-up, and proposes actionable strategies for industry-academia collaboration, standard development, and market integration. By consolidating scattered findings and addressing overlooked dimensions, this review contributes to the global discourse on low-carbon, resource-efficient construction, positioning banana leaf ash as a viable solution for promoting circular economy practices and sustainable infrastructure development.

2 Methodology

This review investigates the potential of agricultural waste products, specifically banana leaf ash (BLA), as an eco-friendly alternative to conventional construction materials. To ensure a comprehensive and systematic analysis, an extensive literature search was conducted using reputable academic databases, including PubMed, ScienceDirect, Scopus, and Web of Science. The search covered publications from 2000 to 2024, limited to peer-reviewed journal articles and conference proceedings published in the English language.

The initial search yielded a broad set of articles, which were screened based on specific inclusion and exclusion criteria. Inclusion criteria encompassed studies that (i) examined the use of banana leaf ash or banana-based composites in construction materials, (ii) provided experimental or analytical data on mechanical, chemical, or durability properties, and (iii) involved partial or full cement replacement. Exclusion criteria included non-English publications, review articles without experimental data, studies focused solely on other types of ash, and articles lacking methodological transparency or sufficient performance data.

Following the preliminary screening of titles and abstracts, a second-level screening assessed full texts for alignment with the research objectives. Studies were evaluated for scientific rigor, methodological clarity, and relevance to the topic of BLA in concrete and mortar applications. The final set of articles was then carefully analyzed for quality, validity, and their contribution to the field as illustrated in the PRISMA-style flow diagram in Fig. 1, which provides a visual representation of the identification, screening, eligibility, and inclusion process.

The extracted data from the selected articles were organized thematically to evaluate the physical and chemical characteristics, pozzolanic behavior, mechanical performance, and durability contributions of BLA when used as a supplementary cementitious material. Gaps in the literature were also identified, including a lack of long-term durability studies and inconsistencies in mix design parameters, which informed the recommendations for future research aimed at improving the practical application of BLA in sustainable construction.

3 Characteristics of banana leaf ash

Banana leaf ash (BLA), derived from the combustion of banana plant leaves, is an abundant agricultural byproduct in tropical regions. Traditionally discarded or burned openly as seen in Fig. 2, leading to environmental concerns, BLA has garnered attention as a sustainable material in the construction industry. Its utilization addresses waste disposal issues and offers potential enhancements in building materials [14].

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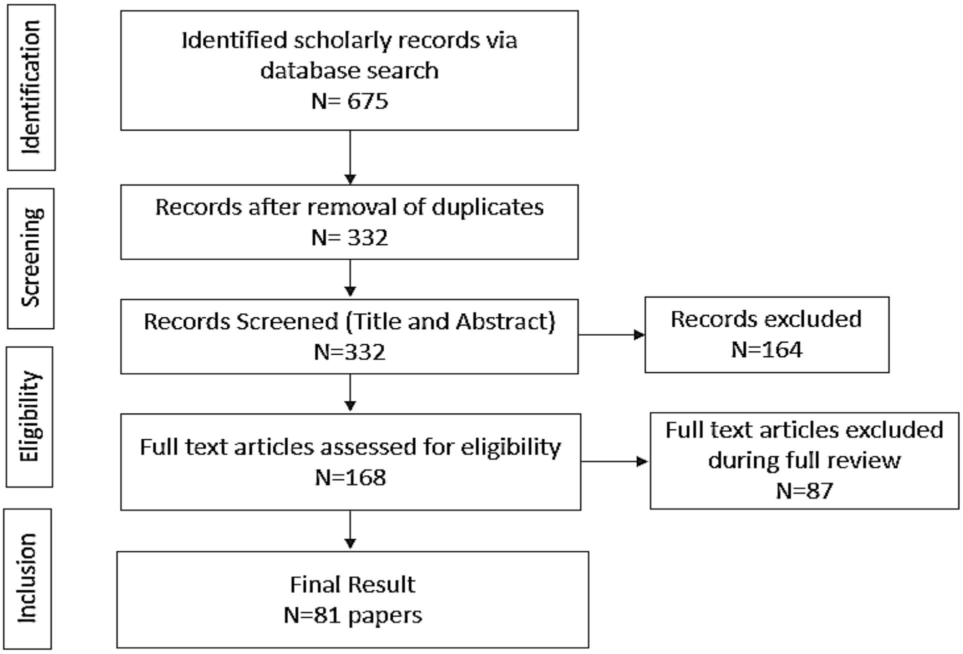

Fig. 1 The flow chart for the study outlining the process of database searches, the number of abstracts screened, and the full texts retrieved

The processing of banana plants generates a substantial amount of banana leaf waste. The quantity of banana leaves produced during agricultural and post-harvest activities is influenced by the efficiency of the processing techniques, which can be assessed by comparing the amount of usable banana fruit and fiber recovered to the volume of residual leaf waste generated. The amount of banana leaf waste produced varies depending on the technology and methods used in harvesting and processing. A study by Payal et al. [15] highlights that inadequate processing equipment in banana farming operations can result in a significant accumulation of banana leaf waste during post-harvest handling. If these leaves are discarded as waste, they pose a considerable environmental challenge, contributing to organic waste accumulation and potential greenhouse gas emissions from decomposition.

Table 1 below presents the annual production quantities of bananas in some key global locations. India leads global banana production with 35.2–52.58 million tonnes, utilizing the largest cultivation area of 880,000 hectares. The country's dominance is attributed to favorable climatic conditions, extensive agricultural land, and a variety of banana cultivars catering to its vast domestic market. China and Brazil follow, with productions of 17.6–26.4 million and 18.8–28.2 million tonnes respectively, primarily serving their domestic demands. Uganda and Nigeria, Africa's top producers, harvested over 8 million tonnes, reflecting the crop's significance as a staple food. Ecuador stands out as the world's leading banana exporter, producing approximately 7.2 million tonnes and exporting over 6.5 million tonnes annually. Its success in exports is due to favorable growing conditions, established infrastructure, and access to major markets like the United States (U.S) and European Union (E.U). Tanzania's data indicates 350,204 hectares dedicated to banana cultivation, underscoring its role in regional food security.

Fig. 2 Ditching of banana leaves in the open.(**a**)Burning of banana leaves close to residential area(**b**) Open burning of banana plant leaves[14]

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Table 1 Estimated measures of bananas produced annually at different locations

Country	Estimated banana cultivation area (Million ha)	Estimated yield (Tons/ha)	Estimated annual production (Million Tons)	References
India	0.88	40–60	35.2–52.8	[16]
China	0.44	40–60	17.6–26.4	[16]
Philippines	0.45	40–60	18.0–27.0	[17]
Uganda	1.8	5–30	9.0–54.0	[18]
Ecuador	0.35	40–60	14.0–21.0	[16]
Nigeria	0.54	14.8	8.0	[19]
Brazil	0.47	40–60	18.8–28.2	[16]
Indonesia	–	–	8.0–12.0	[16]
Tanzania	0.350	–	–	[16]
Ecuador	–	–	7.2 (6.5 exported)	[16]
Colombia	–	–	1.57	[16]

– Data not reported

This comparative overview highlights the diverse roles bananas play globally from being a staple food in countries like India, Nigeria, and Uganda to serving as a major export commodity in nations like Ecuador and the Philippines. Proper utilization of this agricultural byproduct can help mitigate environmental concerns and enhance sustainability in various industries.

3.1 Physical properties

Banana leaf ash (BLA) has several physical properties that influence its performance and suitability for construction-related applications. One of the most visible attributes is its color, which typically ranges from gray to off-white. This variation depends on the combustion temperature, oxygen availability, and the presence of unburnt carbon and mineral impurities during the ash preparation process [19, 20]. Another key property is particle size distribution, which plays a critical role in determining the consistency and reactivity of BLA. To achieve the desired consistency for specific uses, the ash is often sieved or ground to obtain finer particles suitable for blending into cementitious systems. Studies report average particle sizes ranging from 45 to 150 µm, with enhanced performance noted when the ash is processed below 75 µm, a range often recommended for pozzolanic activity [21]. Fineness testing confirms that the passing rate through a 75 µm sieve typically exceeds 90% in optimized samples. Closely related to fineness is the specific surface area, which significantly affects the reactivity of BLA. BET (Brunauer–Emmett–Teller) analysis, used to measure this property, indicates that BLA may have a surface area between 5 and 20 m^2/g, depending on grinding and treatment conditions [22, 23]. A higher specific surface area facilitates greater interaction with cement hydration products [24].

Bulk density is another essential parameter, generally ranging from 800 to 1100 kg/m^3, depending on moisture content and compaction [25]. This low density compared to Portland cement influences both the mix design and handling procedures in construction applications. Porosity and hygroscopic behavior also define the practical use and storage conditions of BLA. Its internal pore structure enables high water absorption capacity, which may enhance bonding in composites but also necessitates moisture-controlled storage environments to prevent early hydration or degradation [26, 27]. In hygroscopic testing, BLA samples stored in humid environments demonstrated moisture gain ranging from 4 to 8%, which can alter flowability and mixing behavior [28]. Abrasion resistance, although not a primary concern in cement replacement materials, affects transportation and storage, particularly in bulk handling. BLA shows moderate abrasion resistance, making it suitable for most handling scenarios with minimal material loss [29].

Color stability is another factor, especially in aesthetic concrete applications. While the ash color may initially appear consistent, long-term exposure to light and moisture can lead to mild discoloration, typically shifting from light gray to a yellowish tint due to oxidation and surface reactions [22, 30].

Lastly, one useful characteristic that affects how well BLA incorporates into dry or wet solutions is flowability. In cement matrices, BLA with homogeneous granulometry and smaller particles usually exhibits good flowability, guaranteeing even dispersion. This makes concrete mixes more workable and helps them develop uniformly in strength [31, 32].

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Understanding these physical properties is key to assessing BLA's potential as a sustainable alternative in various industries. Since different sectors have specific material requirements, conducting thorough physical property tests is essential to ensure it meets those standards. Additionally, factors such as production methods can influence these properties, making quality control and consistency vital in its practical applications [19].

3.2 Chemical properties

Banana leaf ash (BLA) is a chemically diverse material derived from the combustion of banana leaves [5, 6, 33]. Its composition can vary based on factors like the banana plant species, combustion conditions, and post-processing methods [33]. One of its most notable chemical components is silica (SiO_2), primarily in an amorphous form [34]. Silica plays a crucial role in enhancing pozzolanic reactivity, making BLA particularly valuable for cementitious applications. Additionally, BLA contains small amounts of aluminum oxide (Al_2O_3), which can influence its reactivity and potential use in concrete and other construction materials [33].

Another key compound in BLA is calcium oxide (CaO), with its concentration largely dependent on the combustion process [33, 35]. For instance, as shown in Table 2, while most studies report CaO levels between 6.4 and 7.1%, one source [36] reports a significantly higher CaO content of 40.52%. This discrepancy can be attributed to differences in combustion methods (e.g., temperature and duration), raw leaf mineral composition, or the presence of mineral impurities absorbed during banana plant growth. High-temperature calcination and variable soil nutrient uptake can result in elevated calcium content in the final ash product. Potassium oxide (K_2O) is also commonly found due to its natural presence in plant materials, affecting the chemical behavior of BLA in various applications. Similarly, sodium oxide (Na_2O) may be present, influencing the material's interactions, particularly in alkaline environments, as shown in Table 2. While Table 2 presents the major oxides found in BLA, it does not include minor constituents such as magnesium oxide (MgO), titanium dioxide (TiO_2), and sulfur trioxide (SO_3), among others. Therefore, the oxide totals do not sum to exactly 100%.

The carbon content of BLA varies depending on the combustion conditions and the degree of carbonization. Controlling residual carbon levels is crucial, especially in applications that require high purity [36]. Additionally, trace elements such as iron (Fe), magnesium (Mg), and sulfur (S) may be present, largely influenced by the soil in which the banana plants were grown [37]. These trace elements can subtly affect the material's chemical properties and reactivity.

BLA is inherently alkaline, typically having a pH between 9 and 11 [25]. This high alkalinity can be advantageous in applications like soil stabilization and water treatment, where pH regulation is important. However, depending on environmental conditions and potential contaminants, BLA may also contain trace amounts of heavy metals, which must be carefully monitored to meet safety and environmental standards [25, 38]. Additionally, BLA can retain small amounts of organic matter, depending on how it was processed. The presence of organic compounds can impact its purity and stability, making it important to control their levels, especially in high-performance applications [39].

Understanding the chemical composition of BLA is key to determining its potential for sustainable construction and other industrial uses. Ensuring it meets quality and environmental standards is essential for making the most of its benefits while minimizing potential drawbacks.

These compositions indicate that BLA contains significant amounts of silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3), which are essential for pozzolanic activity in cementitious materials.

Table 2 Basic oxides in banana leaf ash from different studies

Oxide composition (%)	[33]	[34]	[35]	[37]	[38]	[36]
SiO_2	48.70	47.24	48.70	48.70	47.80	45.89
Al_2O_3	2.60	2.71	2.60	2.60	2.60	3.48
Fe_2O_3	1.40	0.85	1.40	1.40	1.40	1.97
CaO	6.8	6.9	7.1	6.4	6.9	40.52
K_2O	4.9	5.0	2.8	4.8	1.9	1.3
Na_2O	0.21	0.00	0.21	0.21	0.21	0.42
LOI	5.06	6.90	5.06	5.06	5.06	3.02

LOI stands for Loss on Ignition

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3.3 Mineralogical analysis

The mineralogical composition of banana leaf ash (BLA) is influenced by several factors, including the type of banana plant, combustion conditions, and post-processing methods. Understanding its mineralogical properties is essential, as they determine both its reactivity and suitability for various applications [36, 40, 41]. One of the most important components of BLA is amorphous silica (SiO_2) which is a non-crystalline form of silica that significantly enhances its pozzolanic reactivity, making BLA an effective supplementary cementitious material for concrete production, as illustrated in Fig. 3. In addition to amorphous silica, BLA contains crystalline silica, primarily in the form of quartz. The presence of crystalline silica can influence BLA's overall reactivity and affect its performance in different applications. Another key component is calcium silicates, which form under specific combustion conditions. These compounds contribute to pozzolanic reactions, enhancing the binding properties of concrete mixtures and improving their durability [42]. Additionally, BLA includes aluminum oxides (Al_2O_3) in both crystalline and non-crystalline forms. These aluminum oxide impacts BLA's chemical interactions, affecting its effectiveness in construction materials [36, 42]. Furthermore, potassium and sodium compounds are present in BLA, existing in either crystalline or amorphous forms, depending on the banana leaf source. These compounds can alter the chemical behavior of BLA in different applications [43, 44]. BLA contains trace minerals such as iron, magnesium, sulfur, and others, which vary based on the soil conditions where the banana plants were grown [36]. These trace minerals can subtly affect both the physical and chemical properties of BLA. Furthermore, BLA contains minor crystalline and non-crystalline phases, which depend on combustion parameters and any residual impurities from the banana leaves.

To accurately analyze the mineralogical composition of BLA, techniques such as X-ray diffraction (XRD) and scanning electron microscopy (SEM) equipped with energy-dispersive X-ray spectroscopy (EDS) are commonly used. These methods provide precise identification and quantification of mineral phases, offering valuable insights into optimizing BLA for sustainable construction and other industrial applications [36, 45].

3.4 Loss on ignition

The Loss on Ignition (LOI) of banana leaf ash (BLA) refers to the weight loss that occurs when the ash is heated to high temperatures, typically between 500 and 1000 °C [38]. This reduction in weight happens due to the combustion of volatile and organic components, such as residual carbon, organic matter, and moisture that may still be present in the ash. LOI is an important parameter in evaluating the purity of BLA, as it helps determine the proportion of stable inorganic materials versus combustible impurities [36, 46].

A low LOI value indicates a higher degree of purity, meaning that most of the organic substances and moisture have been eliminated, leaving behind a higher concentration of inorganic compounds like silica (SiO_2). This is particularly beneficial when BLA is used as a supplementary cementitious material (SCM) in concrete, as a lower LOI enhances pozzolanic reactivity and contributes to better overall material stability [36].

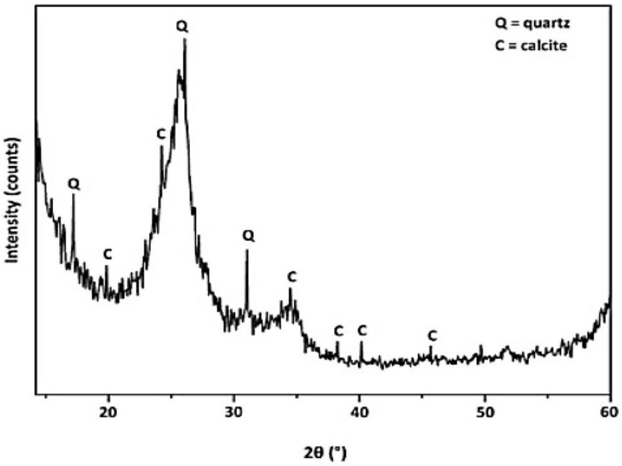

Fig. 3 XRD analysis of banana leaf ash [42]

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3.4.1 Determination of LOI in BLA

The Loss on Ignition (LOI) of banana leaf ash (BLA) is measured through a precise process that involves several steps to ensure accuracy [36, 38]. First, a representative sample of BLA is carefully selected and weighed. The sample is then placed in a muffle furnace and heated to a controlled temperature, typically between 550 and 900 °C, for a specified duration. Once the heating process is complete, the sample is allowed to cool to room temperature inside a desiccator to prevent moisture absorption. After cooling, the sample is reweighed, and the percentage weight loss is calculated, representing the LOI value of the BLA sample. The LOI value is typically expressed as a percentage of the original sample weight and varies depending on factors such as the combustion conditions of the banana leaves and the presence of impurities. In construction and cementitious applications, a lower LOI is preferred, as it indicates that the ash contains minimal volatile organic compounds and a higher concentration of stable inorganic materials. This, in turn, enhances the pozzolanic activity of BLA, improving its ability to contribute to the strength and durability of concrete.

High-quality BLA with a low LOI is widely recognized as a sustainable and eco-friendly alternative to conventional cementitious materials [47]. Its consistent composition and predictable behavior make it an attractive option for the construction industry, supporting the development of greener building materials while reducing reliance on traditional cement.

3.5 Pozzolanic and hydraulic properties

3.5.1 Pozzolanic properties

Banana leaf ash (BLA) has remarkable pozzolanic properties, meaning it can chemically react with calcium hydroxide (lime) in the presence of water to create additional cementitious compounds. This characteristic makes BLA a valuable addition in construction, particularly in concrete production, where it helps improve strength and durability.

3.5.1.1 Pozzolanic reaction and cementitious properties When BLA is added to concrete mixtures containing calcium hydroxide, a pozzolanic reaction occurs. During this process, BLA interacts with calcium hydroxide to form calcium silicate hydrates (C–S–H), which are the essential binding components in concrete [10, 48]. These compounds play a critical role in enhancing the structural integrity and lifespan of concrete.

A key advantage of incorporating BLA into concrete is its ability to reduce the amount of free lime present [49]. Free lime, a byproduct of cement hydration, can negatively impact the durability of concrete if left unreacted. By consuming excess calcium hydroxide, BLA helps prevent harmful chemical reactions, ensuring long-term stability and improved performance of concrete structures.

3.5.1.2 Enhancing concrete performance Banana leaf ash (BLA) exhibits pozzolanic properties that provide numerous benefits in concrete applications. One of its key advantages is the improvement of compressive strength, reduction of permeability, and enhanced resistance to chemical attacks, leading to stronger and more durable concrete structures [50–52]. Additionally, BLA contributes to lowering the heat generated during the cement hydration process, which is particularly beneficial in large-scale concrete pours where excessive heat buildup can result in thermal cracking. Another significant benefit is its ability to mitigate alkali-silica reaction (ASR), a detrimental process in concrete that occurs when alkalis react with silica in aggregates, causing expansion and cracking. By reacting with excess alkalis, BLA helps control this reaction and enhances the long-term stability of concrete structures.

3.5.1.3 Sustainability and economic benefits BLA is not only beneficial for concrete performance but also contributes to sustainability. Since it is derived from agricultural waste, its use as a supplementary cementitious material reduces the demand for Portland cement, which in turn lowers carbon emissions and minimizes environmental impact. Additionally, BLA serves as a cost-effective alternative to traditional cementitious materials, offering a more affordable solution without compromising performance.

3.5.1.4 Quality control and standardization Despite its many advantages, the effectiveness of BLA can vary depending on factors such as processing methods, particle size, and chemical composition [53]. To ensure consistent performance, it is crucial to implement rigorous quality control measures and standardization protocols. Proper testing and characteri-

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zation of BLA will help maximize its benefits while ensuring its reliability in concrete and other construction applications [54, 55].

3.5.2 Hydraulic properties

Unlike Portland cement, BLA does not have inherent hydraulic properties, meaning it does not set and harden independently when mixed with water [56]. Hydraulic materials like Portland cement undergo a chemical hydration process, forming crystalline compounds such as calcium silicate hydrates (C–S–H) and calcium hydroxide, which are essential for strength and durability [57, 58]. While BLA does not exhibit these properties on its own, it functions as a pozzolanic material, meaning it reacts with calcium hydroxide in the presence of water to form additional cementitious compounds. This pozzolanic reaction significantly enhances concrete strength and durability, although it is fundamentally different from the hydration process that occurs in hydraulic cements. One of BLA's most important characteristics is its ability to chemically interact with calcium hydroxide released during the hydration of Portland cement [4]. This reaction leads to the formation of additional C–S–H compounds, strengthening the concrete microstructure and improving overall durability [59]. However, since BLA does not harden independently with water, it is primarily used as a supplementary cementitious material (SCM) rather than a standalone binder.

As SCM, BLA is combined with Portland cement in concrete mixtures to enhance mechanical properties and longevity. Its inclusion increases compressive strength, reduces permeability, and improves resistance to chemical attacks, contributing to more durable concrete structures [60]. Importantly, BLA does not significantly alter the setting time of concrete when used in appropriate proportions, meaning construction processes remain largely unchanged [60, 61]. Beyond its technical benefits, BLA presents both environmental and economic advantages. By partially replacing Portland cement, BLA helps lower the carbon footprint of concrete production, as cement manufacturing is a major contributor to CO2 emissions. Additionally, using agricultural waste as an SCM promotes sustainability and cost savings by reducing reliance on expensive cementitious materials [62].

In summary, while BLA itself is not a hydraulic binder, its pozzolanic properties play a crucial role in enhancing concrete's hydraulic performance. By reacting with calcium hydroxide to generate additional cementitious compounds, BLA improves concrete strength, durability, and overall quality. Furthermore, its sustainable and cost-effective nature makes it an attractive alternative for reducing the environmental impact of cement-based construction materials..

4 Engineering properties of banana leaf ash

According to Dhage et al. [38], partially replacing cement with banana leaf ash (BLA) influences the compressive, flexural, and split tensile strengths of concrete. Their study observed a general decrease in compressive strength as the BLA content increased. However, an improvement in split tensile strength was reported at 20% and 30% BLA replacement by weight, with only a slight decline at 40% and 50%. Flexural strength was maximized at 30% BLA replacement, followed by a minor reduction at higher percentages. These findings suggest that BLA can enhance specific strength properties up to a certain replacement threshold and may offer cost savings due to reduced cement usage. Dhage et al. concluded that an optimal replacement level of 30% could be suitable for applications prioritizing flexural and tensile performance.

This is consistent with Jugal et al. [7] experimental investigations on the properties of concrete by partial replacement of cement with banana leaves. They analyzed properties such as compressive, tensile, and flexural strength by casting cubes, cylinders, and beams. The BLA replacement ranges from 0%, 15%, and 25%. It was reported from their findings that at 15% replacement, there was an increase in strength of the concrete but as the percentage of BLA in the concrete increases to 25%, the compressive strength decreases for a curing age of 28 days. The flexible and split tensile strength increases for replacement of 15% and decreases at 25% replacement respectively. They conclude that a 15% replacement of cement with BLA increases compressive, flexural, and split tensile strength. Similarly, Kanning et al. [33] found that mortars with 10–20% BLA demonstrated superior compressive and flexural strength compared to the control mix. Their samples reached compressive strengths of 47.0–47.2 MPa after 28 days, which represented increases of 25–40% over the control. These results are reflected in Fig. 4, where compressive strength data from various studies shows that performance is largely dependent on the replacement percentage and curing age. While high BLA content (≥ 50%) results in substantial strength reductions, low to moderate replacement levels (up to 15%) can maintain or even improve compressive performance.

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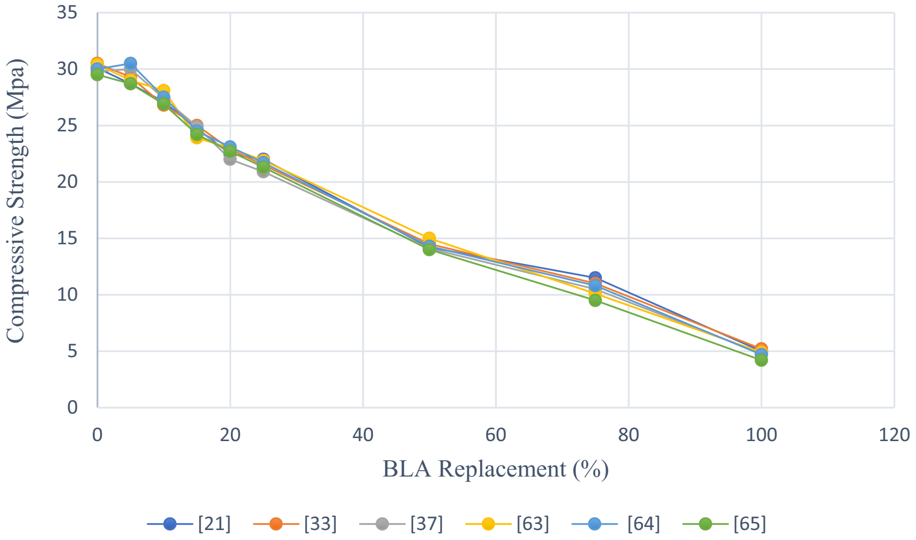

Fig. 4 Variation in 28-day compressive strength of concrete with different weight-based replacement percentages of cement using BLA [21, 33, 38, 63–65]

Ndubuisi [63] and Prasad et al. [64] reported a steady decline in compressive strength and density with increasing BLA content. Ndubuisi [63] reported that the strength and density of the specimens decreased as the cement levels were replaced with banana leaf ashes, but the concrete remains of its plastic nature. Replacing 15–20% weight of cement with banana leaf ash can be used for works requiring medium-strength concrete as it exhibits sufficient compressive strength [63]. He also reported that banana leaf ash (BLA) has a lower specific gravity value than normal cement. This makes the resulting concrete lighter with greater proportions of cement. Replacement of cement with banana leaf ash will be beneficial for low-income areas due to its high availability and ease of source [63]. Prasad et.al. [64] Investigated the strength value of concrete with different replacement proportions of cement with banana leaf ash. They reported a slight decrease in strength by increasing the amount of ash in the concrete mix. The use of BLA in concrete helps to transform it from an environmental concern into a useful resource for the production of a highly effective alternative cementing material [64]. By using BLA in variable amounts as a replacement for cement in concrete, concrete with higher durability and better strength can be obtained [64].

In contrast, Islam et al. [66], whose results are plotted in Fig. 5, demonstrated a more linear and consistent decrease in compressive strength across all replacement levels (0–30% by weight) over multiple curing periods (3, 7, 14, and 28 days). At 28 days, compressive strength dropped to 93%, 78%, and 68% of the control mix for 5%, 10%, and 15% BLA replacement, respectively. These findings highlight that while BLA can be incorporated into concrete without severely compromising performance, excessive replacement can negatively affect strength development. Sakthivel et al. [21] further support the strength-enhancing potential of BLA at low replacement levels. Their study found that 2% and 6% BLA by weight, in combination with 0.2% banana fiber, led to increase compressive and tensile strength. This underscores the importance of mix design and the role of synergistic materials, such as natural fibers, in optimizing concrete performance.

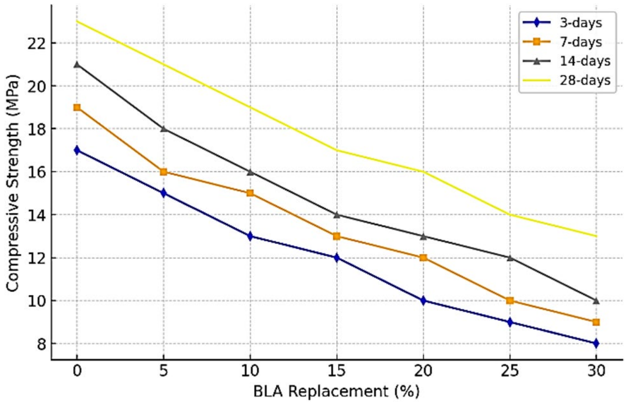

Fig. 5 Comparative effects of different hydration periods on the compressive strength of concrete mixed with varying proportions of BLA [66]

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In summary, the variation in reported outcomes across these studies can be attributed to differences in mix design, curing conditions, additive combinations, and particle fineness. While Figs. 4 and 5 clearly show a trend of strength reduction at higher BLA contents, they also reveal potential for strength retention or enhancement at lower levels (≤ 15%). The use of BLA in cementitious materials appears promising, particularly for sustainable construction in resource-limited settings, but optimal performance depends on carefully controlled replacement levels and supplementary additives.

5 Use of banana leaf ash in alkali-activated materials

Recent studies highlight the potential of banana leaf ash (BLA) as a viable raw material in the production of alkali-activated materials (AAMs), offering a sustainable alternative to ordinary Portland cement (OPC)-based binders. AAMs are known for their high durability, low carbon footprint, and versatility across various structural applications, especially in environmentally focused construction projects [67–70]. BLA exhibits strong pozzolanic activity due to its high content of amorphous silica and other reactive oxides. These react with alkaline activators such as sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) to form calcium silicate hydrate (C–S–H) and alumino-silicate gels that are responsible for binding and strength development [71, 72].

In a study by Adamu et al. [73], banana peel ash (BPA), which shares similar chemical and pozzolanic characteristics with BLA, was successfully used as a binder in geopolymer mortars. Their results showed that increasing the concentration of NaOH from 4 to 10 M significantly improved compressive strength. The maximum strength of 33.17 MPa was achieved with a 10 M NaOH solution using a mix of 52.5% sugarcane bagasse ash (SCBA) and 47.5% BPA after 20 h of curing, while a 4 M mix reached only 21.27 MPa under similar conditions. Flexural strength peaked at 9.95 MPa for a mix with 77.25% SCBA and 22.5% BPA [73].

The effectiveness of BLA in AAMs is also influenced by mix proportions and curing conditions. Studies have shown that BLA can partially substitute materials like fly ash or ground granulated blast-furnace slag (GGBS), with optimized proportions necessary to ensure balanced workability, strength, and durability. Adjustments to the water-to-binder ratio and incorporation of superplasticizers are often required due to BLA's fine particle size and absorptive nature [74].

Curing plays a critical role in strength development. While ambient curing has shown acceptable performance, elevated temperature or steam curing can significantly accelerate the geopolymerization process and improve early-age strength in agro waste based AAMs [73, 74].

AAMs incorporating BLA can be applied in various construction projects, such as concrete, mortar, and precast elements. They are particularly beneficial in environmentally conscious projects that prioritize sustainability [72]. By utilizing BLA, construction industries can reduce their reliance on conventional cement, thereby lowering carbon emissions and mitigating environmental pollution caused by agricultural waste disposal [74].

Moreover, AAMs are known for their durability, exhibiting excellent resistance to chemical attacks and harsh environmental conditions, making them suitable for infrastructure projects and applications in aggressive environments. However, proper testing and quality control are essential to ensure that AAMs containing BLA meet the required performance standards and structural integrity.

Thus, BLA offers significant promise in alkali-activated systems. When incorporated under optimized conditions, it enhances compressive and flexural strength, contributes to lower embodied carbon, and helps divert agricultural waste from landfills. Continued experimental validation and standardization of mix designs are needed to fully integrate BLA into commercial AAM formulations.

6 Sustainability of banana leaf ash

The sustainability of banana leaf ash (BLA) is influenced by its production processes, application methods, and overall environmental footprint. As a byproduct of banana cultivation, BLA offers a highly renewable and locally available resource, with banana plants producing abundant biomass throughout the year without being harmed during leaf harvesting [75, 76]. This continuous supply makes BLA a sustainable raw material, especially in tropical and subtropical regions. BLA is derived from banana leaves typically discarded as agricultural waste post-harvest. Utilizing this waste in construction aligns with circular economy principles by converting it into a valuable supplementary cementitious material (SCM), thereby reducing landfill burden and promoting resource reuse [6, 76]. The production of BLA requires relatively low energy compared to the calcination process used in Portland cement manufacturing [76]. For example,

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while cement clinker production demands temperatures exceeding 1400 °C, the combustion of banana leaves to produce ash can occur at 400–700 °C. This lower energy demand translates to significant energy savings of up to 60–70%, depending on combustion methods and scale [77].

Life Cycle Assessment (LCA) studies on similar agro-waste ashes suggest that replacing 10–20% of Portland cement with ashes like BLA can reduce CO_2 emissions by approximately 150–300 kg per ton of cement replaced, considering that each ton of Portland cement typically emits around 850–900 kg of CO_2 during production [78, 79]. These reductions contribute meaningfully to climate change mitigation in the construction industry. BLA's pozzolanic properties improve the strength and durability of concrete, leading to longer-lasting structures that require fewer repairs, ultimately reducing material waste over time [80]. The local availability of BLA further enhances its sustainability. Since banana plants are widely cultivated in tropical regions, BLA can be produced near banana farms, minimizing transportation distances and lowering emissions associated with material transport. Using banana leaves that would otherwise be discarded also helps manage agricultural waste, reducing environmental pollution. This approach aligns with the principles of a circular economy, which emphasizes efficient resource use, waste reduction, and sustainable material repurposing.

In addition to environmental gains, BLA supports socio-economic development by creating income opportunities for banana farmers and local processing industries. Its use in construction encourages sustainable agricultural practices while reducing dependence on industrial SCMs like fly ash and slag, which are regionally limited and energy-intensive to process. To fully realize the potential of BLA, ongoing research should continue to explore its long-term durability, performance consistency, and LCA-based benchmarks across diverse geographic regions. Adopting standardized production and quality control measures will also be crucial for ensuring safety, scalability, and environmental compliance [81].

7 Challenges and future trends

7.1 Challenges

Despite the growing interest in banana leaf ash (BLA) as an environmentally friendly and economically viable material for construction, its widespread adoption is currently limited by several challenges spanning technical, logistical, environmental, and policy dimensions. Although studies have demonstrated its promising pozzolanic properties and potential for carbon emission reduction, large-scale implementation is still in its infancy, with limited pilot projects or institutional support serving as case studies. To date, there is a lack of documented full-scale construction projects successfully incorporating BLA, and few government-led initiatives or policies explicitly promote its use, which hinders broader adoption and investment.

One of the core technical limitations is the variability in BLA's chemical composition and pozzolanic activity. This variability, driven by factors such as banana plant species, soil conditions, climate, and combustion methods, can result in inconsistent mechanical performance of BLA-modified concrete. Consequently, without region-specific technical standards or characterization protocols, reliable replication across diverse construction contexts becomes difficult. These inconsistencies can lead to unpredictable outcomes in concrete strength and durability.

Additionally, optimizing mix designs remains a critical issue. Although BLA can improve durability and reduce environmental impact, studies have shown that higher substitution levels may compromise early-age strength and workability due to the slower pozzolanic reaction rate compared to conventional cement. For example, Islam et al. [66] observed that strength reductions occur beyond 10–15% substitution, highlighting the need for performance-based replacement limits. Furthermore, BLA's high surface area and porous texture increase water demand, requiring admixtures or water-to-binder ratio adjustments to maintain proper consistency and mechanical performance.

Standardization and quality control pose further challenges. The combustion and grinding processes must be carefully monitored to ensure complete calcination and consistent fineness, as unburnt carbon can reduce reactivity. At present, there are no internationally recognized standards for BLA processing or application, though efforts by local research institutions are emerging. Region-specific standards that account for variations in ash source, production methods, and performance expectations will be crucial for regulatory acceptance and market integration.

Environmental concerns must also be addressed. While BLA originates from agricultural waste, large-scale demand could inadvertently lead to unsustainable practices such as overharvesting, monoculture intensification, or increased deforestation in some regions. In addition, inefficient combustion processes could result in harmful emissions if not properly controlled, thus offsetting the environmental benefits.

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Finally, scaling up BLA production involves challenges related to resource collection, processing infrastructure, and transportation. While banana cultivation is widespread in tropical regions, consistent supply chains for post-harvest waste remain undeveloped. In this context, successful implementation would benefit from policy frameworks that incentivize agro-waste valorization, along with local partnerships between academia, industry, and government. Such collaborations are essential to validate performance, develop region-specific technical guidelines, and build public and private sector confidence in BLA-based technologies.

7.2 Future trends

The future of BLA as a sustainable cement alternative looks promising, with ongoing research and technological advancements aimed at overcoming its current limitations.

Optimizing combustion process: One of the main areas of focus is optimizing the combustion process to achieve a consistent chemical composition and higher pozzolanic activity. Standardized production protocols will help ensure that BLA meets engineering and regulatory requirements, making it more suitable for large-scale construction applications. Improved grinding techniques are also being explored to enhance reactivity and particle fineness, making BLA more compatible with cement and other SCMs.

Integration with nanotechnology and chemical admixtures: Another emerging trend is the integration of BLA with nanotechnology and chemical admixtures to enhance its mechanical properties. Researchers are investigating the use of nano-silica, graphene oxide, and superplasticizers to counteract BLA's higher water demand, thereby improving workability, strength, and setting time. There is also growing interest in developing hybrid cementitious binders that blend BLA with geopolymer, bio-based materials, and recycled industrial byproducts to create innovative construction materials such as self-healing concrete, lightweight composites, and carbon–neutral cement alternatives. Additionally, advancements in artificial intelligence (AI) and machine learning are being applied to optimize BLA-cement mixtures, allowing for more accurate predictions of mix proportions, curing conditions, and structural performance.

Sustainability: As the global focus on sustainable construction increases, BLA is expected to play a key role in green building initiatives and circular economy policies. Governments and industries are likely to encourage its adoption through incentives such as green certifications, carbon credits, and tax benefits for using sustainable materials. Future research will continue to assess BLA-based concrete under real-world conditions, evaluating its long-term durability against factors such as sulfate attack, carbonation, alkali-silica reaction, and freeze–thaw cycles. The expansion of BLA applications into large-scale infrastructure projects, precast elements, and rural housing will further validate its structural performance and environmental benefits.

Cost effectiveness: BLA also has the potential to become a cost-effective and locally sourced cement alternative in developing countries, where access to Portland cement is limited. Its use in affordable housing, rural infrastructure, and disaster-resistant construction could significantly reduce reliance on expensive imported cement while promoting local economic growth.

Nonetheless, for BLA to be widely adopted, addressing challenges related to standardization, large-scale production, and industry awareness will be crucial. With continued research and improvements in processing, durability, and performance, BLA is well-positioned to become a viable and eco-friendly alternative binder, contributing to sustainable construction and environmental conservation.

8 Conclusion and recommendation

8.1 Conclusion

Banana leaf ash (BLA), a byproduct derived from agricultural waste, presents a promising yet evolving alternative material for sustainable construction. Its incorporation into concrete as a partial cement replacement has shown potential to enhance pozzolanic activity, improve long-term durability, and moderately reduce the environmental burden associated with traditional Portland cement. While BLA cannot yet be classified as a widely recognized sustainable material in a standardized context, its localized availability and circular economy potential make it an appealing candidate for low- to medium-strength applications, particularly in regions with abundant banana cultivation. Experimental findings reviewed in this study suggest that BLA, when used within optimal replacement thresholds (typically ranging between 5 and 15% by weight), can contribute positively to compressive and tensile strength, provided the material is properly processed

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and characterized. Furthermore, its relatively low embodied energy compared to cement and ability to reduce agricultural waste support regional sustainability goals. However, the lack of technical standardization, inconsistent chemical composition, and limited pilot-scale demonstrations remain key barriers to mainstream adoption.

Future efforts should prioritize the development of region-specific guidelines for mix design, combustion protocols, and performance evaluation. Establishing reliable supply chains, quality assurance mechanisms, and integrating BLA into existing construction codes and sustainability frameworks will be essential for its broader application. Additionally, targeted research, particularly involving life cycle assessment (LCA), mechanical property benchmarking, and field performance validation, will be instrumental in positioning BLA as a credible, data-backed alternative in the growing field of sustainable construction materials.

8.2 Recommendation for future studies

Given the promising properties of banana leaf ash (BLA) as a supplementary cementitious material, there is substantial potential to further develop its application in sustainable construction. However, to fully harness its benefits and ensure safe, efficient, and standardized use in concrete production, several key research areas must be addressed.

I. Standardization of Processing and Mix Proportions: Future studies should focus on establishing standardized protocols for banana leaf ash (BLA) preparation, including combustion temperature, duration, and particle fineness. These parameters significantly influence the pozzolanic activity and consistency of BLA. Standardization will enable repeatable and reliable results across different geographical and laboratory settings.
II. Advanced Life Cycle Assessment (LCA) and Environmental Impact Analysis: There is a need for comprehensive and region-specific LCA studies to quantify the actual environmental benefits of BLA substitution in concrete. Using AI-enhanced LCA tools such as machine learning-assisted modeling can help in forecasting emissions, energy use, and environmental trade-offs more accurately under varying production and transport scenarios.
III. Exploration in Alkali-Activated and Geopolymer Systems: The potential of BLA as a precursor or additive in alkali-activated materials (AAMs) and geopolymers needs further exploration. Studies should utilize advanced characterization techniques like TGA, FTIR, XRD, and SEM to analyze reaction kinetics, bonding phases, and microstructural development. AI-driven image analysis can also aid in quantifying pore structure and micro-crack behavior in SEM images.

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