
SUGARCANE BAGASSE ASH AS A SUSTAINABLE SILICA PRECURSOR FOR ZEOLITE SYNTHESIS: A REVIEW OF EXTRACTION ROUTES

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ABSTRACT

Zeolite synthesis requires reactive silica sources, which are conventionally supplied by costly and energy-intensive reagents such as tetraethyl orthosilicate and sodium silicate. Sugarcane bagasse ash (SCBA), an abundant sugar-industry residue, provides a low-cost, renewable alternative due to its high silica content. In Nigeria, the three major sugar industry generates an estimate of 1 million metric tonnes of bagasse annually, highlighting the potential for converting this underutilised residue into a valuable feedstock. This review compares principal silica extraction routes from SCBA and evaluates their suitability for ZSM-5 synthesis from SCBA and metakaolin. The conventional route involves acid leaching, calcination near 600 °C, alkaline dissolution in sodium hydroxide, and acid precipitation. Although this route produces amorphous, high-surface-area silica and high recovery but high energy and reagent consumption. Calcination-free acid–alkali extraction offers a more sustainable alternative by directly dissolving SCBA in sodium hydroxide and precipitating silica using hydrochloric acid, producing silica with purity of approximately 98% while reducing energy demand. Characterisation using XRD, FTIR, BET, and electron microscopy provides information on phase composition, functional groups, surface area, and morphology. The extraction route strongly influences silica purity, recovery, reactivity, and sustainability. Calcination-free approaches are particularly promising for green ZSM-5 synthesis, although optimisation of yield, impurity removal, reagent consumption, and scale-up remains necessary for industrial application.

Keywords: sugarcane bagasse ash; silica extraction; ZSM-5 zeolite; green synthesis; waste valorisation

1. INTRODUCTION.

There is an increasing focus on the development of sustainable processes for the conversion of industrial and agricultural wastes into valuable products. Among agricultural residues, sugarcane bagasse is particularly important because it is generated in large quantities during sugar production. Bagasse is commonly combusted in sugar mills to generate heat and electricity, producing sugarcane bagasse ash (SCBA) as a solid residue. Although part of the ash can be used in construction materials and other applications, substantial quantities remain underutilised. SCBA is of particular interest because silica can constitute a significant fraction of its inorganic content. The concentration of silica varies considerably with sugarcane variety, geographical origin, soil conditions, combustion conditions, and ash-processing history. Consequently, SCBA should not be regarded as a chemically uniform raw material; rather, its composition must be established before it is incorporated into a silica-recovery process. Previous reviews have identified SCBA as a promising source of silica and have examined different extraction and purification strategies for producing silica and silicon-based materials (September *et al.*, 2023). The conversion of SCBA into silica is especially relevant to zeolite production. Zeolites are crystalline microporous aluminosilicates with well-defined pore structures, high internal surface areas, ion-exchange capacity, and catalytic properties. They have extensive applications in adsorption, ion exchange, petroleum refining, petrochemicals, environmental remediation, and chemical catalysis. ZSM-5, which is widely used because of its shape-selective properties and hydrothermal stability (Manyepedza *et al.*, 2025). Conventional synthesis of zeolites often uses

commercially available silica sources such as sodium silicate, colloidal silica, silica sol, or organosilicon compounds. Although these materials provide relatively consistent composition and reactivity, their production can increase the cost and environmental footprint of zeolite synthesis. Replacing conventional silica sources with waste-derived silica can therefore improve the sustainability of the overall process (Manyepedza *et al.*, 2025). The potential of SCBA as a zeolite precursor has already been demonstrated. For example, SCBA-derived silica has been used to synthesise zeolite A under hydrothermal conditions, demonstrating that agricultural waste can serve as a viable silicon source for zeolite production (Cordeiro *et al.*, 2013). More recent research has also demonstrated the extraction of high-purity silica from SCBA and its subsequent use in zeolite synthesis (Keawkumay *et al.*, 2024). This review therefore focuses on emphasising the relationships among extraction conditions, silica quality, environmental performance, and suitability for zeolite synthesis. Particular attention is given to the potential application of SCBA-derived silica in of ZSM-5 from SCBA and metakaolin.

2.0 SUGARCANE BAGASSE ASH AS A SOURCE OF SILICA

2.1 Sugarcane Bagasse ash generation

Much research has been conducted to extract silica from various sources, such as plants, clay, rocks, and agricultural wastes, considering that it is a vital material for industrial applications. Waste from agricultural activities is produced daily and can result in a significant amount (September *et al.*, 2023). Sugarcane bagasse is an agricultural waste, a fibrous residue remaining after the extraction of juice from sugarcane. Because of its relatively high organic content, bagasse is commonly burned as a fuel in sugar-processing facilities. The figure 1. illustrates the potential for bagasse generation from major Nigerian sugar-producing companies. The three companies represented in Figure 1 shows the industrial substantial availability of sugarcane-derived biomass for valorisation into value-added products such as silica and zeolite precursors.

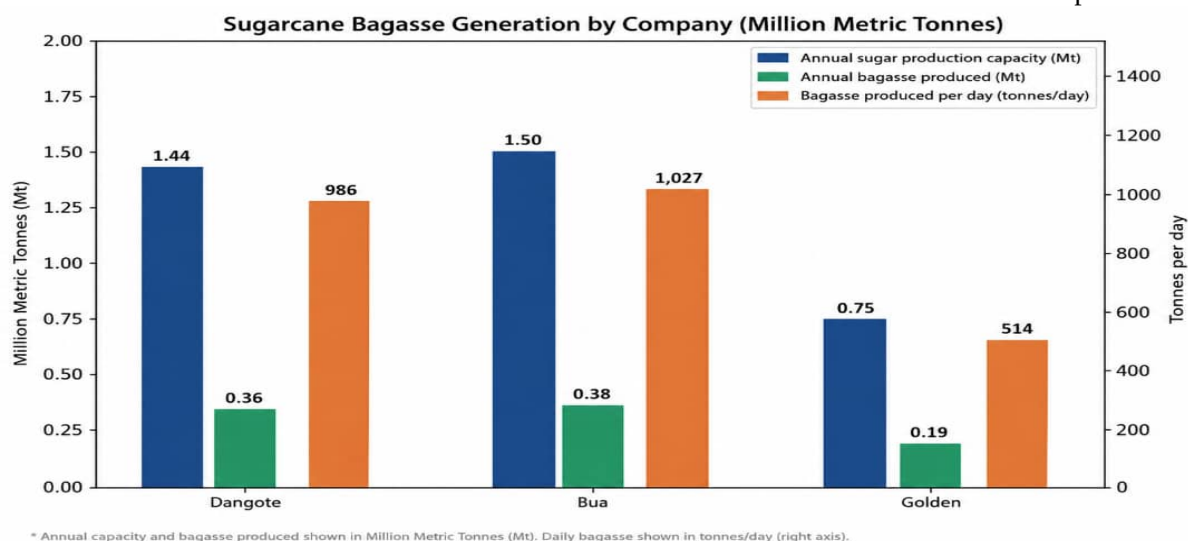


Figure 1: Sugarcane Bagasse Generation by Company (Million Metric Tonnes) (Companies report 2025)

The amount and composition of SCBA depend on combustion efficiency, ash collection practices, and the composition of the original bagasse. Silica is generally the major inorganic component of SCBA, although the ash may contain other mineral constituents. The presence of these impurities is important because they can influence both silica recovery and subsequent zeolite crystallisation (Seroka *et al.*, 2022). The high silica content of SCBA provides an opportunity to convert an agricultural residue into a value-added chemical feedstock. Rather than treating ash exclusively as a disposal problem, silica extraction offers an opportunity to integrate waste management with advanced materials production.

2.2 Importance of silica reactivity

The physical and chemical form of silica is of great importance. The state of silica determines its reactivity, as amorphous silica is more reactive than crystalline silica under alkaline hydrothermal

conditions; therefore, extraction procedures are used not only to increase purity but also to increase chemical reactivity (September *et al.*, 2023).

SCBA → impurity removal → silica dissolution → silica recovery → purified reactive SiO₂ can be seen as the objective of silica extraction, where the purified reactive silica can be used to form an aluminosilicate synthesis gel when combined with an alumina source.

3.0 PRETREATMENT AND PURIFICATION

3.1 Physical pretreatment

Size reduction increases mass transfer. However, particle-size reduction increases energy demand, so it should be matched to the extraction kinetics. Removal of visible unburnt carbon and foreign mineral particles can improve subsequent filtration. Washing can remove soluble salts but may also increase wastewater generation. A practical flowsheet should therefore include only those physical operations that measurably improve downstream silica quality.

3.2 Acid leaching

Acid leaching is a purification process that remove soluble metallic impurities, thereby increasing the relative concentration and purity of silica (Farirai *et al.*, 2021). The principal disadvantage of mineral-acid leaching is reagent consumption and the production of acidic effluent containing dissolved salts and metals. Citric acid has therefore attracted interest as a milder, bio-based alternative. The SCBA review by September *et al.* (2023) reports citric acid pretreatment as a green approach, while broader agricultural-waste literature similarly considers organic acids, lower temperatures, and reduced chemical severity as routes to improve environmental performance.

3.3 Calcination

Calcination increases reactivity of the silica structure. The environmental cost of thermal treatment includes energy demand and direct or indirect greenhouse-gas emissions. The correct calcination temperature is therefore feedstock-specific. A temperature high enough to remove residual carbon can be beneficial, whereas excessive temperature can promote silica crystallisation and sintering (Karumanchi *et al.*, 2022). For a ZSM-5 precursor, preservation of reactive amorphous silica is usually more important than maximising thermal treatment. This is consistent with broader work showing that the structure and reactivity of biomass-derived silica depend on combustion and post-treatment history.

4.0 SILICA EXTRACTION ROUTES FROM SCBA

The silica in raw SCBA is usually associated with carbonaceous residues and mineral impurities such as calcium, potassium, iron, magnesium, and aluminium. Therefore, the purity and reactivity of silica before its use as a precursor for zeolite synthesis (September *et al.*, 2023).

4.1 Conventional acid–calcination–alkali route

The conventional route can be represented as: SCBA → size reduction → acid leaching → washing/drying → calcination → NaOH dissolution → solid–liquid separation → HCl precipitation → washing/drying → silica. Acid leaching removes metallic impurities; calcination removes carbon and stabilises the ash; NaOH extracts sodium silicate; and HCl forms a silica xerogel (Louis *et al.*, 2026). The sequence is chemically robust but may require multiple unit operations and substantial amounts of water, acid, base, and thermal energy.

4.2 Calcination-free acid–alkali extraction

A calcination-free route reduces or eliminates the need for deliberate post-leaching thermal treatment. The route followed was acid-treated SCBA, then extracted with 1.0 M NaOH at 90 °C for 2 h at a reported 1:8 solid-to-liquid ratio, followed by filtration and precipitation with 1.0 M HCl. Approximately 98 wt% purity silica was recovered and was subsequently used to synthesise zeolite NaA (Keawkumay *et al.*, 2024). This is especially relevant to sustainable processing because it demonstrates that suitable silica can be obtained without a separate high-temperature calcination step.

4.3 Organic leaching agents

Citric acid and other organic acids are attractive because they can complex metal impurities and reduce dependence on strong mineral acids. Their suitability depends on ash mineralogy and the intended silica application (Seroka *et al.*, 2022). An organic leaching agent is not automatically more sustainable if large quantities are required or if recovery is poor. Therefore, comparison should be based on acid consumption per kilogram of purified SiO₂, water demand, wastewater treatment, energy use, silica yield, and product performance rather than on acid identity alone.

Table 1: Comparative Assessment of Extraction Routes

Route	Main purpose	Major advantage	Major limitation	Typical product	Suitability for ZSM-5	REFERENCES
Acid–calcination–alkali	Purification + activation	High controllability	High energy/reagent demand	High-purity amorphous silica	High, if SiO ₂ remains reactive	Louis <i>et al.</i> , 2026
Calcination-free acid–alkali	Purification+ direct extraction	Lower thermal demand	Requires effective impurity control	High-purity silica	Very promising	Keawkumay <i>et al.</i> , 2024
Organic-acid + alkali	Greener purification	Milder leaching chemistry	Potentially slower/greater acid demand	Purified silica	Promising after optimisation	Seroka <i>et al.</i> , 2022

5.0 ZSM-5 SYNTHESIS USING SCBA-DERIVED SILICA AND METAKAOLIN

In the synthesis of ZSM-5 zeolite, the extracted silica from SCBA undergoes a chemical reaction with alumina derived from metakaolin after dihydroxylation and depolymerisation of kaolin. This allows the Si/Al ratio to be adjusted independently of the variable Al content of SCBA. It also reduces the need to force a single waste stream to provide both framework elements. (Nguyen *et al.*, 2023). In ZSM-5 synthesis, the key parameters include Si/Al ratio, Na₂O/SiO₂ ratio, H₂O/SiO₂ ratio, structure-directing-agent concentration, ageing, crystallisation temperature, and crystallisation time. Recent review shows that silica sourced from natural and waste material can be used successfully to synthesis ZSM-5, but impurities and inconsistent precursor reactivity can shift the product toward competing phases. Consequently, SCBA-derived silica should be characterised and standardised before gel preparation. (Bensafi *et al.*, 2023). For a high-silica ZSM-5 target, an initial design window may use a Si/Al molar ratio in the approximate range of 25–50, followed by experimental optimisation. The desired acidity, crystallinity and catalytic application should be the final optimum goal rather than assumed from a generic recipe. The sodium content introduced during silica extraction is particularly important, excessive Na can alter nucleation and favour undesired phases, while insufficient alkalinity may limit precursor dissolution. Recent studies on waste-derived ZSM-5 show that post-extraction adjustment of sodium and Si/Al ratios can substantially affect phase purity and yield (Manyepedza *et al.*, 2025). Where an organic structure-directing agent is used, the environmental advantage of SCBA-derived silica can be weakened if the SDA is expensive, toxic or difficult to remove.

6.0 ENVIRONMENTAL AND ECONOMIC CONSIDERATIONS

The environmental benefit of SCBA valorisation depends on the complete process rather than on waste substitution alone. Acid consumption, NaOH demand, water use, drying energy, calcination energy, filtration, wastewater neutralisation and chemical by-product generation can all contribute to the environmental footprint of silica extraction. (Keawkumay *et al.*, 2024) noted that conventional calcination of SCBA consumes significant energy and generates CO₂, while their alternative HCl–NaOH extraction route still involved chemical treatment and neutralisation steps. Life-cycle studies of biomass valorisation similarly demonstrate that chemical consumption, energy demand, wastewater treatment and downstream processing can become important environmental hotspots (Munagala *et al.*, 2021; Zhang *et al.*, 2021). Therefore, a route that avoids calcination but consumes excessive quantities

of NaOH may not necessarily outperform a thermally optimised conventional route. Life-cycle assessment should consequently compare the complete system against commercial silica production and alternative waste-management pathways. Recent studies increasingly incorporate process intensification and life-cycle thinking into biomass and waste valorisation. In particular, microwave-assisted SCBA extraction has been reported to reduce processing time and electricity demand compared with conventional heating, while a screening LCA showed approximately 33–40% lower environmental impacts for bagasse-ash-derived sodium silicate than soda-ash fusion of silica sand for an equivalent SiO₂ output; calcination was identified as a major environmental hotspot (Krainara et al., 2025). Similarly, comparative LCA of zeolite production has shown that replacing conventional chemical Si and Al sources with natural mineral feedstocks can reduce environmental impacts and improve resource utilisation (Chen *et al.*, 2024).

7.0 CHALLENGES AND RESEARCH GAPS

Silica purity alone is insufficient; reactivity toward NaOH and compatibility with zeolite gel chemistry should become routine performance metrics. Water and chemical consumption can become dominant sustainability burdens. Scale-up of filtration and gel washing is likely to be more difficult than laboratory precipitation. Direct ash-to-zeolite routes require careful control of impurity accumulation. The role of sodium introduced during extraction needs explicit mass balance because it can influence zeolite nucleation and phase selection. Another important gap is the limited number of studies that connect silica extraction conditions directly to final ZSM-5 performance. Many studies stop at XRF, XRD, FTIR and SEM of silica or demonstrate a different zeolite topology. A stronger research programme should compare extraction route → silica structure/reactivity → gel chemistry → crystallisation → ZSM-5 acidity/porosity → catalytic performance. This chain would identify whether a lower-purity but highly reactive silica is preferable to a very pure but poorly soluble silica.

8.0 CONCLUSION

Recent literature supports SCBA as a credible renewable and waste-derived silica precursor for zeolite synthesis. The key finding is that the value of SCBA is governed not only by its total SiO₂ content but by silica phase, impurity composition and chemical reactivity. Conventional acid–calcination–alkali processing can produce high-quality silica but carries greater energy and chemical burdens. Calcination-free acid–alkali extraction is therefore particularly attractive, and the demonstration of approximately 98 wt% silica followed by successful zeolite A synthesis provides direct evidence of technical feasibility. For ZSM-5, SCBA-derived silica should be considered a promising silicon source that can be paired with metakaolin to provide controlled aluminium. The most important future direction is an integrated process in which silica extraction and zeolite synthesis are designed together. This approach should optimise reactive silica recovery, impurity removal, Si/Al ratio, alkali concentration, SDA demand and crystallisation conditions simultaneously. The strongest sustainability case will come from a route that minimises calcination, water and hazardous reagents while maintaining high silica recovery and high-purity ZSM-5.

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