

Valorisation of Sugarcane Bagasse Ash from Malawian Sugar Mills for Zeolite Precursor Synthesis: A Compositional and Thermal Analysis

Jona Gowa Nyirenda ¹, Thabo Falayi ², Vincent Mwale ³ and Richard Nkhoma ^{1*}

¹ Department of Engineering, Malawi University of Science and Technology, Malawi

² Department of Civil, Mining and Process Engineering, University of Johannesburg, Johannesburg, South Africa

³ Department of Energy Systems, Mzuzu University, Mzuzu, Malawi.

Abstract. This study investigates the chemical suitability of sugarcane bagasse ash (SBA) sourced from three Malawian sugar production facilities of Nchalo, Dwangwa, and Salima, for use as a precursor in zeolite synthesis. SBA samples were thermally treated at 500°C, 600°C, and 800°C, followed by elemental characterisation using X-ray fluorescence spectroscopy. Emphasis was placed on the quantification of silicon dioxide (SiO₂) and aluminium oxide (Al₂O₃), both of which serve as essential precursors in hydrothermal zeolite formation. Across all samples and temperatures, silica concentrations remained consistently high, with Dwangwa ash at 600°C recording the highest level at 76.22%. Alumina content exhibited greater variability, with Nchalo ash at 800°C yielding the most enriched profile at 15.97%. Although silica levels met the criteria for zeolite production, measured alumina concentrations were insufficient to achieve the required Si/Al molar ratio for direct synthesis. As a corrective measure, the study incorporated secondary aluminium sources, such as recycled metallic waste, to meet stoichiometric thresholds and enable effective framework formation. Variations in oxide content were traced to both calcination-induced phase transitions and regional differences in soil composition, which influence mineral uptake during cultivation. Statistical analysis confirmed that source location materially affects ash composition, with clay-dominant soils in the Nchalo region contributing to higher Al₂O₃ content. The results establish SBA as a viable source of silica and a partial source of alumina for engineered zeolite synthesis, contingent on precise process control and composition adjustment. This approach promotes the reuse of agro-industrial residues and supports the production of cost-effective water treatment materials using regionally available resources.

1 Introduction

Bagasse ash is the residue left after burning sugarcane bagasse, a by-product of the sugar industry [1]. Sugarcane Bagasse Ash (SBA) contains significant amounts of calcium and magnesium ions, which support plant growth. However, when these ions dissolve in water, they can increase soil salinity, which may negatively affect plant growth [2]. Fig. 1 shows sugarcane bagasse ash produced by calcination under controlled conditions.



Fig. 1. Sugar cane bagasse and sugar cane bagasse ash

Sugarcane bagasse ash (SBA) contains key elements, such as silica and alumina, which are essential for producing zeolites used in water softening [3]. Zeolites are porous crystalline materials known for their ability to remove impurities from water, making it safe for consumption and other uses [2].

The silica and alumina content in SBA vary widely due to factors such as soil type, sugarcane variety, climate, and harvest time [4], [5], [6], [7], [8], and [9]. For instance, soils rich in silicon lead to higher silicon uptake by sugarcane [10]. Additionally, fertilizers and pesticides influence the concentration of these elements, fertilisers containing aluminium or silicon compounds may be absorbed by the plants [11]. The quality of irrigation water also affects mineral uptake, while environmental factors such as rainfall, temperature, and humidity influence how plants absorb nutrients [12]. In regions with high rainfall, for example, mineral leaching reduces the mineral content available to plants [13]. Conversely, in arid and semi-arid regions, increased water availability has been shown to enhance silicon uptake by plants [14]. This trend was observed in Israel, where the mean annual rainfall (MAR) ranges from 80 to 900 mm [15].

The sugar extraction process can further impact the concentration of silica and alumina in bagasse indirectly through moisture extraction [16]. The harvesting process itself also plays a role in the mineral

* Corresponding author: rnkhoma@gmail.com

composition of SBA [6], [17]. The harvesting process affects the silica and alumina content in sugarcane bagasse and its ash. Mature plants, harvested later, tend to have higher mineral levels due to extended nutrient uptake; moreover, manual harvesting often excludes parts like leaves, while mechanical harvesting includes them, leading to differences in mineral composition [6]. These variations contribute to differences in the quality and quantity of silica and alumina in bagasse and its ash. Therefore, the main purpose of this study is to characterise SBA samples from three different sugar mills in Malawi, Nchalo, Dwangwa, and Salima calcinated at different temperatures, to identify which sample contains the highest percentage of alumina and silica. This guides the selection of the most suitable SBA source for synthesising potassium-based zeolite for water softening.

2 Literature Review

The use of sugarcane bagasse ash (SBA) as a precursor for zeolite synthesis has drawn attention due to its abundant silica content and compatibility with alkaline extraction processes. Bagasse ash, a by-product of sugar mills, can contain SiO₂ concentrations ranging from 55 to 90% depending on combustion conditions and biomass source [18]. SBA from Philippines was found to contain approximately 88 wt% SiO₂, which when subjected to NaOH extraction and aged with sodium aluminate, yielded clinoptilolite-type zeolite with Si/Al ratio of approximately 1.59 [19]. In another study, SBA-derived silica was added to kaolinite systems under controlled NaOH concentration (2.50 M) at 100 °C for 3 hours, resulting in the formation of Na-P zeolite with cation exchange capacity (CEC) of 351 meq/100 g [20]. These findings illustrate the efficacy of SBA as a silica donor, and the importance of controlling alkalinity and temperature during extraction to tailor zeolite structure and performance.

Calcination temperature plays a pivotal role in determining the silica reactivity within SBA. Several studies have investigated the morphology of silica extracted from sugarcane bagasse ash calcined at different temperatures, concluding that amorphous silica persists below 700 °C, whereas transformation to crystalline polymorphs, such as cristobalite, occurs above 800 °C [11], [21]. This phase transition diminishes solubility in alkaline media and adversely affects zeolite yield and framework quality. The infrared bands near 787 cm⁻¹ and 1046 cm⁻¹ reported by MDPI Nanomaterials for silica analysed by FTIR further validate the presence of reactive amorphous silica functional groups up to moderate calcination temperatures [21]. These observations suggest that maintaining calcination between 500 and 700 °C optimises the balance between organic elimination and structural preservation, ensuring efficient dissolution in alkaline synthesis.

Hydrothermal synthesis of zeolites from SBA generally follows a two-step alkali extraction, crystallisation path. For example, high-purity SiO₂, approximately 98 wt%, was obtained through acid pre-

treatment followed by alkali leaching, and was subsequently used to synthesise NaA zeolite with CO₂ adsorption capacities ranging from 4.1 to 4.3 mmol/g, comparable to those of commercial materials [22]. This highlights the potential of SBA as a valuable precursor for environmental applications, especially in gas adsorption. Similarly, zeolite NaA was successfully synthesised from SBA via alkaline fusion at 550 °C with a fusion ratio of 1:1, yielding phase-pure zeolite A as confirmed by XRD and FTIR analysis [23]. Collectively, these studies demonstrate the viability of converting SBA into high-performance zeolites, provided that key operational parameters, such as temperature, alkali concentration, and ageing time, are carefully optimised.

The Si/Al greatly influences zeolite type, structural framework, thermal stability, and ion-exchange properties [24]. Naturally derived SBA lacks sufficient Al₂O₃ to reach stoichiometric evaluation for many zeolite frameworks. However, the addition of sodium aluminate can compensate for the deficiency, enabling the formation of zeolite such as clinoptilolite with Si/Al ratio of approximately 1.6 [18]. The NaOH-to-ash ratio has also been shown to control Si/Al and the resulting CEC. In geopolymer and zeolite synthesis from bagasse bottom ash and China clay, optimal mechanical strength was achieved at a SiO₂/Al₂O₃ ratio of approximately 2.7 after calcination at 900 °C [23]. Although geopolymer and zeolite frameworks differ, this example highlights the critical influence of Si/Al ratio on final material properties.

Several studies have demonstrated that modifying SBA processing enhances alumina availability for zeolite synthesis. For example, the use of cetyltrimethylammonium bromide (CTAB) as a surfactant has been shown to increase porosity and support targeted nutrient loading in clinoptilolite-like nanozeolites [6], [19]. In addition, structure-directing agents such as CTAB have facilitated the formation of zeolites Na-X, Na-A, and Na-Y from various ash precursors [25]. These findings indicate that supplementing SBA with aluminium sources, adjusting surfactant conditions, and optimising hydrothermal synthesis parameters can tailor the crystalline structure, porosity, and adsorption capacity of the final product.

Evidence from the natural environment supports the role of soil geochemistry in influencing SBA composition. Peer-reviewed agronomic surveys on Malawi indicate that Lower Shire Valley soils, where Nchalo is located, are Vertisols and Luvisols enriched with kaolin-group clays and gibbsite, rich aluminium sources [26]. This geological context aligns with the elevated Al₂O₃ concentrations observed in Nchalo SBA. In contrast, Dwangwa's granitic and quartz-rich soils provide a natural surplus of silica, corroborated by the high silica levels in its SBA. Although detailed soil analyses are beyond the capacity of the cited studies, FAO soil maps and local geological field data support these compositional trends and justify regionally differentiated SBA sourcing.

Comparison to other agro-waste ashes such as rice husk, fly ash, and bagasse bottom ash indicates that SBA can perform similarly or better in silica yield and

amorphous phase content. For instance, rice husk ash is often valorised for its high silica approximately 90% and used in zeolite synthesis alongside sodium aluminate [27], while fly ash geopolymers have been studied for construction applications. The clear advantage of SBA lies in its availability and the built-in circularity in sugar-producing regions. Synthesis strategies that use waste aluminium metal, such as cans, create a closed-loop solution addressing raw material deficits and waste accumulation simultaneously.

3 Materials and Methods

3.1 Sampling area

Sugarcane bagasse samples were collected from Dwangwa, Nchalo, and Salima Sugar Mills in Malawi and processed at the Malawi University of Science and Technology (MUST) Ceramics Studio. A 50 kg sample of bagasse was collected from each source. Random grab sampling was implemented.

3.2 Sample preparation

The collected samples were taken to the ceramic studio for calcination. The sample preparation procedure consisted of the following steps:

3.2.1. Initial drying

Bagasse samples were initially dried in an oven at 200°C for 4 hours to remove moisture. This step was undertaken to prevent steam formation during subsequent high-temperature calcination, which could disrupt the process and affect the desired outcome. The drying process ensures the material is suitable for the intended application by eliminating potential issues caused by moisture. After drying, the samples were allowed to cool to room temperature and stored in clean, airtight containers.

3.2.2. Sample division

The dried samples from each sugar mill were divided into three equal portions. Each portion was calcined at a specific temperature to investigate the effect of thermal treatment on ash composition.

3.2.3. Controlled calcination

Each portion of dried bagasse was placed in a muffle furnace and calcined at 500°C, 600°C, and 800°C for 3 hours. These temperatures were chosen based on previous studies [7], [28]. The temperature was increased gradually at a rate of 10°C per minute until the target calcination temperature was reached. Once the set temperature was achieved, it was maintained for a 3-

hour duration, ensuring full calcination of organic matter.

3.2.4. Cooling

After the calcination phase, the resulting ash was left to cool naturally inside the furnace for 24 hours. This slow cooling prevents thermal shock and stabilise the ash for further processing.

3.2.5. Grinding and Sieving

The respective SBA was then ground using a mortar and pestle to obtain a fine powder. The powder was subsequently sieved through a 1.5 mm mesh to ensure uniform particle size for accurate chemical analysis. The sieved SBA samples were carefully labelled according to their origin (Dwangwa, Nchalo, and Salima) and calcination temperature. The samples were then stored in a clean, sealed plastic bags for chemical analysis, particularly to determine the percentage composition of alumina and silica. Figure 2 shows sugarcane bagasse ash samples that were prepared for characterisation.



Figure 2: SBA Samples that were prepared for characterisation

3.3. Chemical analysis

Chemical analysis using the X-ray fluorescence (Spectro Xepos P) was done at the Department of Geological Survey Laboratory in Zomba, Malawi, to determine the elemental composition of the SBA samples, with particular attention to silica and alumina content. Thirty-six samples were analysed, four samples from each sugar mill at each temperature condition (500°C, 600°C, and 800°C). This analysis aimed to investigate the impact of combustion temperature on the composition of sugarcane bagasse ash. Figure 3 shows an XRF (Spectro Xepos) that was used for characterisation.

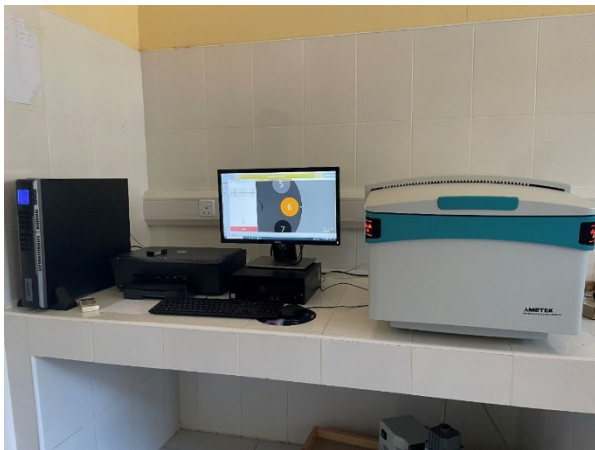


Figure 3: XRF (Spectro Xepos P) that was used for SBA characterisation

4. Results

The X-ray fluorescence (XRF) analysis results of sugarcane bagasse ash (SBA) are presented in Tables 1, 2, and 3. These tables summarise the mean elemental composition of four samples from each mill at three different combustion temperatures: 500°C, 600°C, and 800°C. Silica content was consistently high across all mills, with the Dwangwa Sugar Mill demonstrating the highest concentration at 76.22% at 600°C (Table 2), indicating its suitability as an ideal source for zeolite synthesis. For alumina, the highest content was found in samples from Nchalo Mill, reaching 15.94% at 800°C (Table 3).

Table 1. Elemental composition of SBA burnt at 500 0C

No.	Element	Nchalo	Dwangwa	Salima
1	Magnesium Oxide (MgO)	2.492 %	2.250 %	2.58 %
2	Aluminium Oxide (Al ₂ O ₃)	14.89 %	10.68 %	12.934 %
3	Silicon Dioxide (SiO ₂)	73.40 %	75.95 %	73.39 %
4	Phosphorus Pentoxide (P ₂ O ₅)	2.945 %	1.142 %	1.525 %
5	Sulphur Trioxide (SO ₃)	0.7342 %	0.4597 %	0.8102%
6	Potassium Oxide (K ₂ O)	2.148 %	2.810 %	1.354 %
7	Calcium Oxide (CaO)	1.330 %	1.275 %	0.6516%
8	Other Elements	2.7538%	5.433 %	9.54 %

Table 2: Elemental composition of SBA burnt at 600 0C

No.	Element	Nchalo	Dwangwa	Salima
1	Magnesium Oxide (MgO)	2.203 %	1.8282 %	0.7137 %
2	Aluminium Oxide (Al ₂ O ₃)	15.631 %	10.81 %	12.482 %
3	Silicon Dioxide (SiO ₂)	73.38 %	76.22 %	73.08 %
4	Phosphorus Pentoxide (P ₂ O ₅)	1.807 %	1.663 %	1.604%
5	Sulphur Trioxide (SO ₃)	0.7442%	0.3931 %	0.6350%
6	Potassium Oxide (K ₂ O)	2.126 %	2.3313 %	2.072 %
7	Calcium Oxide (CaO)	1.490 %	1.713 %	1.498 %
8	Other Elements	2.6188%	5.4345%	7.9153%

Table 3: Elemental composition of SBA burnt at 800 0C

No.	Element	Nchalo
1	Magnesium Oxide (MgO)	2.222%
2	Aluminium Oxide (Al ₂ O ₃)	15.970%
3	Silicon Dioxide (SiO ₂)	74.21%
4	Phosphorus Pentoxide (P ₂ O ₅)	2.103%
5	Sulphur Trioxide (SO ₃)	0.4963%
6	Potassium Oxide (K ₂ O)	1.681%
7	Calcium Oxide (CaO)	1.219%
8	Other Elements	2.1077 %

The results were plotted in Excel, as shown in Figures 4 and 5, which illustrate the mean distribution of aluminium oxide (Al₂O₃) and silicon dioxide (SiO₂) across the Dwangwa, Salima, and Nchalo regions. Nchalo exhibited the highest average Al₂O₃ content compared to Salima and Dwangwa, while Dwangwa exhibited the highest SiO₂ concentration among the three areas. The high Al₂O₃ content in Nchalo's SBA is particularly valuable for zeolite synthesis, suggesting it as the optimal choice for this application.

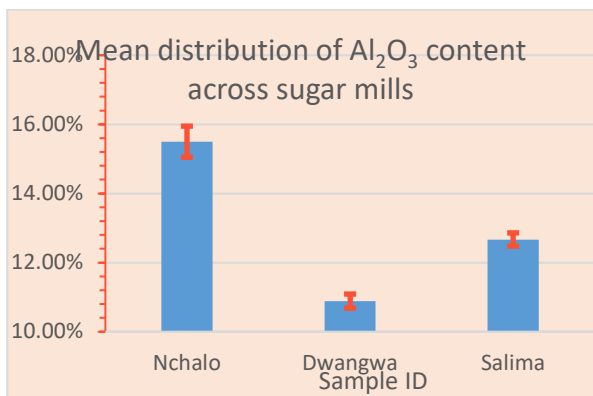


Fig. 4: Estimated marginal means of Al₂O₃

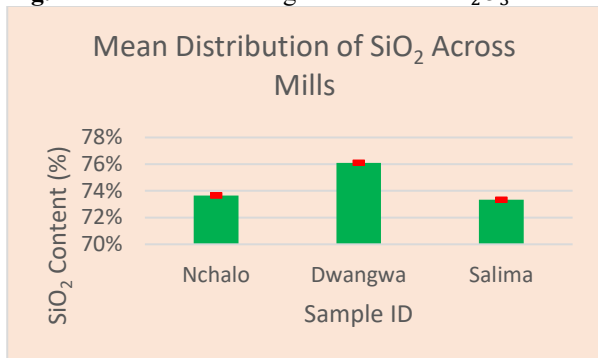


Figure 5: Estimated marginal means of SiO₂

Variations in Al₂O₃ composition across different temperatures appeared minimal but remained significant for optimizing the synthesis process.

One-way analysis of variance (ANOVA) was performed to assess whether the observed variations in SiO₂ and Al₂O₃ content among the three SBA sources were statistically significant. Table 4 presents the results of the statistical tests performed on samples from the three mills, evaluated at a 99% confidence level. For alumina, ANOVA yielded an F-statistic of 114.831 is much larger than the F critical value of 10.92477, indicating that the variation between the group means exceeds what would be expected by chance. The P-value is very small 1.7×10⁻⁵, which is less than the significance level (α=0.01). This represents significant differences between the group means of Al₂O₃ across the three SBA sources.

Table 4: Summary of statistical test for content Al₂O₃ across mills at 99 % Confidence level

ANOVA: Single Factor						
Al ₂ O ₃ at 99 % CI						
SUMMARY						
Groups	Count	Sum	Average	Variance		
Nchalo	3	0.46491	0.15497	3.05E-05		
Dwangwa	3	0.32654	0.108847	6.27E-06		
Salima	3	0.38	0.126667	5.62E-06		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.00325	2	0.001623	114.831	1.7E-05	10.92477
Within Groups	8.5E-05	6	1.41E-05			
Total	0.00333	8				

Table 5 summarises the statistical test results performed on SiO₂ composition across mills. Nchalo has significantly the highest content of SiO₂ at different calcination temperatures.

Table 5: Summary of statistical test for content of SiO₂ across mills at 99 % Confidence level

ANOVA: Single Factor						
SiO ₂ at 99 % CI						
SUMMARY						
Groups	Count	Sum	Average	Variance	std.dev	
Nchalo	3	2.2099	74%	2.24E-05	5.02806E-10	
Dwangwa	3	2.2832	76%	1.96E-06	3.85468E-12	
Salima	3	2.2001	73%	5.5E-06	3.02867E-11	
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.001375	2	0.000687	69.00045	7.23366E-05	10.92477
Within Groups	5.98E-05	6	9.96E-06			
Total	0.001435	8				

Analysis for silica content showed an F-statistic of 69.0045 is much larger than the F critical value of 10.92477, indicating that the variation between the group means is more than what would be expected by chance. The P-value is very small 7.23366×10⁻⁵, which is less than the α=0.01. This represents significant differences between the group means of SiO₂ in the three SBA sources

To further investigate the relationship between two key oxides, a correlation analysis was conducted. As illustrated in Figure 6, a weak positive correlation was observed between SiO₂ and Al₂O₃ content in SBA. While a weak correlation was observed, the high levels of SiO₂ in all SBA samples ensure the viability of the material for zeolite synthesis. However, the lower alumina content in all samples necessitates the supplementation of an external aluminium sources, (like aluminium cans or foils) to achieve the optimal silica-to-alumina ratio for zeolite synthesis.

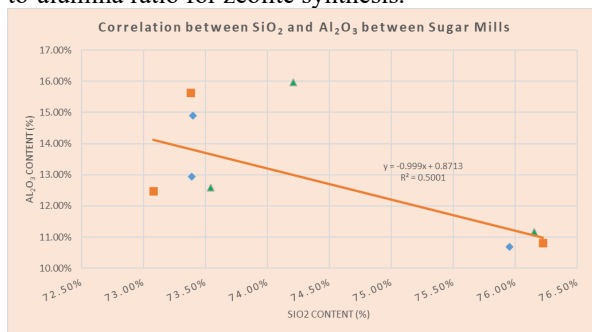


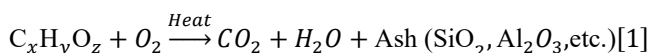
Fig 6: Correlation for SiO₂ & Al₂O₃(own figure)

The negative slope of the line of best fit indicates that higher SiO₂ content is associated with lower [“Al”] ₂ O₃ content in the samples from the sugar mills. However, the (R²) value of 0.5001 suggests moderate correlation, implying that the variation in SiO₂ content cannot adequately explain a significant portion of the variation in Al₂O₃ content.

5. Discussion

The compositional variation of silica (SiO₂) and alumina Al₂O₃ in sugarcane bagasse ash (SBA) obtained from the three study regions of Nchalo, Dwangwa, and Salima, can be traced to both the high-temperature thermal decomposition during calcination and the geochemical profiles of the cultivation zones. The chemical trends observed in the ash are governed by the interplay between thermal processes and region-specific soil chemistry, which control elemental uptake during sugarcane growth.

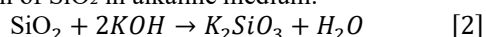
Thermal treatment of biomass initiates a sequence of physicochemical transitions, most notably the utilisation of organic constituents and the concentration of non-volatile oxides. As biomass undergoes combustion, organic carbon, hydrogen, and oxygen are oxidized, while minerals including silicon and aluminium persist in the ash. This reaction progression can be approximated by:



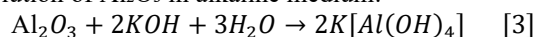
The data across calcination temperatures suggest that while SiO₂ content remains relatively stable between 73% and 76%, the reactivity of the silica phase is influenced by thermal exposure. Below 700°C, silica remains predominantly amorphous, a structural form essential for efficient dissolution in alkaline media used during zeolite synthesis. Above this temperature, partial transformation to crystalline polymorphs such as cristobalite and tridymite occurs, which reduces the surface area and lowers chemical reactivity in aqueous alkali conditions [11]. Conversely, Al₂O₃, which originates from both organic complexes and mineral inclusions in the biomass, responds to heat treatment with more dynamic behaviour. Dehydroxylation of gibbsite and boehmite into γ-Al₂O₃ and subsequently α-Al₂O₃ is known to occur progressively within the 300–900°C range [29]. The γ-phase, forming near 600°C, exhibits a high degree of surface activity and dissolves readily in alkaline conditions.

The following reactions outline the chemical transformations in ved in zeolite synthesis:

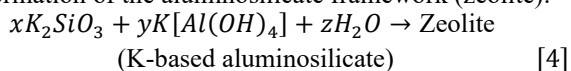
Dissolution of SiO₂ in alkaline medium:



Dissolution of Al₂O₃ in alkaline medium:

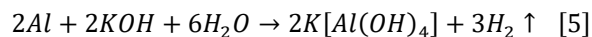


Formation of the aluminosilicate framework (zeolite):



The optimal synthesis of zeolite types such as A or X requires a Si/Al molar ratio between 1.0 and 1.5. Experimental data from this investigation reveal that SBA from Dwangwa calcinated at 600°C, while rich in SiO₂ (76.22%), presents an Al₂O₃ concentration of only

10.81%, resulting in a molar ratio approaching 7. This discrepancy necessitates the incorporation of auxiliary aluminium sources, such as recycled aluminium cans or foil, to adjust the reaction stoichiometry. In alkaline solution, metallic aluminium undergoes oxidative dissolution according to:



The integration of such additives corrects the Si/Al ratio and supports the generation of a structurally sound zeolite network with desired cation-exchange and sorption capacities.

Beyond thermal chemistry, the spatial distribution of Al₂O₃ and SiO₂ in the ash samples is influenced by the soil geochemistry in the cultivation areas. The sugarcane estates in Nchalo are located in the Lower Shire basin, an agro-ecological zone characterised by clay-rich Vertisols and Luvisols. These soils contain secondary minerals such as kaolinite, montmorillonite, and gibbsite, which serve as natural reservoirs of aluminium. The uptake of aluminium by sugarcane from these soils, particularly under acidic pH conditions that enhance metal solubility, can explain the elevated Al₂O₃ concentration in Nchalo SBA. The ash derived from this region, calcinated at 800°C, reached 15.97% Al₂O₃ exceeding values from other locations.

Dwangwa's soils, in contrast, derive primarily from granitic alluvium and are relatively siliceous. Quartz and feldspar weathering products dominate the mineral fraction, facilitating silicon absorption by sugarcane. The high SiO₂ concentration observed in Dwangwa ash aligns with this geological profile. Salima soils, known for their sandy texture and susceptibility to nutrient leaching due to coastal rainfall, exhibit lower retention of both aluminium and silicon. Consequently, SBA from Salima showed relatively diminished oxide concentrations, a trend consistent with reduced mineral retention and bioavailability.

Agronomic practices further modulate elemental content in sugarcane biomass. In Malawi, conventional fertiliser regimes employed by sugar producers emphasize nitrogen (ammonium nitrate, urea) and phosphorus inputs, with minimal or no inclusion of silicon or aluminium compounds. This management approach limits the exogenous contribution of these elements to the plant system, thereby making soil-derived minerals the dominant source. Irrigation water composition, although not analysed directly in this study, is an ancillary factor worth noting. Water from aquifers or rivers with variable ionic content can alter the speciation and mobility of trace minerals in the rhizosphere, influencing plant absorption kinetics over the growth cycle.

The statistical assessment using ANOVA supports the hypothesis that spatial origin has a measurable impact on the elemental profile of SBA. High F-values and low p-values confirm the presence of strong compositional disparities across samples. Furthermore, correlation analysis between SiO₂ and Al₂O₃ reveals an inverse trend, indicating that regions exhibiting high silica content often correspond to lower alumina levels. While this pattern suggests a trade-off potentially rooted in

plant physiological limitations or elemental competition during uptake, the R^2 value (~ 0.5) indicates that this relationship is moderate and subject to influence from other, unquantified variables such as genotype, microbial activity, and plant age at harvest.

The thermal evolution of SBA is further complicated by the structural transformation of the ash matrix. At lower calcination temperatures, ash retains higher porosity and amorphous characteristics. These features enhance solubility and surface reactivity, which are crucial during hydrothermal zeolite synthesis. As temperature increases, densification of ash particles and crystalline phase development reduce dissolution rates. Thus, the calcination window around 600°C appears optimal, ensuring sufficient removal of organics while preserving the amorphous nature of silica and the transitional phases of alumina necessary for high-yield synthesis.

The compositional data and processability characteristics collectively indicate that SBA from different regions may be suited for distinct roles in zeolite precursor formulation. For instance, Dwangwa ash, given its high SiO_2 content, could serve as a silica-rich base, supplemented by alumina derived either from Nchalo ash or secondary sources. Conversely, Nchalo SBA, particularly from 800°C calcination, offers an alumina-enriched profile useful for balancing formulations where silica content is already sufficient. This suggests the feasibility of regionally optimised material integration, enabling tailored synthesis routes based on available feedstocks.

Moreover, the integration of aluminium waste streams into the synthesis pathway aligns with broader sustainability goals. By converting both agricultural and metallic waste into high-performance adsorbents, the process achieves dual waste valorisation. From an economic standpoint, the reliance on locally sourced SBA and aluminium waste reduces dependency on imported raw materials for zeolite production, thus offering scalability in decentralised or resource-limited settings.

To enhance compositional predictability and support future material development, additional studies could incorporate soil mineralogical surveys, irrigation water analysis, and sugarcane varietal profiling. A more granular understanding of these parameters would allow the establishment of predictive models linking agronomic variables to ash reactivity, thereby optimising upstream cultivation for downstream materials engineering.

This investigation offers a technically grounded assessment of SBA's chemical suitability for zeolite synthesis. The ash from Malawian sugar mills, particularly when strategically selected and supplemented, presents a viable input for producing aluminosilicate materials. Process design must take into account the origin-dependent chemical composition, optimal calcination regime, and the necessity of controlled Si/Al ratio adjustment to ensure consistent zeolite quality. The approach bridges agricultural residue utilisation with advanced material synthesis, reinforcing the role of integrated systems thinking in circular resource engineering.

6. Conclusion

This study provides a systematic evaluation of sugarcane bagasse ash (SBA) obtained from three sugar-producing regions in Malawi of Nchalo, Dwangwa, and Salima, focusing on its composition following controlled calcination and its applicability in zeolite synthesis. Through quantitative analysis, it becomes evident that all SBA samples offer consistently high concentrations of silica across the temperature range investigated, especially between 500°C and 800°C , with Dwangwa ash emerging as the richest in SiO_2 content. This silica is primarily in the amorphous phase at moderate temperatures, making it chemically suitable for transformation into aluminosilicate structures via hydrothermal processes.

The capacity of SBA to supply aluminium oxide, however, presents variation more sensitive to both geographical origin and calcination regime. Among the samples tested, Nchalo ash treated at 800°C produced the highest concentration of Al_2O_3 , which is attributable to the clay-dominated soils of the Lower Shire Valley and their alumina-bearing minerals. Although this offers a more favourable basis for zeolite formation compared to the other regions, the aluminium levels measured across all samples remain insufficient for producing stoichiometrically balanced zeolites without supplementary input. This necessitates the introduction of aluminium-bearing additives, such as post-consumer metal waste, to achieve the required Si/Al molar ratios, particularly in formulations aimed at synthesising zeolites for water softening.

The role of soil geochemistry, combined with fertilisation practices and possible irrigation water quality differences, contributes to regional disparities in SBA composition. Soil texture, mineral content, and cation exchange capacity appear to directly influence plant uptake and, by extension, the elemental profile of the resulting ash. These findings support a location-specific sourcing strategy, whereby ash from different mills can be selectively blended or modified to meet defined synthesis requirements.

Thermal treatment remains a key variable in shaping both the chemical concentration and mineralogical phase of SBA. The study affirms that calcination temperatures around 600°C provide an optimal balance, removing volatile organics while preserving the amorphous structure and high reactivity of silica. Beyond this threshold, structural changes may reduce the effectiveness of ash as a reactive precursor unless process adjustments are made. The material from Dwangwa, due to its elevated silica content, presents itself as a suitable base when paired with additional alumina, while Nchalo ash provides a higher-alumina counterpart. Salima SBA, although lower in both target oxides, may still serve as a bulk filler or be considered in hybrid formulations where cost reduction is prioritised over purity.

In its entirety, the work demonstrates that SBA derived from Malawian sugar industries offers a reliable and accessible foundation for zeolite production, provided that careful attention is paid to ash characterisation, temperature control, and alumina supplementation. The

integration of agricultural by-products with post-consumer waste inputs aligns with resource-efficient manufacturing principles and opens pathways for decentralised, low-cost production of high-value water treatment materials. Future research incorporating mineralogical mapping, bioavailability studies, and pilot-scale synthesis will further advance the development of SBA-based zeolites and contribute to the broader field of sustainable materials engineering.

Author Contributions: J. Nyirenda: Conceptualisation, investigation, sample collection and analysis, data analysis, writing and editing. R. Nkhoma, T. Falayi, T. Ngonda and Mr Vincent Mwale: Conceptualisation, resources, review, writing and editing.

Funding: This study received financial support from the Skills for Vibrant Economy (SAVE Project).

Acknowledgements: The Authors are grateful to Dr Tiwonge Gawa (SAVE Project Coordinator) for the financial support. Special thanks to the management of Illovo Sugar Nchalo Mill, Illovo Sugar Dwangwa Mill, and Salima Sugar for allowing us to collect the sugarcane bagasse samples. We would also like to express our gratitude to the Department of Geological Survey, Zomba, who contributed to producing high-quality analytical data.

Conflicts of Interest: The authors declare that there is no conflict of interest, as the research was not conducted for commercial or financial gain. The funders had no role in the design of the study, the collection, analysis, or interpretation of data, the writing of the manuscript, or the decision to publish the results.

References

1. Q. Xu, T. Ji, S.-J. Gao, Z. Yang, and N. Wu, Characteristics and applications of sugar cane bagasse ash waste in cementitious materials, *Materials*, **12**(1),39,(2018), <https://doi.org/10.3390/ma12010039>.
2. L. Nthunya, S. Maifadi, B. Mamba, A. Verliefe, and S. Mhlanga, Spectroscopic determination of water salinity in brackish surface water in Nandoni Dam, Vhembe District, Limpopo Province, South Africa, *Water*, **10**(8),990,(2018), <https://doi.org/10.3390/w10080990>.
3. J. A. Oliveira, F. A. Cunha, and L. A. M. Ruotolo, Synthesis of zeolite from sugarcane bagasse fly ash and its application as a low-cost adsorbent to remove heavy metals, *Journal of Cleaner Production*, **229**,956–963,(2019), <https://doi.org/10.1016/j.jclepro.2019.05.069>.
4. V. K. Yadav et al., Extraction of value-added minerals from various agricultural, industrial and domestic wastes, *Materials*, **14**(21),6333,(2021), <https://doi.org/10.3390/ma14216333>.
5. M. A. Maldonado-García, P. Montes-García, and P. L. Valdez-Tamez, A review of the use of sugarcane bagasse ash with a high LOI content to produce sustainable cement composites, *Academic Journal of Civil Engineering*, **35**(2),597–605,(2017), <https://doi.org/10.26168/icbbm2017.90>.
6. N. Ungureanu, V. Vlăduț, and S.-Ș. Biriș, Sustainable valorisation of waste and by-products from sugarcane processing, *Sustainability*, **14**(17),11089,(2022), <https://doi.org/10.3390/su141711089>.
7. Anisah None, L. Letournel, A. M. Salsabila, Y. Luthfiana, and N. Anisa, Composition of chemical ingredients in sugarcane bagasse ash with variation of final calcination temperature, *Journal PenSil*, **12**(2),187–195,(2023), <https://doi.org/10.21009/jpensil.v12i2.34855>.
8. M. J. Khalil, M. Aslam, and S. Ahmad, Utilisation of sugarcane bagasse ash as cement replacement for the production of sustainable concrete – A review, *Construction and Building Materials*, **270**, 121371,(2021), <https://doi.org/10.1016/j.conbuildmat.2020.121371>.
9. G. P. Lyra, M. V. Borrachero, L. Soriano, J. Payá, and J. A. Rossignolo, Comparison of original and washed pure sugar cane bagasse ashes as supplementary cementing materials, *Construction and Building Materials*, **272**, 122001,(2021), <https://doi.org/10.1016/j.conbuildmat.2020.122001>.
10. A. M. Usman, A. Raji, N. H. Waziri, and M. A. Hassan, A study on silica and alumina potential of the savannah bagasse ash, *IOSR Journal of Mechanical and Civil Engineering*, **11**(3),48–52,(2014), <https://doi.org/10.9790/1684-11354852>.
11. L. A. September, N. Kheswa, N. S. Seroka, and L. Khotseng, Green synthesis of silica and silicon from agricultural residue sugarcane bagasse ash – a mini review, *RSC Advances*, **13**(2),1370–1380,(2023), <https://doi.org/10.1039/d2ra07490g>.
12. G. Falk, G. P. Shinhe, L. B. Teixeira, E. G. Moraes, and A. P. N. de Oliveira, Synthesis of silica nanoparticles from sugarcane bagasse ash and nano-silicon via magnesiothermic reactions, *Ceramics International*, **45**(17),21618–21624,(2019), <https://doi.org/10.1016/j.ceramint.2019.07.157>.
13. I. Rashmi, A. Shirale, K. S. Kartikha, K. C. Shinogi, B. P. Meena, and S. Kala, Leaching of plant nutrients from agricultural lands, *Essential Plant Nutrients*, –,465–489,(2017), https://doi.org/10.1007/978-3-319-58841-4_19.
14. C. Vander Linden, Z. Li, A. Iserentant, E. Van Ranst, F. de Tombeur, and B. Delvaux, Rainfall is the major driver of plant Si availability in perudic gibbsitic Andosols, *Geoderma*, **404**,115295,(2021), <https://doi.org/10.1016/j.geoderma.2021.115295>.
15. O. Katz, S. Lev-Yadun, and P. Bar (Kutiel), Plasticity and variability in the patterns of phytolith formation in Asteraceae species along a large rainfall gradient in Israel, *Flora*, **208**(7),438–444,(2013), <https://doi.org/10.1016/j.flora.2013.07.005>.
16. G. A. Habte, T. A. Bullo, and Y. Ahmed, Statistical optimization characterizations and eco-friendly synthesis of silica from sugarcane bagasse, *Scientific Reports*, **15**(1),(2025), <https://doi.org/10.1038/s41598-025-89366-6>.
17. P. Worathanakul, Characterisation for post-treatment effect of bagasse ash for silica extraction, (2018).
18. A. P. Capêto et al., Fire-resistant bio-based polyurethane foams designed with two by-products derived from sugarcane fermentation process, *Waste and Biomass Valorisation*, **15**(4),2045–2059,(2023), <https://doi.org/10.1007/s12649-023-02274-6>.
19. Q. Ybañez, P. Sanchez, M. I. Buladaco, and J. E. Rosales, Synthesis and characterisation of nanozeolite from sugarcane bagasse ash and its nutrient loading potential, *The Philippine Agricultural Scientist*, **105**(4),317–324,(2022), <https://doi.org/10.62550/ik111021>.
20. P. Thuadaj, Synthesis and characterisation of zeolite derived from Buriram sugarcane bagasse ash and Narathiwat kaolinite, *Creative Science*, **8**(3),320–326,(2016).
21. N. S. Seroka, R. Taziwa, and L. Khotseng, Green synthesis of crystalline silica from sugarcane bagasse ash: physico-chemical properties, *Nanomaterials*, **12**(13),2184,(2022), <https://doi.org/10.3390/nano12132184>.
22. C. Keawkumay et al., Extraction of silica from sugarcane bagasse ash and its utilisation in zeolite

- 4A synthesis for CO₂ adsorption, RSC Advances, **14(27)**,19472–19482,(2024),
<https://doi.org/10.1039/d4ra02207f>.
23. M. P. Moisés, C. T. P. da Silva, J. G. Meneguim, E. M. Giroto, and E. Radovanovic, Synthesis of zeolite NaA from sugarcane bagasse ash, Materials Letters, **108**,243–246,(2013),
<https://doi.org/10.1016/j.matlet.2013.06.086>.
24. A. Khaleque et al., Zeolite synthesis from low-cost materials and environmental applications: a review, Environmental Advances, **2**,100019,(2020),
<https://doi.org/10.1016/j.envadv.2020.100019>.
25. N.-A. Noor-ul-Amin, M. Faisal, K. Muhammad, and W. Amin, Geopolymerization with bagasse bottom ash and china clay, effect of calcination temperature and silica to alumina ratio, RSC Advances, **5(83)**,67814–67819,(2015),
<https://doi.org/10.1039/c5ra04525h>.
26. Government of Malawi, Ministry of Agriculture, Irrigation and Water Development, Shire Valley irrigation project soil report (Final),(2016).
27. S. Sriatun, T. Taslimah, and L. Suyati, Synthesis of zeolite from sugarcane bagasse ash using cetyltrimethylammonium bromide as structure directing agent, Indonesian Journal of Chemistry, **18(1)**,159,(2018),
<https://doi.org/10.22146/ijc.22197>.
28. T. A. Santos, R. A. Argolo, and D. V. Ribeiro, The effect of the calcination temperature on the physical, chemical and mineralogical characteristics of sugar cane bagasse ash (SCBA) for use as pozzolan, Journal of Solid Waste Technology and Management, **47(3)**,546–556,(2021),
<https://doi.org/10.5276/jswtm/2021.546>.
29. H. Abdelghani, A. Ahmed, and E. B. Abdellah, The impact of limescale on home appliances in a building, Proceedings of the International Conference of Computer Science and Renewable Energies, **1**, 423–428, (2018),
<https://doi.org/10.5220/0009773804230428>.