
PRODUCTION OF SILICA FROM AGRICULTURAL WASTES FOR APPLICATION IN FCC/RFCC CATALYST DEVELOPMENT: A MINI REVIEW

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ABSTRACT

Fluid catalytic cracking (FCC) and its residue variant (RFCC) are central to converting heavy petroleum fractions into gasoline and light olefins, and their catalysts depend on silica as both a binder and a precursor for the zeolite-Y active component and the active matrix. Conventional silica sources—tetraethyl and tetramethyl orthosilicate, sodium silicate, and fumed silica—are pure but costly, toxic, and energy-intensive, motivating a search for green alternatives. This mini-review examines the production of silica from agricultural wastes and its application in FCC/RFCC catalyst development. Rice husk, rice straw, sugarcane bagasse, and corn cob yield amorphous silica of high purity (commonly 90–98%) after acid leaching, controlled calcination, and alkaline dissolution to sodium silicate. In Nigeria alone, these residues are generated at an estimated 10.79 million tonnes per year, much of it burnt or left to create a nuisance. This can approximately generate 1.09 million tonnes per year of pure amorphous silica. The review considers how agricultural-waste silica can supply the sodium-free silica binder and the silica source for seeded zeolite-Y synthesis, with metakaolin as the alumina source, and how it must satisfy the low-sodium, high-purity, reactivity, and attrition-resistance requirements specific to cracking catalysts. It concludes that agricultural-waste silica is a viable, sustainable precursor for FCC/RFCC catalysts, and identifies impurity control, feedstock variability, catalyst-grade specification, and scale-up as the principal challenges to industrial adoption

Keywords: Agricultural-waste silica; Rice husk ash; FCC/RFCC catalyst; Zeolite-Y; Green materials

1. INTRODUCTION

Silica (SiO₂) is an inorganic material with impressive physiochemical properties for many industrial applications, such as construction materials and heterogeneous catalysis. Its chemical stability, surface functionality, and ability to form silicate and aluminosilicate frameworks make it particularly important in the preparation of catalytic materials. In petroleum refining, silica-containing materials are fundamental sources of silicon for zeolitic catalysts used in fluid catalytic cracking (FCC) and residue fluid catalytic cracking (RFCC).

According to a US patent, Preparation of cracking catalyst involves: (i) Preparing a slurry consisting clay, Zeolite, a sodium-free silica source, quasi-crystalline hydrated alumina, and microcrystalline alumina; (ii) Addition of monovalent acid to the slurry (iii) The slurry pH adjustment to a value above 3; (iv) Shaping the particle to form particles. This process resulted in a catalyst with sufficient attrition resistance and accessibility (Stamires *et al.*, 2016).

Agricultural waste such as rice husk, rice straw, sugarcane bagasse, and corn cob are rich in silica and can be utilised for the synthesis of zeolite catalysts. According to National Agricultural Extension and Research Liaison Services (NAERLS) and United States Department of Agriculture (USDA) report 2025, Nigeria alone produces 9.35 metric tonnes (MT) of rice, 11.44 MT of corn and forecasts 3.50 MT of sugarcane production. This amounts to 1.87 MT, 6.56 MT, 437,550 T, and 1.92 MT of 20% rice husk, 70% rice straw, 50% dry bagasse of 25% wet bagasse and 16.8% maize

cob, respectively and overall sums to 10.79 MT of agricultural waste generated (Table 1). These estimated wastes are often burnt either in a processing plant to generate process steam or in an open field, and the ash, rich in silica, is left underutilized, creating a public nuisance and releasing carbon monoxide, carbon dioxide and fine particulate matter. The silica present in the agricultural waste ash makes it a favourable precursor, and it can be used to complement high-alumina materials like Kaolin. Previous studies have reported the use of rice-husk-derived silica in the synthesis of zeolite Y, ZSM-5, mesoporous silica, and other functional materials. Wang et al. (2018) prepared NaA, NaX and NaZSM-5 zeolites from RHA via hydrothermal method. Zeolite Y in the sodium form (NaY) was synthesized using silica sourced from rice husk (Mohammed et al., 2012). Silica powder with approximately 96% purity was extracted from rice husk (RH) and used as a silica source for NaY (Yunusa et al., 2016)

An important benefit of utilizing silica derived from agricultural sources is the conversion of an abundant agricultural residue into a useful industrial raw material. Secondly, it provides a potentially low-cost and sustainable source of silica for catalyst development. For FCC/RFCC catalyst development, the quality of the silica precursor is critical because silica contributes to the zeolite framework, catalyst matrix, binder system, and overall pore architecture. Therefore high-purity silica with appropriate structural and surface characteristics is desirable.

This study reviews the use of silica prepared from major agricultural wastes (Corn cob, sugarcane bagasse, rice husk and straw), particularly in Nigeria, which are often combusted, leaving heaps of ash that disturb public serenity and environmental cleanliness. The outcomes of the review were assessed in relation to the potential utilisation of the material as a sustainable precursor for future FCC/RFCC catalyst development.

2. AGRICULTURAL WASTE FROM INDUSTRIAL PROCESSES IN NIGERIA

Land and water are the drivers of agriculture, Nigeria has over 79 million hectares of arable land, sufficient surface and groundwater and over 3 million hectares available for irrigation (FOA, 2026). Among the notably agricultural produce are: Maize, cassava, sorghum, cowpea, rice, yam, and millet. Maize, rice and Sugarcane are among the crops processed at an industrial scale, leading to the generation of waste such as rice husk, rice straw, corn cob and sugarcane bagasse. Nigeria's 2025 crop production from NAERLS and USDA report 2025 are shown in Table 1, alongside the estimated waste generated and the corresponding estimated residue generated in 2025. These account for the waste rarely fed to livestock and are often burnt, leaving the ash causing public disturbances.

Table 1: Estimated agricultural waste generated from rice, corn and sugarcane

Crops	2025 Production (t)	Residue	% Waste	Estimated Waste (t)
Corn	11,441,214.70	Cob	16.8	1,922,124.07
Rice	9,372,328.70	Husk	20	1,874,465.74
		Straw	70	6,560,630.09
Sugarcane	3,500,000.00	Bagasse	50 dry of 25 wet	437,550
Total				10794769.9

2.1 Silica from Agricultural Waste Ashes (AWA)

AWA particularly from silica-accumulating crops, represent an increasingly important sustainable source of amorphous SiO₂. Upon controlled combustion, rice husk yields ash containing 86–97% SiO₂ by weight, predominantly in the amorphous phase (Rodriguez-Otero et al., 2023). Other agricultural waste silica sources include sugarcane bagasse ash (50–70% SiO₂), and corn cob ash, although these are less rich in silica than rice husk ash and have received comparatively less research attention (Okoye et al., 2025; Islam et al., 2024).

The silica content varies with crop variety, soil conditions, and combustion parameters. Estimated Nigerian silica production was presented in Table 2, based on the estimated waste in Table 1. Acid leaching of rice husk prior to calcination has been found to remove alkali and alkaline earth metal impurities (K, Ca, Mg, Na), yielding ash with silica purity of 90–97%, comparable to or exceeding many commercial silica products (Phoungthong et al., 2026). This makes rice husk ash a compelling sustainable substitute for commercial silica in catalyst synthesis applications

Table 2: Nigeria Estimated Silica Content from Rice, Corn and Sugarcane in 2025

Agricultural Waste	Ash content%	AWA (t)	% Silica	Silica (t)
Corn Cub	2.8	53819.47	53.95	29035.60
Rice Husk	15.3-24.6	373955.92	92	344039.44
Rice Straw	13.5	885685.06	79.8	706776.31
Sugarcane Bagsse	2	8751	71.85	6287.59
Total		1322211.45		1086138.94

2.2 Process of Silica Extraction from Agricultural Waste

The extraction of silica from agricultural residues involves the conversion of biogenic silica embedded within plant tissues into a usable and relatively pure inorganic form. The physicochemical properties of the extracted silica, including its purity, surface area, porosity, and crystallinity, are strongly influenced by the processing method and operational conditions. Figure 1 shows the various routes for silica extraction from AWA.

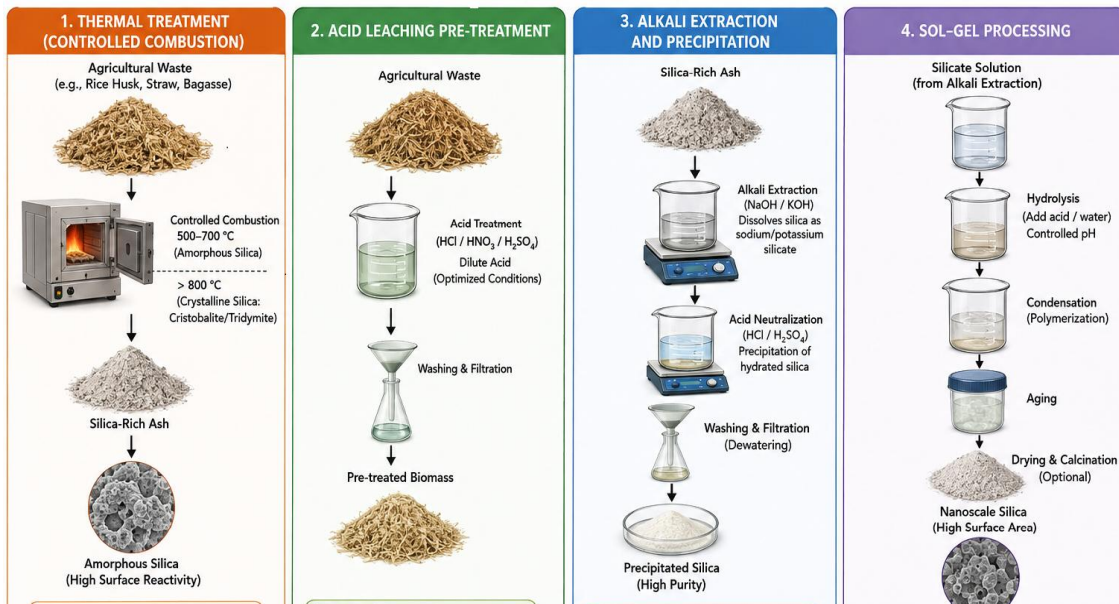


Figure 1: Paths for different grades of silica from agricultural waste

2.2.1 Thermal Treatment

Agricultural wastes such as rice husk, rice straw, corn cob, and sugarcane bagasse are subjected to pyrolysis to remove cellulose, hemicellulose, lignin, and other organic constituents. Controlled Combustion at approximately **500–700 °C** usually favours the formation of **amorphous silica**, which possesses higher surface reactivity and greater availability of silanol groups (Si-OH) that influence the surface chemistry of the silica. At temperatures above approximately **800 °C**, amorphous silica transforms into crystalline phases such as cristobalite and tridymite, resulting in reduced surface area and reactivity. Therefore, a controlled low-temperature combustion is preferred when highly reactive amorphous silica is required (Aharipour et al., 2022; Barani et al., 2024;

Carraro et al., 2021; Falk et al., 2019; Farirai et al., 2021a; Hamidu et al., 2025; Mohd et al., 2017; Pieła et al., 2020; Shahbaz et al., 2023).

2.2.2 Acid-Leaching Pretreatment

Acid leaching is generally employed as a pretreatment step before combustion or subsequent silica extraction. Dilute acids (30 % w/w conc.) such as HCl, HNO₃, and H₂SO₄ dissolve metallic impurities, particularly potassium, calcium, magnesium, and iron, that are naturally associated with agricultural residues. Removing these impurities improves silica purity and helps suppress reactions that could promote silica crystallisation. For rice husk, acid pretreatment can therefore produce ash with higher silica content and improved surface characteristics. However, acid concentration and treatment duration must be controlled which lead to partial silica dissolution (Pa et al., 2013).

2.2.3. Alkali Extraction and Precipitation

Alkali extraction is an effective route for producing high-purity silica from silica-rich agricultural ash. In this process, the ash is treated with an alkaline solution, typically NaOH or KOH, to dissolve silica and form soluble sodium or potassium silicate. Subsequent acid neutralisation converts the soluble silicate into precipitated hydrated silica (Zero Gel), which is recovered through filtration, washing, and drying. The process provides greater control over silica purity, particle size, and morphology. Parameters such as pH, temperature, and acid addition rate strongly influence the properties of the final silica. Nevertheless, the process involves several treatment stages and generates alkaline wastes streams that require appropriate management (Harun et al., 2024; Kamari & Ghorbani, 2021; Kouadri et al., 2023; Okoronkwo et al., 2013; Seghir et al., 2023).

2.2.4. Sol-Gel Processing

Sol-gel processing is a more advanced approach for producing high-surface-area, nanoscale silica. Silicate precursors obtained from agricultural waste undergo controlled hydrolysis and condensation reactions, followed by ageing and drying to form a three-dimensional silica network. The method provides improved control over particle size, pore structure, surface area, and morphology and can also facilitate the incorporation of functional groups or dopants. However, careful control of pH, temperature, hydrolysis, condensation, and ageing is required, and the process can be more expensive and operationally demanding than direct thermal or precipitation methods (Adebisi et al., 2020; Ni'mah et al., 2023; Okoronkwo et al., 2013).

3. REFINERY CRACKING CONVERSION UNITS (FCC&RFCC)

Petroleum is refined into various fractions through the distillation process. The lighter fractions such as gasoline, naphtha, light distillate, are the most valuable products and are in high demand. According to the Global Oil Products Utilization 2024 report, gasoline accounts for about 27% of demand, while diesel/gas oil has the highest share at 33%, followed by jet fuel. Petroleum distillation produces only a fraction of these products and therefore can not meet global demand. The heavier, less desirable fractions, such as bottom residue, vacuum gas oil and vacuum residue, are further processed and converted to lighter, valuable product fractions via thermal or catalytic cracking. Catalytic cracking converts heavy fractions; also known as fluid catalytic cracking or its counterpart, residue fluid catalytic cracking (FCC/RFCC), is a major conversion process to produce more of these valuable products, such as gasoline and light olefins. These units account for about 35 -50% of the refinery gasoline production (Adenenche et al., 2023). The feed to the FCC and the RFCC, is mainly Vacuum gas oil (VGO) and atmospheric residue/vacuum residue, respectively. FCC/RFCC processes have been operated across the globe in more 300 of the 646 refineries since 2014 (Zhu et al. 2013, Palos et al., 2020). It is estimated that 0.16 kg of FCC catalyst is used per barrel of feedstock (vacuum gas oil). For heavy feed materials, such as vacuum or atmospheric residue, 0.20 kg of RFCC catalyst is used per barrel (Vogt et al., 2015). Figure 2 shows a typical refinery conversion unit.

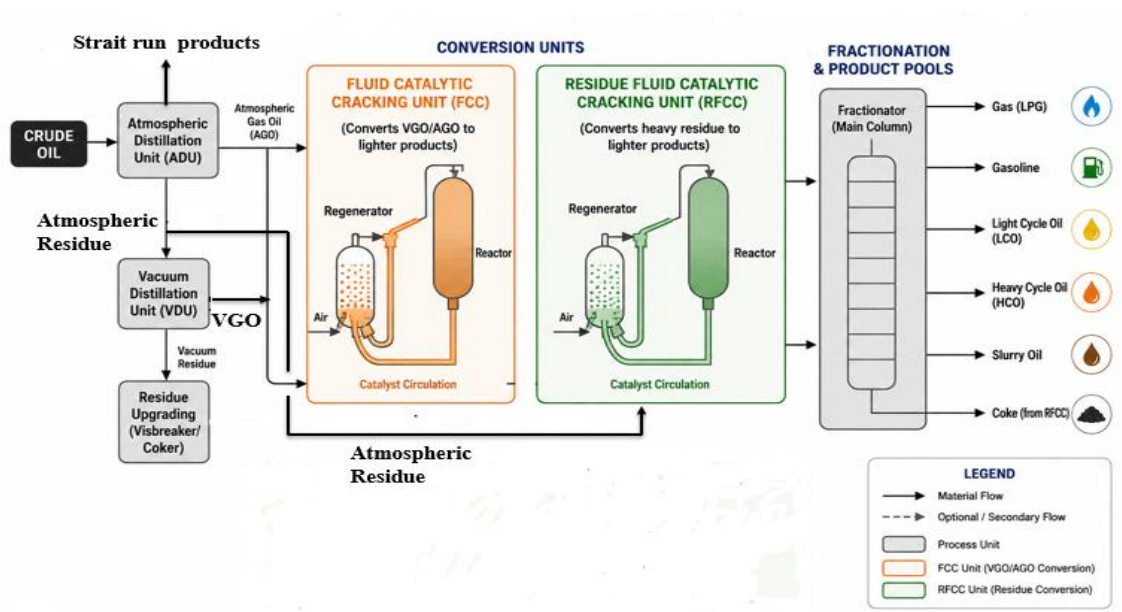


Figure 2: A side-by-side representation of FCC and RFCC in the refinery.

3.1 Application of Silica In FCC/RFCC Catalyst

FCC/RFCC Catalyst is composite material made up of a complex formulation of active and inactive components. Figure 2 shows the major structural composition of FCC/RFCC catalyst. The nature of the feed, the processing unit objectives, and constraints are the primary drivers of catalyst formulation and composition. The nature of the components and the processing steps determine the physicochemical properties of the catalyst (Ferreira et al., 2023).

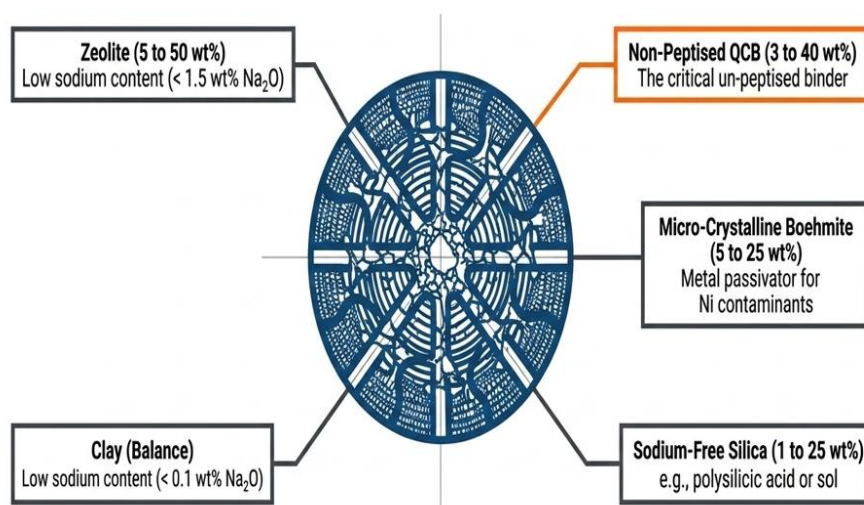


Figure 2: Typical structural composition of an FCC/RFCC particle.

The catalyst lowers the activation energy of the cracking reaction and also tailors the yield and selectivity towards the desired product. Other minor constituent and their roles were highlighted in Table 3. Silica appears have a significant role in both in the matrix development and the synthesis of active components. It form in the structural integrity of the catalyst and is also used as a binder for glueing all the components together. The active components are the zeolites such as the Zeolite-Y which is the major active component.

Table 3: Constituent of FCC/RFCC catalyst

Component	Chemical Constituents	Sources	Functions	Ref.
Active Component (Zeolite-Y)	Alumina, Silica Rare earth elements (RE), Lanthanum (La), Cerium (Ce), Neodymium (Nd), Praseodymium (Pr)	Natural clays, Agricultural waste, Inorganic chemicals	Responsible for catalytic activity and selectivity toward Naphtha	Borges ,2011 Stamires et al. 2016
ZSM-5, MCM-22, and MCM-36, metal-exchanged Zeolites, ITQs, SAPOs, ALPOs,	Alumina, Silica, transition metals.	Natural clays, Agricultural waste, Inorganic chemicals	Boost gasoline octane, increase light olefin yields or improve production of a particular product	Stamires et al.2016, Borges, 2011, Sadeghbeigi, 2000
Active matrix	Alumina (Al ₂ O ₃)	Bauxite, Natural clays	improve bottom cracking, i.e., cracking of large, high-boiling-point molecules	Sadeghbeigi, 2020
Inert matrix	Kaolin	Natural clay Kaolinite	Embedded as a filler in the catalyst to impart structural integrity to it and dilute its activity	Ferreira et al., 2023
Synthetic matrix (Binder)	Polymerized Silica, Alumina, Aluminosilicate, or Aluminium phosphate	Inorganic chemicals, Natural clays and Agricultural wastes	As glue to hold the zeolite, matrix, and clay together. The binder may or may not have catalytic activity. It provides physical integrity, (density, attrition resistance, particle size distribution), heat transfer medium.	Vogt et al., 2015

Component	Chemical Constituents	Sources	Functions	Ref.
Structural Directing Agent (SDA)	Quaternary ammonium, Cetyltrimethylammonium bromide (CTAB), Metal Cation (Na ⁺ , K ⁺ etc) plants extract, Sugars,	Organic, Inorganic, Biodegradable	Control and dictate the formation of crystal framework	Ferreira et al., 2023
Pore Regulating Agent	Surfactants (CTAB), carbon materials, Polymer beads, silica spheres, starch, cellulose, chitosan	Organic (MCM-41), inorganic, Biodegradables	Regulate the pore size distribution, connectivity, shape and pore architecture	Borges 2011
Metal Passivators	Antimony (Sb), Boron		Reduces effect of metals on catalyst	Sadeghbeigi, 2000
Bottom conversion additives			Selectively pre-crack large feed molecules	Sadeghbeigi, 2000
CO combustion promoter	Platinum (Pt), Palladium (Pd), Iridium (Ir), Rhodium (Rh), Osmium (Os) Ruthenium (Ru)		Combustion of CO to CO ₂ in the regenerator	Sadeghbeigi, 2000
SO ₂ reducing additives			Promote oxidation of SO ₂ to SO ₃ in the regenerator	Sadeghbeigi, 2000
NO _x reducing additives			Reduce NO _x to N ₂ in the regenerator	Sadeghbeigi, 2000

3.2 Zeolite Synthesis

According to Musyoka et al. (2014) zeolite synthesis begins with the preparation of super-saturated aluminosilicate solution, and proceeds with dissolution, nucleation, and crystallization processes at high temperatures. This is referred to as an in-situ reaction at elevated temperature and pressure in an aqueous solution. It is important to note that, when natural clays or ash are used as precursors in the synthesis process, the first step is to extract alumina and silica from the raw material, followed by washing and drying the resulting product to remove impurities and organic matter. The next step involves mixing the precursor with an alkali solution, such as NaOH or KOH, at particular temperature to create a reactive aluminosilicate gel in an alkaline fusion or activation process. The alkaline solution dissolves the aluminum and silicon ions in the clay, forming a gel. Subsequently, the gel is subjected to hydrothermal treatment in an autoclave at high temperature and pressure, which facilitates the crystallization of the gel into a zeolite product. The resulting zeolite crystals' size, shape, and purity can be influenced by the duration of the hydrothermal treatment and the composition of the gel. Finally, the synthesized zeolite undergoes washing, drying, and calcination processes to remove any residual organic matter and stabilize the structure of the zeolite (El Bojaddayni et al. 2023).

Several limitations and factors are considered when synthesizing zeolites from these precursors. The purification process, which can be time-consuming and costly, is a critical factor

that impacts the feasibility of the synthesis method for commercial applications. Optimal conditions for zeolite synthesis from various source material require precise control of several factors, including temperature, pressure, reaction time, and solid/liquid ratio. It is important note that the optimal conditions may vary depending on the specific source material and desired product properties. Product purity, is at the peak of all factors and can affect the quality of the final product. Rice-husk-derived silica has demonstrated good characteristics purity, with reported SiO_2 purities of approximately 96–98% and successful application in NaY/zeolite-Y synthesis (El Bojaddayni et al. 2023; Yunusa et al., 2016).

For the preparation FCC/RFCC Catalyst, low sodium ($<\text{wt}\%\text{Na}_2\text{O}$) or sodium free FAU type of zeolites are used including: Y-Zeolites such as HY, USY, dealuminated Y. RE-Y, and RE-USY; Zeolite beta, Zeolite Socony Mobil-5(ZSM-5), Mobil Composition of Matter No. 22(MCM-22), MCM-36, Metal-exchanged zeolites, Instituto de Tecnologia Quimica (ITQs), Silico-Alumino-Phosphates (SAPOs) all have corresponding high amount of silica/Alumina ratios of >1.5 with the exception of Aluminophosphate (ALPOs) mainly consist of Aluminium, Phosphorus and Oxygen (Stamires et al. 2016).

3.2.1 Zeolite Synthesis from Agricultural Waste Ash

Ash is the solid by-product generated from the combustion of coal, or agricultural residue. Although the chemical and mineralogical composition of ash varies by different factors, it is well-known that its main constituents are SiO_2 , Al_2O_3 , CaO , Fe_2O_3 , and un burnt material (Belviso, 2018; Cardoso et al., 2015; Yang et al., 2019). The prepared solution gradually transforms into zeolite after the dissolution of Al and Si, geopolymer formation, nucleation, and crystallization steps (Belviso, 2018). Several methods exist for zeolite synthesis from ash as were highlighted in Table 4. Detailed description of these methods can be found in the cited publications.

Table 4: Methods of zeolites Synthesis from Ash

Method	Description	Advantage	Disadvantage	Ref.
Conventional hydrothermal method (CH)	The precursor containing Si and Al is mixed with an alkaline solution, aged to form a reactive aluminosilicate gel, and subsequently crystallized hydrothermally in a sealed reactor/autoclave at elevated temperature and autogenous pressure. The resulting zeolite is filtered, washed and dried.	• Simple and well-established technique. • Relatively inexpensive equipment. • Good control of zeolite phase through adjustment of Si/Al ratio, alkalinity, temperature and crystallization time. • Suitable for relatively large-scale production	• Relatively long crystallization time. • Conventional external heating can produce temperature gradients. • High water and energy requirements may occur during prolonged synthesis. • Some raw materials show poor dissolution/reactivity, reducing zeolite yield.	Cardoso et al. (2015)
Alkaline-fusion-assisted hydrothermal method (AFH)	The precursor is first mixed/fused with a strong alkali, commonly NaOH, at elevated temperature. This pretreatment converts relatively inert Si/Al phases into more reactive soluble or amorphous species. The fused material is then subjected to conventional hydrothermal ageing and crystallisation. conventional hydrothermal aging and crystallization	• Enhances dissolution of poorly reactive Si and Al phases. • Improves conversion of difficult industrial wastes into zeolites. • Can increase zeolite yield and crystallinity. • Provides better control of zeolite formation from refractory feedstocks.	• Requires an additional high-temperature fusion stage. • Increases energy consumption and process complexity. • Strong alkaline reagents create corrosion and handling concerns. • Excessive alkali/fusion temperature can promote undesirable phases.	Yang et al. (2019)

Method	Description	Advantage	Disadvantage	Ref.
Sonication-assisted hydrothermal method (SAH)	Ultrasonic irradiation is incorporated into the synthesis process before or during hydrothermal treatment. Acoustic cavitation improves mixing, mass transfer and disruption/dissolution of precursor particles, thereby accelerating nucleation and crystallisation. Sivalingam and Sen used sonication-assisted hydrothermal treatment to rapidly produce nanozeolite X from coal fly ash.	• Significantly reduces synthesis/crystallization time. • Promotes nucleation and formation of smaller zeolite crystals. • Enhances mass transfer and precursor dissolution. • Can produce nanozeolites with high external surface area. • Potentially lower energy requirement than prolonged conventional hydrothermal treatment.	• Requires ultrasonic equipment and process optimisation. • Scale-up of ultrasonic energy distribution can be challenging. • Excessive sonication may affect particle morphology. • Energy efficiency depends strongly on reactor configuration and ultrasonic intensity.	Sivalingam & Sen (2019)
Microwave-heating-assisted method (MWH)	Microwave radiation is used as the heating source for the zeolite precursor rather than relying solely on conventional external heating. Microwaves provide rapid volumetric heating, accelerating nucleation and crystallisation. Fukasawa et al. demonstrated microwave-assisted synthesis of K-type zeolites using a reverse-micelle approach.	• Very rapid heating and crystallisation. • Can substantially shorten synthesis time. • More direct heating of the reaction medium. • Can promote formation of small crystals. • Potential reduction in overall energy consumption and processing time.	• Microwave reactors can be more expensive than conventional autoclaves. • Scale-up and uniform microwave penetration can be difficult. • Heating behaviour depends on the dielectric properties of the reaction mixture. • Poor control of microwave conditions can lead to non-uniform crystallization.	Fukasawa et al. (2018)

Method	Description	Advantage	Disadvantage	Ref.
Multi-step treatment method (MST)	The synthesis is divided into several sequential stages, typically involving pretreatment/extraction of the silica-rich precursor, preparation of the aluminosilicate precursor or gel, ageing/crystallisation, and subsequent washing and post-treatment. Such staged processing can improve precursor purity and control of zeolite formation. Note: the frequently cited Parthasarathy & Narayanan (2014) paper focuses specifically on the green synthesis of nano-silicalite-1 using biomass fly ash as a silica source and mother-liquid recycling, rather than on a general multi-step zeolite synthesis method.	• Allows individual stages to be optimised independently. • Can improve precursor purity and reactivity. • Provides better control over nucleation and crystal growth. • Mother-liquid recycling can reduce chemical/water consumption. • Particularly attractive for biomass-derived silica resource	• More processing steps increase operational complexity. • Longer overall preparation procedure may result. • Requires additional washing/separation operations. • A Greater number of processing stages can increase cost and material losses.	Narayanan (2014).

These five approaches can be viewed as progressively modifying conventional hydrothermal synthesis to overcome particular limitations. Conventional hydrothermal is the simplest and most established method, but it can be slow. Alkaline fusion-assisted improves the reactivity/dissolution of refractory precursors, but adds an energy-intensive fusion stage. Sonication-assisted primarily improves mixing, mass transfer and nucleation, making it attractive for rapid nanozeolite synthesis. Sivalingam and Sen reported nanozeolite X with crystal sizes around 22–27 nm. Microwave-assisted primarily improves heating rate and crystallisation kinetics; microwave treatment has been reported to shorten zeolite crystallisation compared with external heating. Multi-step treatment provides greater process control and precursor purification, making it particularly relevant to sustainable synthesis from Agricultural waste-derived silica.

Table 5 reviews some recent literature that demonstrates that ash is increasingly being used as a low-cost alternative source of Si and/or Al for zeolite synthesis, particularly because rice husk ash is silica-rich, whereas coal and fly ashes generally provide both silica and alumina (Zhen et al., 2024).

Table 5: Recent advances in the synthesis of zeolites from ash-derived silica

Precursor source	Product	Method	Conditions	Ref.
Rice husk ash (RHA)	NaX	Direct hydrothermal synthesis	SiO ₂ /Al ₂ O ₃ molar ratio = 4; Na ₂ O/Al ₂ O ₃ = 10; reaction time = 4 h; no ageing; zeolite NaX obtained with high crystallinity and surface area of about 388 m ² g ⁻¹	Nguyen et al. (2021)
Rice husk ash (RHA)	Potassium zeolites (chabazite-K and mordenite)	Hydrothermal synthesis	5 mol L ⁻¹ KOH; solution/RHA ratio = 2 mL g ⁻¹ ; optimum temperature = 125 °C; reaction time = 8 h; template-free synthesis	Flores et al. (2021)
Rice husk ash (RHA)	ZSM-5	Low-temperature, template-free hydrothermal synthesis of	Investigated temperature, crystallisation time and seed concentration; optimum product exhibited CO ₂ adsorption capacity of 2.39 mmol g ⁻¹ at 273 K and 15 bar	Jia et al., (2021)
Rice husk ash (RHA)	NaA and NaX	Template-free hydrothermal synthesis	RHA calcined at 600 °C for 6 h; acid purification with 1 M HCl at 80 °C for 1.5 h; sodium silicate extraction using 2.5 M NaOH at 90 °C for 5 h; zeolite crystallisation at approximately 90–100 °C	Madhu et al. (2022)
Coal fly ash (CFA)	FAU	Hydrothermal synthesis	68h ageing, 1:10 ash-to-water mass ratio	Joseph et al., (2020)
CFA	13X	Hydrothermal synthesis	1.2:1 NaOH/CFA weight ratio, 7 h crystallisation time and 90 °C crystallisation temperature	Verrecchia et al., (2020)
RHA	NaA, NaX and NaZSM-5	Seeding-assisted hydrothermal method	-	Wang et al., (2018)

Most recent studies have focused on ash from CFA and RHA for the zeolite synthesis. There were no reported studies from a reputable source on zeolites synthesized from other agricultural waste such as rice straw, corn cub and sugarcane bagasse, particularly Zeolite Y. Exploitation of other agricultural waste could complement the already established RHA precursor for the development of FCC/RFCC catalyst at an industrial level.

3.2.2 Important Properties of Agricultural-Waste-Derived Silica for Catalyst Development

Agricultural-waste-derived silica intended for FCC/RFCC catalyst preparation should possess a combination of high chemical purity, amorphous structure, high reactivity, suitable textural properties, low contaminant levels, and adequate thermal stability. The functionalities of these

properties are shown in Table 6. These are particularly important when silica is used as a precursor for zeolite-Y synthesis, a principal active component of many FCC catalysts.

Table 6: Properties of Silica for catalyst application

Property	Level	Significance
High SiO ₂ purity	Preferably ≥ 90 wt.% after purification	Minimises unwanted impurities and provides a consistent silica source for zeolite synthesis.
Structure	Amorphous SiO ₂	Provides greater chemical reactivity than highly crystalline silica during zeolite synthesis.
Metallic impurities	Low Fe, Ca, Mg, K, Na and other mineral oxides	Minimises interference with zeolite crystallisation and unwanted catalytic reactions.
Reactivity	High	Facilitates incorporation of silica into the aluminosilicate framework.
Surface area	High	Provides greater accessible surface for interaction with synthesis components and catalyst matrix.
Pore size	Micro & meso-porosity	Facilitates the diffusion of reactants and products, particularly important for residual molecules.
Particle size	Fine, relatively uniform particles	Improves dispersion and mixing during catalyst preparation.
Surface hydroxylation	$\equiv\text{Si}-\text{OH}$ groups	Provides chemically active surface functionalities.

FCC/RFCC catalyst are made from silica that possesses high SiO₂ purity, a predominantly amorphous structure, low concentrations of metallic impurities, high chemical reactivity, suitable surface area and pore characteristics, controlled particle morphology, and adequate thermal stability. High-purity amorphous silica is particularly desirable as a precursor for zeolite-Y synthesis because its reactive structure facilitates interaction with aluminium-containing species during hydrothermal crystallisation (Hamdan et al., 1997; Yunusa et al., 2016). Rice-husk-derived silica has demonstrated these characteristics, with reported SiO₂ purities of approximately 96–98% and successful application in NaY/zeolite-Y synthesis (Wittayakun et al., 2008; Yunusa et al., 2016). Furthermore, controlled combustion and chemical pretreatment can minimise crystalline silica phases and inorganic impurities, thereby improving the suitability of the resulting silica as a zeolite precursor (Hamdan et al., 1997; Ngoc et al., 2018). For RFCC applications, these precursors' properties should ultimately translate into zeolite-Y with high crystallinity, appropriate Si/Al ratio, accessible porosity, suitable acidity, and sufficient thermal and hydrothermal stability

4. CONCLUSION

This review demonstrates that agricultural-waste-derived silica is a promising sustainable precursor for developing of FCC/RFCC catalysts, particularly zeolite-Y-based systems. It was also highlighted that rice husk, rice straw, sugarcane bagasse, and corn cob yield amorphous silica of high purity (commonly 90–98%) after acid leaching, controlled calcination, and alkaline dissolution to sodium silicate and in Nigeria alone, these residues are generated at an estimated 10.79 million tonnes per year, much of it burnt or left to create a nuisance where it can approximately generate 1.09 million tonnes per year of pure amorphous silica. The review considers how agricultural-waste silica can supply the sodium-free silica binder and the silica source for seeded zeolite-Y synthesis, with metakaolin as the alumina source, and how it must satisfy the low-sodium, high-purity, reactivity, and attrition-resistance requirements specific to cracking catalysts. Although, agricultural-waste silica is a viable,

sustainable precursor for FCC/RFCC catalysts, the impurity control, feedstock variability, catalyst-grade specification, and scale-up are the principal challenges to industrial adoption

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