



## ENERGY-EFFICIENT QUICKLIME PRODUCTION FROM EGGSHELL AND SNAIL SHELL WASTE IN NIGERIA: AN OPTIMIZATION STUDY

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### ABSTRACT

*Conventional quicklime production from quarried limestone is an energy-intensive process with a significant carbon footprint. This study investigates an energy-efficient, sustainable alternative by valorizing a composite of waste eggshells and snail shells sourced from Bauchi State, Nigeria. The primary objective was to determine the optimal calcination parameters—temperature, time, and particle size—to maximise quicklime yield while minimising energy consumption. Using a One-Variable-at-a-Time (OVAT) experimental approach, the feedstock was first characterized and then subjected to a series of controlled thermal decomposition tests. Characterization revealed a high calcium oxide content of 53.1%, confirming the material's suitability. The optimization study identified the ideal process conditions to be a calcination temperature of 900 °C, a duration of 60 minutes, and a particle size of 450 µm. Operating at these parameters ensures complete feedstock conversion without the wasteful energy expenditure of over-processing. These findings provide a practical blueprint for converting a common agricultural waste stream into a valuable industrial commodity, offering a tangible pathway to enhance industrial sustainability and support the circular economy in Nigeria.*

### 1. INTRODUCTION

The production of quicklime (calcium oxide) is a foundational process for key industries, including cement, steel, and chemical manufacturing, which are critical for economic growth in developing nations like Nigeria (Akande, 2015). Conventionally, quicklime is produced through the thermal calcination of quarried limestone, an energy-intensive process that accounts for a significant portion of the global industrial sector's energy consumption and carbon dioxide emissions (Oates, 2008).

The reliance on virgin mineral extraction also carries a substantial environmental footprint, including habitat destruction and landscape degradation. As nations strive to meet sustainable development goals, there is a pressing need for alternative, low-energy, and circular pathways for producing essential industrial materials.

Nigeria, as one of Africa's largest economies, faces the dual challenge of meeting its industrial raw material demands while managing substantial streams of agricultural waste. The country's large poultry industry, for instance, generates vast quantities of eggshell waste, which, along with snail shell waste from local consumption, represents a significant disposal problem but also a valuable, untapped resource (Adesina et al., 2021). These biogenic materials are predominantly composed of calcium carbonate ( $\text{CaCO}_3$ ), the same chemical precursor found in limestone. Valorizing this waste as a feedstock for quicklime production offers a compelling circular economy solution: it can divert waste from landfills, reduce the environmental burden of limestone quarrying, and create a local, sustainable supply chain for a vital industrial commodity.

While the concept of using eggshell waste for calcium oxide production has been explored, a critical knowledge gap remains in establishing the most energy-efficient processing conditions, particularly within the specific context of locally sourced materials in a developing country. Without optimised parameters, the calcination process can consume excessive energy, rendering the sustainable feedstock economically unviable. This study, therefore, addresses the question: What are the optimal calcination temperature, time, and particle size settings required to maximise the yield of high-quality quicklime from Nigerian eggshell and snail shell waste with the minimum energy input?

This research determines these optimal processing parameters using a One-Variable-at-a-Time (OVAT) approach<sup>66</sup>. By identifying the most energy-efficient conditions for this waste-to-value process, this study contributes practical, evidence-based knowledge to support the development of sustainable, low-carbon industrial practices in Nigeria and other emerging economies.

## **2. LITERATURE REVIEW**

### **2.1 The Energy and Environmental Case for Limestone Alternatives**

The global production of quicklime and cement, which relies on the calcination of quarried limestone, is a major source of anthropogenic  $\text{CO}_2$  emissions and a significant consumer of thermal energy (Benhelal et al., 2021). The process releases  $\text{CO}_2$  from both the combustion of fuel and the chemical decomposition of calcium carbonate ( $\text{CaCO}_3$ ). This substantial environmental footprint has driven a global search for sustainable, low-carbon alternatives to virgin limestone (UN Environment Programme, 2022). One of the most promising strategies is the valorization of calcium-rich waste streams, which aligns with the principles of a circular economy by transforming a disposal liability into a valuable industrial feedstock.

### **2.2 Biogenic Wastes as Sustainable Sources of Calcium Carbonate**

A growing body of research has identified various biogenic wastes—notably eggshells, snail shells, and seashells—as excellent alternative sources of  $\text{CaCO}_3$ . Chemically, avian eggshells contain approximately 94-97% calcium carbonate in the calcite form, making them a high-purity natural precursor for quicklime (Pliya & Cree, 2015). Similarly, snail shells have been characterized as having a  $\text{CaCO}_3$  content often exceeding 95% (Eletta et al., 2020). Studies conducted in Nigeria have confirmed the high calcium content of local snail and eggshell waste, underscoring their potential as a locally abundant, sustainable resource for industrial applications (Olutoge et al., 2019). Utilizing this waste not only avoids the environmental damage of quarrying but also addresses waste management challenges in the agricultural and food sectors.

### 2.3 Optimizing Calcination for Energy Efficiency

The viability of using biogenic waste for quicklime production depends critically on the energy efficiency of the calcination process. The goal is to achieve complete decomposition of  $\text{CaCO}_3$  into  $\text{CaO}$  and  $\text{CO}_2$  at the lowest possible temperature and in the shortest time, thereby minimizing fuel consumption. Recent research has focused on optimizing these parameters for various biogenic feedstocks. For instance, Okoye et al. (2021) used Response Surface Methodology (RSM) to optimize biodiesel production using an eggshell-derived catalyst, finding an optimal calcination temperature of 950 °C for 2.5 hours. Similarly, Mosaddegh (2017) investigated seashell calcination, demonstrating that both temperature and duration significantly impact the resulting  $\text{CaO}$ 's physical properties and reactivity.

These studies consistently show that while the theoretical decomposition temperature of pure  $\text{CaCO}_3$  is around 900 °C, the optimal practical conditions vary depending on the feedstock's unique microstructure, particle size, and presence of impurities (Ali et al., 2022). While advanced methods like RSM are effective, simpler and more accessible methods like One-Variable-at-a-Time (OVAT) can provide valuable baseline data for process design, especially in contexts where advanced statistical software may not be readily available. The critical gap, therefore, lies in establishing these locally-optimised, energy-efficient parameters for specific regional feedstocks, such as the eggshell and snail shell composites found in Nigeria.

### 2.4 Synthesis of Key Studies and Research Gap

Table summarizes recent relevant research, highlighting the gap this study aims to fill. Table 1 highlights calcination studies using biogenic calcium carbonate feedstocks, showing temperature and time as critical determinants of  $\text{CaO}$  yield. While prior work emphasized catalysts or general reviews, this study addresses Nigerian-specific optimization for quicklime production efficiency.

**Table 1.** Summary of Selected Studies on Calcination of Biogenic Calcium Carbonate Feedstocks and Research Gaps Addressed

Study	Feedstock	Methodology	Key Findings	Limitation / Gap Addressed by This Study
Okoye et al. (2021)	Chicken Eggshells	RSM Optimization	Optimal calcination at 950 °C for 2.5 h for catalyst use.	Focus on catalyst production; uses complex RSM. This study focuses on quicklime yield via simpler OVAT.
Eletta et al. (2020)	Nigerian Snail Shells	Characterization	Confirmed >97% $\text{CaCO}_3$ content; calcined at 900 °C for 2 h.	Did not optimize for time, temperature, or particle size for maximum yield.
Mosaddegh (2017)	Seashells	Parametric Study	Temperature >800 °C and time >2 h significantly affect $\text{CaO}$ properties.	Investigated a different feedstock (seashells). Optimal conditions are feedstock-specific.
Ali et al. (2022)	Review (Various)	Literature Review	Calcination temperature is a key determinant of $\text{CaO}$ catalyst activity.	A general review; lacks specific experimental optimization for Nigerian feedstocks.

The existing literature confirms the feasibility of using biogenic waste for quicklime production, but also reveals that optimal, energy-efficient conditions are highly dependent on the specific material. No study has systematically optimized the calcination parameters

(temperature, time, and particle size) for a composite of eggshell and snail shell waste sourced specifically from Nigeria. This research addresses this practical gap, providing essential data for developing a localised, sustainable, and energy-efficient industrial process.

### **3. METHODOLOGY**

#### **3.1 Materials**

The primary feedstock consisted of a composite of waste eggshells and snail shells collected from a deposit in Bauchi State, Nigeria. The exact ratio of eggshells to snail shells in the composite was not specified. Deionized water was used for washing the samples.

#### **3.2 Sample Preparation**

The collected shells were first washed thoroughly with deionized water to remove surface impurities and then dried at ambient temperature. The dried material was crushed and ground using a jaw crusher. The resulting powder was then mechanically sieved using Tyler series sieves to obtain distinct particle size fractions of 250  $\mu\text{m}$ , 300  $\mu\text{m}$ , 450  $\mu\text{m}$ , 500  $\mu\text{m}$ , and 600  $\mu\text{m}$  for the experiments.

#### **3.3 Feedstock Characterization**

The physicochemical properties of the prepared feedstock powder were analysed as follows:

- *Elemental Composition:* The chemical composition, including the concentration of calcium oxide (CaO) and other metallic oxides, was determined using X-Ray Fluorescence (XRF) spectroscopy. A 0.5 g subsample of the oven-dried feedstock was used for the analysis.
- *Surface Morphology:* The surface microstructure of the powder was examined using a HITACHI S-3400N Scanning Electron Microscope (SEM). Prior to analysis, samples were mounted on SEM stubs, sputter-coated with gold for five minutes to ensure conductivity, and held at 40 °C in an oven.
- *Surface Area and Porosity:* The specific surface area, total pore volume, and pore size distribution were determined by nitrogen adsorption-desorption isotherm analysis at 77 K using a Micromeritics ASAP 2010 analyser. The Brunauer-Emmett-Teller (BET) method was used to calculate the surface area, and the Barrett-Joyner-Halenda (BJH) method was applied to the desorption data to determine the pore size distribution.

#### **3.4 Optimization of Calcination Process**

The calcination was performed in a Carbolite electric muffle furnace (Model AAF 11/18). The effects of three key process variables—calcination temperature, calcination time, and particle size, on the quicklime yield were investigated using a One-Variable-at-a-Time (OVAT) approach. In this method, one parameter was varied while the other two were held constant across three sequential experiments.

1. *Effect of Particle Size:* A 30 g sample for each of the five particle sizes (250, 300, 450, 500, and 600  $\mu\text{m}$ ) was calcined at a fixed temperature of 900 °C for a fixed duration of 45 minutes to identify the optimal particle size.
2. *Effect of Temperature:* Using the optimal particle size (450  $\mu\text{m}$ ) identified in the first experiment, 30 g samples were calcined for a fixed duration of 45 minutes at five different temperatures: 600 °C, 700 °C, 800 °C, 900 °C, and 1000 °C.
3. *Effect of Time:* Using the optimal particle size (450  $\mu\text{m}$ ) and optimal temperature (900 °C), 30 g samples were calcined at varying time intervals: 5, 7, 15, 30, 45, 60, and 75 minutes.

After each calcination run, the hot crucible was immediately transferred to a desiccator, allowed to cool for 25 minutes, and then weighed using a digital balance to determine the final mass.

### 3.5 Calculation of Quicklime Yield

The degree of calcination, or quicklime yield ( $\alpha$ ), was determined from the mass loss during the experiment. First, the Loss on Ignition (LOI) was calculated as the ratio of the mass lost to the initial sample mass, as shown in Equation 1:

$$\text{LOI} = \frac{X_1 - X_2}{X_3} \quad 1$$

Where

$X_1$  is the mass of empty crucible plus limestone sample before calcination measured in (g)

$X_2$  is the mass of crucible plus limestone sample after calcination measured in (g)

$X_3$  is the mass of limestone sample charged into the calciner measured in (g)

where  $X_1$  is the mass of the crucible plus sample before calcination,  $X_2$  is the mass of the crucible plus sample after calcination, and  $X_3$  is the initial mass of the sample.

The degree of calcinations, alpha,

$$\text{Yield } (\alpha) = \frac{\text{LOI}}{0.4392} \quad 2$$

The quicklime yield ( $\alpha$ ) was then calculated using Equation 2. This equation normalises the experimental mass loss (LOI) against the theoretical maximum mass loss from the complete decomposition of pure  $\text{CaCO}_3$ .



The denominator, 0.4392, represents the stoichiometric mass fraction of  $\text{CO}_2$  in  $\text{CaCO}_3$  (2), which is the maximum possible LOI. A yield of 1.0 (or 100%) thus corresponds to the complete conversion of  $\text{CaCO}_3$  to  $\text{CaO}$ .

## 4. RESULTS AND DISCUSSION

This section presents the findings from the feedstock characterization and the process optimization experiments, interpreting the results in the context of developing an energy-efficient and sustainable pathway for quicklime production.

### 4.1 Feedstock Characterization: A Viable Alternative to Limestone

The suitability of the eggshell-snail shell composite as a feedstock was first evaluated through physicochemical characterization. X-Ray Fluorescence (XRF) analysis, shown in Table 2, revealed a calcium oxide ( $\text{CaO}$ ) content of 53.1% by weight. This high calcium concentration is consistent with findings for other biogenic feedstocks (Pliya & Cree, 2015) and confirms that the material is a high-purity source of calcium carbonate, making it a viable and direct substitute for geological limestone. The low levels of impurities such as magnesium oxide ( $\text{MgO}$ , 1.97%) and silica ( $\text{Si}$ , 0.79%) are advantageous, as these compounds can interfere with the calcination process and reduce the final quicklime quality.

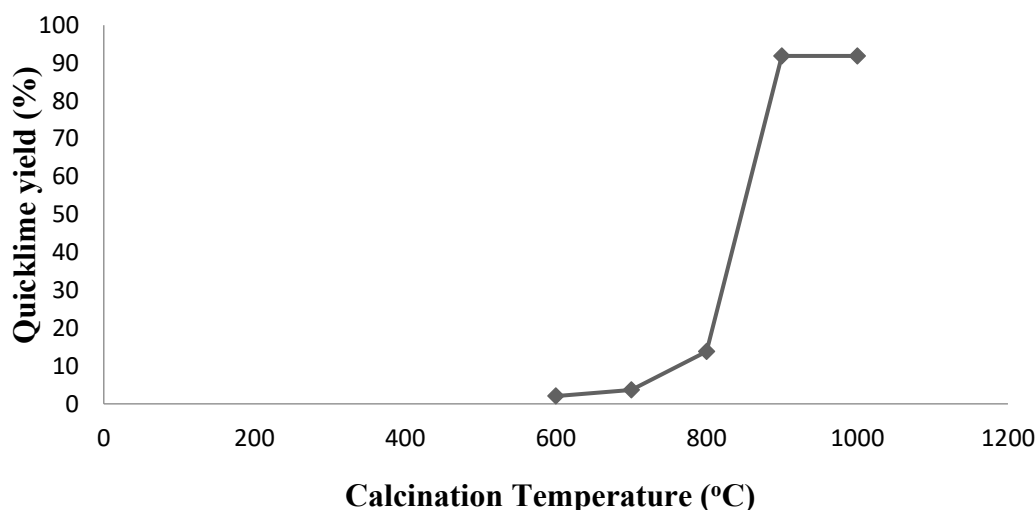
**Table 2.** Elemental Composition of the Eggshell–Snail Shell Feedstock

Chemical Compound	CaO	MgO	Si	Fe	Al	Other Oxides	LOI
Composition (%)	53.1	1.97	0.79	0.13	0.11	0.10	43.81

The physical properties, determined by BET analysis, showed a specific surface area of 1.65 m<sup>2</sup>/g and a total pore volume of 0.0065 m<sup>3</sup>/g<sup>4</sup>. This relatively high surface area is beneficial for the calcination process, as it facilitates more efficient heat transfer from the furnace to the particles and allows for easier diffusion of the released CO<sub>2</sub> gas (Ali et al., 2022). This inherent physical property suggests that the feedstock is well-suited for a lower-energy conversion process compared to more compact materials like dense limestone.

#### 4.2 Effect of Calcination Temperature on Energy Efficiency

The effect of calcination temperature on quicklime yield was investigated to identify the minimum energy input required for complete conversion. As shown in Figure 1, the quicklime yield increased sharply as the temperature rose from 600 °C (2.0% yield) to 900 °C (91.9% yield) for a fixed 45-minute duration and 450 µm particle size<sup>5</sup>. Critically, increasing the temperature further to 1000 °C resulted in no additional increase in yield.



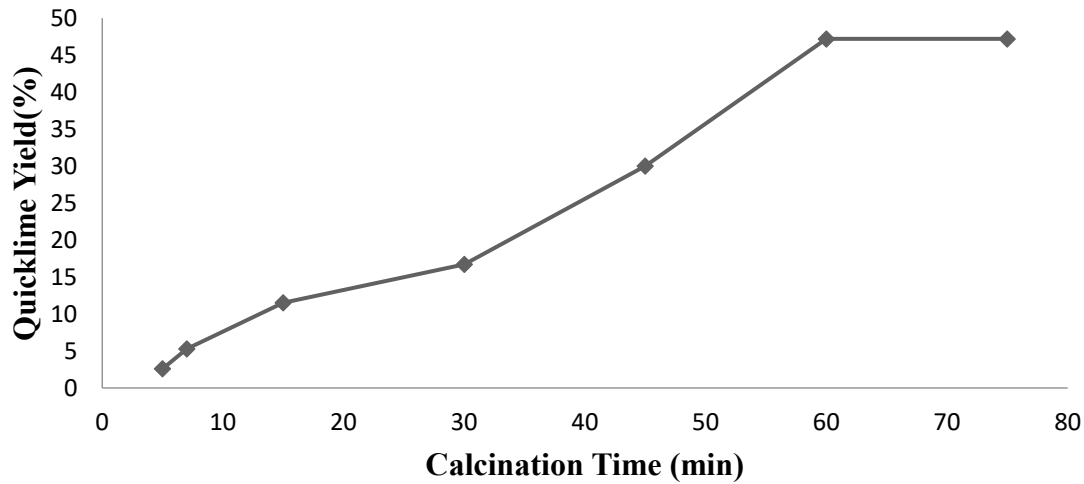
**Figure 1.** Effect of Calcination Temperature on Quicklime Yield

This plateau at 900 °C represents the energy-optimal temperature for this specific feedstock. Operating at higher temperatures would needlessly consume more energy and increase operational costs without any process benefit. Furthermore, excessive heating can lead to "over-burning" or sintering, where the pores on the quicklime surface close up, reducing the material's reactivity and quality (Mosaddegh, 2017). This finding aligns with the theoretical decomposition temperature of CaCO<sub>3</sub> and is consistent with optimization studies on other biogenic wastes, which typically report optimal temperatures in the 900–950 °C range (Okoye et al., 2021). Thus, 900 °C was identified as the optimum temperature and used in subsequent experiments.

#### 4.3 Effect of Calcination Time on Process Throughput

Using the optimal temperature (900 °C) and particle size (450 µm), the influence of calcination time was examined. The results, depicted in Figure 2, show a progressive increase in quicklime yield from 2.6% at 5 minutes to 47.2% at 60 minutes. However, when the duration was

extended to 75 minutes, the yield remained constant at 47.2%<sup>7</sup>. This indicates that the calcination reaction reached its practical completion for this batch size and condition within 60 minutes.

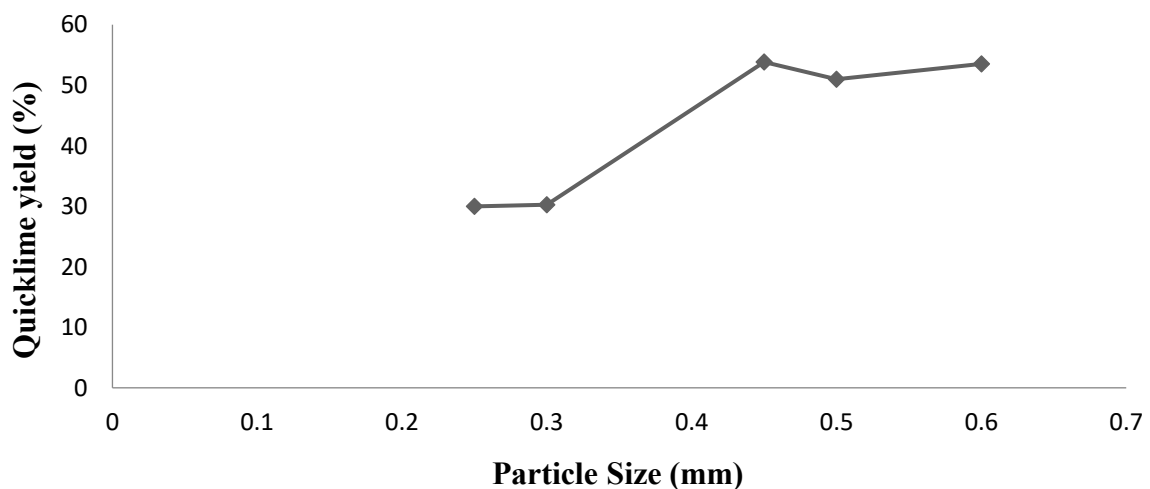


**Figure 2.** Effect of Calcination Time on Quicklime Yield

The optimal time of 60 minutes represents a crucial balance between ensuring complete conversion and maximizing process throughput. Shorter durations would leave unreacted  $\text{CaCO}_3$  in the core of the particles, while longer durations would waste furnace time and energy. This finding is essential for designing an economically viable continuous or batch process, ensuring that residence time in the kiln is sufficient but not excessive.

#### 4.4 Effect of Particle Size on Reaction Efficiency

The final parameter investigated was the feedstock particle size, with the temperature and time held constant at 900 °C and 45 minutes, respectively. The results in Figure 3 demonstrate a clear optimum, with the highest quicklime yield of 53.8% achieved with a particle size of 450  $\mu\text{m}$  (0.45 mm)<sup>9</sup>. Both smaller (250–300  $\mu\text{m}$ ) and larger (500–600  $\mu\text{m}$ ) particles resulted in lower yields.



**Figure 3.** Effect of Particle Size on Quicklime Yield

This outcome can be explained by the interplay of heat and mass transfer phenomena. For larger particles (>450 µm), the lower surface-area-to-volume ratio impedes efficient heat penetration to the particle's core, resulting in incomplete calcination. Conversely, very fine particles (<450 µm) may lead to dense packing within the crucible, which can trap the evolving CO<sub>2</sub> gas, locally increasing the partial pressure and hindering the forward decomposition reaction. The 450 µm particle size, therefore, represents the optimal balance, allowing for rapid heat transfer while maintaining sufficient porosity for the CO<sub>2</sub> to escape efficiently.

In summary, the optimization study successfully identified the ideal conditions for energy-efficient quicklime production from this Nigerian biogenic waste: a calcination temperature of 900 °C, a duration of 60 minutes, and a particle size of 450 µm. These parameters provide a practical blueprint for valorizing this waste stream in a manner that minimises energy consumption and maximises product yield.

## **5. CONCLUSION**

This study addressed the dual challenge of industrial energy consumption and agricultural waste management in Nigeria by establishing an energy-efficient pathway for producing quicklime from a composite of local eggshell and snail shell waste. The research successfully determined the optimal calcination parameters required to maximize product yield while minimizing energy input.

The key findings demonstrate that the feedstock is a high-purity, viable alternative to quarried limestone. The optimal processing conditions were found to be a calcination temperature of 900 °C, a calcination time of 60 minutes, and a feedstock particle size of 450 µm. Adhering to these parameters ensures the complete conversion of the biogenic waste to high-quality quicklime without the excessive energy consumption and material degradation associated with over-processing. These findings provide a practical, evidence-based blueprint for valorizing this common waste stream, contributing directly to the development of a circular economy and more sustainable industrial practices in Nigeria.

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## **Conflicts of Interest**

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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