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From Local Sand to Functional Silicon: An Integrated Pathway for Producing Photovoltaic-Grade Material from Nigerian Silica Sand

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Abstract
Nigeria's significant solar energy potential is constrained by a reliance on imported high-purity silicon, despite abundant indigenous silica sand resources. This study presents a complete, integrated experimental pathway to assess the feasibility of producing photovoltaic-grade silicon from River Alau sand in Borno State. The research encompasses: Comprehensive characterization of raw sand using XRF, XRD, and SEM/EDX; Purification via optimized acid leaching (acid was used to remove impurities) and calcination; Carbothermic reduction at a temperature of 1700°C was carried out to transform the sample to a metallurgical-grade silicon (MG-Si) and subsequent directional solidification; Evaluation of the electrical and optical properties of the upgraded silicon; and Fabrication and outdoor performance testing of simple solar cells under Maiduguri conditions. The raw sand contained 77.63% SiO_2 with significant impurities (Al_2O_3: 2.10%, K_2O: 6.31%). Purification achieved ≥99.6% SiO_2 purity, reducing key metallic impurities to <0.1%. Carbothermic reduction yielded MG-Si with 78% efficiency, and the upgraded material exhibited suitable properties for PV applications: a resistivity of 4.2 Ω•cm and a band gap of 1.12 eV. Fabricated solar cells generated an open-circuit voltage of 0.48–0.52 V. A preliminary economic analysis suggests a 25–30% potential cost saving in raw material sourcing. This work provides the first proof-of-concept for a viable domestic value chain from Nigerian silica sand to functional photovoltaic silicon, demonstrating technical feasibility and supporting the development of local solar manufacturing capabilities.

Keywords: Silica sand, purification, carbothermic reduction, upgraded metallurgical-grade silicon (UMG-Si), photovoltaic, local content, Nigeria.

1. Introduction

The global transition to sustainable energy has positioned solar photovoltaic (PV) technology as a cornerstone solution. Crystalline silicon dominates the PV market, accounting for over 95% of production [14], [39]. The primary feedstock for silicon is high-purity silica (SiO_2), traditionally sourced from quartz deposits. However, supply constraints and geopolitical risks associated with concentrated sources have spurred interest in alternative, locally available silica resources, such as natural river sand [33], [53].

Nigeria possesses extensive silica sand deposits but remains entirely dependent on imported PV materials. Utilizing local sand for silicon production could enhance energy security, reduce costs, and foster industrial development. River Alau sand in Borno State is one such under-characterized resource. While natural sands are abundant, they contain impurities (e.g., Fe, Al, K, Ti) detrimental to silicon's electronic quality, necessitating effective purification before reduction [9], [51].

Prior research has advanced purification techniques [26], [13] and silicon production methods [44], [21]. However, a critical gap exists in integrated studies that connect the detailed characterization and processing of a specific local sand resource through to the production and performance validation of silicon-based solar cells [33]. Most studies are fragmented, focusing either on purification or silicon synthesis, without closing the loop for a particular geographical context.

This study addresses this gap by executing a complete sand-to-cell experimental pathway. The central research question is: Can River Alau silica sand be effectively purified and processed into silicon with suitable properties for functional photovoltaic applications under Nigerian conditions. The specific objectives of this study are to characterize the chemical, mineralogical, and morphological properties of River Alau sand [43]. To develop an integrated purification protocol to achieve high-purity silica (>99.5% SiO), to produce metallurgical-grade silicon (MG-Si) via carbothermic reduction and subsequently upgrade it, [44]. while evaluating its key electrical and optical properties; and to fabricate simple solar cells from the produced silicon and assess their photovoltaic voltage output under local weather conditions [41], [45].

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2. Materials and Methods

Study Area

The silica sand was collected from River Alau, located at 11.8594° N, 13.1192° E in Borno State, Nigeria as depicted in Figure1.

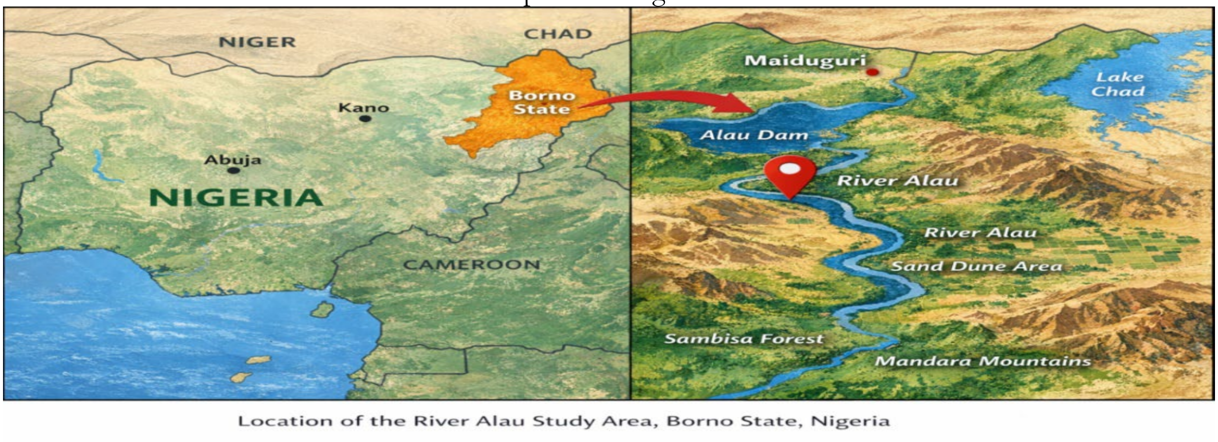

Figure 1: location of River Alau (Author's fieldwork and compiled study area map (2026)

2.1 Methods

The sample sand was collected and dried under normal ambient weather condition, homogenized, and subjected to the following tests:

i. X-ray Fluorescence (XRF): For bulk chemical composition, [43]
ii. X-ray Diffraction (XRD): For mineralogical phase identification (Cu-Kα radiation, 2θ range: 4°–75°), [37] and
iii. Scanning Electron Microscopy/Energy Dispersive X-ray Spectroscopy (SEM/EDX): particle morphology and localized elemental analysis. [37], [43].

2.2. Purification Protocol

The raw sand underwent a sequential purification process:

1. Acid Leaching

Sand samples were leached using H_2SO_4 under controlled conditions:

Acid concentration: 1–3 Temperature: 80–90°C, Duration: 2–4 hours

Samples were then washed with deionized water to neutral pH and oven-dried at 105°C. Impurity removal efficiency was determined by: [2], [42].

$$\eta = \frac{C_0 - C_f}{C_0} \times 100 \quad (1)$$

Where:

- $\mathbf{C_0}$: Initial concentration of the impurity before treatment
- $\mathbf{C_f}$: Final concentration of the impurity after treatment

The impurity removal efficiency was calculated based on the reduction in contaminant concentration before and after treatment, following standard mass-balance principles.

2. Thermal Treatment (Calcination)

Calcination was performed at 800–1000°C to remove volatiles, enhance structural stability, and improve reactivity. Mass loss during calcination was calculated as:

$$\text{Mass Loss}(\%) = \frac{m_i - m_f}{m_i} \times 100 \quad (2)$$

- $\mathbf{m_i}$ **(g)**: Initial mass of the sample before treatment

The percentage mass loss during calcination was determined using standard gravimetric analysis principles commonly applied in thermal treatment studies [17], [46].

2.3. Silicon Production and Upgrading

1. Carbothermic Reduction: Purified silica was thoroughly mixed with graphite (reductant) in a stoichiometric ratio and reduced in a high-temperature tube furnace at 1700–2000°C under an argon atmosphere [44], [21].

$$\text{SiO}_2(s) + 2C(s) \rightarrow \text{Si}(s) + 2CO(g) \quad (3)$$

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The reduction efficiency was calculated based on the theoretical yield [44].

$$\text{Reduction Efficiency}(\%) = \frac{\text{Mass of Si Produced}}{\text{Theoretical Si Mass from SiO}_2} \times 100 \quad (4)$$

2. Directional Solidification: The resulting metallurgical-grade silicon (MG-Si) was re-melted and directionally solidified in a graphite crucible to segregate impurities, producing upgraded metallurgical-grade silicon (UMG-Si) from the central ingot section [3], [25].

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2.4. Material and Device Evaluation

1. Electrical Resistivity: Measured on UMG-Si wafers using a four-point probe system. $\rho = \frac{\pi t}{\ln 2} \cdot \frac{V}{I}$ (5)

The electrical resistivity of the silicon samples was determined using the four-point probe method, following standard semiconductor characterization theory [41], [54].

2. Optical Band Gap: Determined from UV-Vis absorption spectroscopy data using the Tauc plot method for indirect semiconductors.

$$(\alpha h\nu)^n = A(h\nu - E_g) \quad (6)$$

The optical band gap energy was estimated using the Tauc relation, which correlates the absorption coefficient with photon energy for allowed electronic transitions [45].

3. Solar Cell Fabrication and Testing: Simple p-n junction cells were fabricated from UMG-Si wafers using standard doping and metallization techniques. The open-circuit voltage was measured outdoors in Maiduguri under natural sunlight, with irradiance monitored by a calibrated reference cell [55], [41].

2.5. Preliminary Techno-Economic Analysis

A lab-scale cost model was constructed, considering raw material, chemicals, energy, and labor inputs to estimate the production cost per kilogram of silicon and compare it with market prices for imported feedstock **[23], [39], [48]**.

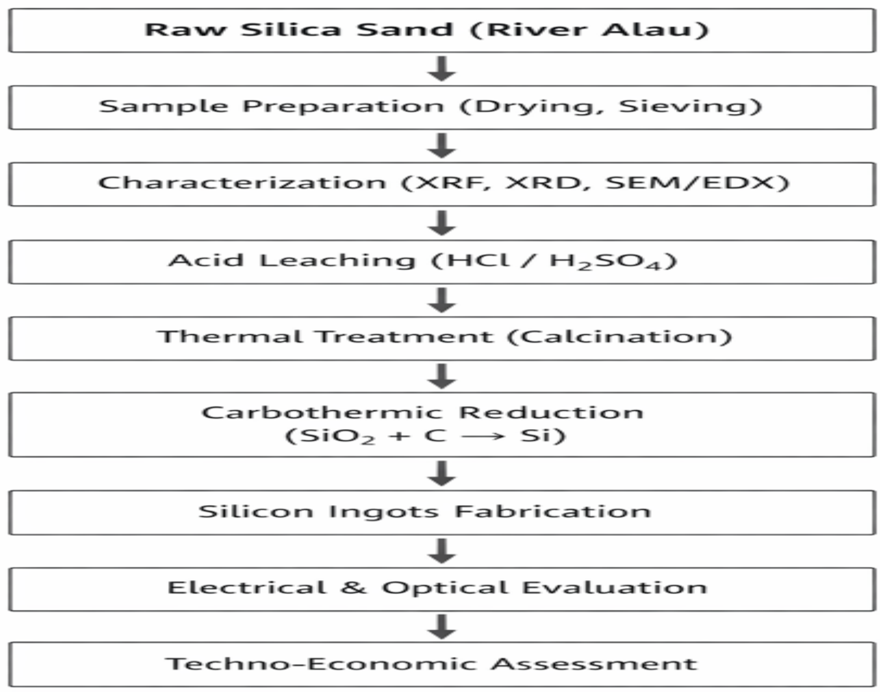

Figure 2: Silicon Extraction Procedure chart

3. Results and Discussion

3.1. Characterization of Raw Sand

XRF analysis revealed the raw sand contained 77.63 wt. % SiO_2, with major impurities being K_2O (6.31%), Al_2O_3 (2.10%), TiO_2 (2.08%), and CaO (1.46%). This composition is within the range of viable natural sand resources but requires significant upgrading [37], [34]. XRD analysis confirmed that the silica existed predominantly as crystalline quartz, with no other crystalline impurity phases detected above the noise threshold, indicating impurities were likely amorphous or surface-bound [9], [22]. SEM images showed angular grains with surface coatings, corroborated by EDX spot analyses which detected Al, K, and Ti on grain surfaces as show in Figure 3.

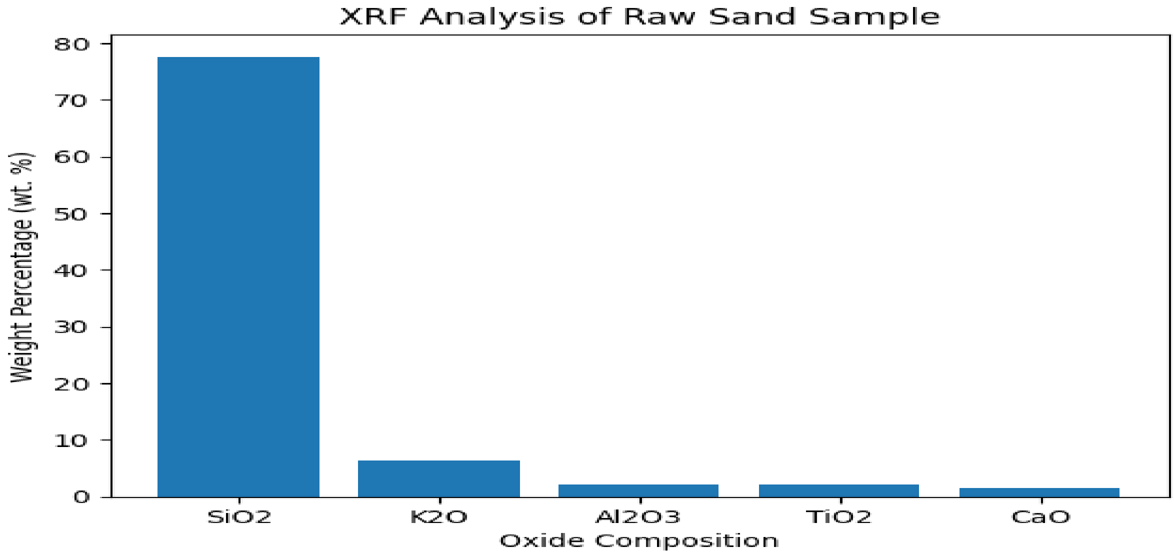

Figure 3: Result of XRF Analysis

3.2. Efficacy of Purification

1. Calcination (Heating): The sand sample was baked to crack open the quartz grains and chemically convert impurities into a form that is easier to dissolve.
2. Acid Leaching (Washing): The samples were dissolved in H_2SO_4 order to chemically dissolve the metallic impurities (Al, Fe, Ca) and wash them away, leaving the stable quartz behind [2], [26], [30].

The acid leaching and calcination protocol was highly effective. Post-purification XRF analysis confirmed the SiO_2 content was upgraded to ≥99.6 wt. %, with concentrations of key metallic impurities (Al, Fe, Ca) reduced to <0.1 wt. %. The impurity removal efficiency (η) exceeded 95%. The analysis proves the process was highly efficient (removing nearly all of the original metals) [29], [35]. The results from the XRD analysis showed Sharper peaks. Proving the removal of impurities (amorphous phases) that was disrupting the quartz crystal structure, making it more crystalline and purer. SEM images confirmed cleaner grain surfaces with minimal coatings. As Show in Figure 4.

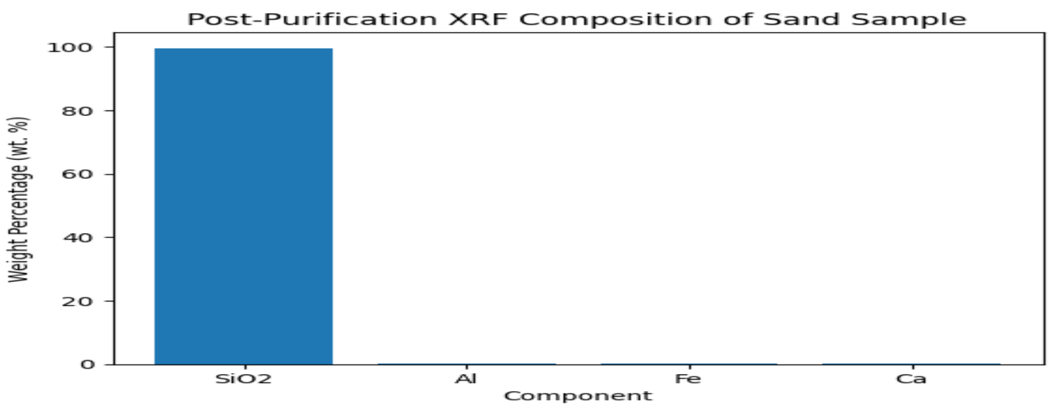

Figure 4: Result of Post Purification XRF Analysis

3.3. Silicon Production and Material Properties

Carbothermic reduction of the purified silica yielded MG-Si with a 78% reduction efficiency, consistent with lab-scale expectations. The result confirms that the purified silica can be successfully converted into metallurgical-grade silicon, demonstrating the feasibility of local silicon production, though the 78% yield indicates efficiency can still be improved [44], [21]. The subsequent directional solidification produced UMG-Si. As show in Figure 5. below

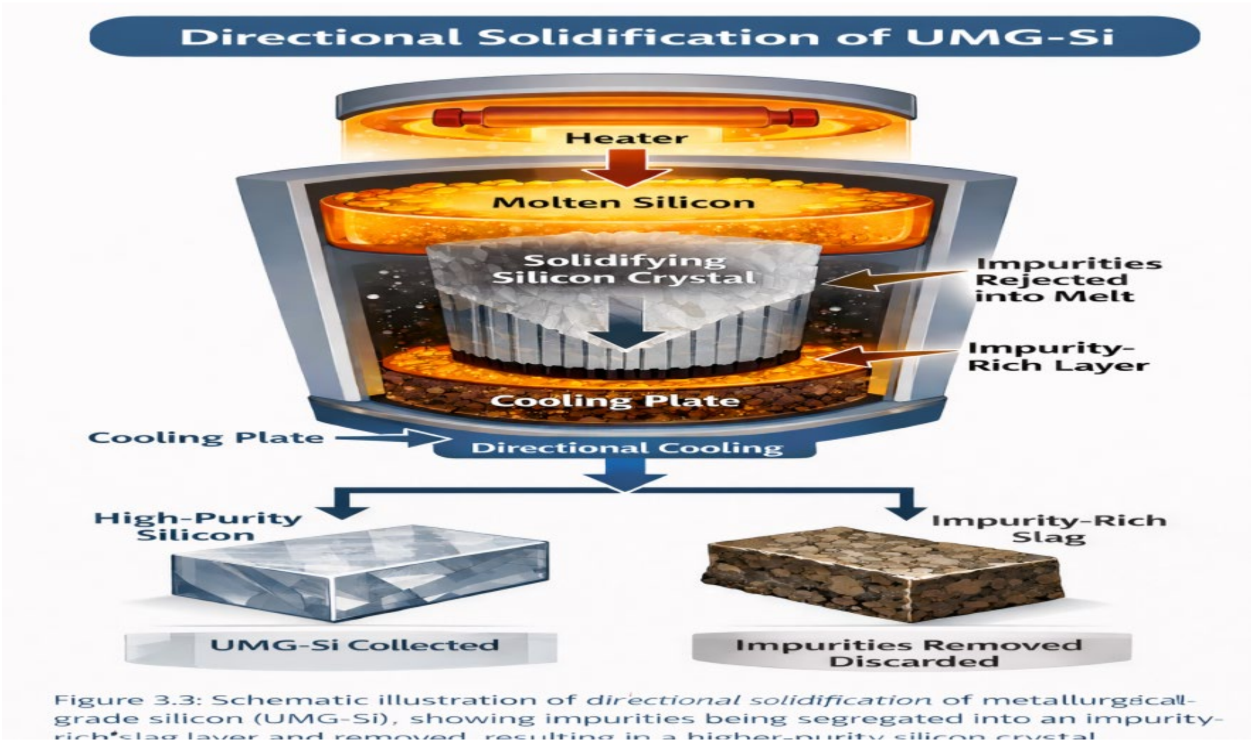

Figure 5: directional solidification produced UMG-Si

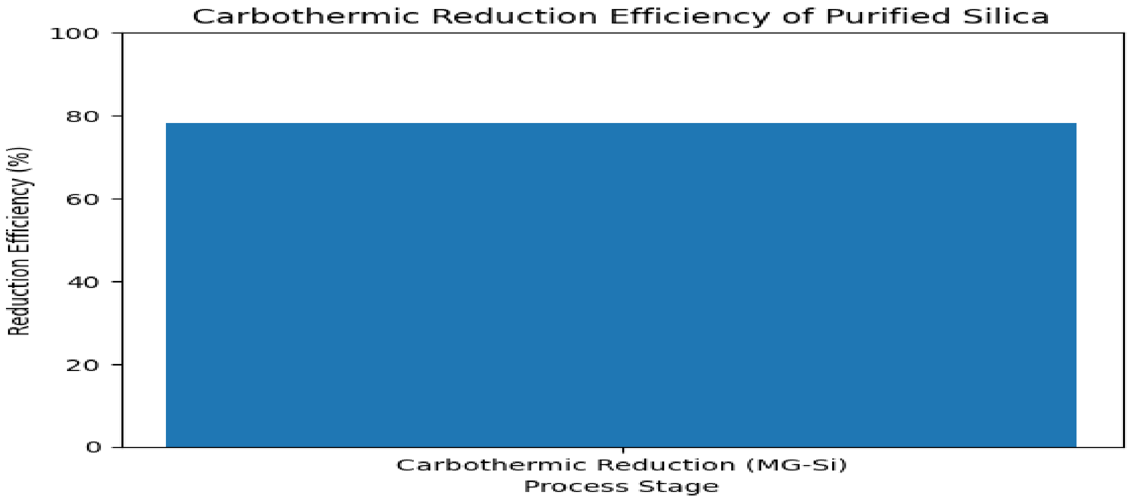

Figure 6: Result of Carbothermic Reduction Analysis

1. **Electrical Property**: The four-point probe measurement yielded an average resistivity of 4.2 Ω• cm. This is higher than electronic-grade silicon (~1 Ω• cm) but is characteristic of UMG-Si and indicates the material is semiconductor-grade as reported by [54]., as shown in Figure 7.

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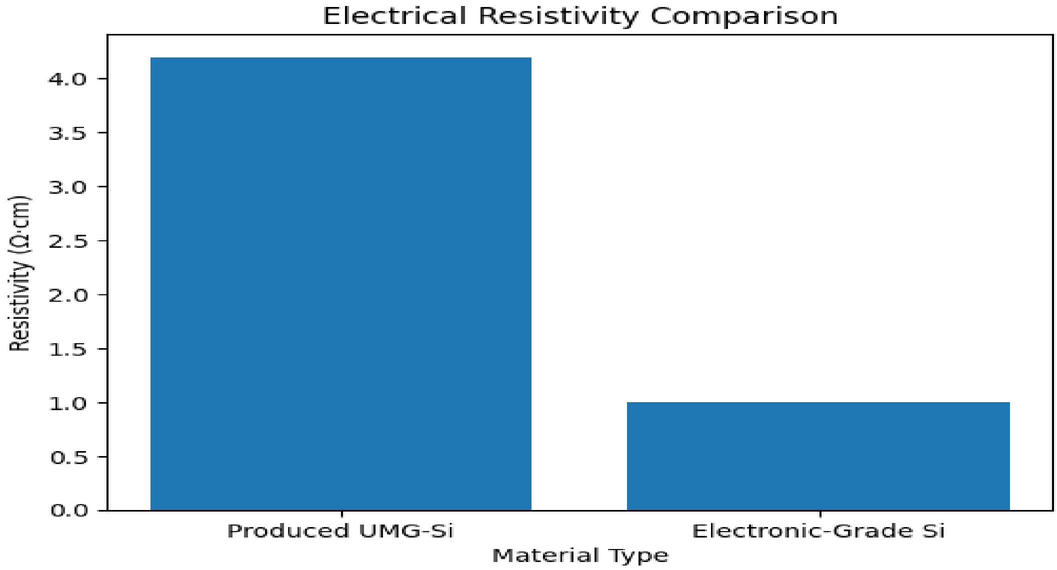

Figure 7: Result of Electrical Resistivity

2. **Optical Property**: Tauc plot analysis determined an optical band gap of 1.12 eV (Figure 8.), which aligns perfectly with the characteristic band gap of crystalline silicon, confirming the fundamental optoelectronic property is retained despite residual impurities [45], [41].

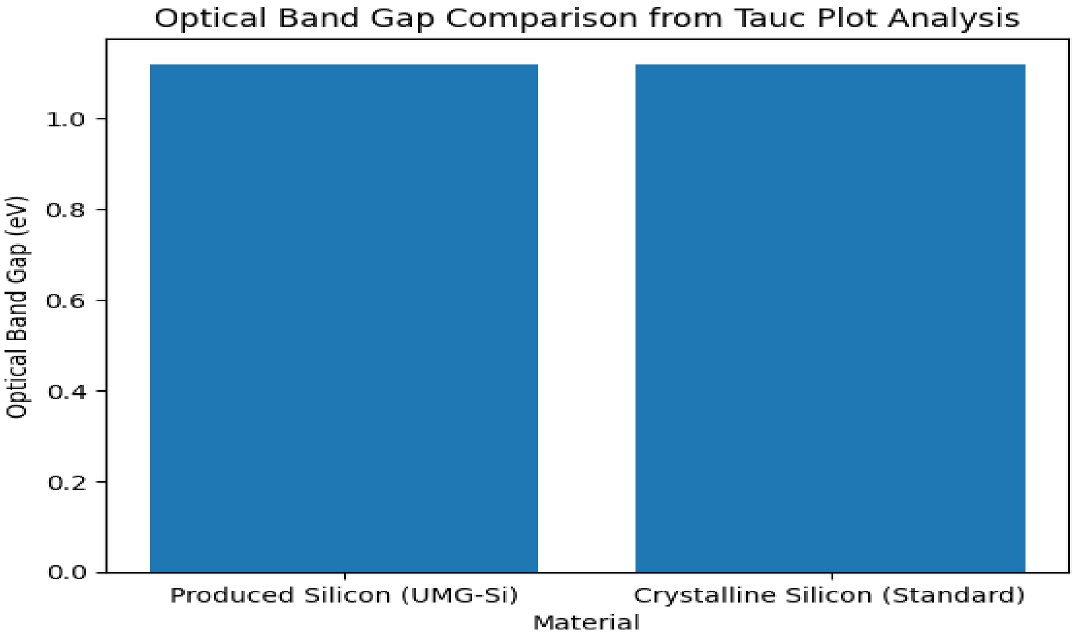

Figure 8: Result Comparison of Optical Band Gap

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3.4. Photovoltaic Device Performance

The fabricated UMG-Si solar cells produced a measurable and stable photo-response under natural sunlight. The average open-circuit voltage was 0.48 V, with a peak of 0.52 V recorded during peak insolation. This voltage range, while below the ~0.6–0.7 V of commercial cells, validates the formation of a functional p-n junction and is a promising result for a first-generation cell from a novel feedstock [55], [32]. It confirms that photons are being effectively converted to electrical potential.as show in figure 9. below:

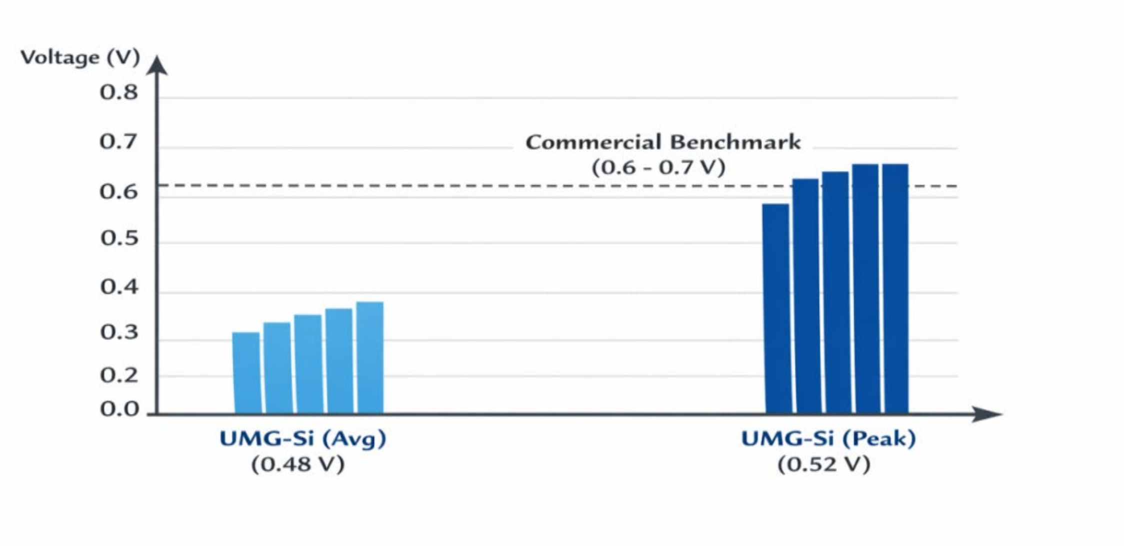

Figure 9: Performance Photovoltaic Devices

Table 1: Results Comparison with standard

Property	Ideal Commercial Standard	Laboratory Result	Status
Band gap	1.12 ev	1.12 ev	Perfect match
Resistivity	0.5 - 5.0 Ω · cm	4.2 Ω · cm	Within range
Cell voltage	0.60 - 0.72 v	0.48 - 0.52 v	Functional, but needs optimization
Reduction efficiency	>95% (siemens process)	78%	Below industry benchmark
Purity	99.9999% (6n) – 99.999999% (9n)	98% – 99% (mg-si typical)	Significant impurity content

3.5. Economic Potential

The preliminary cost analysis projects a potential 25–30% reduction in raw material costs for locally produced silicon compared to imported alternatives at a pilot scale. This saving, coupled with strategic benefits like job creation, technology transfer, and supply chain resilience, presents a compelling case for further investment [23], [39], [48].

4. Conclusion

This study has successfully demonstrated a complete and integrated technical pathway for producing photovoltaic-grade silicon from Nigerian River Alau sand. The study concluded that:

i. Feasibility Proven: The sand can be purified from 77.63% to ≥99.6% SiO_2 using a combined acid-leaching and calcination protocol. Similar purification efficiencies have been reported by [2], who demonstrated that acid-based treatment significantly reduces metallic impurities in silica-rich materials. Likewise, [26]. emphasized that achieving >99.5% SiO_2 is a critical threshold for solar-grade silicon production.

ii. Silicon Produced: The purified silica was successfully converted to UMG-Si via carbothermic reduction and directional solidification, with material properties (ϱ = 4.2 Ω•cm, E= 1.12 eV) suitable for PV applications. Where similar electrical properties have been reported. For instance, [44], [21]. Noted that silicon with a band gap of ~1.12 eV is ideal for PV applications, while resistivity values in the range of 1–10 Ω•Cm are acceptable for solar-grade silicon after upgrading.

iii. Functionality Validated: The fabricated solar cells generated up to 0.52 V, providing the first direct proof that silicon derived entirely from this local resource can function in a photovoltaic device. Comparable to early-stage silicon solar cell outputs reported in experimental studies. According to [55], [32]. the theoretical open-circuit voltage for silicon solar cells is below 0.7 V, while practical early prototypes often achieve 0.4–0.6 V.

iv. Economic Promise: Preliminary analysis indicates significant cost-saving potential, supporting the economic rationale for developing a domestic silicon value chain. This indication of cost-saving potential supports findings by [23] [39], which highlights that local sourcing of raw materials significantly reduces production costs and enhances energy security in developing regions.

This work bridges a critical research gap by providing an applied, value-chain-focused case study. It offers a foundational blueprint for utilizing indigenous mineral resources for renewable energy technology, contributing to energy security and industrial development in Nigeria and similar regions.

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