



Characterization and Numerical Analysis of the Silicon Content in Alau Dam Sand for Solar Photovoltaic Application

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ABSTRACT

This study dwells on the characterization and numerical analysis of sand from Alau Dam for the development of solar photovoltaic (PV) panels. The study utilized various analytical techniques such as X-Ray Fluorescence (XRF), X-Ray Diffraction (XRD), Potential of Hydrogen (pH), electrical conductivity (EC), Scanning Electron Microscopy (SEM), Energy Dispersive X-ray Spectroscopy (EDX), and MATLAB simulations to characterize the properties of the sand sample. The study revealed that the sand has a silicon atomic concentration of 86.16% and Silicon weight concentration of 85.43%. The simulation analysis also shows that with the Silicon concentration of 86.16% and under normal operational conditions, at maximum solar radiation of 1000W/m², a panel produced from Alau Dam Sand can generate an energy output of about 173.34W. It was found that Alau Dam's sand shows a promising future due to its higher Silicon content and might require additional processing or blending with higher silicon sources for optimal panel manufacturing.

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INTRODUCTION

Renewable energy sources such as solar energy, wind energy, biomass energy, ocean, and geothermal energy are currently prominent areas of research and energy generation. Photovoltaic (PV) is an outstanding energy generation technology that is prominent in reducing the carbon footprint of electricity production (Shahsavari and Akbari, 2018). As of the year 2022, global energy production from renewable sources has reached 3371 GW, with an increase of around 294 GW and are expected to reach 8,519 GW by the year 2050 (International Renewable Energy Agency (IRENA), 2019 and Sah, et al., 2023). Solar energy in particular has garnered significant global attention, contributing more than half (approximately 191 GW) of the total renewable energy added in 2022 (Sah, et al., 2023). A recent projection by the International Energy Agency (IEA) anticipates that solar PV will fulfil about 32% of the world's total energy demand by the year 2050, necessitating the installation of 14 TW of PV capacities, more than three times the

previous target of 4.5 TW (IEA, 2021a). However, the widespread adoption of solar PV systems may lead to an escalation in the demand for raw materials used in the PV panel production like silicon, posing a potential constraint on the sustainable growth of the PV industry.

The IEA (IEA, 2021b) reported that the demand for silicon for PV solar in the year 2020 was about 390 thousand tonnes and this is projected to reach 452 thousand tonnes by the year 2030. The crystalline silicon PV system utilizes extremely pure silicon wafers to convert solar energy into electricity. Silicon PV (Si PV) represents 97% of the current PV market and should remain the dominant technology until the year 2040, but raw material shortage could reduce the market share of Si PV (Masson and Kaizuka, 2020). It is estimated that more than three million metric tons of metallurgical grade silicon (MG-Si) will be required to meet the demand for Si PV manufacturing in the next ten years (Heidari and Anctil, 2021).

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Silicon ranks as the Earth's second most plentiful element in the crust. Although typical sand is found everywhere, high-quality and industrial-grade silica sand resources are not equally distributed, and some countries suffer from a high-quality deposits' shortage (Heidari and Anctil, 2021). High-quality silica sand is scarce, and only a few high-quality deposits, such as the Spruce Pine in North Carolina, USA, exist in the world (Müller et al., 2007; Vatalis et al., 2015).

Currently, silicon has revolutionized various aspects of our daily existence due to its versatile applications, encompassing solar cells, energy storage, sensors, biological imaging, drug delivery, photonics, and electronic components. Silicon does not exist naturally in its free state but is typically found in combination with silica or silicates (Arunmetha, et al., 2018). Silicon is produced industrially by reduction of silicon dioxide with carbon in an electric arc furnace at temperatures higher than 2000 °C in the hottest parts (Boussaa, et al., 2017). To be suitable for industrial purposes, a specific source of sand must not only have a high silica content but must also adhere to strict limitations on metallic elements

such as iron, aluminium, titanium, and others (Boussa, et al., 2016). Further purification is necessary to remove impurities such as Fe, Al, B, and P to produce solar-grade silicon (Ramírez-Márquez et al., 2018) used in photovoltaic cells. This study intends to characterise and numerically analyse the potential of sand from Alau Dam from Borno state, Nigeria for solar PV application.

MATERIALS AND METHODS

Area of Study

The study area is situated in the north-eastern region of Nigeria, with geographical coordinates at approximately 11.8311° N latitude and 13.1510° E longitude with mean annual temperature of 27.4°C and means annual precipitation of 552.1 mm. The area is situated in the semi-arid region, near the border of Nigeria, Chad, Cameroon, and Niger. Its location in the Lake Chad Basin has a profound impact on its climate, with distinct wet and dry seasons. These seasons correspond to northern hemisphere summer and winter respectively (Ezenwora *et al.*, 2011).

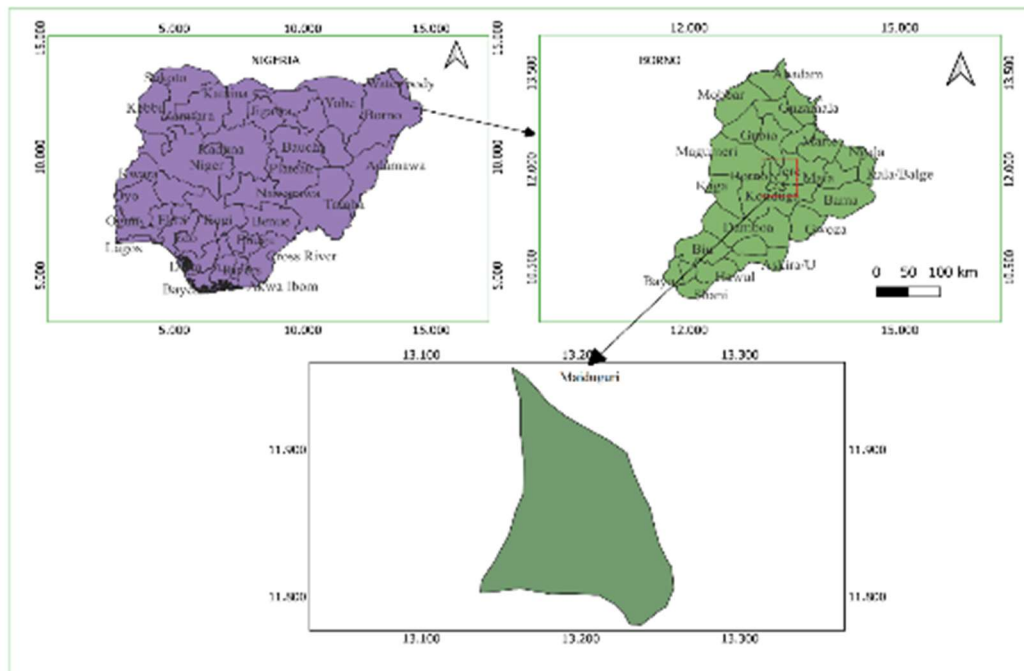


Figure 1: Map of the study area

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Materials

A diverse array of materials and equipment has been assembled to facilitate various experimental procedures and analyses. The following list outlines the essential tools, instruments and substances used to this investigation:

1. Furnace
2. Filter paper
3. Conical flask
4. Amimia acetal
5. Calcium chloride
6. Stirrer
7. Crucible
8. Digital balances
9. Conductivity meter
10. Sample bag
11. Ph meter
12. SEM Machine
13. XRD machine

Method

Soil samples were obtained randomly by digging down the ground to a depth of about 1m at three different points at the Alau Dam site. The samples were then characterized and analysed at the Multi-user Science Laboratory of Ahmadu Bello University Zaria.

Physical and Chemical Properties Characterization of the Sample

The following characterization and analysis of physical and chemical properties were carried out on the sand sample

X-Ray Fluorescence (XRF)

X-ray fluorescence (XRF) is a non-destructive analytical method that allows the identification and quantification of the chemical elements present in the surface of a wide variety of objects. It is currently widely applied in the investigation and characterization of art objects as well as geological and archaeological materials (Anal. Methods, 2017). XRF give details as to the chemical composition of a sample but will not indicate what phases are present in the sample. This XRF analysis serves as a fundamental step in understanding the chemical composition of the

sand samples, laying the groundwork for subsequent analyses and considerations in assessing their potential utilization in solar PV panel manufacturing. XRF analysis procedure includes; user fires an XRF gun at a sand sample. The firing leads to the development of stimulated by x-rays, the sample displaces inner-shell electrons, and outer-shell electrons take their place. The XRF gun receives the fluorescent x-ray emissions, converts them to electrical pulses, and sends the pulses to an internal preamplifier.

Potential of Hydrogen (pH) and Electrical Conductivity (EC)

Soil pH is the measure of soil acidity or alkalinity, specifically the inverse log of the Hydrogen ion concentration on a scale from 0-14. Neutral pH is around 7, with 'acids' being below 7 and 'bases' being from 7 to 14 (Khaleel and Anderson, 2023) and Soil electrical conductivity, referred to as EC, is the ability of soil to conduct (transmit) or attenuate electrical current (Hawkins, 2017). Plate 1 depicts the pH tester used for pH analysis. The procedure for potential of hydrogen (ph) and electrical conductivity (EC) analysis involves, 10g sample of dry soil was weighed and placed in either 50 or 100-ml beakers, with the addition of 25 ml of water to achieve a soil-to-water ratio of 1:2.5 w/v. The mixture was shaken, allowed to settle for 60 minutes, and then the water separated from the mixture. Subsequently, a pH/EC meter was inserted to obtain readings. To ensure accuracy, the process was repeated three times for obtaining precise results.



Plate 1: Measuring pH value using pH meter

X-Ray Diffraction (XRD)

X-ray diffraction (XRD) is a powerful non-destructive technique for characterizing crystalline materials. It provides information on

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structures, phases, preferred crystal orientations (texture), and other structural parameters, such as average grain size, crystallinity, strain, and crystal defects (Bunaciu et al., 2015). XRD machine shown in Plate 2 was used in carrying out the analysis. In analysis, the sand material was finely ground, homogenized, and average bulk composition was determined. The powdered sample was then prepared using the sample preparation block and compressed in the flat sample holder to create a flat, smooth surface that was later mounted on the sample stage in the XRD cabinet.

The sample was analysed using the reflection-transmission spinner stage using the Theta-Theta settings. The two-Theta starting positions were 4 degrees and ends at 75 degrees with a two-theta step of 0.026261 at 8.67 seconds per step. Tube current was 40mA and the tension was 45VA. A Programmable Divergent Slit was used with a 5mm width mask and the Goni Scan was used. The intensity of diffracted X-rays is continuously recorded as the sample and detector rotate through their respective angles. A peak in intensity occurs when the mineral contains lattice planes with d-spacings appropriate to diffract X-rays at that value of θ . Although each peak consists of two separate reflections ($K\alpha_1$ and $K\alpha_2$), at small values of 2θ the peak locations overlap with $K\alpha_2$ appearing as a hump on the side of $K\alpha_1$. Greater separation occurs at higher values of θ . Typically these combined peaks are treated as one.

The 2λ position of the diffraction peak is typically measured as the centre of the peak at 80% peak height. Results are commonly presented as peak positions at 2θ and X-ray counts (intensity) in the form of a table or an x-y plot (shown above). Intensity (I) is either reported as peak height intensity, that intensity above background, or as integrated intensity, the area under the peak. The relative intensity (RI) is recorded as the ratio of the peak intensity to that of the most intense peak as shown by Equation 1.

$$RI = \frac{I}{I_x} \times 100 \quad 1$$

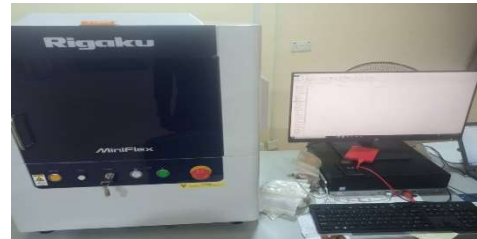


Plate 2: XRD machine

Scanning Electron Microscopy (SEM)

The scanning electron microscope (SEM) is one of the most versatile instruments available for the examination and analysis of the microstructure morphology and chemical composition characterizations (Dunlap & Adaskaveg, 1997). The method is also known as SEM analysis and SEM microscopy, and is used very effectively in microanalysis and failure analysis of solid inorganic materials. Plate 3 presents the SEM machines setup. The SEM analysis procedures involves; the model was specified (in the model specification, the researcher specifies the model by determining every relationship between variables relevant to the researcher's interest). The first step is identification of the model. Then followed by model estimation and test fit and finally manipulate the model to suit the desired analysis.



Plate 3: SEM Machines Setup

Energy Dispersive X-Ray Analysis (EDX)

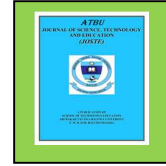
The Energy Dispersive X-ray (EDX) microanalysis is a technique of elemental analysis associated to electron microscopy based on the generation of characteristic X rays that reveals the presence of elements present in the specimens (Scimeca et al., 2018). Applications include materials and product research, troubleshooting, de-formulation, and more. XRD can determine the presence and amounts of minerals species in

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sample, as well as identify phases. In EDX analysis, X-rays were generated using EDX following a two-step process. First, energy was transferred to an atomic electron and it knocks it off, leaving behind a hole. Thereafter, its position was filled by another electron from a higher energy shell, and the characteristic X-ray was released.

Simulation and Analysis

MATLAB software was employed in the simulation analysis and the test was performed based on the PV panel capacity of 230 W.

Output Power

In general, the power output of a PV device is the product of the voltage and current on that product. For V and I respectively denoting voltage in Volts and current in Amperes, the power generated by a PV with resistance R is presented in Equation 2:

$$P = VI = I^2 R = \frac{V^2}{R} \quad 2$$

In particular for a solar module,

$$P = V_{mp} I_{mp} \quad 3$$

V_{mp} and I_{mp} correspond to the maximum voltage and current at maximum power P_{max} . These voltage and current values can be determined empirically when rating a module. Hence, the pair (V_{mp}, I_{mp}) can be obtained from the device simultaneously.

Solar Panel Efficiency

The efficiency (η) of the module is the ratio of output power to input power as shown in Equation 4:

$$\eta = \frac{P_{max}}{P_{in}} \quad 4$$

Simulation Execution

The simulation was run by using the developed model (developed program) in the MATLAB environment and incorporating the EDX-derived silicon atomic concentration data.

Analysis of Result

The power output was simulated and evaluated under varying conditions (light intensity, temperature and irradiance) and analyses show changes in silicon atomic concentration affect performance.

RESULTS

Characterization of Results

The X-Ray Fluorescence (XRF) analysis result is presented in Figure 2, the figure provides a detailed overview of the oxide concentrations within the sand samples obtained from Alau Dam. The unit percentages of various oxides are crucial indicators of the chemical composition of the samples, shedding light on their suitability for solar photovoltaic (PV) panel formation.

The sand sample (Alau Dam sand) exhibited an Aluminum Oxide and Barium Oxide concentrations of 2.100% and 0.010% respectively. Other oxides concentrations in the sand are Calcium Oxide (1.462%), Potassium Oxide (6.305%), Titanium Dioxide (2.080%) with Magnesium Oxide, Sulfur Trioxide, Strontium Oxide and Nickel Oxide showing negligible percentages. Silicon Dioxide (SiO_2) shows a higher concentration of 87%. While silicon content is essential, other oxides' concentrations might influence the overall suitability of the sand for solar panel formation. While SiO_2 content is crucial for solar panels, the presence of other oxides in the sand, such as aluminum oxide and calcium oxide, could influence its properties in unexpected ways. For instance, elevated aluminum oxide content might affect the sand's melting point or behavior during the manufacturing process. Similarly, increased calcium oxide levels could influence the sand's reactivity or its performance in panel fabrication. Despite the fact that the silicon purity is below the standard (99.99%), the findings of this research is similar to the findings of Darwis et al., (2020) for the characteristic study of SiO_2 content of quartz rock as a raw material for making silicon metal for solar cells.

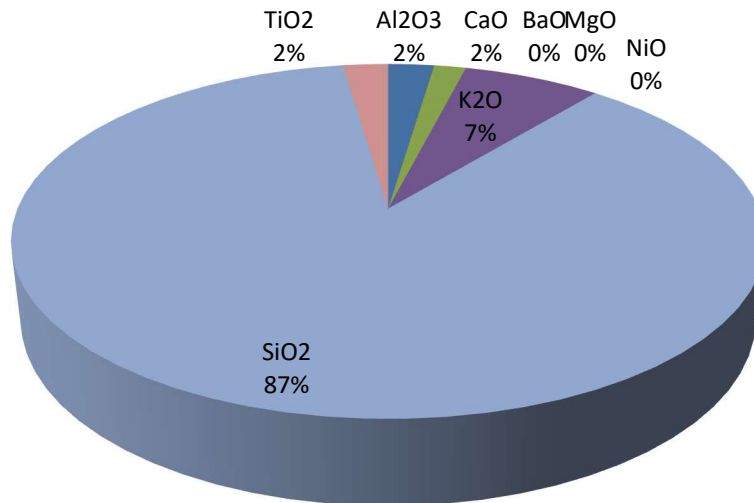


Figure 1: Alau Dam Sand XRF analysis

SEM and EDX Analysis Results Silicon Content Analysis

The result of the SEM and EDX are presented in Table 1. The SEM and EDX analyses revealed the atomic and weight concentrations of silicon in the Alau Dam sand sample. The analysis depicted that the silicon content in the sand was detected as having atomic concentration of 86.16% and a weight concentration of 85.43%. While this sample demonstrates significantly silicon, it still falls short of meeting the industrial standard of 99.9% silicone content, which is necessary for PV cell

production. The presence of impurities, even in sands with decent silicon concentrations, could negatively impact the quality and efficiency of PV cells. Additional processing methods might be necessary to increase the silicon content and purity of these sands to meet the standards required for efficient PV cell production. Refinement techniques like purification or extraction methods could be explored to enhance the silicon content.

Table 1: SEM and EDX Silicon Content Analysis Result

Element Number	Element Symbol	Element Name	Atomic concentration	Weight Concentration
14	Si	Silicon	86.16	85.43
13	Al	Aluminum	7.08	6.75
26	Fe	Iron	0.78	1.55
16	S	Sulfur	1.05	1.19
12	Mg	Magnesium	1.29	1.10
11	Na	Sodium	1.32	1.07

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Element Number	Element Symbol	Element Name	Atomic concentration	Weight Concentration
15	P	Phosphorus	0.92	1.01
17	Cl	Chlorine	0.56	0.70
19	K	Potassium	0.35	0.49
20	Ca	Calcium	0.29	0.421
22	Ti	Titanium	0.18	0.30

Ph and Electrical Conductivity Measurements

Table 2 presents the Ph and electrical conductivity (EC) measurements of the sand. These parameters provide crucial insights into the chemical nature and suitability of the sand for specific applications, including their potential use in solar PV panel production. The Ph measurement of the sample was recorded at 6.68, indicating a slightly acidic nature. A Ph value close to 7 suggests a neutral to slightly acidic environment. This Ph level might influence the sand's chemical reactions and interactions during processing stages for solar panel fabrication. The electrical conductivity of the sand stands at 8.51µS/cm, indicating a relatively low conductivity level. Low electrical conductivity can suggest a lower concentration of dissolved ions in the sand,

which could impact its behaviour during certain industrial processes. This markedly elevated electrical conductivity suggests a higher concentration of dissolved ions or salts in the sand. Higher conductivity might influence the sand's behaviour in various manufacturing processes.

Further investigations are necessary to precisely identify the specific ions or salts present and their concentrations, as well as to understand how these factors might affect the sand's behaviour during solar panel manufacturing processes. This analysis lays the groundwork for more detailed studies to assess the overall suitability of this sand for use in solar PV panel production.

Table 2: Potential of hydrogen (ph) and Electrical Conductivity (EC) results

S/No.	Sample	Ph	Conductivity (µS/CM)
1	Alau Dam Sand	6.68	8.51

Simulation Analysis Using MATLAB

The simulations provided insights into the potential challenges and advantages of using this sand for solar panel formation, allowing for informed decision-making in panel manufacturing. Table 3 depicts the power output as function of silicon concentration. The Table shows that for a given solar irradiance; the power output increases with increase in silicon concentration. The simulation result revealed that with the silicon concentration of about 86% and under normal operational conditions, at maximum solar radiation of 1000W/m², the panel can generate an energy

output of about 173.34W. And at minimum solar radiation of 100W/m² the panel can generate power output of about 17.334W. The underlying reason for this pattern is attributed to the semiconductor properties of silicon. As the concentration of silicon in the samples rises, it enhances the material's ability to efficiently convert solar energy into electrical power. Therefore, the positive correlation between silicon concentration and power output suggests that higher silicon levels contribute to improved energy conversion efficiency in the studied samples. This finding underscores the significance of silicon

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concentration in influencing the overall performance of the power generation system under various solar irradiance conditions.

Table 3: Alau Dam Simulated Power Output Data (100 - 1000 w/m²)

Atomic Conc.	P1(w)	P2(w)	P3(w)	P4(w)	P5(w)	P6(w)	P7(w)	P8(w)	P9(w)	P10(w)
0	0	0	0	0	0	0	0	0	0	0
10	1.926	3.852	5.778	7.704	9.63	11.556	13.482	15.408	17.334	19.26
20	3.852	7.704	11.556	15.408	19.26	23.112	26.964	30.816	34.668	38.52
30	5.778	11.556	17.334	23.112	28.89	34.668	40.446	46.224	52.002	57.78
40	7.704	15.408	23.112	30.816	38.52	46.224	53.928	61.632	69.336	77.04
50	9.63	19.26	28.89	38.52	48.15	57.78	62.41	77.04	86.67	96.3
60	11.556	23.112	34.668	46.224	57.78	69.336	80.892	92.448	104.004	115.56
70	13.482	26.964	40.446	53.928	67.41	80.892	94.374	107.856	121.338	134.82
80	15.408	30.816	46.224	61.632	77.04	92.448	107.856	123.264	138.672	154.08
90	17.334	34.668	52.002	69.336	86.67	104.004	121.338	138.672	156.006	173.34

CONCLUSION

Characterization of a sand sample from Alau Dam site was carried out in this study. The physical properties such as grain size distribution, porosity, and density were measured. The chemical analyses conducted identified trace elements and impurities, affecting the suitability for solar panel formation with the sand sample was also determined. The study revealed that the sand has a silicon concentration of 86.16% and also, the simulation result revealed that with the silicon concentration of 86.16% and under normal operational conditions, at maximum solar radiation of 1000W/m², the panel can generate an energy output of about 173.34W. And at minimum solar radiation of 100W/m² the panel can generate a power output of 17.334W. It was found that Alau Dam's sand shows a promising future due to its higher silicon content and might require additional processing or blending with higher silicon sources for optimal panel manufacturing. The physical and chemical properties, along with simulation results, collectively indicate the complexities and considerations involved in utilizing sand for solar panel development which shows that the objectives of the study have been achieved.

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