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Production of Silica from ABU Zaria Dam Sand as an Eco-Friendly Corrosion Inhibitor Using Nanotechnology

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Abstract

This research is centered on the production and characterization of silica synthesized from sand collected from the ABU Zaria Dam, assessing its suitability as an eco-friendly corrosion inhibitor, using nanotechnology principles. The sand samples available in abundance were collected, processed and analyzed using Scanning Electron Microscopy (SEM) which revealed irregularly shaped grains surrounded by fine agglomerated particles. EDS (Energy-Dispersive X-ray Spectroscopy) was used to confirmed silica as the dominant constituent, with silicon accounting for 53.52 wt%. Silica nanoparticles were synthesized using a modified sol–gel technique involving alkaline extraction, gel precipitation, washing, and calcinations to produce purified nanoscale silica particles. Fourier Transform Infrared Spectroscopy (FTIR) analysis showed characteristic Si–O asymmetric and symmetric stretching vibrations, alongside O–H and C=O functional groups, indicating the presence of silicate structures and surface hydroxyl species. X-Ray Diffraction (XRD) results showed sharp crystalline quartz peaks together with a broad hump between 20–35°, confirming the coexistence of both crystalline and amorphous silica. The average crystallite size calculated using the Scherrer equation was 20.15 ± 3.96 nm, confirming the nanoscale nature of the prepared silica. The combination of nanosized particles, functional groups with high adsorption potential, and significant silica purity suggests that silica sourced from the ABU Zaria dam has strong potential as a sustainable and environmentally friendly corrosion inhibitor which makes it a viable alternative to conventional toxic corrosion-inhibiting chemicals used in industrial systems. Moreover, the adaption of this material as a corrosion inhibitor will definitely increase the National Gross Domestic Product (GDP and comply with the Federal Government 9th millennium development goals, scalable and affordable to the common citizens.

Keywords: *Sand, Silica nanoparticles, Eco-friendly, Corrosion inhibitor, Adsorption potential.*

1.0 Introduction

Corrosion of metallic materials is a global industrial challenge, especially in environments characterized by high humidity, acidity, salinity, or temperature fluctuations. It leads to structural failures, safety hazards, environmental degradation, and significant economic losses [1]. However, many conventional corrosion inhibitors are based on synthetic chemicals, such as chromates, nitrites, and phosphates, which are often non-biodegradable and toxic to both humans and the environment [2]. The increasing environmental regulations and global push for sustainability have necessitated the development of eco-friendly or green corrosion inhibitors derived from natural, renewable sources. Silica (SiO_2), a naturally occurring oxide of silicon, is abundant in the Earth's crust and commonly found in sand, clay, rice husk, and water sediments. It is chemically inert, non-toxic, and environmentally benign. Recent studies have explored its potential as a corrosion inhibitor, particularly when processed into nanoparticles, which possess superior surface area and adsorption properties. It has emerged as a promising alternative due to its chemical inertness, biodegradability, and capacity to form protective films on metal surfaces [3]. The application of nanotechnology enhances these properties by improving surface area and reactivity, making silica nanoparticles more effective as green inhibitors [4]. The ABU Zaria Dam has been identified as a rich, underutilized source of silica-bearing sediment. Hence, extracting and processing silica from this location for use in corrosion inhibition will aligns with both sustainability and economic efficiency goals. Moreover, this study aims to explore this possibility of using nanotechnology to produce and characterize silica from ABU Zaria Dam, evaluating its effectiveness as a corrosion inhibitor for mild steel. In addition, the development of this material will discourage the use of synthetic corrosion inhibitors, despite their toxicity, significant environmental health risks and incessancy increases in operational costs in industries that contributes to foreign exchange burdens.

1.1 Physicochemical Properties of Silica for Inhibition

The anticorrosive efficacy of silica was derived from its particle size, surface chemistry, porosity, and dispersion stability. Comprehensive characterization is therefore essential: Fourier-transform infrared spectroscopy (FTIR) was used by researchers to confirm Si–O–Si and surface hydroxyls; X-ray diffraction (XRD) to verify amorphous and crystalline phases; Brunauer–Emmett–Teller (BET) analysis for specific surface area and porosity; scanning/transmission electron microscopy (SEM/TEM) for morphology and size; dynamic light scattering (DLS) and zeta potential for colloidal stability; and thermogravimetric analysis (TGA) for surface modification loading [5]. These descriptors correlate with film-forming ability on steel, inhibitor loading capacity, and release behaviour.

1.2 Mechanisms of Silicate-Based Corrosion Inhibition

For carbon and low-alloy steels in neutral or mildly alkaline electrolytes, silicates can reduce corrosion by: (i) adsorbing negatively charged silicate species onto positively polarized surface sites; (ii) precipitating as a protective iron-silicate/iron-oxide–silicate mixed layer that impedes charge and mass transport; and (iii) enhancing alkalinity locally at cathodic sites, suppressing cathodic reactions. Electrochemical studies report that sodium silicate reduces uniform corrosion rates and can shift corrosion potentials depending on dosage and hydrodynamics in simulated water systems [5; 6; 7]. At higher loadings, silicate films behave as diffusion barriers, whereas at insufficient concentrations protection may be negligible or even unstable under flow. When silica is used as nanoparticles, two complementary effects arise: barrier enhancement by pore-filling in polymer matrices and interfacial adsorption onto metal surfaces. In hybrid sol–gel/silane coatings, hydrolysed alkoxysilanes condense to form a crosslinked Si–O–Si network bonded to the metal via M–O–Si linkages, which significantly improves adhesion and reduces under-film corrosion [8; 9; 10; 11].

1.3 Function of Nanotechnology in Corrosion Control

Nanotechnology offers advanced strategies for corrosion mitigation. Nanoparticles, owing to their high reactivity and surface area, can provide uniform and effective protective films [3]. Silica nanoparticles, in particular, are widely studied for their stability and functionalizability [12]. Functionalized silica nanoparticles can be incorporated into paints, coatings, or directly applied in solution to form nanoscale barriers against corrosion agents [13]. Silica has emerged as a promising material for corrosion inhibition due to its chemical stability, non-toxicity, and film-forming properties. It can adsorb onto metal surfaces and reduce contact with aggressive media. Moreover, its performance is enhanced when processed into nanoparticles due to higher surface area and improved coverage [14]. The silica used in corrosion protection is often obtained from sand, clay, volcanic ash, agricultural waste (e.g., rice husk ash), and water sediment such as dam deposits. Studies showed that silica nanoparticles, particularly mesoporous and functionalized forms, can improve corrosion resistance in both acidic and neutral environments [3].

2.0 Materials and Methods

Materials used for the study include: sediment samples from ABU Zaria Dam, Hydrochloric acid (HCl), sodium hydroxide (NaOH), sulphuric acid (H_2SO_4), distilled water and ethanol.

Model Method 1: Specimen Preparation

This study adopts an experimental research design, involving the collection of dam sediment samples, synthesis of silica nanoparticles through chemical and thermal treatments, and characterization using advanced analytical techniques. The design enables systematic investigation of the relationship between preparation conditions and the properties of synthesized silica. Sand samples were collected from the ABU Zaria Dam (Samaru, Zaria) along the shoreline to ensure representativeness. Samples were stored in clean, high-density container to prevent contamination. The collected sample of sand as showed in Figure 1 was purified through several stages to remove organic and inorganic impurities:

1. Washing with deionized water until the supernatant was clear.
2. Acid leaching using 2 M HCl at 80°C for 4 hours under stirring to dissolve metallic oxides.
3. Rinsing the sample with deionized water until neutral pH, followed by drying at 110°C for 24 hours.
4. Grinding and sieving through a 100-mesh sieve to obtain fine powder for extraction.

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Figure 1: Collected sample of sand

Model Method 2 Synthesis of Silica Nanoparticles (SiO_2 NPs)

Silica nanoparticles were synthesized via a sol–gel process in accordance to the research work of [15] and [16]. Their procedure involved alkaline extraction, gel precipitation, washing, and calcinations as stated in the Figure 2.

Alkaline Extraction: Purified sand was mixed with NaOH pellets in a 1:1.25 weight ratio and calcined at 700°C for 4 hours to form sodium silicate. The fused mass was cooled, crushed, and dissolved in deionized water at 80°C for 2 hours. The resulting solution was filtered to remove insoluble residues

Precipitation of Silica Gel: The sodium silicate solution was titrated slowly with 2 M HCl under constant stirring at 50°C until pH ≈ 7.0, forming a white silica gel, which was aged for 24 hours to improve stability.

Washing, Drying, and Calcination: The aged gel was washed repeatedly with deionized water until free from chloride ions, dried at 110°C for 12 hours, and calcined at 600°C for 6 hours to obtain fine, amorphous nano-silica powder.

Model Method 3: Characterization of Nano-Silica: A Fourier-Transform Infrared Spectroscopy (FTIR) was used to Identify the functional group contained in the synthesized silica (Si–O–Si and Si–OH) bonds and confirmed BTA loading. X-Ray Diffraction (XRD) was used to determine the amorphous/crystalline structure of the silica material produced, using Cu Kα radiation at an angle of 2theta (2ϴ) while the Scanning Electron Microscopy (SEM) and EDS-examined morphology and elemental composition of the silica material synthesized.

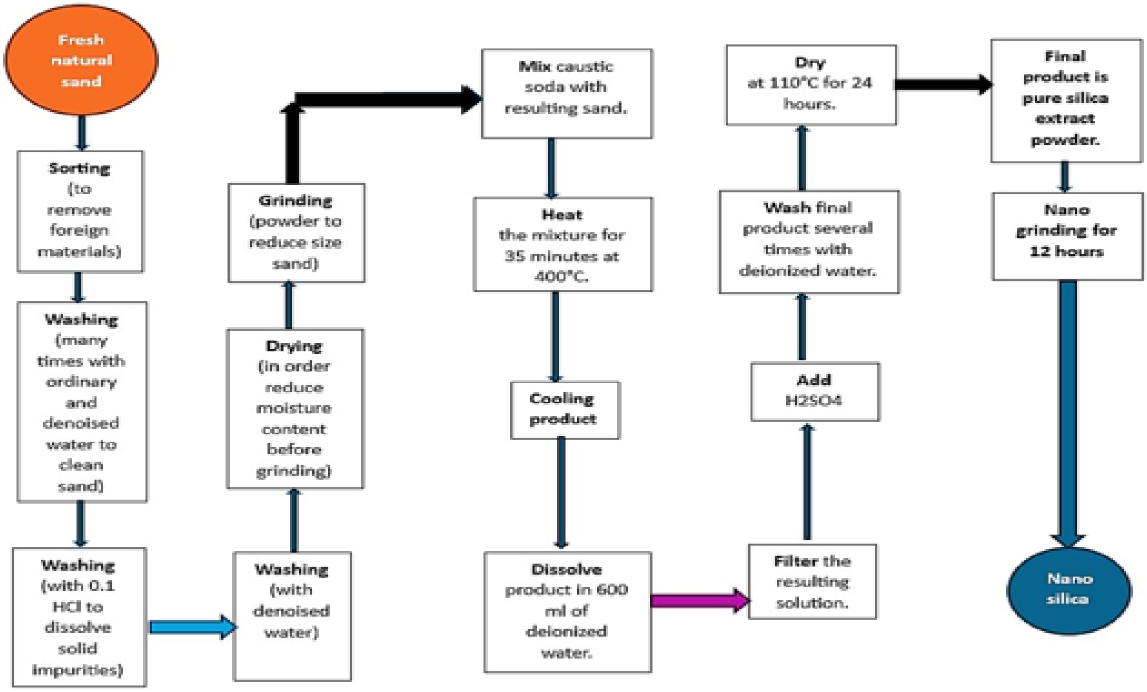

Figure 2: Schematic diagram of the preparation process of nano-silica by the sol-gel method

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Figure 3: Silica production stages of nano silica (SiO_2) by sol-gel.

3.0 Results and Discussion

The surface morphology of the sand sample was carried out using a scanning electron microscope (SEM) which revealed large and irregular particles and large grains surface covered with much finer particles. Though, the fine powder is agglomerated, forming irregular clusters rather than separated particles as indicated in the Figure 4. This feature is common in sand and silica particles [17].

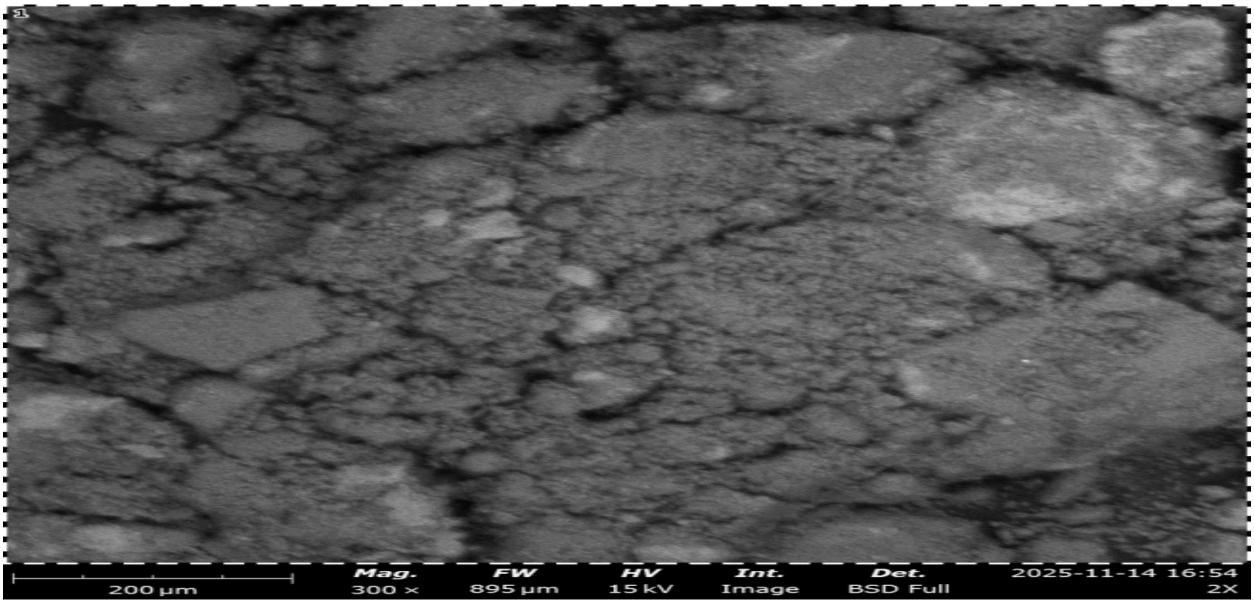

Figure 4: SEM image of the Sand sample

Table 1 presents the elemental composition of the sample, as determined by energy-dispersive (EDS). Based on the EDS analysis, the dominant element is Silicon (Si) at 53.52 wt%. Other elements seen are chlorine (Cl), carbon (C), Sodium (Na), Zinc (Zn), Aluminium (Al), and Iron (Fe). Minor amounts of silver (Ag) and potassium (K) were observed at 1.07 and 0.41 wt.%, respectively.

Table 1: Chemical composition of the sand sample

Element Name and Symbol	**Weight Conc.**
Silicon (Si)	53.52
Chlorine (Cl)	18.38
Carbon (C)	10.66
Sodium (Na)	5.07
Zinc (Zn)	4.45
Aluminium (Al)	3.48
Iron (Fe)	2.94
Silver (Ag)	1.07
Potassium (K)	0.41

The functional group in the sand sample is examined using the Fourier-transform infrared spectroscopy (FTIR) technique as shown in Figure 5. An adsorption band was seen within 3693 and 2957 cm^{-1}, attributed to the O-H band, which shows the presence of absorbed water. The peak at 1643 cm^{-1} is assigned to C=O, confirming the presence of carbonyl groups, suggesting components like aliphatic esters and acids are in the sand

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sample [18]. A strong broad absorption peak is observed at 1031 cm$^{-1,}$ which is attributed to the Si-O asymmetrical stretching vibration, while the Si-O symmetrical stretching vibration is seen within 735 and 830 cm^{-1} [19]. The Si-O bonds indicate the presence of a silicate structure.

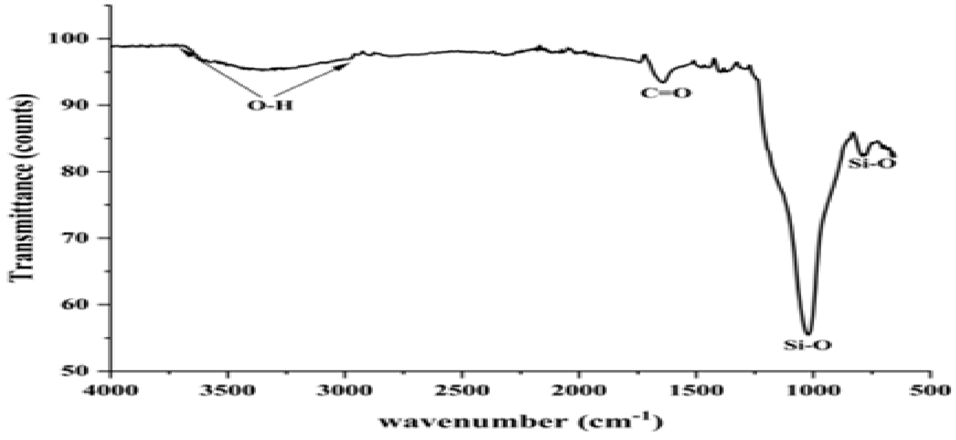

Figure 5: FTIR spectrum of the Sand Sample

The XRD analysis was carried out and it revealed sharp crystalline peaks, which is a feature of quartz (SiO_2) rich sand as reported by Qiu *et al.* (2023) [20]. Also revealed was a broad background hump seen within the range of 20^0 and 35^o, which suggests the presence of amorphous silica (Figure 6). The XRD analysis aligns with the SEM/EDS result, which shows that the sample is made of fine particles, dominantly quartz. The high intensity and sharp peaks could result in highly crystalline quartz. Hence, using the Scherrer equation as stated in equation 1, the average crystalline size is 20.15±3.96 nm.

$$D = \frac{K\lambda}{\beta \, Cos\, \theta} \quad (1)$$

where:
D = crystallite size (nm)
K = Scherrer constant or shape factor (usually 0.9)
$\lambda =$ wavelength of X-ray radiation (nm)
$\beta =$ Full Width at Half Maximum (FWHM) of the diffraction peak in radians
$\theta =$ Bragg diffraction angle (in degrees, but use cosine of angle in calculation)

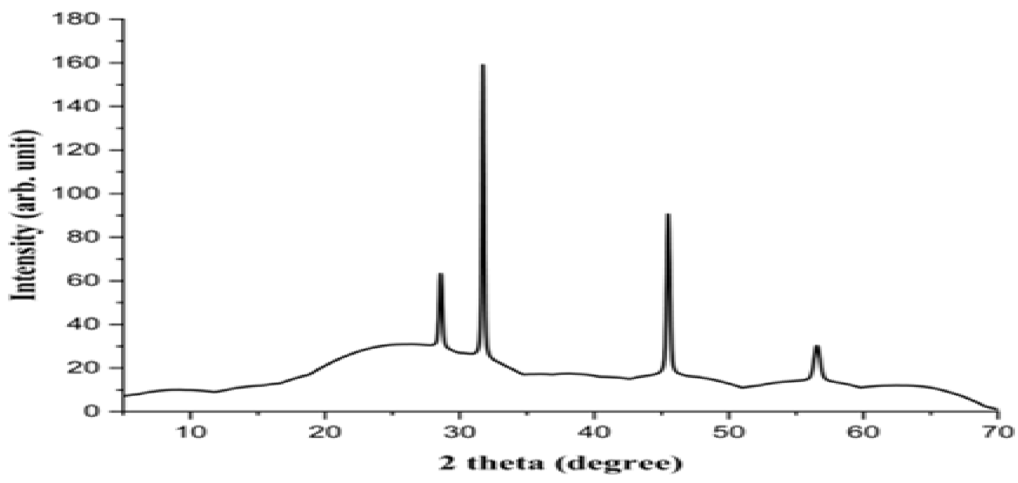

Figure 6: XRD pattern of the Sand Sample

4.0 Conclusion

This research has established that, silica obtained from ABU Zaria dam sand can be successfully synthesized, characterized as a nanomaterial and found suitable for corrosion inhibition of mild steel. In addition, the studies have equally revealed that, the extracted silica possesses the desirable qualities for forming protective layers on metal surfaces and given environmental concerns associated with synthetic corrosion inhibitors.

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