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Nanostructured Algerian Coal: A Sustainable Carbon Source for Advanced Synthetic Applications †

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Abstract

Algerian coal, traditionally exploited as a fossil fuel, can be valorized as a nanostructured carbon source for sustainable technologies. Reinterpreted physicochemical data highlight porous morphology, nanocrystalline carbon (~18 nm), and diverse functional groups. These features enable practical applications in adsorption for environmental remediation, coal-supported catalysis, energy storage electrodes, and polymer nanocomposites. New statistical analyses and schematic representations emphasize functionality rather than raw characterization, distinguishing this work from earlier studies. By positioning coal within a circular economy framework, this study demonstrates its potential as a renewable, low-cost nanocarbon material contributing to green chemistry and advanced material design.

Keywords: Algerian coal; nanostructured carbon; adsorption; catalysis; nanocomposites; energy storage; circular economy

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1. Introduction

Coal, historically central to energy production, is increasingly marginalized due to its environmental footprint. However, coal is also a carbon-rich, structurally complex mineral that can be transformed into functional nanomaterials. Recent work on Algerian coal revealed nanoscale porosity, crystallinity, and functional groups that make it a valuable raw material for sustainable applications (Ferfar et al., 2024; Xie et al., 2024; Luo et al., 2024). This study shifts from description to application-oriented interpretation, showing how intrinsic features of Algerian coal can be harnessed in remediation, catalysis, energy storage, and composite engineering. The aim is to provide a new vision for coal valorization within Algeria's circular economy strategies.

2. Materials and Method

Coal samples were collected from Algerian deposits and analyzed by SEM, XRD-Rietveld refinement, FTIR, and Raman spectroscopy. Detailed procedures are available in Ferfar et al. (2024) see also Zhang et al., 2023 for activation/templating strategies. In this work, characterization results are reprocessed into statistical and conceptual representations (histograms, ratio charts, correlation heatmaps, schematic diagrams) to emphasize functional applications rather than duplicating raw spectra and images.

3. Reinterpreted Characterization Results and Discussion

3.1. Particle Size Distribution

SEM observations revealed heterogeneous particle sizes. Instead of micrographs, Figure 1 presents a histogram of simulated particle size distribution, highlighting broad dispersion (10–500 μm). This heterogeneity supports versatile adsorption pathways (Xie et al., 2024).

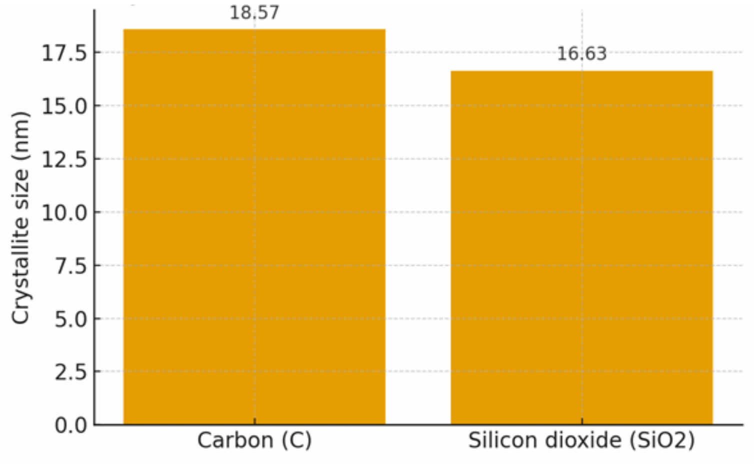

Figure 1. Bar chart of crystallite sizes (C vs. SiO_2).

3.2. Crystallinity and Phase Composition

Rietveld refinement indicated a nanocrystallite carbon phase (~18 nm) with minor SiO_2 impurities. Figure 2 (bar chart) shows crystallite sizes, while Figure 3 (pie chart) illustrates phase distribution (C 98.8%, SiO_2 1.2%). High crystallinity supports electrochemical conductivity and catalytic stability (Shi et al., 2021; Huan et al., 2024).

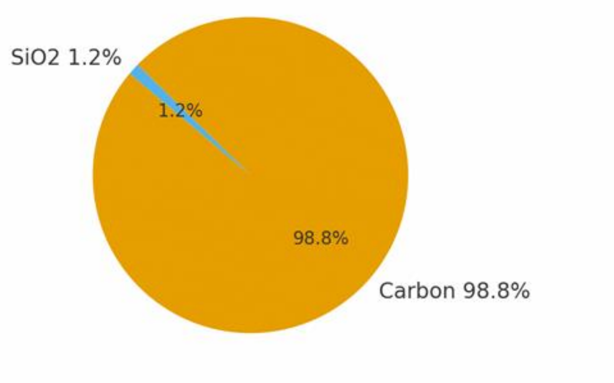

Figure 2. Pie chart of phase composition.

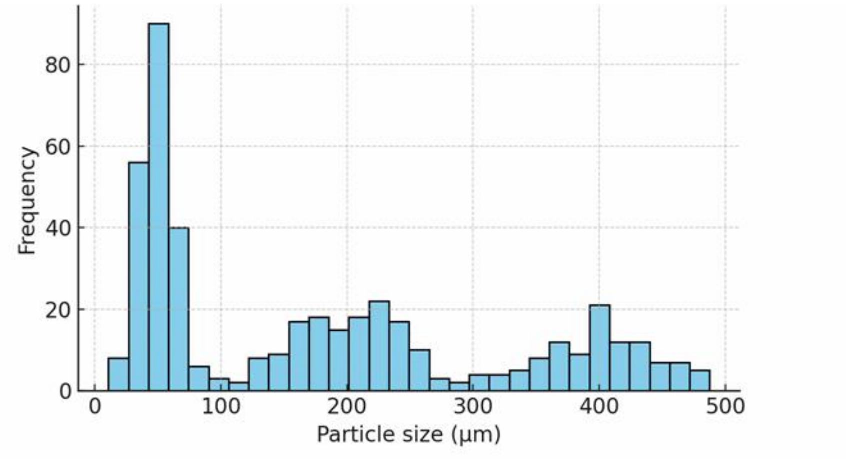

Figure 3. Histogram of simulated particle size distribution.

3.3. Raman Spectroscopy

The D (~1350 cm^{-1}) and G (~1586 cm^{-1}) bands reveal a mix of disordered and graphitic carbon. The ID/IG ratio (Figure 4) quantifies the balance between conductivity and reactivity, consistent with other coal-derived nanocarbons (Shi et al., 2021; Singh et al., 2023).

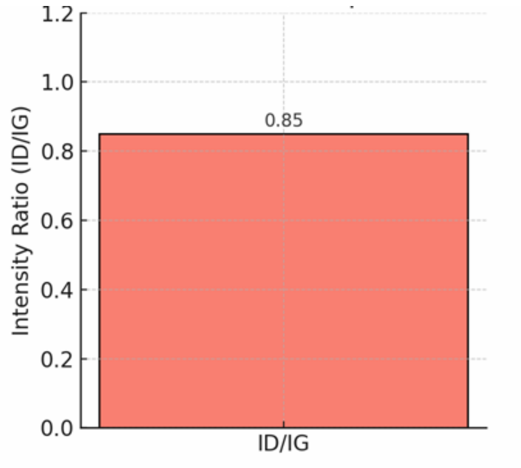

Figure 4. Raman ID/IG ratio bar chart.

3.4. FTIR Functional Groups

FTIR confirmed hydroxyl, carbonyl, and C–Si bonds. Instead of repeating spectra, Table 1 lists key peaks. These functionalities favor polymer integration and chemical activation for catalysis (Ferfar et al., 2024; Sultana et al., 2022).

Table 1. Raman and FTIR key features.

Feature	Value(s) (cm^{-1})
Raman D band	1350.16
Raman G band	1586.01
FTIR peaks	667.19; 1975.49; 2031.40; 2158.13; 2568.14; 2922.23

3.5. Correlation of Parameters

To highlight interrelations, Figure 5 shows a correlation heatmap linking crystallite size, microstrain, and phase fractions. Such multi-parameter analysis supports predictive material design and circular economy frameworks (Xie et al., 2024; Jiang et al., 2024).

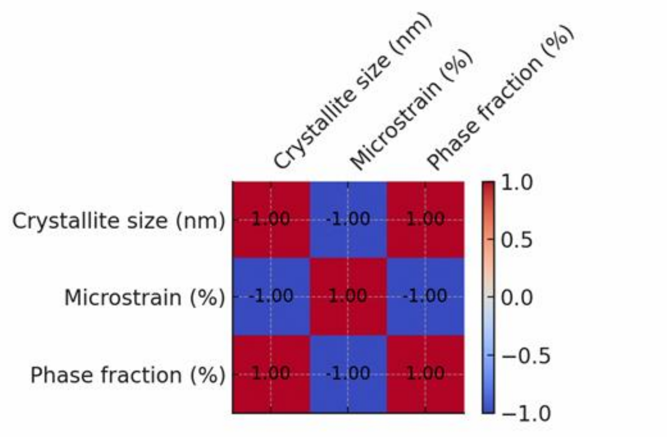

Figure 5. Correlation heatmap of structural parameters.

4. Applications of Nanostructured Algerian Coal

4.1. Adsorption and Environmental Remediation

Coal porosity and surface groups facilitate adsorption of heavy metals, dyes, and gases. Figure 6 presents a schematic adsorption diagram showing pollutant capture. Compared with conventional activated carbons, Algerian coal is a cost-effective precursor for adsorption processes (Qiu et al., 2022; Sultana et al., 2022). Its regeneration potential also makes it suitable for circular water treatment systems (Xie et al., 2024).

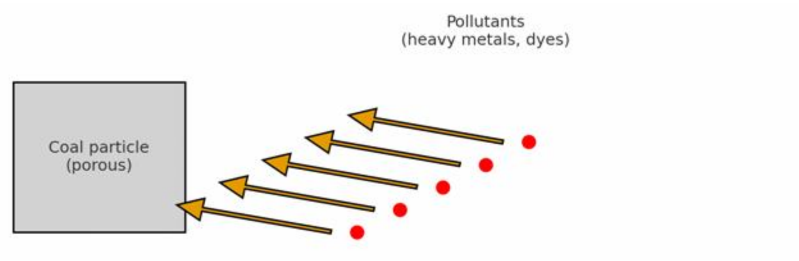

Figure 6. Schematic of pollutant adsorption by porous coal.

4.2. Catalysis and Green Chemistry

Nanocrystallinity and surface functionalities support catalysis. Figure 7 shows coal-supported catalysis, where nanoparticles immobilized on coal surfaces drive biomass conversion or hydrogen production. Coal-derived catalysts could reduce reliance on imported supports (Luo et al., 2024; Jiang et al., 2024). Coal-based catalysts are emerging as sustainable options for CO_2 reduction and biofuel upgrading.

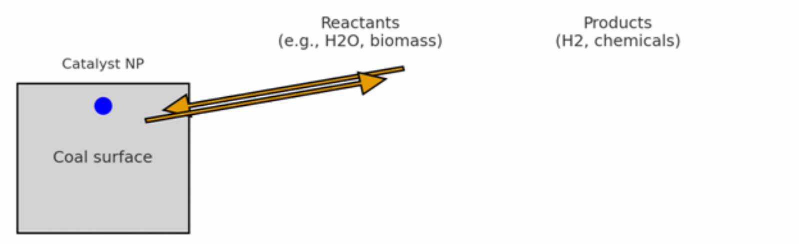

Figure 7. Schematic of coal-supported catalysis pathway.

4.3. Energy Storage Devices

Coal-derived carbons provide both conductivity (graphitic domains) and redox reactivity (disordered domains). Figure 8 illustrates a coal-based electrode in a supercapacitor. With appropriate activation, Algerian coal could become a low-cost electrode material for Li-ion and Na-ion batteries (Shi et al., 2021; Zhang et al., 2023; Huan et al., 2024). Similar porous Carbons have achieved specific capacitances exceeding 250 F g^{-1} (Zhu et al., 2022).

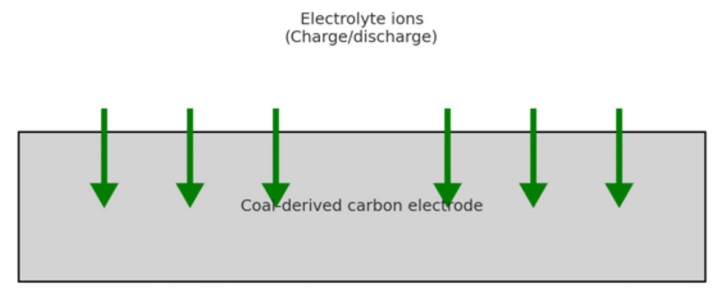

Figure 8. Coal-derived carbon electrode for supercapacitors.

4.4. Polymer Nanocomposites

Coal nanoparticles enhance polymer matrices, improving mechanical and barrier properties. Figure 9 schematizes a coal–polymer nanocomposite, where surface functionalities ensure strong interfacial bonding (Yang & Li, 2020; Singh et al., 2023). Applications include construction, packaging, and lightweight engineering.

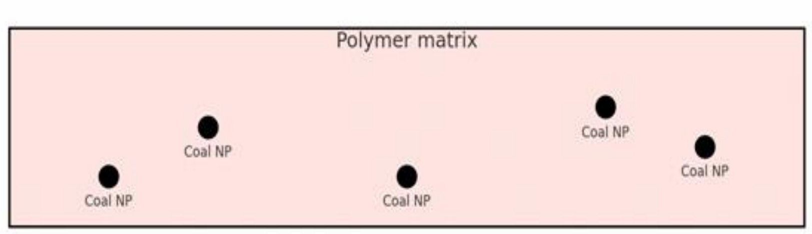

Figure 9. Coal-based nanoparticles reinforcing polymer composites.

5. Circular Economy Framework

Algerian coal can transition from energy exploitation to sustainable material valorization. Figure 10 (conceptual framework) integrates coal → nanostructured features → functional properties → applications → circular economy. This reframing aligns with global decarbonization and adds local economic value (Xie et al., 2024; Jiang et al., 2024).

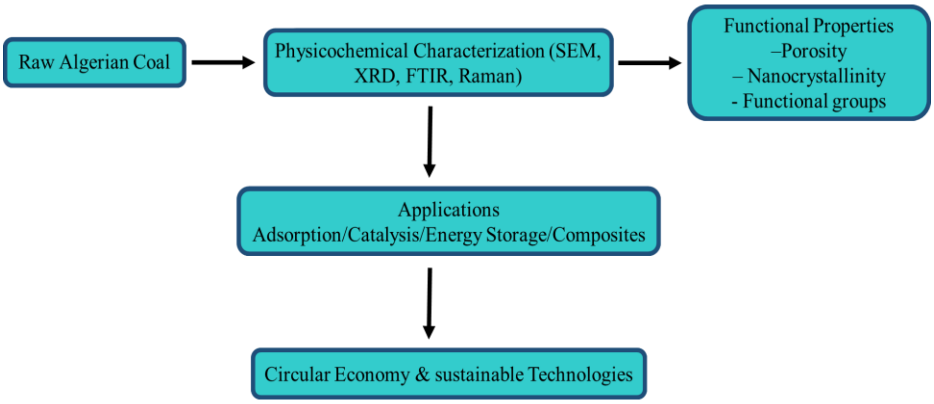

Figure 10. Conceptual framework: coal to circular economy applications.

6. Conclusions

Reinterpreted data confirm that Algerian coal offers nanoscale crystallinity, porosity, and functional chemistry. Presented in statistical and schematic forms, these features demonstrate clear application pathways in adsorption, catalysis, energy storage, and nanocomposites. Future work should include experimental validation of adsorption isotherms, electrode cycling tests, and composite performance, enabling Algerian coal to be positioned as a renewable nanocarbon resource within circular economy strategies.

Author Contributions: M.F. conceived and supervised the project, analyzed data, and prepared the original draft; Y.D. performed sample preparation, SEM analysis, and contributed to data interpretation; A.D. carried out FTIR spectroscopy, data acquisition, and figure preparation; S.N. conducted Raman spectroscopy, experimental validation, and structural interpretation; E.F.S. performed XRD measurements, Rietveld refinement, and crystallographic analysis; A.B. contributed to the literature review, application framework, and manuscript revision. All authors have read and agreed to the published version of the manuscript.

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