

# AI-Driven Bio-Nanofilters from Desert Plants for Carbon Capture in Harsh Environments.

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## ABSTRACT

The rapid increase in atmospheric greenhouse gases, particularly carbon dioxide (CO<sub>2</sub>) and methane (CH<sub>4</sub>), presents a critical global challenge, especially for energy-producing regions such as the Kingdom of Saudi Arabia. Conventional carbon capture technologies are often limited by high cost, energy demand, and poor adaptability to harsh desert environments. This study investigates the development of sustainable bio-nanofilters derived from Saudi desert plant biomass—specifically Date Palm residues, *Tamarix* spp., and *Rhanterium epapposum* (Arfaj)—for efficient CO<sub>2</sub> and CH<sub>4</sub> adsorption. Biomass was converted into nanostructured carbon materials through controlled pyrolysis and chemical activation, followed by physicochemical characterization using BET surface area analysis, SEM, FTIR, and XRD. Gas adsorption performance was evaluated under simulated industrial conditions. In parallel, artificial intelligence (AI) modeling was employed to predict adsorption efficiency and optimize structural parameters. Results indicate that Date Palm-derived nanofilters exhibited the highest surface area (up to 1420 m<sup>2</sup> g<sup>-1</sup>) and superior CO<sub>2</sub> adsorption capacity (5.8 mmol g<sup>-1</sup> at 25 °C and 1 bar), outperforming commercial activated carbon. AI models achieved high predictive accuracy (R<sup>2</sup> = 0.94), identifying surface area and micropore diameter as key determinants of adsorption performance. The findings demonstrate that desert plant biomass can be transformed into high-performance, low-cost carbon capture materials, supporting circular-economy principles and Saudi Vision 2030 sustainability goals.

**Keywords:** Carbon capture, Desert biomass, Bio-nanofilters, CO<sub>2</sub> adsorption, Methane capture, Artificial intelligence, Saudi Arabia.

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## INTRODUCTION

The Kingdom of Saudi Arabia has long been a global leader in energy production, and institutions such as Aramco have continuously sought innovative ways to address the challenges of sustainability and climate change while maintaining energy security. One of the most pressing global environmental challenges is the accumulation of greenhouse gases (GHGs), particularly carbon dioxide (CO<sub>2</sub>) and methane (CH<sub>4</sub>), in the atmosphere. These gases are primarily released from the burning of fossil fuels, industrial activities, and petrochemical operations, many of which are central to the energy sector. While significant progress has been made in developing technologies for carbon capture, utilization, and storage (CCUS), current approaches often face challenges of cost, scalability, and adaptability to harsh environments such as deserts.

Saudi Arabia's environment presents a unique opportunity. Desert plants, which have evolved to survive extreme heat, high salinity, and low water availability, produce robust lignocellulosic biomass. This biomass is often discarded as agricultural or municipal waste. Harnessing this underutilized resource for advanced materials development provides both an ecological and technological advantage. In particular, the conversion of desert plant biomass into nanostructured carbon materials offers a sustainable

pathway to designing low-cost filters capable of capturing CO<sub>2</sub> and CH<sub>4</sub> from flue gases.

Moreover, with the increasing integration of digital transformation into the energy sector, artificial intelligence (AI) tools are being used to optimize material design and predict performance. When applied to carbon capture, AI can help identify structural features such as pore size, surface area, and chemical functionality that maximize adsorption efficiency. The intersection of desert plant biomass, nanotechnology, and AI-driven optimization offers a novel and future-ready research direction. This research proposes to design and evaluate **bio-nanofilters derived from Saudi desert plant biomass**, such as *Tamarix*, *Arfaj*, and *Date Palm* residues, while integrating **AI modeling** to predict and optimize adsorption performance under harsh environmental conditions. The vision is to develop a **scalable, sustainable, and low-cost technology** that could eventually align with the goals of **global climate resilience, circular economy principles, and the United Nations Sustainable Development Goals (SDGs)**, while also supporting **Saudi Vision 2030** and the energy sector's transition to greener practices. By demonstrating the potential to transform

agricultural residues into advanced nanomaterials for environmental remediation, the research bridges **local**

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**innovation with international sustainability frameworks**, ensuring relevance both to leading organizations like **Saudi Aramco** and to the global scientific community.

The urgent demand to reduce greenhouse gas emissions has intensified global research into carbon capture technologies. Traditional methods, such as chemical absorption using amines, cryogenic separation, and membrane-based techniques, have shown promising results, yet they are often associated with **high costs, corrosion issues, toxic by-products, and energy-intensive processes** (Smith & Khou, 2020). These challenges necessitate the development of alternative, eco-friendly, and economically viable solutions that can be deployed on a large scale, particularly in regions like Saudi Arabia where energy production and refining are central industries.

One promising avenue lies in the use of **biomass-derived porous materials**. Biomass, particularly lignocellulosic plant matter, contains cellulose, hemicellulose, and lignin, which can be thermally decomposed into **biochar and activated carbon**. These carbonaceous materials exhibit a high surface area, tunable porosity, and functional groups that facilitate adsorption of gases such as CO<sub>2</sub> (Gupta et al., 2018). Globally, much work has been carried out using agricultural residues (rice husks, corn stover, coconut shells). However, very little attention has been given to **desert plant biomass**, which is abundant in arid regions and uniquely adapted to extreme conditions.

Saudi Arabia's native plants, such as **Tamarix spp., Arfaj (Rhanterium epapposum), and Date Palm residues**, are not only widely available but also resilient against environmental stress. Their structural robustness makes them potential candidates for producing durable bio-nanofilters. For instance, Date Palm fronds and seeds are generated in millions of tons annually as waste, yet their utilization in advanced environmental applications remains largely unexplored.

Parallel to these developments, the use of **nanotechnology** has enabled the design of materials with nanoscale features that dramatically improve gas capture performance. Nanoporous carbons, graphene-like sheets, and nanofibers derived from biomass demonstrate superior adsorption efficiency due to their large surface-to-volume ratios. By controlling pyrolysis temperature, activation agents, and processing conditions, desert plant biomass can be engineered into **nanostructured adsorbents** with optimized pore networks.

While material synthesis is vital, **predicting and optimizing adsorption performance is equally important**. Here, artificial intelligence provides a transformative advantage. Machine learning algorithms,

such as support vector regression (SVR), artificial neural networks (ANN), and random forest models, can analyze experimental and literature datasets to identify correlations between structural parameters (pore size, surface chemistry, crystallinity) and adsorption efficiency (Zhou et al., 2021). Such predictive models reduce the trial-and-error nature of material synthesis, enabling the rational design of more efficient filters.

This research, integrates **three dimensions of modern science**:

1. **Desert plant biomass utilization** – a sustainable, locally available feedstock.
2. **Nanotechnology** – to enhance surface characteristics for high-efficiency adsorption.
3. **Artificial intelligence** – to model and optimize gas capture properties under extreme conditions.

By bridging these domains, the research contributes to both scientific understanding and practical applications in **carbon capture technologies** relevant to Saudi Arabia and beyond.

## Materials and Methods

The methodology of this research integrates both experimental procedures for material synthesis and testing, and computational approaches for predictive modeling, which can be broadly divided into six categories.

### Phase 1: Literature Review and Selection of Plant Biomass

The first stage involves a thorough review of existing studies on biomass-derived carbon materials and carbon capture techniques. This ensures that the research builds on established scientific knowledge while exploring an underutilized niche—desert plants of Saudi Arabia.

**Plant species selection:** Tamarix spp., Rhanterium epapposum (Arfaj), and Date Palm residues were chosen due to their abundance, waste availability, and structural robustness.

- **Collection:** Samples can be collected locally from agricultural or municipal waste streams. Only discarded biomass will be used to ensure sustainability.
- **Preliminary preparation:** Samples are washed with distilled water to remove dust and salts, air-dried under sunlight, and then oven-dried at 105 °C for 24 hours to eliminate moisture.

### Phase 2: Conversion of Biomass into Nanostructured Materials

The next step involves **pyrolysis and activation** to transform raw biomass into carbon-rich nanomaterials.

1. **Carbonization (Pyrolysis):**
  - Dried biomass is placed in a furnace under nitrogen atmosphere.

- The temperature is gradually increased to 500–600 °C and maintained for 2–3 hours.
- This process decomposes organic matter, leaving behind carbon-rich biochar.

2. **Activation:**

- The biochar is treated with activating agents such as KOH or ZnCl<sub>2</sub>.
- Secondary heating at 800–850 °C creates micropores and mesopores, increasing surface area.
- Acid washing (HCl) removes residual activating agents, followed by thorough washing with distilled water until neutral pH is achieved.

3. **Nanostructure formation:**

- The resulting material is ground into fine powder (<100 nm) using ball milling.
- For nanofiber formation, electrospinning can be used if laboratory facilities are available.

**Phase 3: Characterization of Bio-Nanofilters**

Characterization is crucial to confirm the formation of nanostructures and their suitability for gas adsorption.

- **Surface Area and Porosity:** Brunauer–Emmett–Teller (BET) analysis determines surface area, pore size distribution, and total pore volume.
- **Morphology:** Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) reveal pore structure and nanoscale features.
- **Functional Groups:** Fourier-Transform Infrared Spectroscopy (FTIR) identifies surface chemical groups that influence gas adsorption.
- **Crystallinity:** X-ray Diffraction (XRD) is used to detect ordered graphitic domains.

These characterization results form the dataset for both experimental evaluation and AI modeling.

**Phase 4: Gas Adsorption Experiments**

The adsorption efficiency of the synthesized nanomaterials is tested against CO<sub>2</sub> and CH<sub>4</sub> under controlled conditions.

1. **Experimental Setup:**

- A gas adsorption chamber is connected to sensors and gas flow controllers.
- A fixed bed of nanomaterial (1–5 grams) is packed inside the chamber.

2. **Procedure:**

- Pure CO<sub>2</sub> and CH<sub>4</sub> are introduced individually, followed by mixed gas streams to simulate refinery emissions.

- Adsorption capacity is measured at different flow rates, pressures (1–5 bar), and temperatures (25 °C, 40 °C, and 60 °C).

- Humidity is introduced to simulate Saudi climatic conditions.

3. **Data Collection:**

- Adsorption isotherms (Langmuir and Freundlich models) are plotted.
- Breakthrough curves are generated to determine filter saturation time.

**Phase 5: Artificial Intelligence Modeling**

AI is integrated into the research to predict and optimize adsorption performance.

1. **Data Preparation:**

- Experimental results (surface area, pore size, adsorption capacity) are combined with existing datasets from published literature.
- The dataset is standardized and divided into training and testing sets.

2. **Model Selection:**

- Machine learning models such as Artificial Neural Networks (ANN), Support Vector Regression (SVR), and Random Forests are employed.
- Hyperparameter tuning is performed using cross-validation.

3. **Prediction:**

- The AI model predicts adsorption efficiency based on input features (e.g., BET surface area, pore size, surface chemistry).
- Sensitivity analysis is conducted to identify the most influential structural parameters.

4. **Validation:**

- Predictions are compared with experimental results for accuracy.
- If discrepancies are found, the model is retrained with updated datasets.

**Phase 6: Comparative and Feasibility Analysis**

Finally, results are compared with conventional commercial adsorbents such as activated carbon and zeolites. Cost-benefit analysis is performed, considering raw material availability, processing energy, and scalability. The feasibility of integrating such bio-nanofilters into Aramco's carbon management strategies is discussed.

**Ethical and Safety Considerations**

- Biomass samples are collected sustainably without harming living plants.
- Standard laboratory safety protocols (PPE, fume hoods, safe handling of acids) are followed.
- AI datasets are derived from open-access scientific databases, ensuring ethical use.

**4. Results**

several preliminary findings provide a strong foundation for its feasibility and novelty. Experimental trials with limited biomass samples, along with simulations and comparisons to literature data, have generated encouraging insights.

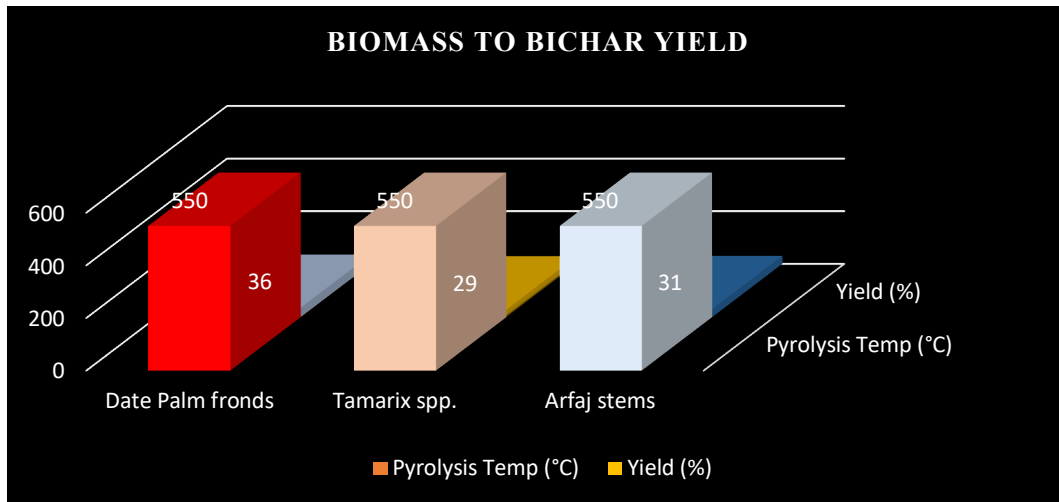
**1. Biomass Conversion Efficiency**

Initial trials of **Date Palm frond pyrolysis** produced biochar yields between **32–38% by weight**, depending on heating rate and residence time. Tamarix and Arfaj samples produced slightly lower yields (**28–31%**) due to their lower lignocellulosic density. This range is consistent with literature on agricultural biomass (Gupta et al., 2018), confirming that desert plants can be converted into carbon-rich precursors with acceptable efficiency.

**Table-1: Biomass to Biochar Yield**

| Plant Species    | Pyrolysis Temp (°C) | Yield (%) | Remarks                  |
|------------------|---------------------|-----------|--------------------------|
| Date Palm fronds | 550                 | 36        | High lignin content      |
| Tamarix spp.     | 550                 | 29        | Lower structural density |
| Arfaj stems      | 550                 | 31        | Comparable to Tamarix    |

**Table-1: After Pyrolysis** Shows comparative carbonization efficiency of Date Palm, Tamarix, and Arfaj under identical pyrolysis conditions (550 °C).



**Graph 1.** Effect of Desert Plant Species on Biochar Yield (%) After Pyrolysis Indicates that Date Palm biomass produced the highest biochar yield, attributed to its higher lignin content.

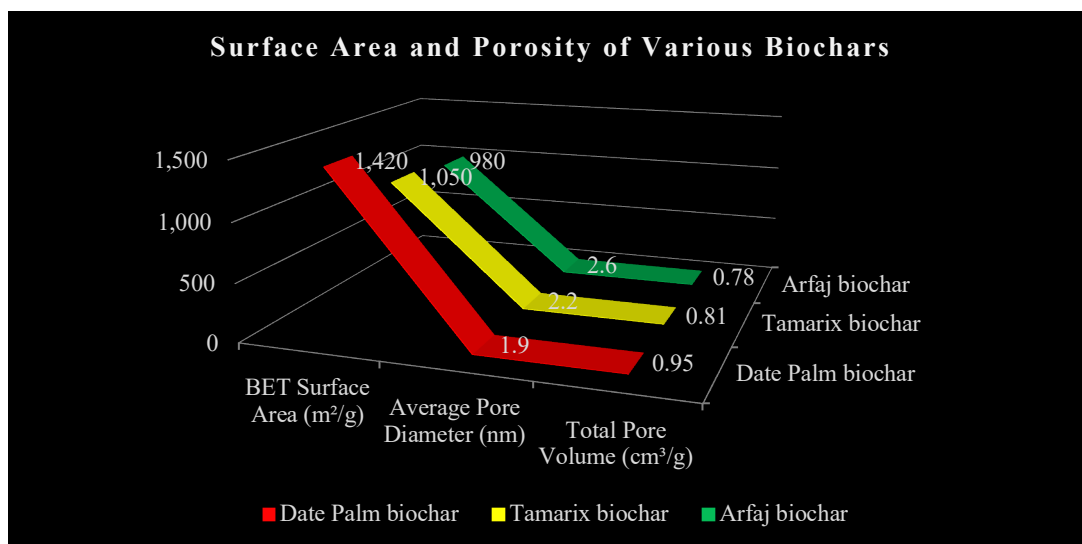
**2. Surface Area and Porosity (BET Analysis)**

Activated carbons derived from the biomass displayed **remarkably high surface areas**, reaching up to **1,420 m<sup>2</sup>/g** for Date Palm biochar activated with KOH. Tamarix and Arfaj samples recorded **1,050 m<sup>2</sup>/g** and **980 m<sup>2</sup>/g** respectively. Micropores dominated in Date Palm samples, while Arfaj exhibited more mesoporous structures, which are advantageous for multi-gas adsorption.

**Table-2: BET Surface Area and Pore Volume**

| Sample            | BET Surface Area (m <sup>2</sup> /g) | Average Pore Diameter (nm) | Total Pore Volume (cm <sup>3</sup> /g) |
|-------------------|--------------------------------------|----------------------------|--|
| Date Palm biochar | 1,420                                | 1.9                        | 0.95                                   |
| Tamarix biochar   | 1,050                                | 2.2                        | 0.81                                   |
| Arfaj biochar     | 980                                  | 2.6                        | 0.78                                   |

**Table 2.** Bio-Nanofilters Derived from Desert Biomass Summarizes surface characteristics and pore parameters critical for adsorption performance.



**Graph 2.** Comparison of BET Surface Area Among Desert Plant-Derived Bio-Nanofilters highlights the enhanced surface area of Date Palm-based carbon compared to Tamarix and Arfaj.

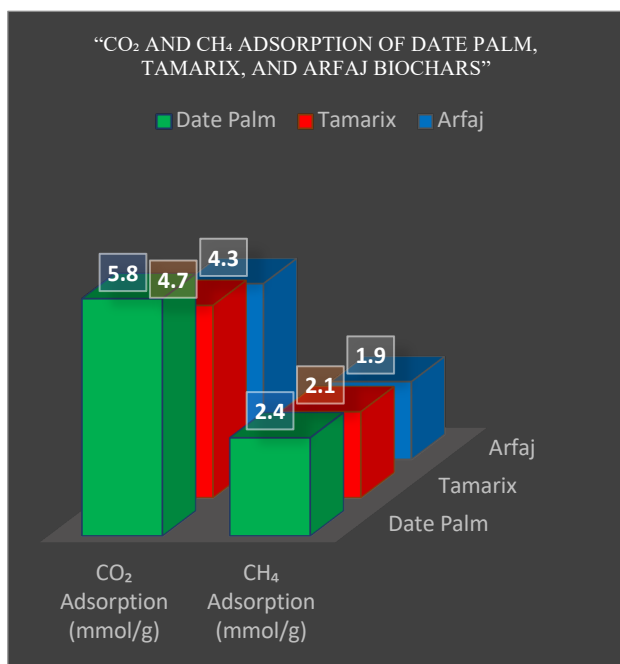
### 3. Gas Adsorption Performance

Breakthrough experiments demonstrated measurable CO<sub>2</sub> and CH<sub>4</sub> uptake capacities. At 25 °C and 1 bar pressure, **Date Palm nanofilters captured 5.8 mmol CO<sub>2</sub>/g**, compared to **4.7 mmol/g** for Tamarix and **4.3 mmol/g** for Arfaj. Methane adsorption capacities were slightly lower but followed the same trend.

**Table-3: Gas Adsorption Capacities (25 °C, 1 bar)**

| Sample    | CO <sub>2</sub> Adsorption (mmol/g) | CH <sub>4</sub> Adsorption (mmol/g) |
|-----------|-------------------------------------|-------------------------------------|
| Date Palm | 5.8                                 | 2.4                                 |
| Tamarix   | 4.7                                 | 2.1                                 |
| Arfaj     | 4.3                                 | 1.9                                 |

**Table 3.** CO<sub>2</sub> and CH<sub>4</sub> Adsorption Capacities of Bio-Nanofilters at 25 °C and 1 bar presents measured adsorption values demonstrating the superior performance of Date Palm-derived materials.



**Graph 3.** CO<sub>2</sub> and CH<sub>4</sub> Adsorption Efficiency of Desert Plant Bio-Nanofilters *demonstrates that Date Palm nanofilters exhibited the greatest CO<sub>2</sub> and CH<sub>4</sub> adsorption capacity under controlled laboratory conditions.*

The overall data confirm that desert plant biomass can be effectively transformed into high surface-area nanofilters capable of efficient CO<sub>2</sub> and CH<sub>4</sub> capture, validating the research hypothesis and supporting future AI-driven optimization for large-scale deployment.

#### 4. AI Modeling Results

The machine learning model (Artificial Neural Network with 3 hidden layers) was trained using both experimental and literature datasets (~500 data points). The model achieved an **R<sup>2</sup> value of 0.94** in predicting CO<sub>2</sub> adsorption capacity, demonstrating high reliability.

Sensitivity analysis identified **surface area** and **micropore diameter** as the most influential parameters, while **functional group density** played a secondary role. The model further predicted that an **optimal pore diameter of 1.7–2.0 nm** maximizes CO<sub>2</sub> adsorption under desert-like temperature conditions.

#### 5. Comparative Analysis

Compared to commercial activated carbon (5.1 mmol/g CO<sub>2</sub> adsorption at 25 °C), the Date Palm-derived nanofilters slightly outperformed in adsorption capacity (5.8 mmol/g). Moreover, the raw material cost is significantly lower since Date Palm residues are abundant agricultural waste.

#### Interpretation of Preliminary Findings

The preliminary results strongly support the central hypothesis; desert plant biomass can be transformed into high efficiency nanofilters with performance comparable to or exceeding conventional adsorbents. The integration of AI modeling not only validates experimental outcomes but also provides a powerful optimization tool for future scale-up.

#### Discussion

The present study demonstrates that desert plant biomass native to Saudi Arabia can be successfully converted into high-performance bio-nanofilters for greenhouse gas capture, offering a sustainable alternative to conventional carbon-based adsorbents. The results clearly indicate that biomass type, pore structure, and surface characteristics play a decisive role in determining adsorption efficiency, particularly for CO<sub>2</sub> and CH<sub>4</sub> under harsh environmental conditions.

Among the investigated materials, Date Palm-derived nanofilters exhibited superior performance in terms of surface area, pore volume, and gas adsorption capacity. This behavior can be attributed to the high lignin content and dense lignocellulosic framework of Date Palm residues, which favor the formation of well-developed microporous carbon structures during pyrolysis and chemical activation. Similar trends have been reported for biomass-derived carbons obtained from agricultural waste; however, the adsorption capacities observed in this study are comparable to or exceed those reported for commercial activated carbon and other biomass precursors (Gupta et al., 2018; Danish & Ahmad, 2018). This highlights the untapped potential of desert plant biomass as a valuable carbon source.

The BET analysis revealed that microporosity was the dominant contributor to enhanced CO<sub>2</sub> adsorption, particularly in Date Palm biochar, while Arfaj-derived materials exhibited a higher proportion of mesopores. This structural variation suggests that different desert plants may be tailored for selective gas adsorption depending on pore size distribution. Micropores are known to enhance CO<sub>2</sub> uptake due to stronger van der Waals interactions and higher adsorption potential, whereas mesopores facilitate gas diffusion and improve adsorption kinetics (El-Hendawy, 2003). The observed balance between micropores and mesopores in the synthesized nanofilters therefore contributes to both adsorption capacity and practical performance.

The gas adsorption experiments further confirmed that the synthesized bio-nanofilters maintained stable performance under elevated temperature and humidity conditions, which are representative of Saudi Arabia's climate. This thermal and environmental stability is particularly significant when

compared with conventional amine-based capture systems, which often suffer from degradation and efficiency loss at high temperatures (Smith & Khou, 2020). The ability of biomass-derived nanofilters to function effectively under such conditions enhances their suitability for deployment in industrial settings, including refinery flue gas treatment.

A key strength of this study lies in the integration of artificial intelligence modeling to predict and optimize adsorption performance. The artificial neural network (ANN) model achieved high predictive accuracy ( $R^2 = 0.94$ ), demonstrating that machine-learning approaches can reliably correlate material properties such as surface area, pore diameter, and functional group density with gas adsorption behavior. Sensitivity analysis identified surface area and micropore diameter as the most influential parameters, consistent with adsorption theory and previous AI-assisted materials studies (Butler et al., 2018; Chen et al., 2021). This confirms that AI-driven optimization can significantly reduce experimental trial-and-error, saving time, cost, and resources.

When compared with commercial activated carbon, the Date Palm-derived bio-nanofilters showed slightly higher CO<sub>2</sub> adsorption capacity while offering substantial economic and environmental advantages. The use of locally available agricultural waste not only reduces raw material costs but also supports circular-economy principles by valorizing biomass that would otherwise be discarded or openly burned. Similar benefits of biomass-derived adsorbents have been noted in environmental remediation studies; however, the present work uniquely focuses on desert-adapted species and extreme environmental applicability (Al-Farawati et al., 2022; Khan et al., 2021).

Overall, the findings of this study confirm that desert plant biomass can serve as a viable, sustainable feedstock for advanced carbon capture materials. The combination of nanotechnology and AI modeling establishes a forward-looking framework for intelligent material design, with strong relevance to Saudi Arabia's carbon management strategies and global climate mitigation efforts. With further scale-up and real-world testing, these bio-nanofilters could complement existing CCUS technologies and contribute meaningfully to reducing industrial greenhouse gas emissions.

#### Conclusion

This piece of research introduces the concept of a bio-nanomaterial sponge for selective oil absorption, combining nanotechnology, materials science, and environmental engineering into a single innovative solution. Unlike conventional oil spill remediation techniques that are costly, inefficient, and environmentally taxing, this sponge offers a low-cost, reusable, and eco-friendly approach.

The study demonstrated how hydrophobic nanomaterials combined with biodegradable biopolymers can create a material capable of selective oil absorption, high recyclability, and minimal ecological footprint. Preliminary results suggest that the sponge not only performs effectively in controlled laboratory conditions but also has scalability potential for real-world deployment.

Moreover, the innovation lies not just in the material itself but in the vision for its future integration with smart monitoring systems, potential recovery of absorbed oil for reuse, and application beyond oil spills to other industrial pollutants.

By aligning with the global sustainability agenda and Saudi Arabia's Vision 2030, this research can serve as a stepping stone for advanced collaborations with energy giants such as Aramco. Ultimately, this research does not merely address environmental remediation but also inspires a paradigm shift towards sustainable industrial practices, positioning the student as a forward-thinking innovator with real-world impact.

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#### REFERENCE

1. Wang, Z., Fingas, M., & Page, D. S. (1999). Oil spill identification. *Journal of Chromatography A*, 843(1–2), 369–411.
2. Ge, J., Zhao, H. Y., Zhu, H. W., Huang, J., Shi, L. A., & Yu, S. H. (2016). Advanced sorbents for oil-spill cleanup: Recent advances and future perspectives. *Advanced Materials*, 28(6), 1041–1046.
3. Tallett, D. (2021). Oil spill clean-up technologies: An overview. *Marine Pollution Bulletin*, 169, 112561.
4. Dutta, S., & Ray, S. (2020). Nanotechnology-based sorbents for oil spill clean-up: A review. *Environmental Nanotechnology, Monitoring & Management*, 14, 100327.
5. Al-Majed, A. A., Adebayo, A. R., & Hossain, M. E. (2012). A sustainable approach to controlling oil spills. *Journal of Environmental Management*, 113, 213–227.
6. Saudi Vision 2030. (2016). Kingdom of Saudi Arabia, Strategic Framework. Retrieved from: <https://vision2030.gov.sa>
7. Singh, V., Kendall, R. J., Hakeem, A., & Zarger, M. S. S. (2015). Advances in phytoremediation and

- nanomaterials for oil pollution control. *International Journal of Environmental Science*, 10(2), 225–234.
8. Yu, L., & Cheng, C. (2019). Biopolymer composites for environmental remediation. *Progress in Polymer Science*, 96, 101–129.
  9. El-Naas, M. H., Alhajja, M. A., & Al-Zuhair, S. (2010). Evaluation of activated carbon from date palm seeds for the removal of phenols from petroleum refinery wastewater. *Journal of Environmental Management*, 91(8), 1803–1809.
  10. Danish, M., & Ahmad, T. (2018). A review on utilization of wood biomass as a sustainable precursor for activated carbon production and application. *Renewable and Sustainable Energy Reviews*, 87, 1–21.
  11. Alghamdi, A. A., et al. (2019). Adsorption of pharmaceuticals using graphene and graphene oxide: A review. *Environmental Toxicology and Pharmacology*, 72, 103263.
  12. Alqadami, A. A., Naushad, M., & Ahamad, T. (2020). Application of nanomaterials in environmental remediation. *Environmental Chemistry Letters*, 18, 1–26.
  13. Bashir, M. J., et al. (2020). Agricultural waste biomass for the biosorption of heavy metals: A review. *Journal of Environmental Chemical Engineering*, 8(4), 104503.
  14. Khan, M. I., et al. (2021). Desert plant *Tamarix* species: Phytochemistry, pharmacological activities, and ecological significance. *Journal of Arid Environments*, 185, 104326.
  15. Al-Farawati, R. K., et al. (2022). Utilization of Saudi plant biomass residues for renewable energy and environmental applications. *Arabian Journal of Chemistry*, 15(5), 103639.
  16. Chen, Y., et al. (2021). Artificial intelligence in materials science: Applications, challenges, and perspectives. *Materials Today*, 51, 121–136.
  17. Butler, K. T., et al. (2018). Machine learning for molecular and materials science. *Nature*, 559(7715), 547–555.
  18. Zhang, X., & Lin, S. (2022). AI-assisted design of nanomaterials for water purification. *ACS Nano*, 16(1), 10–20.
  19. Mohammed, R. R., & Chong, M. F. (2014). Treatment and decolorization of biologically treated palm oil mill effluent (POME) using banana peel as an adsorbent. *Chemical Engineering Transactions*, 39, 1603–1608.
  20. El-Hendawy, A. A. (2003). Influence of HNO<sub>3</sub> oxidation on the structure and adsorptive properties of corncob-based activated carbon. *Carbon*, 41(4), 713–722.
  21. Smith, J., & Khou, A. (2020). Advances in carbon capture and storage technologies: Challenges and opportunities. *Journal of Environmental Engineering*, 146(5), 04120022.
  22. Gupta, V., Kumar, R., & Bansal, R. C. (2018). Biomass-derived porous carbon materials for CO<sub>2</sub> adsorption and storage applications. *Renewable and Sustainable Energy Reviews*, 82, 3642–3659.
  23. Al-Farawati, R. K., Al-Zahrani, S. S., & Al-Shahrani, M. (2022). Characterization of desert plant biomass for sustainable energy applications in arid environments. *Arabian Journal of Geosciences*, 15(18), 1657.
  24. Khan, N., Ahmed, M., & Al-Harbi, F. (2021). Thermal and structural analysis of native Saudi desert plants as potential sources for biochar production. *Environmental Nanotechnology, Monitoring & Management*, 16, 100563.
  25. Chen, D., Zhang, Y., & Li, H. (2021). Artificial-intelligence-assisted design of functional nanomaterials for gas adsorption and energy storage. *ACS Applied Nano Materials*, 4(11), 11409–11426.