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SYNTHESIS AND CHARACTERIZATION OF CARBON QUANTUM DOTS DERIVED FROM OIL PALM MESOCARP FIBRE EMBEDDED IN XEROGEL FOR CO_2 REMOVAL

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ABSTRACT

Malaysia's palm oil industry generates substantial quantities of lignocellulosic biomass residues, including oil palm mesocarp fibre (MF), which remain underutilised for high-value environmental applications. Concurrently, CO_2 emissions have increased by 10.74% over the past decade, underscoring the need for sustainable and low-cost carbon capture technologies, underscoring the need for sustainable carbon mitigation strategies. This study addresses these dual challenges by valorising MF, a lignocellulosic by-product, as a carbon precursor for CO_2 adsorbent development. Despite extensive research on carbon-based adsorbents, the instability of carbon quantum dots (CQDs) in aqueous systems and their limited application in fixed-bed CO_2 capture remain key research gaps. In this study, MF was valorised into nitrogen/sulfur/oxygen doped carbon quantum dots embedded within a xerogel matrix (X-N/S/O-CQDs-MF) via hydrothermal synthesis using thiourea and KOH as doping and activating agents. The research gap addressed lies in the limited understanding of how ternary-heteroatom doping, CQDs embedment, and process parameters collectively govern CO_2 adsorption mechanisms in biomass-derived CQD–xerogel systems. Among the synthesised formulations, X-N/S/O-CQDs-MF 133, prepared at an MF: thiourea: KOH ratio of 1:3:3 and a dilution ratio of 1:50, exhibited the highest CO_2 adsorption capacity of 583.56 mg/g, supported by a high quantum yield (36.86%), effective heteroatom incorporation, and a well-developed mesoporous structure (20–50 Å). Breakthrough experiments revealed best adsorption capacity performance at 30 °C and a total gas flow rate of 100 mL/min, with enhanced CO_2 uptake under dilute conditions (678.05 mg/g at 2 wt.% CO_2). Isotherm analysis showed that CO_2 adsorption followed the Redlich–Peterson model (R^2= 0.9991), indicating heterogeneous surface interactions involving both monolayer and multilayer adsorption. Kinetic data fitted well with the pseudo-second-order model (R^2 = 0.9935), indicating surface-controlled interactions consistent with chemisorption tendencies. However, the relatively low enthalpy change (ΔH = –8.75 kJ/mol) suggests that physisorption also contributes significantly. This supports a hybrid adsorption mechanism combining surface functional-group (i.e., (O–H, N–H, C–S) interactions (chemisorption) with weaker physical adsorption processes. Overall, this study demonstrates that xerogel-immobilised, heteroatom-doped CQDs derived from oil palm mesocarp fibre constitute a stable, tuneable, and effective CO_2 adsorbent, operating through a temperature-sensitive hybrid adsorption mechanism suitable for low-concentration gas streams.

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CHAPTER 1
INTRODUCTION

1.1 Research Background

Over the last decade (2010–2019), Malaysia observed a 10.74 % rise in CO_2 emissions per capita (Temitayo B et al., 2023). This has risen significantly due to rapid industrialization, urbanization, and increased energy and transportation demands exacerbating greenhouse gas emissions (Shamsul Azlan et al., 2023a). Rapid urbanization has resulted in higher population densities, increasing the demand for transportation and construction, thereby enhancing carbon footprints (Musarat et al., 2024). While Malaysia's regulatory frameworks encourage cleaner energy practices, implementing cost-effective CO_2 capture technologies remains critical to achieving its Paris Agreement targets, as emission reductions alone are insufficient to meet the 45 % cut by 2030 and net-zero goals by 2050 (Shamsul Azlan et al., 2023b). Various technologies have been proposed, such as chemical absorption (amine scrubbing), solid adsorption, cryogenic process and membrane separation process to mitigate CO_2 emissions (Kammerer et al., 2023). Adsorption has emerged as a promising CO_2 capture technology due to its high capacity (>85 %), cost-effectiveness, low regeneration energy requirements, and operational simplicity, achieving CO_2 purity levels above 95 % in post-combustion applications (Y. Wu et al., 2020; Yoro et al., 2021; Ziobrowski & Rotkegel, 2022).

Based on the Intergovernmental Panel on Climate Change (IPCC) special report in 2005, one of the CO_2 capture alternatives is CO_2 adsorption on a solid surface (Sepideh et al., 2015). Solid adsorbents offer a promising solution for CO_2 capture due to their inherent stability, safety, and scalability. Porous materials such as activated carbon and zeolites typically exhibit CO_2 adsorption capacities in the range of 3.3–5.0 mmol/g and 3.5–5.0 mmol/g respectively, while metal–organic frameworks (MOFs) commonly reported between 5.5 and 8.0 mmol/g. In contrast, inorganic sorbents such as clay mineral–based materials generally show much lower adsorption capacities (i.e., 3–15 mg CO_2/g) highlighting the better performance of porous carbonaceous and framework-based adsorbents for CO_2 capture applications (Chouikhi et al., 2019;