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# Synergistic effect of nitrogen and molybdenum on activated carbon matrix for selective adsorptive Desulfurization: Insights into surface chemistry modification



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**Abstract** This study reports the synthesis of mesoporous metal-modified nitrogen doped activated carbon (AC-N-Mo) from date seeds by  $\text{ZnCl}_2$  activation and its applicability for selective adsorptive desulfurization of dibenzothiophene (DBT). The AC-N-Mo exhibits higher adsorption capacity for DBT at 100 mg-S/L with the maximum removal percentage of 99.7 % corresponding to 19.94 mg-S/g at room temperature than the unmodified carbon with 17.96 mg-S/g despite its highest surface area and pore volume of  $1027 \text{ m}^2 \text{ g}^{-1}$  and  $0.55 \text{ cm}^3 \text{ g}^{-1}$  respectively. The adsorption capacity breakthrough follows the order AC-N-Mo > AC-Mo > AC > AC-N. Also, AC-N-Mo displays excellent selectivity in the presence of aromatics (toluene, naphthalene, and 1-methylisoquinoline). The enhancement in the DBT uptake capacities of AC-N-Mo is attributed to the synergistic effect of nitrogen heteroatom that aids the dispersion of molybdenum nanoparticles on carbon surface thereby improving its surface chemistry and promising textural characteristics. The kinetic studies showed that the DBT adsorption proceeds via pseudo-second order kinetics while the isotherm revealed that Langmuir fit the data more accurately for the adsorbents. The physical properties (surface area, pore volume, particle size, etc.) and chemical properties (carbon content, etc.) of as-prepared adsorbents namely; AC, AC-N, AC-N-Mo, and AC-Mo were characterized by  $\text{N}_2$ - physisorption, X-ray Diffraction (XRD), X-ray Photoelectron Spectroscopy (XPS), Scanning Electron Spectroscopy/Energy Dispersive Spectroscopy (SEM/EDS), Raman Spectroscopy (RS), Fourier Transform Infrared Spectroscopy (FTIR) and Ammonia-Temperature-Programmed Desorption ( $\text{NH}_3$ -TPD).

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## 1. Introduction

It is a reliable fact that the emission of sulfur compounds from transportation fuels poses a harmful impact on the environment as well as the psychological well-being of humans



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(Song, 2003). First, many sulfur compounds such as heavier thiophenes can cause cancer and genetic mutation upon human exposure to a particular level (Willey et al., 1981). Thiols can cause muscular spasms, unconsciousness and are known for their offensive odor that can cause breathing problems, headache, nausea, irritations to the eyes, the lungs, and the throat under the influence of long-term exposure to high concentration (Saleh et al., 2016). Sulfur compounds present in fuel present a severe threat to the flora and fauna and can combust to produce  $\text{SO}_x$  resulting in acid rain and contribute to the occurrence of photochemical smog (Hanif et al., 2020). It poisons catalytic converters used to reduce  $\text{CO}_x$  and  $\text{NO}_x$  in automotive engines and also causing numerous corrosion problems in pumping, pipeline, and refinery equipment (Muzic et al., 2008). Owing to the damaging impact of sulfur compounds, the regulatory authorities in many countries set stringent regulations to limit the concentration of sulfur present in industrial and transportation fuels, which becomes stricter with time. The highest permissible sulfur content has been set to 10 ppm and 15 ppm for gasoline and diesel oil respectively by the European Union (EU) and in countries like the USA and Japan (de Lima et al., 2018).

The conventional hydrodesulfurization (HDS) technology developed in the 1930s, is largely utilized in the refineries to remove compounds of sulfur available in crude oil distillates (Song, 2007). Although, HDS is an excellent desulfurization technology especially for disulfides, sulfides, thiols, and mercaptans, its activity towards thiophene and its alkylated derivatives is energy and cost-intensive, especially towards achieving ultra-deep desulfurization (Sadare and Daramola, 2019). HDS limitations also include severe operation conditions such as working at a higher pressure and elevated temperature of 3–7 MPa and 300–400 °C respectively, thereby resulting in excessive energy consumption. These drawbacks are unavoidable and involve significant capital investment, thus increasing fuels cost (Ghahramaninezhad and Ahmadpour, 2020). Several desulfurization technologies such as desulfurization by ionic liquids (ILs), adsorptive desulfurization (ADS), bio-desulfurization and oxidative desulfurization (ODS) have been adapted as an alternative and complementary process towards traditional HDS technology (Bhatia and Sharma, 2012; Ghahramaninezhad and Ahmadpour, 2020; Guo et al., 2019; Haghighi and Gooneh-Farahani, 2020; Rekos et al., 2020; Tireli et al., 2020). Meanwhile, ADS using porous adsorbents is gaining rising attention as an alternative to achieve ultra-deep desulfurization owing to its promising characteristics that include easy accessibility of adsorbents, renewability of spent adsorbents, workability at moderate temperature and pressure, low-energy consumption, thermal stability, and satisfying textural features like elevated surface area, desirable micropores volume as well as thoroughly developed pore size (Wang et al., 2009). Various sorbent materials used in adsorptive desulfurization studies have been reported. Among others, metal-organic frameworks (MOFs), zeolites, amorphous silica-alumina, activated carbon (AC), silica gel, metal oxides, sorbents were studied for desulfurization of fluid catalytic cracking feedstock, model oils, coker naphtha, and distillates (Ahmed and Jung, 2016; Namchot and Jitkarnka, 2016; Shi et al., 2010).

AC are carbonaceous materials specially treated to give a highly-developed internal pore structure and a large surface

area (Al-Qodah Z, Shawabkah, 2009). Oxidation of the carbon atoms present on the interior and exterior surfaces distinguished AC from the elemental carbon. The usage of non-renewable, high-cost precursors namely; peat, petroleum residue, lignite, bituminous coal, and wood make commercial AC expensive (Yahya et al., 2015). Thus, reasonably cheap, environmentally friendly, and desirable adsorbents have been investigated using agricultural by-products and waste as precursors for AC production. Several reported articles show how activated carbon surfaces were oxidized with the incorporation of metals to positively enhanced the adsorption efficiency of DBTs (Danmaliki and Saleh, 2017; Ganiyu et al., 2016; Olajire et al., 2017). It should be mentioned that surface chemistry modification and special treatments of AC that include both the physical and chemical modification of carbon surfaces and the treatments such as oxidation, steaming, sulfidation, acidification, metal loading, and metal-oxides incorporation play an essential role in adsorption capacity breakthrough as well as in the enhancement of carbon selectivity towards sulfur containing compounds (Ganiyu et al., 2016).

(Xiong et al., 2010) synthesized zirconium dioxide-modified activated carbon ( $\text{ZrO}_2/\text{AC}$ ) adsorbent and applied it for adsorptive removal of refractory sulfur compound DBT from simulated diesel oil. The adsorption capacity of  $\text{ZrO}_2/\text{AC}$  was found to outperform bare AC by a magnitude of 17 % and the spent  $\text{ZrO}_2/\text{AC}$  was found exhibited a higher adsorption capacity breakthrough than unmodified AC after recycling three times. The improved adsorption efficiency was ascribed to the surface acidic sites impregnated  $\text{ZrO}_2$ . Cerium-loaded activated carbon was prepared by (Xiong et al., 2012) and its applicability was studied for refractory sulfur compound removal from model fuel (dissolution of DBT in petroleum ether). The study confirmed that the cerium-loaded activated carbon showed higher adsorption selectivity and capacity for DBT compared to a virgin carbon attributed primarily to the enhanced active site created through surface chemistry modification. (Danmaliki and Saleh, 2017) prepared four composites named AC, AC/Ce, AC/Fe, and AC/Ce/Fe and were examined closely for the removal of organosulfur compounds of DBT, benzothiophene (BT), and thiophene (TP) in a simulated fuel. The research confirmed that AC/Ce/Fe exhibited improved adsorption efficiency with the sorbent performance in the order of  $\text{AC} < \text{AC/Fe} < \text{AC/Ce} < \text{AC/Ce/Fe}$ , despite the highest pore volume and surface area of 0.71  $\text{cm}^3/\text{g}$  and 460.27  $\text{m}^2/\text{g}$  respectively recorded for bare AC. This excellent performance of AC/Ce/Fe was attributed to the crystalline nature of iron and the acidic nature of cerium.

It is established that the electronic and surface features of carbon materials can be changed via the introduction of heteroatoms like phosphorus, oxygen, boron, and nitrogen (Fagury et al., 2014). Specifically, modification of carbon with nitrogen to form porous nitrogen-doped carbon and embedding other heteroatoms have gained significant attention in electrochemistry-related applications (supercapacitors fuel cell, batteries, photocatalysis, etc.), as well as in catalysis, separation, and water purification (Shen and Fan, 2013).

Carbon-doped porous boron nitride (C-BN) was investigated for the removal of a sulfur compound by Xiong and co-workers (Xiong et al., 2015). The porous C-BN showed higher adsorption efficiency for DBT as compared to boron nitride materials attributed to the stronger Lewis acid-base

interactions between C-BN and DBT molecule as well as the significant exposure of more atoms along the edges of the pores.

This study reports the usage of synthesized metal-modified nitrogen-doped AC adsorbent and its applicability to selective adsorptive desulfurization of model fuel containing the solution of dibenzothiophene in isooctane. The AC was prepared from agricultural waste material date seeds via  $\text{ZnCl}_2$  activation and subsequently treated with melamine to obtain nitrogen-doped carbon. Nitrogen as a doping agent offers new possibilities in the field of catalysis and due to its similarity to carbon, it can easily be inserted as heteroatoms to give a novel carbon nanostructure. Nitrogen instills an excellent electron density that could augment the catalytic performance due to the better dispersion of the active phase and the changes in the electronic properties (Dongil, 2019). Nitrogen also introduces a basic site for optimum reactant adsorption. Molybdenum nanoparticle is explored owing to its acidic nature and its tendency to form direct sulfur-metal interaction with the electron donor groups containing sulfur such as DBT. Selective performance of as-developed adsorbents was also investigated on DBT in the presence of other aromatics, namely: toluene, naphthalene, and 1-methylisoquinoline. The adsorbents were extensively characterized to obtain structure–activity performance concerning adsorbate-adsorbent interaction.

## 2. Experimental

### 2.1. Materials

Grinded Ajwa Al-Madina date seed was procured from a packaging factory in Saudi Arabia. Dibenzothiophene (99%), 1-methylisoquinoline, toluene were all purchased from Sigma Aldrich, while isooctane and melamine were from Fluka AG. Ammonium heptamolybdate tetrahydrate (molybdenum precursor) and zinc chloride were supplied by ACROS organics and BDH Ltd Poole England, respectively. Naphthalene was obtained from Fisher Scientific Company. Ultrapure distilled water was obtained in-house using ThermoScientific Barnstead NANOPURE, after initial distillation through Labstrong FiSTREEMTMII 2S Glass Still distiller.

### 2.2. Methods

#### 2.2.1. Activated carbon (AC) preparation from date seeds

Grinded Ajwa Al-Madina date seeds were used as a precursor for AC production by chemical activation. 5 g each of both  $\text{ZnCl}_2$  (activator) and precursor (pulverized date seeds) were measured and mixed in a beaker. 25 mL of distilled water was introduced into the mixture of date seeds and  $\text{ZnCl}_2$ , thoroughly agitated at room temperature (RT) for 2 h at 600 rpm. The temperature was increased to boiling point until dryness and the stirring was reduced to 400 rpm to allow homogeneity and prevent aggregation. The resultant mixture was transferred to an oven for further drying at 80 °C and left overnight. The resulting sample was pyrolyzed in a horizontal silica quartz-tube of diameter 60mmx1000mm length and inserted in an electric 1200 °C compact split tube furnace MTI (OTF-1200X-S) set at 950 °C using a heating rate of 5 °C/min, a flow rate of 300 mL/min and maintained at this temperature for 3 h

to allow the complete carbonization. Ultimately, the sample was cooled to room temperature under  $\text{N}_2$  (99.95%) at the same flow rate before it was removed from the furnace. The pristine activated carbon was therefore denoted as AC.

#### 2.2.2. Preparation of nitrogen-doped activated carbon (AC-N)

As-developed activated carbon and melamine were subjected to solid-state impregnation and thermal spreading by direct mixing of the duo in the ratio of 2 to 1 by weight (melamine/AC = 2). The sample mixture was heated up to 900 °C at 10 °C/min under  $\text{N}_2$  (99.95%) for a hold time of 2 h. The resulting sample was cool to RT under  $\text{N}_2$  at the same flow rate before it was removed from the furnace.

#### 2.2.3. Synthesis of Mo-modified nitrogen-doped carbon (AC-N-Mo) and Mo-loaded activated carbon (AC-Mo)

2.5 wt% molybdenum was loaded into nitrogen-doped AC via solid-state impregnation and thermal spreading. This is achieved by direct mixing of 0.023 g of molybdenum ( $(\text{NH}_4)_6\text{Mo}_7\text{O}_{24} \cdot 4\text{H}_2\text{O}$ ) with 1.0 g of AC-N and the resultant mixture was treated under the continuous flow of  $\text{N}_2$  (99.95%) and was heated up to 600 °C at 10 °C/min for a hold time of 1 h. To obtain Mo-loaded activated carbon (AC-Mo), the above procedure was repeated using virgin AC.

### 2.3. Characterization of as-synthesized adsorbents

#### 2.3.1. BET analysis

Surface area and pore volume analysis of the adsorbent was determined by  $\text{N}_2$  adsorption–desorption isotherms by employing BET and BJH-adsorption methods respectively. Samples were analyzed at the boiling point of liquid nitrogen (-196 °C), on a Micrometrics ASAP 2020 equipped with chemisorption set (Micrometrics, USA) after degassing at 300 °C for 3 h (ramping at 10 °C/min) to remove impurities and moisture under vacuum.

#### 2.3.2. X-ray diffraction (XRD)

X-ray Diffraction analysis was done on Rigaku Ultima IV X-ray diffractometer using  $\text{K}\alpha$  radiation of Cu by recording the adsorbents diffraction pattern at  $2\theta$  angle between 10° to 60°, and stepwise of 0.03. The operation was conducted at 40 kv and 40 mA with a scan rate of 3°/min.

#### 2.3.3. Fourier transform infrared spectroscopy (FT-IR)

Surface functional groups of the prepared adsorbents were investigated by FTIR using Thermo Scientific Nicolet™ 6700°FT-IR spectrometer model equipped with deuterated triglycine sulfate detector and OMNIC program. Samples were pelletized with the aid of KBr in right proportion (2: 100 of sample to KBr) in an agate mortar, and spectra were obtained while correcting for the background noise and recorded by adding 64 scans with a resolution of 2  $\text{cm}^{-1}$  at scanning range of 400–4000  $\text{cm}^{-1}$ .

#### 2.3.4. Scanning electron microscopy coupled with energy dispersive x-ray (SEM-EDX)

SEM analysis was carried out at an accelerating voltage of 30 kV using secondary electron (SE) and backscattered electron (BSE) mode on the adsorbents to investigate porosity

development with high vacuum Thermo Scientific™ Quattro ESEM equipped with an electron gun and attached to EDS (Oxford, Inc.). EDS was employed for the identification of elemental composition in and on the surface of the sample for qualitative information.

### 2.3.5. X-ray photoelectron spectroscopy (XPS)

XPS, 250Xi ESCALAB Thermo Scientific equipped with (PHI 5000 Versa Probe II, ULVAC-PHI Inc.) using Al K $\alpha$  as the radiation source. Samples were prepared by mixing the adsorbent with ethanol in drop-wise addition of the solvent, then deposited on glass with the aid of pipette and allowed to air-dry. The samples were mounted on the carbon tape and vacuum before XPS analysis at  $9 \times 10^{-8}$  mBar as analysis chamber vacuum, and deconvolution of peaks was done by Advantage software with adventitious carbon correction at 284.8 eV.

### 2.3.6. Raman spectroscopy (RS)

RS analysis was conducted on the prepared adsorbents using (iHR320 with CCD detector, HORIBA) to analyze functional groups fingerprint on the adsorbents with regards to graphitization or amorphous nature by measuring the energy released from scattered photons when the adsorbents were exposed to monochromatic light from a wavelength (300 mW, green laser), laser (532 nm) observed via rotational, translational and vibrational modes produced.

### 2.3.7. Ammonia temperature programmed desorption (NH<sub>3</sub>-TPD)

NH<sub>3</sub>-TPD was conducted to understand and analyze the acidic sites that are present on the adsorbent surface. This analysis (performed on Micromeritics AutoChem II 2920, Chemisorption Analyzer) was conducted by loading roughly 100 mg of the adsorbents in a quartz tube sealed with cotton wool. Before the analysis, samples were degassed at 100 °C for 30 min in a stream of helium (20 mL/min) to remove water vapor. Thereafter, the temperature was raised to 500 °C at a ramp rate of 10 °C/min and held at that temperature for 1 h to remove strongly bound species. The samples were subsequently cooled to 100 °C under the fixed flow of helium gas. The adsorption process begins by saturating the samples with 10 wt% NH<sub>3</sub> gas for 30 min at 100 °C at the flow rate of 30 mL/min and the excess NH<sub>3</sub> was expelled by flushing with helium gas for 60 min at the same temperature. Subsequently, the temperature was raised to 900 °C at 10 °C/min, and under these conditions; the amount of ammonia desorbed at the ramping temperatures was recorded using the thermal conductivity detector (TCD).

### 2.4. Adsorption experiment

To evaluate the adsorptive performance of the adsorbents, ADS of a simulated fuel was conducted in batch mode using DBT as a model sulfur compound. Various concentrations (50 – 200 mg-S/L) of DBT in isooctane were prepared. In a typical run, 20 mL of the simulated oil of each concentration and adsorbent amounts range from 0.025 g to 0.1 g were added in a capped vial and then subjected to continuous constant shaking at the rate of 600 rpm on a magnetic stirrer (IKA RT 10) maintained at room temperature (25 °C  $\pm$  0.1 °C)

for a fixed time interval of 24 h maximum. The sampling was done at 15 min intervals for the first 30 min using a syringe coupled with a membrane filter for the determination of residual DBT concentration evaluated by gas chromatography (Agilent 7890A) coupled with SCD (Agilent 355) within the experimental error of 2 %. To compare and study the adsorptive selectivity for organo-sulfur and nitrogen compound, a model diesel fuel containing naphthalene (5 vol%), toluene (5 and 10 vol%), and 1-methylisoquinoline (100 mg/L) were prepared in a mixture solvent of DBT and adsorption studies were conducted. The adsorption experiments were repeated three times.

The DBT adsorption ( $q_e$ , mg/g) at equilibrium was calculated with the formula stated below;

$$q_e = (C_0 - C_e) \frac{V}{W} \quad (1)$$

Where V measures in liter and represents the volume of model fuel solution, W (g) denotes the weight of the adsorbent, and  $C_0$  (mg/L) and  $C_e$  (mg/L) are initial and equilibrium sulfur concentration respectively.

## 3. Results and discussion

### 3.1. Surface area and porosity

AC is usually microporous material thus limiting their application to studies involving small molecules such as methanol production from CO<sub>2</sub> and hydrogen (Abotsi and Scaroni, 1989). Recent applications of activated carbon require a higher percentage of mesoporosity to facilitate diffusion of larger molecules to attain effective adsorption efficiency (By Zhonghua Hu, Madapusi P. Srinivasan and Ni, 2000). Thus, commendable efforts have been directed towards s for extensive applications (Moosavi et al., 2012). The nitrogen adsorption-desorption isotherm of AC, AC-N, AC-N-Mo, and AC-Mo are shown in Fig. 1. A. The samples show typical type IV isotherms with an H4 hysteresis loop by IUPAC classification (K. S. W. Sing, D. H. Everett, R. A. W. Haul, L. Moscou, R. A. Pierotti, J. Rouquérol, 1985). H4 loops are often found in micro-mesoporous carbon (K. S. W. Sing, D. H. Everett, R. A. W. Haul, L. Moscou, R. A. Pierotti, J. Rouquérol, 1985). It was observed that the four samples showed a low uptake of nitrogen at relative pressures below 0.1 indicating the availability of micropores within the samples. A hysteresis loop was also seen at high relative pressure between 0.4 and 1, indicating mesoporosity (Danmaliki and Saleh, 2017; Min and Harris, 2006). Table 1 summarizes the textural properties of all prepared adsorbents. The pure AC has the highest surface area of 1026.77 m<sup>2</sup>/g with almost 70 % mesoporosity. Doping of nitrogen and loading of Mo onto AC's surface drastically lowered the pore volume and the overall surface area but increased mesoporosity to about 72 %. AC-Mo gave the least pore volume and surface area as evidenced in Table 1. This reduction in the surface area and pore volume is as a result of pore blockage (Ganiyu et al., 2016). It can be noticed additionally from Table 1 that AC has the highest surface area and was calcined only at once in the preparation. However, the other modified AC samples were calcined over twice in their preparation. The additional calcination

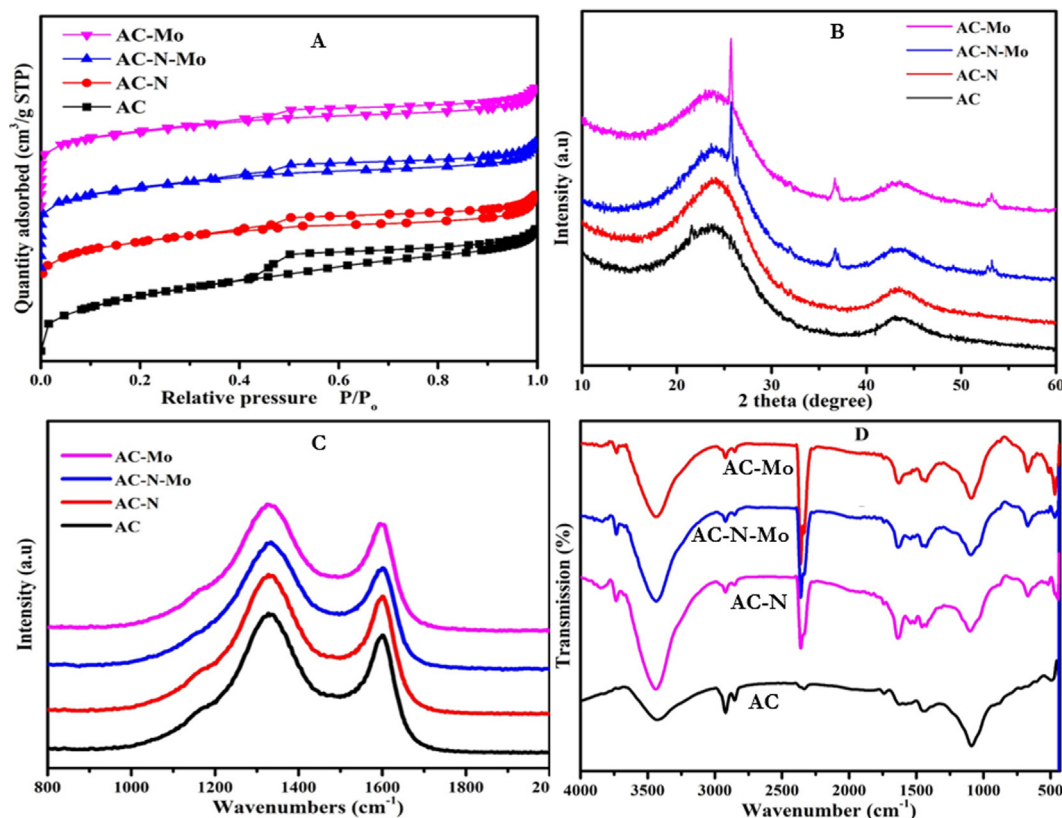


Fig. 1 (A)  $N_2$  sorption isotherms (B) XRD (C) Raman and (D) FTIR of adsorbents.

and annealing may also affect the porosity and ID/IG value of modified AC samples.

### 3.2. XRD pattern of parent activated carbon and the treated AC

XRD is a crucial characterization tool often employed for phase identification of unknown crystalline materials (e.g. minerals, inorganic compounds). Atom has a clear-cut diffraction pattern that is seen upon exposure to an X-ray beam. It is obvious from the Fig. 1. B below, indicating XRD patterns of AC, AC-N, AC-N-Mo, and AC-Mo that all the adsorbents showed a broad diffuse peak at  $2\theta$  around  $24^\circ$  and  $43^\circ$ , assigned to the (002) and (100) reflection planes, indicating the amorphous nature of the ACs (Mahadevan et al., 2012). These peaks resulted from the pores created due to carbon decomposition in the direction of graphitic structures that

proved semi-crystalline nature (Danmaliki and Saleh, 2017). Also, the AC crystallite structure is characterized by the interlayer spacing ( $d_{002}$ ) (Roh, 2008). The (100) reflection correlates with the honeycomb structure formed by  $sp^2$  hybridized carbon (Geng et al., 2011). However, heteroatom (N) activation of activated carbon causes defect sites and modification in the carbon lattice thereby boosted the crystallinity of treated ACs and this agrees with the result of FTIR analysis as evidenced in the intensity of C-N and C = N ( $1640\text{ cm}^{-1}$  and  $1564\text{ cm}^{-1}$  respectively). In addition, the corresponding peaks of Mo on the adsorbents AC-N-Mo and AC-Mo were assigned accordingly. The intensity diffraction peaks of Mo at  $2\theta (^{\circ}) = 25.7$  and  $53.2$  are typical of  $MoO_3$  and the low-intensity diffraction peak at  $2\theta = 37^\circ$  is typical of  $\beta\text{-}Mo_2C$  following Joint Committee on Powder Diffraction Standards (JCPDS N 11-0680) (Puello-Polo et al., 2014). This further

Table 1 Surface area and pore characteristics.

| Adsorbents | BET surface area ( $m^2/g$ ) | Microporous surface area ( $m^2/g$ ) | Mesoporous surface area ( $m^2/g$ ) | Microporous pore volume ( $cm^3/g$ ) | Total pore volume ( $cm^3/g$ ) | Average pore size (nm) | $R = I_D/I_G$ |
|------------|------------------------------|--------------------------------------|-------------------------------------|--------------------------------------|--------------------------------|------------------------|---------------|
| AC         | 1027                         | 313                                  | 714                                 | 0.14                                 | 0.55                           | 2.14                   | 1.17          |
| AC-N       | 886                          | 300                                  | 636                                 | 0.11                                 | 0.48                           | 2.18                   | 1.20          |
| AC-N-Mo    | 885                          | 251                                  | 634                                 | 0.11                                 | 0.48                           | 2.20                   | 1.22          |
| AC-Mo      | 830                          | 236                                  | 594                                 | 0.10                                 | 0.45                           | 2.18                   | 1.19          |

showed that Mo was successfully loaded on carbon surfaces. These Mo peaks are confirmed in the XPS and  $\text{NH}_3$ -TPD results.

### 3.3. Raman Spectroscopy of AC and modified sorbents

Two clear G-band and D-band peaks corresponding to  $E_{2g}$  and  $A_{1g}$  respectively are observed in the Raman spectra of untreated activated carbon (AC) and modified activated carbons AC-N, AC-N-Mo, and AC-Mo with the first peaks at ( $1595\text{ cm}^{-1}$ ), the G-peak ascribed to the scattering peak of graphite and the D-band peak near ( $1340\text{ cm}^{-1}$ ) is seen as a result of the disordered arrangement, lattice defects and low symmetry carbon structure of graphite (Liu et al., 2017) (Fig. 1C). These two sharp peaks suggested that AC material contains typical amorphous structures and is confirmed by the XRD results as indicated by broad diffuse peaks observed around  $24^\circ$  assigned to (002) seen in amorphous carbon. The degree of graphitization can be estimated to D-peak intensities relative to G-peak intensities using the below expression

$$R = \frac{I_D}{I_G} \quad (2)$$

Where  $I_D$  and  $I_G$  represent D-band and G-band intensity respectively and  $R$  denotes the degree of graphitization. The higher the degree of graphitization, the smaller the  $R$  value (Liu et al., 2017). The same pattern was observed in the Raman spectral of all the prepared samples describing an indication of qualitative existence of the disordered structure, a popular characteristic for AC materials (Roh, 2008). Synthesized adsorbents AC, AC-N, AC-N-Mo, and AC-Mo have  $R$  values corresponding to 1.17, 1.20, 1.22, and 1.19 respectively. This shows that AC and AC-Mo have a higher degree of graphitization with little or no defects.

### 3.4. Fourier transform infrared spectroscopy (FTIR)

A non-destructive spectroscopy technique such as FTIR is usually employed to show the energy level of the substance, atomic or molecular structure via electromagnetic interaction effect (Munajad et al., 2018). FTIR analysis as presented in Fig. 1D gave chemical identification about the characteristics of functional groups using an infrared spectrum the materials absorbed. All the spectral follow a similar pattern except that slight changes were observed in the peak intensities of some functional groups that are within expectations. The medium sharp peak at  $3734\text{ cm}^{-1}$  is attributed to the O-H stretching vibration of free alcohols (Tironi et al., 2012). The strong broad band observed at  $3430\text{ cm}^{-1}$  in all the samples was assigned to O-H stretching vibrations of hydroxyl or carboxylic group or perhaps due to chemisorbed water (Danmaliki and Saleh, 2017). Similarly, well-resolved sharp peaks were seen in all the adsorbents at  $2852\text{ cm}^{-1}$  and  $2920\text{ cm}^{-1}$  associated to aliphatic C-H stretching vibration of  $\text{CH}$ ,  $\text{CH}_2$ , and  $\text{CH}_3$  (Danmaliki and Saleh, 2017). A characteristic sharp and strong peak of  $\text{O}=\text{C}=\text{O}$  was also observed at  $2360\text{ cm}^{-1}$ . The broad peak observed at  $1735\text{ cm}^{-1}$  is assigned to the  $\text{C}=\text{O}$  stretching vibration of six-membered ring lactones (Coates, 2006). The medium peak at  $1640\text{ cm}^{-1}$  and  $1564\text{ cm}^{-1}$  can be ascribed to C-N and  $\text{C}=\text{N}$  heterocycles (Lan et al., 2019). This medium peak is

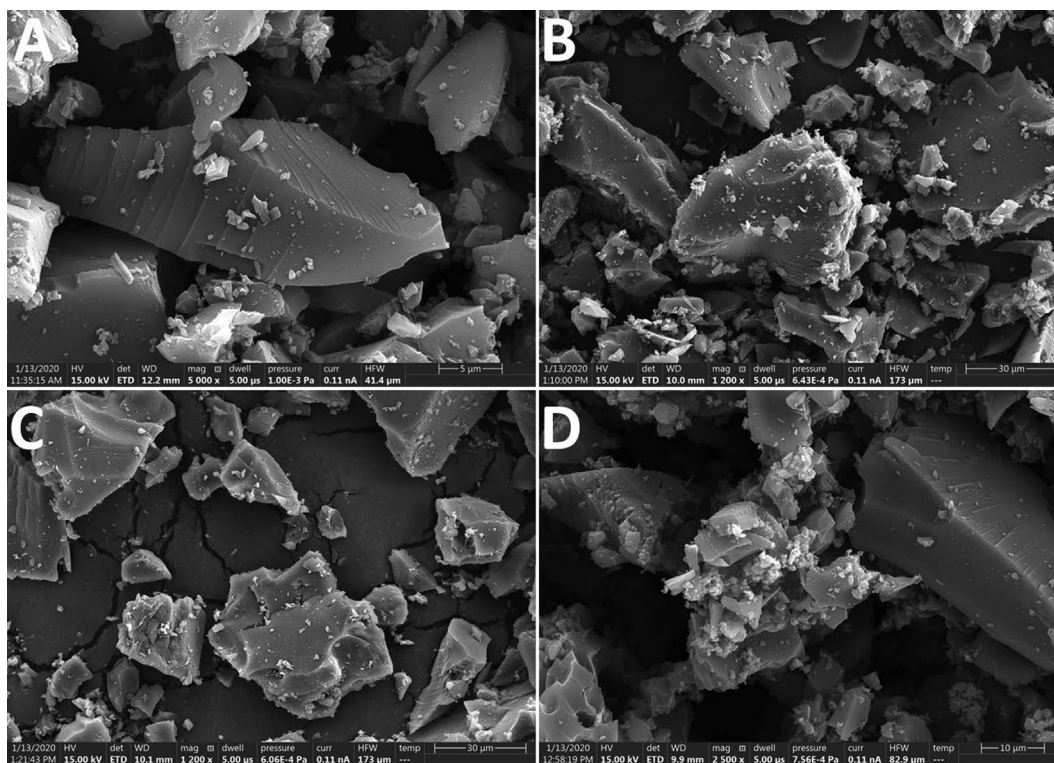
pronounced only in AC-N and AC-N-Mo such that it further supports the dispersion of heteroatom (N) on carbon surfaces. The peak at  $1090\text{ cm}^{-1}$  is a characteristic of amorphous carbon and is attributed with C-O stretching vibration (Danmaliki and Saleh, 2017). This is why parent AC gave the highest intensity of this peak but upon modification, with N and Mo, the intensities decreased. The peak at  $690\text{ cm}^{-1}$  corresponds to the C-H bend of mono-substitution (phenyl) (Coates, 2006) and these peaks are only observed in all the adsorbents except in pure carbon, indicating that the modification on carbon increased the acidic sites on carbon surfaces. The last peak at the fingerprint region is centered at  $468\text{ cm}^{-1}$  and is assigned to bending mode on Mo-O-Mo vibration entity (Ivanova and Kolev, 2011). These peaks were observed only in AC-N-Mo and AC-Mo and reflect that Mo was successfully loaded on carbon surface. This result is in close proximity with the result obtained in XRD, XPS, BET/EDS, and TPD as it confirms the presence of oxygen-containing functional groups.

### 3.5. SEM and EDS of as-synthesized sorbents

The porosity and elemental composition of the prepared adsorbents were examined with SEM/EDS, and the micrograph of the synthesized adsorbents are presented in Fig. 2, and Fig. SI-1. These adsorbents show differences in the degree and nature of porosity owing to modification of surface chemistry of AC-N, AC-N-Mo, and AC-Mo when compared with pure AC derived from date seeds. AC is a diverse adsorbent containing up to 90 % carbon with a unique property of high surface area and a high degree of porosity (Yahya et al., 2015), and this fact was seen to hold in all the adsorbents, as above 90 wt% carbon were recorded in all. Fig. 5. (a) shows carbon and oxygen corresponding to parent AC from date seeds. It has the highest oxygen content of 5.1 wt% but slightly decreases upon nitrogen and metal content loading on the surface of the adsorbent due to the deposition of nanoparticles. Dispersion of heteroatom (N) and Mo on the AC surface increased the porosity as observed in the corresponding SEM micrograph and this agrees with the BET and FTIR results. It is also obvious from the EDS result that nitrogen and metal loading for AC-N-Mo have 2.8 wt% and 1.1 wt% respectively, an indication of sufficient dispersion of heteroatom (N) and successful metal loading. The EDS mapping (not shown) shows that both N and Mo are uniformly distributed yet devoid of particles agglomeration. Thus, further explained why AC-N-Mo appeared as the best performing adsorbent.

### 3.6. X-ray photoelectron spectroscopy (XPS)

The XPS analysis of pure carbon and modified mesoporous carbon (AC, AC-N, and AC-N-Mo,) presented in Fig. 3. (a, b, and c) respectively prove the presence of C, N, O in all the as-developed adsorbents. Additionally, Molybdenum peaks were also seen in the AC-N-Mo and AC-Mo. Two different peaks were observed in the deconvoluted spectrum of carbon in all the adsorbents with the binding energy peaks at 284.5 and 283 eV respectively. The peaks at 284.5 eV correspond to the C-C bond ( $\text{sp}^2$ ) (Velo-Gala et al., 2014) but the second C1s peak at 283 eV is also  $\text{sp}^2$  carbon but shifted to lower BE. The deconvoluted nitrogen spectrum N1s also shows



**Fig. 2** SEM images of adsorbents (A) AC (B)AC-N (C) AC-N-Mo and (D) AC-Mo.

one nitrogen state for AC-N at 396 eV corresponding to nitride nitrogen and three different nitrogen states were seen in the deconvoluted spectrum of AC-N-Mo adsorbent at N1s (398 eV), N1s (396 eV), and N1s (401.6 eV) which correspond to pyridinic N, nitride nitrogen and graphitic nitrogen (N-C = O) respectively (Kim et al., 2012; Moulder et al., 1992; Fu et al., 2016). The AC, AC-N, and AC-N-Mo adsorbents show O1s peak at 530.9 eV, 530.8 eV 531 eV respectively, all were attributed to the oxygen bond state in C = O in quinones, carbonyl group (Moulder et al., 1992; Velo-Gala et al., 2014). In the AC-Mo adsorbent, the O1s peak was observed at 530.2 eV assigned to the oxygen bond state in metal oxide Mo-O. The Mod3 deconvoluted spectrum of AC-N-Mo shows three Mo chemical states 227.8 eV, 230.8 eV, and 233 eV correspond to molybdenum states in Mo<sub>2</sub>C, MoO<sub>3</sub>, and (NH<sub>4</sub>) MoO<sub>4</sub> respectively. As shown in **Table SI-1** AC-N-Mo has the highest oxygen percent. This further supports the reason AC-N-Mo showed the best adsorption capacity towards the DBT. These results confirmed that the adsorption capacity breakthrough of AC-N-Mo is also due to the attachment of oxygen containing functional groups onto the carbon surface.

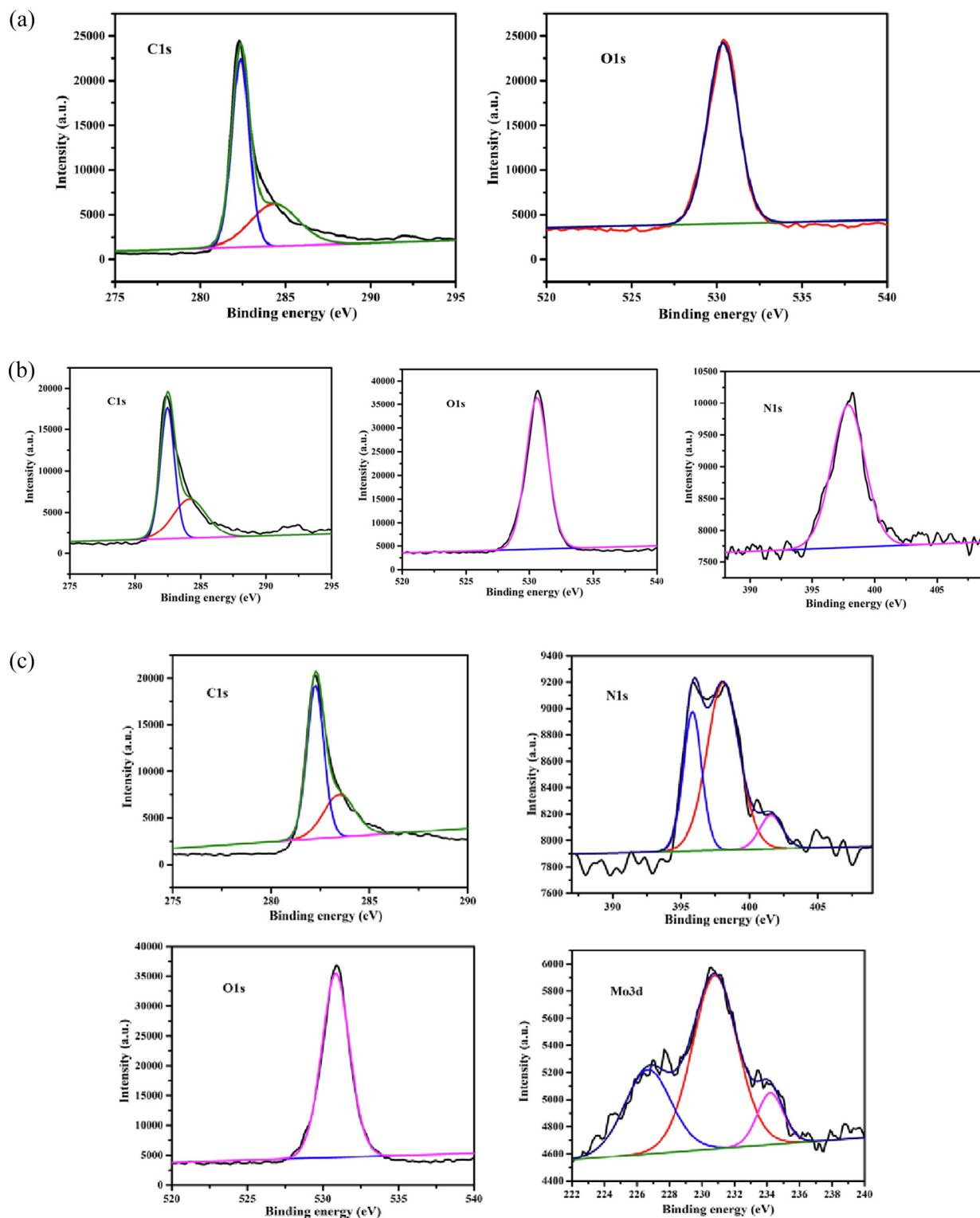
### 3.7. Surface acidity by ammonia-temperature-programmed desorption (NH<sub>3</sub>-TPD)

**Fig. SI-2** presents the NH<sub>3</sub>- TPD profile of as-prepared adsorbents for the determination of surface acidity. The desorbed ammonia at three temperature ranges of 200–300 °C, 400–600 °C, and 800–1000 °C correspond to NH<sub>3</sub> desorption on weak, moderate, and strong acid sites respectively (Glorius et al., 2018; Tanimu et al., 2019). Adsorbent bare AC exhibits two broad desorption peaks at 410 °C, and

844 °C describing two acidic sites of different strength where the former low-temperature NH<sub>3</sub> desorption acid site corresponds to lower strength and the later high-temperature NH<sub>3</sub> desorption represents strong acid sites corresponding to both Lewis and Brønsted acidic sites. Similarly, a single broad diffuse peak is observed at 485 °C for the adsorbent AC-N. This peak is attributed to moderate acid sites. In contrast, AC-N-Mo showed three peaks at 421 °C, 856 °C, and 935 °C. The broad diffuse peak at low temperature 421 °C is ascribed to moderate acid sites and the peak at narrower elevated temperature 856 °C and 935 °C correspond to the strongest Lewis and Brønsted acidic sites on the carbon surfaces (Lónyi and Valyon, 2001; Ganiyu et al., 2017). The carbon composite AC-Mo also displayed three broad desorption maxima at 214 °C, 400 °C, and 847 °C corresponding to acid sites of low, medium, and strong acidic strength respectively. **Table SI-2** enumerates the calculated acidic sites where we have AC-N-Mo exhibited the strongest acidic sites of 1.84 mmol/g at STP attributed to the synergy effect of nitrogen heteroatom and hence aided well dispersion of weakly acidic molybdenum nanoparticles on carbon surface (Mabena et al., 2011). This further provides a clear picture why AC-N-Mo gave higher enhancement of the DBT uptake.

### 3.8. Adsorption evaluation of the developed adsorbents

Adsorption efficiency of pure AC, AC-N, AC-N-Mo, and AC-Mo was studied in a batch system at room temperature (RT) as a function of time for a simulated diesel fuel composed of isooctane and 100 mg-S/L DBT. The effect of carbon surface modification with a heteroatom (N) and molybdenum was also observed for efficient DBT removal at the initial concentration



**Fig. 3** (a). XPS spectra of C1s and O1s in pure AC, (b). XPS spectra of C1s, O1s, and N1s in nitrogen modified AC (AC-N), (c). XPS spectra of C1s, O1s, N1s, and Mo3d in AC-N-Mo.

of 100 mg-S/L. It is obvious from Fig. 4. A that more than 70 % of DBT is adsorbed by as-prepared adsorbents in the first 60 min of equilibration. A relatively much slower adsorption process that continues to 24 h is observed after the fast adsorp-

tion process of the first 60 min. At 24 h, DBT uptake reaches a constant value of approximately 90 % for AC, AC-N, and AC-Mo while AC-N-Mo reached a climax value of 99.7 %. Thus, 24 h was taken as equilibrium contact time. The adsorp-

tion capacity of AC, AC-N, AC-N-Mo, and AC-Mo at 24 h correspond to 17.96 mg-S/g, 17.84 mg-S/g, 19.94, and 17.92 mg-S/g respectively. Adsorption efficiency of bare carbon in the first 15 min is 75 % and gradually increased to 89.8 % at 24 h. This adsorption breakthrough at the shortest possible time was ascribed to its high surface area of 1027 m<sup>2</sup>/g. On the other hand, the DBT uptake of unmodified carbon at an interval of time after 360 min was relatively insignificant and was attributed to transition pores saturation with DBT molecules. AC-N-Mo adsorbent DBT uptake is 62 % in the first 15 min but increases significantly to almost 100 % at 24 h. This adsorption breakthrough capacity could be attributed to both heteroatom and metal modification in that heteroatom allowed a complete dispersion of molybdenum on carbon surfaces to facilitate sulfur-metal interaction through  $\pi$ -complexation and increased the attachment of oxygen-containing functional group (Danmaliki and Saleh, 2017; Ganiyu et al., 2016). This is confirmed in the FTIR, XPS, XRD, and TPD results. The adsorption efficiency follows the order of AC-N-Mo > AC-Mo > AC > AC-N. The chemistry behind this form of adsorption is that metal ions form  $\sigma$ -bonds with the s-orbitals and the d-orbitals will back-donate electron density to the antibonding  $\pi$ - orbitals in the sulfur-containing ring of dibenzothiophene (Saleh et al., 2016). It should be mentioned also that the nitrogen heteroatom (N) influenced well dispersion of metal loading on the surface of AC. Table 2 shows the comparison of adsorption capacities of DBT from model oil on different AC adsorbents. It was discovered that molybdenum-modified nitrogen-doped activated carbon AC-N-Mo showed moderately higher adsorption capacities when compared with adsorbents that were reported in similar research papers (Ganiyu et al., 2016; Saleh and Danmaliki, 2016). Whereas, some authors have reported a higher adsorption capacity for DBT as compared to this current study (Nazal et al., 2019; Yaseen et al., 2021).

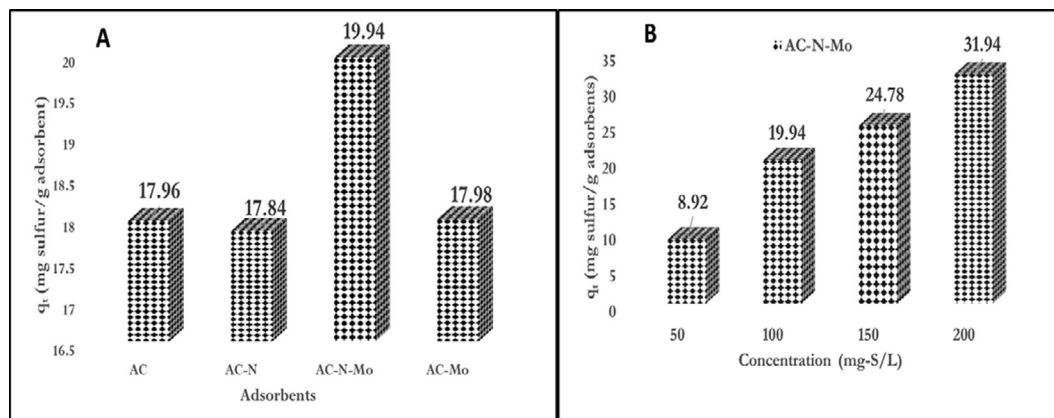
### 3.9. Effect of initial concentration on maximum adsorption capacity

Adsorption capacity breakthrough was studied on the prepared adsorbents where the initial concentration of DBT in a simulated fuel was varied between 50 and 200 mg-S/L as a

function of time under the working condition of room temperature and fixed adsorbent dosage. Fig. 4B shows the equilibrium maximum sulfur adsorbed by AC-N-Mo at 24 h equilibration time. It was seen that the maximum adsorption capacity of AC-N-Mo for a varied concentration of 50 mg-S/L and 100 mg-S/L are 8.92 % and 19.94 % respectively corresponding to 8.92 mg-S/L and 19.94 mg-S/L. The heteroatom-metal modified activated carbon AC-N-Mo displayed higher adsorption efficiency at the varied concentrations owing to the higher amount of surface oxygen it has in combination with enough available acidic sites that aid adsorption of basic organosulfur compounds. However, the highest adsorption capacity dropped between 150 and 200 ppm and the maximum sulfur uptake observed was almost 79 % at these concentrations corresponding to 24.78 mg-S/L and 31.94 mg-S/L respectively. This could be that the surface acidity being a favorable factor to adsorption breakthrough was consumed beyond the initial concentration of 100 ppm-S. It is noteworthy to mention that the adsorbent AC-N-Mo adsorbed about 60 % DBT at the first 15 min but increases slowly to 24 h until no further removal was observed. This was attributed to the adsorbent pore size that was larger than the critical diameter of the DBT (Bu et al., 2011).

### 3.10. Adsorption performance as a function of sorbent dosage

Fig. 5 (A) presents the effect of adsorbent dosage on the adsorption efficiency of organosulfur compound DBT adsorbed by AC-N-Mo at room temperature as a function of time. It is established that a positive correlation exists between sorbent amount and adsorption efficiency (Danmaliki and Saleh, 2017; Olajire et al., 2017; Saleh, 2018). To determine the optimum sorbent dosage that is an essential parameter in adsorption studies, a trend in adsorption capacity breakthrough was closely examined at room temperature as a function of dosage increment from 0.025 g to 0.1 g at a fixed concentration of 100 mg-S/L. Expectedly, an increment is observed in the adsorption efficiency of DBT with dosage increment owing to more active sites introduced by the adsorbent's weight at constant process conditions (Srivastav and Srivastava, 2009; Xu et al., 2014) and also due to  $\pi$ -  $\pi$

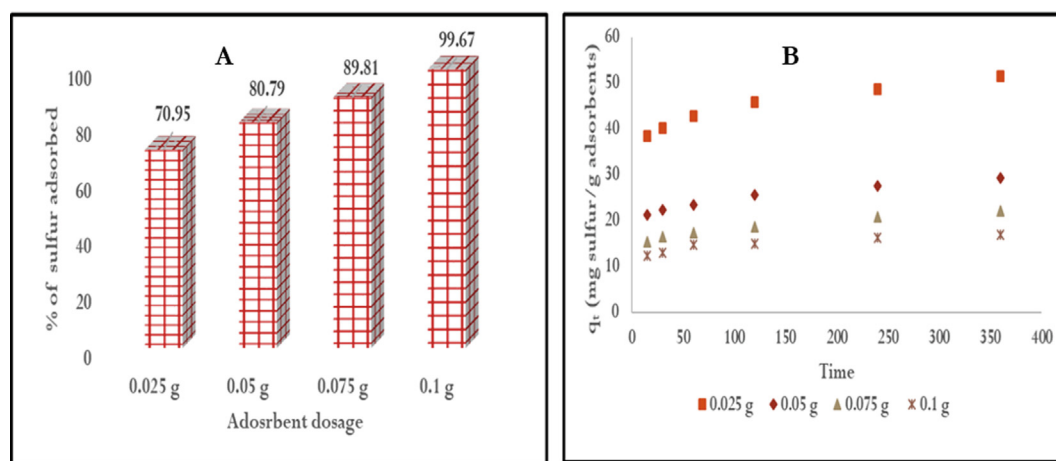


**Fig. 4** (A) Adsorption capacity of adsorbents for DBT at 100 mg-S/L and (B) Effect of initial concentrations (50 – 200 mg-S/L) on the AC-N-Mo. (adsorbent dosage of 100 mg, 20 mL of model fuel, and contact time of 24 h).

**Table 2** Comparison of adsorption capacities of different AC adsorbents for DBT.

| Adsorbents                          | Reactor type | Adsorption capacity (mg/g adsorbent) | Testing Conditions                          | Solvent          | References                  |
|-------------------------------------|--------------|--------------------------------------|---------------------------------------------|------------------|-----------------------------|
| Al-AC                               | Batch mode   | 14.19                                | 24 h, 0.2 g/ 20 mL, 100 ppm and 600 rpm     | Isooctane        | (Ganiyu et al., 2016)       |
| AC/Ce/Fe/                           | Batch mode   | 16.63                                | 30 min, 0.2 g/ 20 mL, 150 ppm and 150 rpm   | n-Hexane/toluene | (Danmaliki and Saleh, 2017) |
| ACFH <sup>a</sup>                   | Batch mode   | 19.0                                 | 8 h, 0.05 g/ 5 mL, and 330 ppm              | n-Hexane         | (Moosavi et al., 2012)      |
| ACFH-Cu (1) <sup>+b</sup>           | Batch mode   | 14.0                                 | 8 h, 0.05 g/ 5 mL, and 330 ppm              | n-Hexane         | (Moosavi et al., 2012)      |
| AC-MnO <sub>2</sub>                 | Batch mode   | 43.8                                 | 24 h, 80 g/ 850 mL, 1000 ppm and 125 rpm    | n-Heptane        | (Abu Safieh et al., 2015)   |
| ACAL5 <sup>d</sup>                  | Batch mode   | 84.5                                 | 120 min, 0.15 g/ 25 mL, 250 ppm and 200 rpm | n-Hexane         | (Nazal et al., 2019)        |
| AC                                  | Batch mode   | 8.6                                  | 90 min, 0.15 g/ 15 mL and 150 ppm           | n-Hexane/toluene | (Saleh and Danmaliki, 2016) |
| AgNP <sup>kp</sup> /AC <sup>d</sup> | Batch mode   | 25.7                                 | 100 min, 0.2 g/10 mL, 100 ppm and 120 rpm   | n-Heptane        | (Olajire et al., 2017)      |
| Zn/AC                               | Batch mode   | 90.09                                | 120 min, 0.15 g/10 mL, 200 ppm, and 100 rpm | n-Heptane        | (Yaseen et al., 2021)       |
| AC-N-Mo                             | Batch mode   | 48.8                                 | 24 h, 0.1 g/ 20 mL, 100 ppm and 600 rpm     | Isooctane        | This work                   |

<sup>a</sup> activated carbon fiber thermally treated, <sup>b</sup>activated carbon thermally treated modified with copper cation <sup>c</sup>1 wt % acetic-acid-treated cobalt-modified activated carbon <sup>d</sup>activated carbon loaded with 5 % aluminum and <sup>d</sup>activated carbon modified with silver nanoparticles synthesized



**Fig. 5** Effect of sorbent dosage as a function of (A) percentage of sulfur adsorbed and (B) equilibrium quantity of sulfur adsorbed (initial conc. = 100 mg-S/L, 20 mL of isooctane containing DBT, and 360 min contact time).

dispersive interaction between the graphene layer on AC and aromatic ring in DBT (Bu et al., 2011). It is observed that the adsorption affinity for organosulfur compound by AC-N-Mo reached a climax at about 99.7% for the adsorbent dosage of 0.1 g in 24 h and no further removal is observed and that formed the basis why adsorbent dosage is restricted to 0.1 g. It is worth mentioning that 0.025 g adsorbent exhibits the highest adsorption performance (percentage of sulfur adsorbed per g-adsorbent dosage) of 70.95 % in 24 h contact time and in all the varied dosage, fast adsorption is seen in the first 15 min followed by a slight increase till it reached equilibrium time of 24 h. AC-N-Mo adsorbent dosage of 0.025 g,

0.05 g, 0.075 g, and 0.1 g correspond to 56.76 mg-S/g, 32.32 mg-S/g, 23.95 mg-S/g, and 19.94 mg-S/g respectively. This shows that the percentage removal of sulfur is directly proportional to adsorbent dosage as shown in Fig. 5(B). The sorbent increment promotes higher adsorption efficiency due to multilayer adsorption being minimal, whereas, the equilibrium adsorption capacity of sulfur increase with a decrease in sorbent dosage as presented in Fig. 5 (B) (contact time up to 360 min is shown). This phenomenon is attributed to large adsorbent mass that could lead to the system being compressed, which will minimize diffusion of DBT to the adsorption sites of the adsorbents (100 mg-S/L).

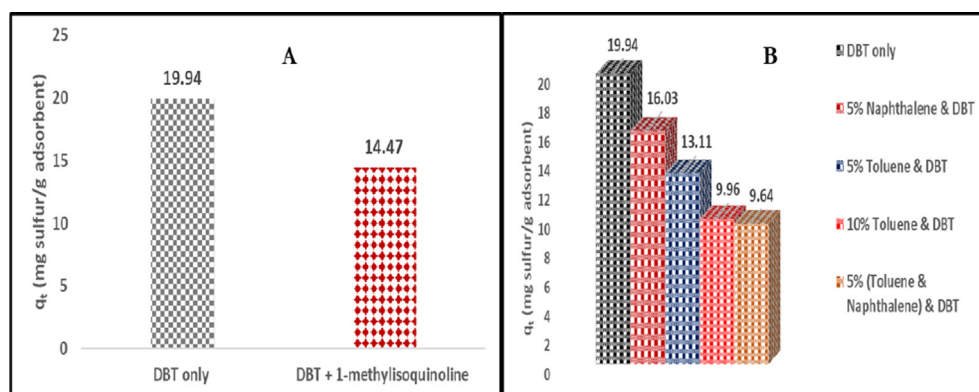
### 3.11. Effect of 1-methyl isoquinoline on adsorption capacity

Aromatic compounds such as pyridine and its derivatives, arenes, toluene, naphthalene, etc. are usually coexisting in middle distillate oil and have a significant tendency to interfere and cause depletion in the adsorption affinity of sulfur-containing organic compounds. In light of this, the competitive effect of pyridine derivative (1-methylisoquinoline) on DBT solution was investigated over the best-performing adsorbent AC-N-Mo as simulated diesel oil. It should be noted that heterocyclic nitrogen compounds could either be basic or non-basic based on the of the availability of lone pair electrons (Mathidala and Ogunlaja, 2019). Pyridine and its derivatives such as quinoline, acridine are classified as basic nitrogen due to nitrogen lone pair not contributing towards the aromatic system (i.e. nitrogen lone pair is localized). This localized lone pair extends in the ring plane thus responsible for its basicity. On the contrary, non-basic/neutral heterocyclic nitrogen compounds such as pyrrole and its corresponding derivatives such as indole, carbazole have delocalized lone pair on nitrogen atoms that are part of the aromatic system. This reveals the reason nitrogen atom on the basic nitrogen-containing compounds are more basic than their neutral counterparts (Liu et al., 2008). The adsorption removal efficiency of DBT (100 mg-S/L) by AC-N-Mo was evaluated in the presence of 100 ppm 1-methylisoquinoline at room temperature. The percentage removal at the equilibration time of 24 h in the presence of competitive heterocyclic nitrogen compound is reduced slightly when compared to the adsorption affinity of DBT in the absence of 1-methylisoquinoline. Fig. 6A shows the removal efficiency of the adsorbent with and without the presence of nitrogen-containing heterocyclic compound. It was seen that at 24 h the highest adsorption capacity achieved is 72.25 % correspond to 14.47 mg-S/g adsorbent as compared to 19.94 mg-S/g adsorbent attained with DBT only. This impressive DBT uptake in the presence of nitrogen heterocyclic compound showed how selective AC-N-Mo adsorbent is towards the DBT. This performance was ascribed to acid-base interaction between the graphene on AC and the basic sulfur compounds. The reduction observed in adsorption capacity can be considered as a result of competition between basic heterocyclic nitrogen compounds and the sulfur compounds to be transported towards the pores on the carbon surface. Also, adsorption of the nitrogen compounds on the

carbon surface could be hindered by the heteroatom nitrogen used to disperse Mo on the sorbent dosage. It is worth mentioning that melamine (67 % nitrogen) was the source of the nitrogen used to modify AC surface that is also basic and as mentioned above isoquinoline is basic and the charge on the nitrogen atom is more negative. Thus the principle of like charges repel might prevent the adsorption of 1-methylisoquinoline onto the carbon surface. Liu et al., used DFT theoretical approach to explain selective adsorption capacity of Cu(I)zeolite adsorbent over heterocyclic nitrogen compounds in terms of adsorption energy in that energetically preferential adsorbate adsorbed on the adsorbent surface which could also be the reason why AC-N-Mo was very selective towards DBT (energetically favorable) in the presence of the competitive nitrogen-containing compound (Liu et al., 2008; Liu et al., 2007).

### 3.12. Effect of aromatics on DBT removal

Toluene and naphthalene were added to DBT dissolved in isooctane and adsorption capacity were investigated accordingly following the addition of 5 vol% each of toluene and naphthalene separately into DBT solution and their mixture in a solution containing DBT. Additionally, 10 vol% toluene was also examined for the maximum adsorption capacity in a solution containing DBT. The adsorption experiments were carried out at the working condition of the initial concentration of DBT (100 mg-S/L) at room temperature over a fixed adsorbent weight. It was observed that the adsorption capacity of the best performing adsorbent (AC-N-Mo) reduced drastically in the presence of 5 % toluene at the equilibration time of 24 h but interestingly, the effect of 5% naphthalene was insignificant. The percentage removal of DBT at 24 h in the presence of the former (toluene) and later (naphthalene) are 65.52 % and 81.17 % respectively corresponding to 13.11 and 16.03 mg-S/g adsorbent as compared to 19.94 mg-S/g adsorbents achieved for DBT In the absence of the two aromatic hydrocarbons. For the 10 % toluene, a maximum adsorption capacity of 9.96 mg-S/g adsorbents (49.78 %) was attained at 24 h. It is quite obvious that the studied adsorbent was very selective towards both of the aromatic compounds but more selective towards DBT in the presence of naphthalene Also, the mixture of toluene and naphthalene (each of the two compounds 5 % by volume) was introduced



**Fig. 6** Selectivity performance of AC-N-Mo in the presence of (A) 1-methylisoquinoline and (B) aromatics toluene and naphthalene. (Co = 100 mg-S/L, contact time = 24 h adsorbent dosage = 100 mg, and 20 mL solution of isooctane containing DBT).

in DBT solution and maximum adsorption capacity was evaluated at 24 h. The adsorption efficiency attained for DBT was 9.64 mg-S/g adsorbent corresponding to 48.20 % sulfur adsorbed. The existence of drastic reduction in the adsorption capacity of the adsorbent with increased aromatic (toluene) different concentrations (vol.%) was attributed to competitive adsorption between DBT and toluene, both possess similar aromatic structures (Bhandari et al., 2006; J. Wang et al., 2009). The investigated adsorbent has a higher affinity for DBT relative to naphthalene as shown in Fig. 6B. This sulfur adsorption affinity of the adsorbent could be ascribed not only to the closest size of the DBT molecules to the size of the adsorbent's pores thereby facilitated the preferential trapping of DBT into the adsorbent but also include the fact that DBT has a higher molar mass, boiling point dipole moment and aromaticity compared to naphthalene resulting to  $\pi$ - $\pi$  interactions and stronger van der Waals with the adsorbent surface. It is also worth mentioning that the basic properties of DBT also played a crucial role in that there exists acid-base interaction between DBT and molybdenum oxide (Lewis acid) on the sorbent surface thereby resulting in elevated adsorption capacity breakthrough of DBT (Nazal et al., 2019). To further understand the inhibiting effects of aromatic on the studied adsorbent, the same vol % of toluene and naphthalene were added into DBT solution and was investigated. The result obtained as shown in Fig. 6B revealed that increasing aromatics negatively inhibited the adsorption capacity of the adsorbent due to higher competitive adsorption between the studied aromatics and DBT (Jha et al., 2019).

### 3.13. Adsorption kinetics

Adsorbents AC, AC-N, AC-N-Mo, and AC-Mo were examined at the concentration range of 50 – 250 mg-S/L. To understand the adsorption process and pathways, different kinetic models named pseudo-first order, pseudo-second order, and intraparticle diffusion were studied. The pseudo-first order is often employed to describe the initial stage of the adsorption process, the pseudo-second order provide an insight of the entire adsorption process and the overall adsorption capacity (Anbia and Parvin, 2011), and the intraparticle diffusion is employed to determine whether the rate-determining step for each adsorbent is only intraparticle diffusion or not (Saleh et al., 2018). The details of the equations are described in SI. The value for  $k_1$  and  $q_e$  were found from the slope and intercept of the plot of  $\ln(q_e - q_t)$  versus  $t$  for the pseudo-first order kinetics, the value of  $k_2$  and  $q_e$  were obtained from the slope and intercept of the plot of  $\frac{t}{q_t}$  versus  $t$  for the pseudo-second order kinetics respectively as shown in Fig. SI-3 and Fig. SI-4.  $K_{i,d}$  and  $C$  were extracted from the slope and intercept of the plot of  $q_t$  versus  $t^{1/2}$  (see Fig SI-5). Table SI-3 showed the summary of the kinetic parameters for the adsorbents studied at the varied sulfur concentration range for both pseudo-first order and pseudo second order kinetics for easy comparison. It is obvious from Table SI-3 that  $q_e$  is lower than  $q_t$  and that  $R^2$  value for pseudo-first order are lower than the  $R^2$  values of pseudo-second order. This implies that the pseudo-second order kinetic is well fitted by the experimental implying that the overall sorption rate was likely controlled by the chemisorption on the adsorbent's surfaces and this indicates that the specificity of the adsorbate-adsorbent

interaction was very high (see Fig. SI-4) (Ho and McKay, 1999). The pseudo-second order kinetics model provides an insight into the rate-limiting step of a reaction. This could be by chemisorption wherein valence forces are shared or electrons are exchanged between the adsorbate and adsorbent (Wang and Wang, 2008). The intraparticle diffusion model plot showed that the intra-particle mass transfer properties that are proportional to  $K_{i,d}$  for the removal of DBT follows the increasing order of  $AC < AC-N < AC-N-Mo < AC-Mo$  (see Fig. SI-5). This implies that the adsorbents AC-Mo and AC-N-Mo are more intraparticle diffusion controlled than the AC-N and AC as shown in the  $R^2$  values in Table SI-3. In addition, for the fact that the intraparticle diffusion model plots for the removal of sulfur-containing compound DBT did not pass through the origin reflect that there could be possibility of combination of complex adsorption mechanisms occurring such that intraparticle diffusion is not the only rate-determining step in the adsorption process (Saleh et al., 2018).

It can be seen from the comparison Table SI-3 that there is slight difference between both the experimental and calculated  $q_e$  and the  $R^2$  values are closer to unity describing that the reaction proceeds via pseudo second order kinetics.

### 3.14. Adsorption isotherm

Adsorption isotherms of the adsorbents were studied by Langmuir and Freundlich models expressed by linear equations 6 and 7, (equations in SI), respectively. The isotherm models describe the nature of interactions between the DBT molecules and the adsorbents (Ayawei et al., 2017). The results are presented in Fig. SI-6. The Langmuir isotherm model is based on the assumption that the adsorption of the DBT occurs homogeneously on the surface of the AC and modified AC adsorbents using specific adsorption sites and energies. The observed  $Q_{max}$  from the Langmuir isotherm revealed that the AC-N-Mo exhibited highest adsorption capacity corresponding to the best adsorbent among the studied ones. This observation can be likened to the excellent characteristics of AC-N-Mo such as textural, chemical and structural properties as observed in BET surface area, pore size distribution, TPD and FTIR. In addition, the AC-N-Mo boosted more oxygenated and acidic surface active sites, which are necessary for effective desulfurization of DBT organosulfur basic compound.

The adsorption isotherms of the adsorbents were also studied by Freundlich and the results are presented in Fig. SI-6. Freundlich explains the surface heterogeneity or multilayer sorption, exponential distribution of active sites as well as their energies (Ayawei et al., 2017). The Freundlich equation is given in SI. It is obvious from Table SI-4 that the data fitted more for the adsorbents with better correlation coefficient ( $R^2$ ) for Langmuir than Freundlich isotherm. The  $R^2$  values for nitrogen modified-AC is comparable, and this sorbent has tendency for both isotherms. This implies that the adsorbent and adsorbate interaction occurred on heterogeneous surface with a well-defined active site and energy, and this is due to its multifunctional surface properties resulted from nitrogen and molybdenum (Langmuir, 1916). The value of  $R_L < 1$  indicates that the reaction is favorable. The inverse of  $1/n$  ( $g\ L^{-1}$ ) greater than 1 indicates the favorable condition of the

adsorption process (Poots and Gordon McKay, 1978).  $K^F$  and  $n$  are both evaluated from the linear plots of  $\ln q_e$  against  $\ln C_e$  corresponding to slope and intercept respectively.

#### 4. Conclusions

This work studied the selective adsorption of DBT using adsorbents synthesized from the agricultural waste product by zinc chloride ( $ZnCl_2$ ) activation. The best performing adsorbent AC-N-Mo was taken as a potential adsorbent for further evaluation of the ADS process. The improved performance can be ascribed to changes in the chemical nature of the adsorbents, the acidic nature of molybdenum (as confirmed in the  $NH_3$ -TPD), and the abundance of surface-containing oxygen functional groups. The kinetic studies showed that the reaction proceeded via pseudo-second order kinetics, indicating that the adsorption process was likely to proceed by chemisorption wherein specificity of adsorbate-adsorbent interaction was very high. While the isotherm revealed that Langmuir fit the data more accurately for the adsorbents. It is obvious as demonstrated in this work that the preparation of activated carbon from date seeds and its applicability for ultra-deep desulfurization is feasible, promising, and worth further studying.

#### Consent for publication

All authors have read and given their consents to the publication of this manuscript entirety.

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#### Ethical approval

Not applicable for this work.

#### Consent to participate

Not applicable for this work.

#### Availability of data and materials

The data that support the findings reported in this work are embedded in the manuscript.

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#### Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.arabjc.2021.103454>.

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