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Removal of Sulfur Dioxide by Carbon Impregnated with Triethylenediamine,
Using Indigenously Developed Pilot Scale Setup

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ABSTRACT

In order to provide protection against extremely toxic gases Activated Carbon (AC) adsorption has long been regarded to be a useful technology in terms of gas removal. AC without chemical impregnation has been considerably less effective than impregnated ACs. AC in present use was modified with an organic amine i.e. triethylenediamine (TEDA) to enhance the physical and chemical properties of AC in order to remove specific poisonous gases. Purpose of this study was to assess the TEDA impregnated AC in terms of adsorption capability for simulant gas like SO₂. Analysis was done in a properly designed setup. By using the scheme reported here, significant adsorption of toxic gas was obtained. Maximum removal capability observed by AC-4 for SO₂ gas was 3.74 g/g-C and its breakthrough time was 264 minutes. Breakthrough time and adsorption capacity of AC-4 was found to be 25 times and 10 times greater as compared to raw AC. Different characterization techniques were also used to study impregnated AC. It was found that chemical adsorption was the crucial means by which TEDA impregnated AC removed the simulant gas. Langmuir model was best to represent equilibrium and adsorption kinetics follow second order model. The process was endothermic, favorable and spontaneous.

Keywords: Activated carbon, impregnation, adsorption capacity, challenge gas, breakthrough time, adsorption isotherms.

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1. Introduction

Due to high adsorptive properties of AC, it has been employed in a huge range of applications as an easy and safe technique for eliminating contaminants from air stream and from water as well. Of the many carbonaceous materials, activated carbon has gained this special property. This is mainly because of porous nature and huge surface area of activated carbon which makes it functional for removal of irritating and toxic gases from the environment. Impregnating activated carbon (IAC) with warily chosen materials, significantly increases its capacity of adsorption for a large number of gases that raw activated carbon is unable to filter. This marvelous property of activated carbon has been used in the manufacturing of canisters and gas mask filters for the last few decades. With the rising concern on environmental pollution, there has been an increased curiosity in ACs as the means for eliminating pollutants from environment (Abdularasheed, Jalil et al. 2018, Huve, Ryzhikov et al. 2018, Eskandari, Andalib et al. 2020, Cai, Yang et al. 2021, Wen, Liu et al. 2021). Both the Occupational Safety and Health Administration (OSHA) and Environmental Protection Agency (EPA) have considered AC adsorption as the “gold standard” technology for optimum removal of contaminants on the priority list (Wu, Chang et al. 2007, Yang, Lu et al. 2020).

AC is a nice adsorbent for some organic vapors but for polar and low molecular weight gases, it is a poor adsorbent. On the other hand, impregnated ACs which have been modified with chemical reagent react strongly with these kinds of gases, bind them on the surface and thus remove them from airstream (Ho, Moon et al. 2019, Kiani, Faiz et al. 2020, Kiani, Farooq et al. 2021).

On the AC surface, pollutant gas molecules can be adsorbed by two approaches, physiosorption and chemisorption. Physiosorption being a surface phenomenon holds the adsorbate pollutant molecules on the surface of AC by Van der Waal’s forces and classical electrostatic interactions. In
chemisorption, adsorbent and adsorbate pollutant molecules are held together on AC interface by means of chemical bond. In case of unimpregnated AC, molecules attach to the surface of AC only by weak physical forces. Owing to the weakness of these interactions between adsorbate and AC, adsorbate can be released into atmosphere easily causing several ecological concerns (Mahle, Peterson et al. 2010, Muzarpar, Leman et al. 2020).

Unimpregnated AC does not have the capability to remove contaminants from airstream to a greater extent. Therefore, processes have been developed to coat chemicals on the AC surface to provide essential filtering capabilities. In order to improve removal mechanism of gases from airstream, various treatments were used. Most important one of them is the use of organic coatings (Ho, Chun et al. 2019, Khayan, Anwar et al. 2019). Several impregnating materials i.e. diisopropylamine (DIPA), triethylenediamine (TEDA), piperidine, di-N-propylamine (DNPA), citric acid and tartaric acid have been used for contaminant removal. These “new generation” impregnated ACs can be used for several applications, most important one being used for toxic gases adsorption from air stream. In nuclear testing, most successful combinations to date consist of coal based carbon impregnated with TEDA for the removal of radioactive methyl iodide (González-García, González et al. 2011, Farooq, Irfan et al. 2012, Zhou, Hao et al. 2014, Lee, Lee et al. 2020). In the present work, various types of TEDA impregnated activated carbon samples were prepared by using a very novel and properly developed setup which involves sublimation process for the impregnation of TEDA on activated carbon using Fluidized bed adsorbing tower (FBT). Breakthrough times of IACs were quantified for SO$_2$ as challenge gases. The intention of present study was to assess the adsorption capacity of AC and TEDA impregnated ACs for SO$_2$ gas. Concentration of gas was measured by using FTIR based gas analyzer. In addition to IACs, an un-impregnated activated carbon was also tested for gas adsorption capacity.
2. Materials and methods

2.1 Materials/Chemicals

Coal based granular AC having surface area 984 m²/g, total pore volume 0.423 cm³/g, density 6.7 g/cm³, moisture content 11% and pH value of 7.8 was used. Chemical used for impregnation was triethylenediamine (C₆H₁₂N₂). Leaching agent used was acetonitrile.

2.2 Design and Scheme of Pilot Scale Impregnation Setup

TEDA was impregnated on AC by using sublimation process. This sublimation process was carried out in a specially designed pilot scale impregnation setup which consists of a fluidized bed adsorbing tower (FBT), TEDA vessel, blower and heat exchanger (HX). These are connected to an electronic control panel (Farooq, Irfan et al. 2012). Design of setup is shown in Fig. 1. Fluidized bed adsorbing tower is the most important part of this setup where TEDA in vapor form impregnates on AC. This technique has the advantage that a uniform impregnant layer can be achieved over all internal and external surfaces of AC.
2.3 Sample Preparation procedure

First of all oil present in the HX is heated by means of heater till it attains 250 °C temperature. Blower is then switched on and air moves towards HX. This hot air then travels directly towards FBT. By this manner, air is recirculated till it attains 100 °C temperature within the FBT. AC bed present inside the FBT is also heated by this hot air. In the meantime, TEDA vessel heater is also operated to attain the temperature of 100 °C for TEDA sublimation. At this time, valve is opened and 100 °C air flows into TEDA vessel, carries TEDA vapors from the vessel and then moves to the FBT. As a result of fluidization of AC bed in FBT, each and every particle of AC from all sides
comes in contact with TEDA laden air. So in this manner, TEDA in vapors form gets impregnated on external and internal surfaces of AC. This cycle is repeated for a specified time period until all the TEDA (in the TEDA vessel) is sublimed and gets adsorbed on AC. This method of fluidization and sublimation by using hot air has a number of advantages over other impregnation methods. Here, post drying process of impregnated AC is not needed and this process also ensures uniform impregnation. The samples prepared with various concentration of TEDA are listed in Table 1.

| Sr. No. | Sample Code | TEDA % | Impregnation temp. (°C) | TEDA vessel temp. (°C) | Activated carbon Amount (kg) | Time (hrs) |
|---------|-------------|--------|-------------------------|------------------------|-----------------------------|------------|
| 1       | AC-1        | 3.2    | 95                      | 90                     | 2                           | 2          |
| 2       | AC-2        | 4      | 95                      | 90                     | 2                           | 2          |
| 3       | AC-3        | 5.5    | 95                      | 90                     | 2                           | 2          |
| 4       | AC-4        | 6.5    | 95                      | 90                     | 2                           | 2          |
| 5       | AC-5        | 7.8    | 95                      | 90                     | 2                           | 2          |
| 6       | AC-6        | 8.5    | 95                      | 90                     | 2                           | 2          |
| 7       | AC-7        | 9.1    | 95                      | 90                     | 2                           | 2          |
| 8       | AC-8        | 10.3   | 95                      | 90                     | 2                           | 2          |

2.4 Sample characterizations

A Hitachi S-4800 SEM was used to image the samples. Beam extraction current of 15µA, accelerating voltage 20kV and working distance of 12mm were the characteristic conditions employed. To attain stability and to facilitate imaging, a conducting carbon paste for fixing the granules of AC was used. Magnification used was 30-500x.
Determination of breakthrough time was done by FTIR based GASMET Analyzer. For gas filtration, samples were tested by using sulphur dioxide (SO$_2$) as a challenge gas. 0.5g of each sample was tested for SO$_2$ gas. These were exposed to 57ppmv challenge gas. Total flow rate comprising SO$_2$ and diluent N$_2$ was 3L/min. In dilution chamber, SO$_2$ gets diluted after mixing with N$_2$ and passed through AC bed for toxic gas adsorption. Breakthrough time ($t_b$) was measured as the time when challenge gas concentration downstream of AC bed reached a value of 5ppmv. Experimental setup flow chart for SO$_2$ testing is shown in Fig. 2.

Fig. 2 Experimental setup to study SO$_2$ adsorption on AC
2.5 ASTM Standard Tests for AC

ASTM standard tests were performed to calculate the Particle size distribution, Ball-pan hardness number, Water solubles, Apparent density, Total ash content, Moisture content, Iodine number and pH of Raw and TEDA impregnated activated carbon sample (ASTM 1996).

2.6 Adsorption capacity

Experimentally, adsorption capacity was calculated by using breakthrough time curve data by subtracting the area below the breakthrough time curve from the total area. This final area above the curve gives value of adsorption capacity. Area below breakthrough curve was calculated by integration method. Theoretically, breakthrough time was determined by using modified Wheeler Jonas equation and this equation is written as:

\[
\frac{t_x}{t_{0.05}} = 1 - \frac{F}{V K_v} \ln \left( \frac{C_o - C_x}{C_x} \right)
\]

Where, \( t_x \) is the breakthrough time (min), \( t_{0.05} \) is saturation time (min), \( F \) is total flow rate (cm\(^3\)/min), \( V \) is volume of packed bed (cm\(^3\)), \( K_v \) is adsorption rate constant (min\(^{-1}\)), \( C_o \) = inlet gas concentration (gm/cm\(^3\)) and \( C_x \) is the concentration at time \( t_x \) (gm/cm\(^3\)).

2.7 Adsorption isotherms

The adsorption data of SO\(_2\) on AC was subjected to three adsorption models i.e. Langmuir, Freundlich and Dubinin-Radushkevich (D-R). Langmuir isotherm was applied in the following linearized form (Lua and Guo 2001):

\[
\frac{C_e}{C_{ads}} = \frac{1}{Q b} + \frac{C_e}{Q}
\]
\( C_e \) is the equilibrium concentration of gas \((\text{SO}_2)\) in ppm, \( C_{ads} \) is the adsorbed concentration of gas on activated carbon in ppm. \( Q \) is the constant which signifies maximum adsorption capacity at monolayer formation and \( b \) is the characteristic Langmuir constant for the adsorption system.

Freundlich adsorption isotherm was applied in the following linearized form (Lua and Guo 2001):

\[
\ln q_e = \ln K_f + \frac{1}{n} \ln C_e
\]

(3)

\( q_e \) is the amount of gas adsorbed, \( C_e \) is the equilibrium concentration of gas, \( K_f \) is the Freundlich rate constant and \( \frac{1}{n} \) is Freundlich adsorption constant strength.

D-R adsorption isotherm was applied in the following linearized form (Lua and Guo 2001):

\[
\ln q_e = \ln q_s - K_D \ell
\]

(4)

Where \( q_s \) is the constant in D-R isotherm which is related to adsorption capacity, \( K_D \) is constant related to mean free energy of adsorption and \( \ell \) is the Polanyi potential which is given by:

\[
\ell = RT \ln(1 + 1/C_e)
\]

(5)

Where \( R \) is gas constant, \( T \) is absolute temperature and \( C_e \) is equilibrium concentration of gas.

2.8 Adsorption kinetic models

Mass transfer phenomenon can be best understood by its thermodynamics and kinetics. Pseudo first order and second order models were applied to analyze the adsorption data for kinetic study. Pseudo first order model is the simplest equation which relates dependence of adsorption rate on adsorption capability. Equation is written as (Sumathi, Bhatia et al. 2010):

\[
\frac{dq}{dt} = k_1(q_e - q_t)
\]

(6)
Linearized form is given as:

\[ \log(q_e - q_t) = \log q_e - K_1 2.303t \]  

(7)

\( q_e \) and \( q_t \) are the amounts of gas adsorbed at equilibrium and at time “t” respectively, \( K_1 \) is rate constant of pseudo first order and t is contact time.

Equation for pseudo second order model is written as:

\[ \frac{dq}{dt} = K_2 (q_e - q_t)^2 \]  

(8)

Linearized form is given as:

\[ \frac{t}{q_t} = \frac{1}{K_2 q_e} + \frac{t}{q_e} \]  

(9)

Where \( t \) is time in min and \( q_t/t \) is the amount of gas adsorbed at time \( t \), \( K_2 \) is rate constant of pseudo second order reaction and \( q_e \) is equilibrium adsorption capacity.

2.9 Thermodynamic parameters

The primary thermodynamic parameters which are used to calculate the probability and spontaneity of adsorption process are change of enthalpy (\( \Delta H \)), change of entropy (\( \Delta S \)) and free energy change (\( \Delta G \)). Following equations can be used to predict these parameters (Myers 2002):

\[ \Delta G = -RT \ln K_d \]  

(10)

\( R \) is gas constant, \( T \) is absolute temperature and \( K_d \) is distribution coefficient and is calculated by following equation.

\[ K_d = (C_0 - C_e)/(ms/V)C_e \]  

(11)
Value of entropy change and enthalpy change was analyzed from intercept and slope of plot between $\ln K_d$ versus $1/T$ respectively.

### 3. Results and Discussion

Comparison of ASTM standard test results of Raw AC and AC-4 was made and shown in Table 2. Results clearly indicate that AC-4 showed an enhancement in properties as compared to the Raw AC. This is mainly because of the impregnant which imparts these improved properties (Al-Qodah and Shawabkah 2009). So we can say that the prepared AC-4 sample might be a sustainable candidate for purification of noxious gases from atmosphere.

| ASTM Standard Tests          | Raw AC | AC-4  |
|------------------------------|--------|-------|
| Mean Particle Size (mm)      | 0.77   | 0.88  |
| Ball Pan Hardness Number     | 91.9   | 94    |
| Water Solubles (%)           | 0.01   | 0.35  |
| Apparent Density (gm/cm$^3$) | 0.41   | 0.43  |
| Total Ash Content (wt. %)    | 5      | 5.5   |
| Moisture Content (wt. %)     | 19.5   | 0.85  |
| Iodine Number (mg/g-C)       | 920    | 1031  |
| Ph                           | 7.8    | 9.54  |

SEM analysis was done to study the distribution of TEDA on AC surface. Fig. 3 (a) and (b) show SEM images of Raw AC at different magnifications which represent cracks and cavities on surface representing a system of complex porous network. Impregnation results in blocking of cavities and cracks and clogging of pore openings (Kiani, Faiz et al. 2020). Fig. 3(c), (d), (e), (f), (g) and (h) represent the distribution of different concentrations of TEDA on surface of AC-1, AC-3, AC-4,
AC-5, AC-7 and AC-8. In all these images, it can be seen that the AC surface is immensely covered with TEDA impregnants. Better the distribution of TEDA on surface, better will be its capability to react with toxic gases in atmosphere by adsorbing them on the surface of AC by means of chemical bond with the impregnant. Apart from the chemical adsorption of gases on AC, some pores are also available on AC which are responsible for physical adsorption of gases (Wu, Chang et al. 2007, Arcibar-Orozco, Rangel-Mendez et al. 2013). As TEDA is basic in nature, it plays a significant role in the removal of acidic gases like SO$_2$ from air.

![SEM images of Raw AC at (a) 60kx and (b) 50kx](image)

Fig. 3(a)  SEM images of Raw AC at (a) 60kx and (b) 50kx
Fig. 3(b) SEM images of impregnated ACs (c): (AC-1), (d): (AC-3), (e): (AC-4), (f): (AC-5), (g): (AC-7) and (h): (AC-8).

pH of samples was measured by ASTM-D3838 method and results are presented in Fig. 4. Results clearly show that as we increase the amount of TEDA, pH value of ACs also increases. This is due to the fact that TEDA is basic in nature and its impregnation makes AC more basic. This increased
basicity of adsorbent (by means of basic adsorbent) is highly desirable for the chemical adsorption of acidic gases as it leads to the filtration of acidic gases from contaminated environment more efficiently (Wu, Chang et al. 2007).

Gas filtration capability was tested for SO$_2$ gas. Comparison of breakthrough time was made between the raw and various TEDA impregnated ACs and shown in Fig. 5(a) and 5(b). These results indicated that Raw AC showed less breakthrough time i.e. 11.6 min as compared to other impregnated samples and so responsible for the purification of toxic gases to lesser extent. In case of TEDA impregnated samples breakthrough time increases initially with the increase in concentration of TEDA but after a certain limit of impregnation, breakthrough time decreases with further increasing the concentration and is shown in Fig. 5(c). The reason behind this is the blocking of pore mouths. Impregnation beyond a certain limit results in the blockage of AC pores and gas molecules do not find more available sites for adsorption, hence its breakthrough time
decreases considerably (Wu, Chang et al. 2007, Bobbitt, Mendonca et al. 2017). After 7% TEDA impregnation, a considerable decrease in breakthrough time was observed. Breakthrough time of AC-1, AC-2, AC-3, AC-4, AC-5, AC-6, AC-7 and AC-8 is 160, 191, 247, 264, 234, 222, 220 and 211 minutes respectively. Breakthrough time of AC-4 is almost 25 times greater than Raw AC. SO₂ adsorption was supposed to occur through subsequent paths (Kiani, Faiz et al. 2020):

For Raw AC: \[ AC + SO₂ → AC − SO₂ \] (12)

For sample: \[ C₆H₁₂N₂ + 2SO₂ → SO₂ − NC₆H₁₂N − O₂S \] (13)

Fig. 5(a) Breakthrough time curves of TEDA impregnated samples for 57 ppmv SO₂ as challenge gas
Adsorption capacity of Raw AC was found to be 0.41 gSO$_2$/g-C whereas all other impregnated samples showed higher adsorption capacities. Maximum adsorption capacity was observed for...
AC-4 which is about 10 times higher than Raw AC as shown in Table 3. The order of adsorption capacities of samples was found as Raw AC<AC-1<AC-2<AC-8<AC-7<AC-6<AC-3<AC-5<AC-4 for SO₂ gas. Impregnation of TEDA on AC surface might be responsible for a greater resistance or reaction sites (Mahle, Peterson et al. 2010, Perera, Ranjith et al. 2012, Zhou, Su et al. 2018, Hyuncheol Lee 2019).

Table 3  Adsorption capacities of Raw and TEDA impregnated ACs

| Sample Code | Adsorption capacity (g SO₂/g-C) |
|-------------|---------------------------------|
| Raw AC      | 0.41                            |
| AC-1        | 1.98                            |
| AC-2        | 2.54                            |
| AC-3        | 3.18                            |
| AC-4        | 3.74                            |
| AC-5        | 3.48                            |
| AC-6        | 3.10                            |
| AC-7        | 3.04                            |
| AC-8        | 2.97                            |

Table 4 shows breakthrough time of samples calculated by using modified Wheeler Jonas equation. A plot of \( \frac{t_x}{t_{0.05}} \) vs \( \ln \left( \frac{c_0-c_x}{c_x} \right) \) gives a straight line with slope equal to \( \frac{F}{Vk_p} \) and intercept 1 (Zhou, Feng et al. 2011). Breakthrough time calculated by this method showed almost the same trend as exhibited by the experimental method, although, the calculated breakthrough times are slightly on higher side as compared to the experimental ones.
Table 4  Breakthrough time by using modified Wheeler Jonas equation

| Sample Code | Calculated Breakthrough Time (min.) |
|-------------|------------------------------------|
| Raw AC      | 18                                 |
| AC-1        | 198                                |
| AC-2        | 241                                |
| AC-3        | 264                                |
| AC-4        | 290                                |
| AC-5        | 259                                |
| AC-6        | 277                                |
| AC-7        | 262                                |
| AC-8        | 249                                |

Fig. 6 shows comparison of breakthrough time calculated by both methods. It can be seen that experimental and model results are linearly varying, but the model breakthrough time is slightly greater than experimental breakthrough time (Lodewyckx, Wood et al. 2004). The reason is that theoretical equations always over predict physical quantities. The regression value is 0.97 which shows a good linear fit between model and experimental results.
4. Adsorption isotherms

4.1 Langmuir adsorption isotherm

Fig. 7 shows plot of $C_e/C_{ads}$ vs $C_e$ for SO$_2$ on AC-4 with initial concentration 57 ppm at 298 K. From the intercept and slope of this plot, values of Langmuir parameters are estimated for the system. Value of $R^2$ determines the favorability of adsorption process and its corresponding data is given in Table 5. Langmuir isotherm considers that the ions remain adsorbed on certain sites that are mono-energetic and each site binds only one adsorbate molecule without any interaction with the neighboring ions. Moreover, it supports the monolayer adsorption of gas on substrate (Lua and Guo 2001).
4.2 *Freundlich adsorption isotherm*

Fig. 8 shows the plot of ln$C_e$ vs ln$q_e$ for the adsorption data of SO$_2$ gas on AC-4 at initial concentration of 57 ppm and 298 K. Slope and intercept were used to determine the Freundlich constant (Muzarpar, Leman et al. 2020). Value of $R^2$ determines the favorability of adsorption process and its corresponding data is given in Table 5.
4.3 D-R isotherm

Fig. 9 shows the plot of $\ln C_{\text{ads}}$ vs $\ell^2$ for adsorption data of toxic gas on AC-4 surface at initial concentration of 57 ppm and 298 K. From intercept and slope of plot we get value of D-R parameters (Sumathi, Bhatia et al. 2010). $R^2$ value provides information about the favorability of adsorption process. Fig. 9 shows D-R isotherm plot and its corresponding data is given in Table 5.
5. Adsorption Kinetics

Plot of log (q<sub>e</sub>-q<sub>t</sub>) vs t for pseudo first order reaction is shown in Fig. 10 and plot of t/q<sub>t</sub> vs T for pseudo second order reaction is shown in Fig. 11 for the adsorption of SO<sub>2</sub> gas on AC-4. Kinetics of adsorption can be predicted from the corresponding value of R<sup>2</sup> (Yi, Wang et al. 2014). Value of R<sup>2</sup> for pseudo first order reaction is 0.7223 and for second order is 1. This concludes that pseudo second order reaction is the most favorable path for adsorption of SO<sub>2</sub> on AC-4 and fits best to adsorption process (Sumathi, Bhatia et al. 2010).
6. Thermodynamic parameters
Plot of ln$K_d$ vs 1/T is shown in Fig. 12. From the slope and intercept of this graph value of $\Delta G$ and $\Delta H$ have been computed respectively. Positive value of $\Delta S$ proposed an increased randomness at the interface in the adsorption process. Positive enthalpy value shows the endothermic reaction while negative free energy indicates the spontaneous nature of adsorption process respectively (Zhou, Yi et al. 2012). Corresponding values are shown in Table 5. Comparison of three isotherm models shows that Langmuir adsorption isotherm model is the best fitted model as compared to Freundlich and D-R isotherms.

![Plot of ln$K_d$ vs 1/T](image)

**Fig. 12** Plot of ln$K_d$ vs 1/T for thermodynamic parameters

**Table 5** Parameters for Langmuir, Freundlich and D-R isotherms for SO$_2$ adsorption

| Gas adsorbed | Models   | Parameters | $\Delta H$ (kJmol$^{-1}$) | $\Delta S$ (JK$^{-1}$mol$^{-1}$) | $\Delta G$ (kJmol$^{-1}$) |
|--------------|----------|------------|---------------------------|----------------------------------|---------------------------|
| SO$_2$       | Langmuir | Q          | 0.017                     |                                  |                           |
|              |          | B          | 0                         |                                  |                           |
|              |          | $R^2$      | 1                         |                                  |                           |
|              |          | $K_d$      | 12.7                      |                                  |                           |
|              | Freundlich | 1/n      | -0.057                    | 6628.2                           | 9.42                      |
|              |          | $R^2$      | 0.941                     |                                  |                           |
Conclusion

In this study different TEDA impregnated ACs were prepared by using sublimation method. All samples displayed higher breakthrough times and gas adsorption capacities to a considerable amount as compared to the Raw AC. Moreover, AC-4 prepared in this work is a sustainable candidate for the purification of toxic gases from contaminated air by chemisorption on porous carbon surface. Its breakthrough time and adsorption capacity was found to be 264 minutes and 3.74gSO$_2$/g-C respectively for 57 ppmv SO$_2$. Being basic in nature, TEDA played a dynamic role in the purification of acidic gases from air. Gas adsorption data are reliable with Langmuir, Freundlich and D-R isotherms. Adsorption data strongly follow Langmuir adsorption isotherm and pseudo second order kinetics. Thermodynamic parameters $\Delta H$, $\Delta G$ and $\Delta S$ have been calculated. However the positive enthalpy change showed the endothermic reaction for adsorption of SO$_2$ on AC. While negative free energy change confirmed the spontaneous nature of adsorption process.

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and materials

Not applicable

Declaration of competing interest
The authors declare no competing financial interest.

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**Author contribution**

Sidra Shaoor Kiani: Literature review, Writing original manuscript

Atif Ullah: Experimentation

Amjad Farooq: Reagents and other analysis tools, Methodology, Validation, Investigation,

Formal analysis, Reviewing manuscript

Naseem Irfan: Instrumentation

Masroor Ahmed: Instrumentation

Mohsan Nawaz: Conceptualization

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