

Design of novel Sb₂S₃/Polythiophene heterojunction for efficient adsorption and Methanol Sensing

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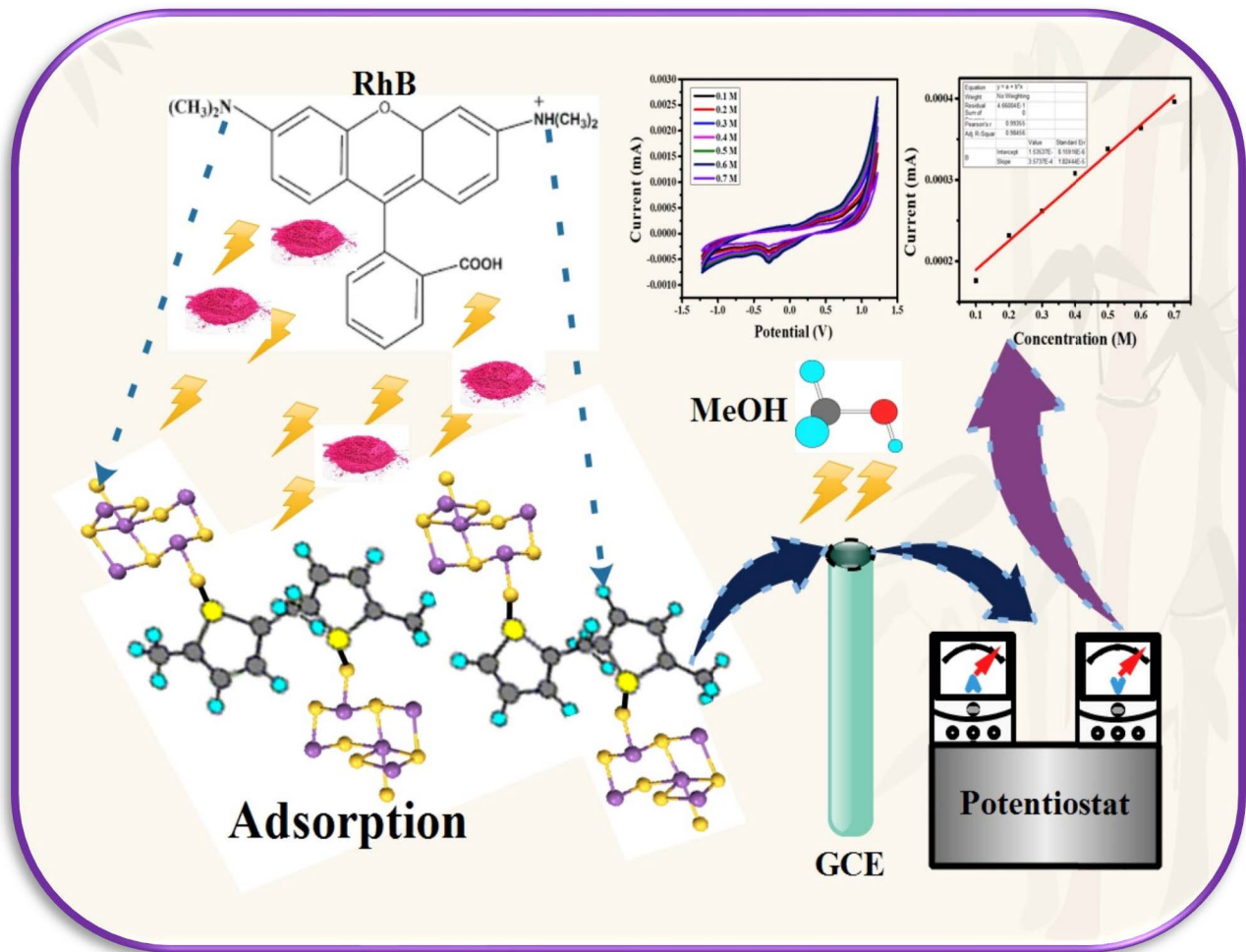
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Abstract

Eliminating micropollutants in trace concentrations in water bodies is crucial and challenging due to their persistent and bioactive characteristics. Due to these characteristics, their detection and removal pose a challenge to the conventional removal methods and to the health of the community. To effectively remove the pollutants, it requires the design and development of an efficient technique compared to the conventional techniques. The design of highly efficient methanol sensor and the adsorption of micropollutants by a heterojunction involving Sb₂S₃ and polythiophene (PTh) looks promising. The adsorption study was targeted on RhB dye whereas methanol was targeted to sensing application. Sb₂S₃ nanoparticles were synthesized by hydrothermal methods and incorporated into thiophene solution during chemical oxidative polymerization of thiophene. The heterojunction was applied to remove RhB dye through the adsorption process. Freundlich isotherm model and Langmuir isotherm model were used to study the adsorption of RhB. The higher adsorption capacity was found in case of Sb₂S₃/PTh is 99.8 mg g⁻¹, and the rate constant (K₂) was found to be 0.0206 min⁻¹. The catalysts follow the pseudo-first and second order kinetics in the removal of RhB dye. The rate constant for adsorption k₁ is 0.1347 min⁻¹ and the rate constant for diffusion is 0.297 min⁻¹. Moreover, the PTh/Sb₂S₃ shows an effective methanol sensing up to 0.7 mM and the current response at 0.6756 V of the oxidation peaks shows the presence of methanol.

Keywords: Sensing, Thermodynamics, Kinetics, Adsorption, heterojunction, methanol sensor

31 Graphical Abstract



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33 Highlights

- Design of a novel dual-function PTh/Sb₂S₃ as a methanol sensor and adsorption property.
- Langmuir model, the equilibrium data exhibits superior fitting as compared to the Freundlich model with ($R_L^2 = 0.97$).
- Lower concentration (0.1 mM) of methanol are detected using cyclic voltammetry technique by PTh/Sb₂S₃.
- The correlation coefficient $R_d^2 = 0.99$ for diffusion and $R_a^2 = 0.76$ for adsorption indicate the catalysts follows both pseudo first and second order kinetics.

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1. INTRODUCTION

The rise of toxic micropollutants in water bodies around the world has emerged as a pressing concern posing significant threats to human health and the environment. This increase is largely attributed to industrial processes, including manufacturing, chemical production, and fuel production, resulting in the increased presence, accumulation, and concentrations of hazardous micropollutants in the environment (Bolisetty et al. 2019, Kümmerer et al. 2019, Ahmad et al. 2021). Of specific concern are textile dyes, due to their complex chemical compositions, stability, and resistance to biodegradation. (Routoula et al. 2020, Katheresan et al. 2018). Their presence in water bodies not only diminishes water quality by reducing dissolved oxygen levels, thus impairing vital processes like photosynthesis and respiration, but also interferes with light penetration through sunlight reflection, disrupting water ecosystems (Al-Tohamy et al. 2022). Conventional techniques for micropollutant remediation, such as adsorption, ion exchange, and advanced oxidation processes, have been employed to varying degrees of success. Among these methods, adsorption stands out for its simplicity, efficiency, and applicability across a wide range of pollutant concentrations without generating harmful byproducts. However, there remains a pressing need for innovative solutions to enhance the effectiveness and sustainability of micropollutant removal from water bodies. Therefore, the adsorption process featuring cost effectiveness, less energy consumption and reusability of the catalysts are an effective approach in the removal of micropollutants (Ahmad et al. 2023, Nure et al.2023).

In this context, the development of novel catalysts with dual functionality such as the simultaneous degradation of micropollutants and sensing of organic solvents like methanol through electrochemical technique holds immense promise. As this dual functionality approach combines the benefits of the adsorption techniques as well as the sensing technology could be a viable solution for the environmental remediation. By using a single catalyst, detection as well as removal of pollutants can be done. (Liang et al. 2023, Saleh et al. 2019, Molla et al. 2019). Methanol is commonly used solvent in various industrial processes for the chemical and fuel production. Monitoring methanol levels in water bodies near industrial facilities helps ensure compliance with regulations and prevents accidental releases or contamination. Detecting methanol in water bodies allows for early identification of contamination events, enabling timely remediation efforts to protect ecosystems and public health. So methanol sensing provides a means to assess water quality and mitigate potential health risks associated with consumption or exposure.

Such catalysts could offer a multifaceted approach to water treatment, addressing both chemical contamination and the real-time monitoring of solvent concentrations in aquatic environments. By integrating adsorption and sensing capabilities into a single catalyst, it allows optimizing resource utilization, streamline water treatment processes, and mitigate environmental risks associated with micropollutant exposure. (Luo et al. 2014). So far, a number of adsorbents have being utilized for the removal of dyes and other toxic micropollutants such as nanoparticles, nanocomposites, polymer, zeolites, metal organic frameworks (MOFs) and covalent organic frameworks (COFs) and carbon rich material such as graphene, single walled carbon nanotubes (SWCNT) and multiwalled carbon nanotubes (MWCNT) (Bano et al. 2019, Ahmad et al. 2017, Uddin et al. 2021, Zhang et al. 2021, Iqbal et al. 2023). Moreover, several biogenic catalysts extracted from leafs of several trees are also quite efficient in the adsorption of micropollutants (Iqbal et al. 2021).

Our study focuses on investigating the potential of a novel catalyst, comprising polythiophene (PTh) and antimony trisulfide (Sb_2S_3), for the dual purpose of micropollutant degradation and methanol sensing. The electrochemical property, redox property and higher surface area of PTh and Sb_2S_3 makes them for suitable catalyst for sensing of methanol and removal of RhB dye (Ayappan et al. 2020, Xiao et al. 2022, Karimi-Shamsabadi et al. 2021). By taking advantage of the unique properties of PTh as a conducting polymer and Sb_2S_3 as a robust catalyst, our study aims to explore the synergistic interactions that enhance surface area, redox activity, and adsorption capacity for waterborne micropollutants and solvent contamination.

2. EXPERIMENTAL SECTION

2.1 Dual function catalyst synthesis

For the synthesis of Sb_2S_3 , antimony chloride (SbCl_3 prepared in HCl) 25mL, was dissolved in 1mmol $\text{Na}_2\text{S} \cdot 9\text{H}_2\text{O}$ (25mL) and stirred for 30 min. The solution was transferred to a Teflon lined hydrothermal autoclave and maintained at 120°C for 12 hrs. The precipitate was then filtered, washed with distilled water and dried at 60°C for 12 hrs (Wang et al. 2016). For the synthesis of PTh/ Sb_2S_3 , the pre-synthesized Sb_2S_3 was incorporated during the polymerization of thiophene. For the chemical oxidation polymerization of PTh, 1 mL of thiophene was added to 30 mL of CHCl_3 . Then 4.5 g of FeCl_3 solution prepared in CHCl_3 was added and the mixture was stirred for

24h. The precipitate was then centrifuged and dried for 60°C for 4 hrs (Faisal et al. 2018). Fig.1 shows the outline for the synthesis of PTh/Sb₂S₃ nanocomposite.

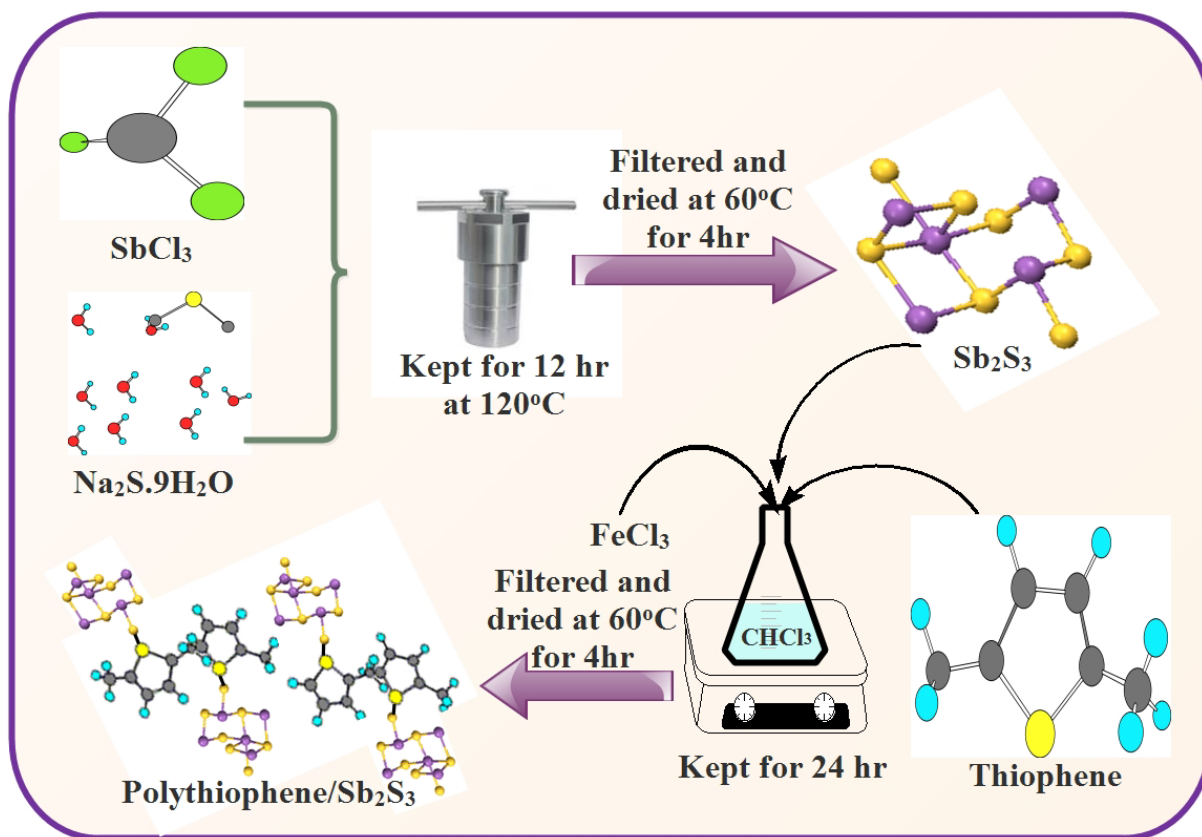


Fig.1 Reaction scheme for the synthesis of PTh/Sb₂S₃ nanocomposite

2.3 Adsorption experiments

The adsorption capabilities of PTh, Sb₂S₃ and PTh/Sb₂S₃ were evaluated against RhB dye using a photochemical reactor (Ahmad et al. 2023). In this study, 100 mg of each catalyst was mixed with 100 ml aqueous solution of RhB (20ppm) in the reactor which was continuously stirred for 30 mins. The reactor containing the photocatalyst-dye solution mixture was sealed, and room temperature was maintained to allow for adsorption equilibrium in 30 mins. Subsequently, aliquots were periodically withdrawn from the reactor to measure absorbance at 554 nm wavelength, indicating the extent of dye adsorption on the catalyst surface. The amount of RhB dye adsorbed on the surface of PTh/Sb₂S₃ was calculated by the following equation (1):

$$\text{Amount of dye adsorbed} = \frac{C_0 - C_e}{M} * V \quad (1)$$

where C_0 and C_e represents the initial and equilibrium concentration in ppm, V is the volume of the RhB solution taken and M is the mass of the catalyst in (mg). The percentage adsorption efficiency of PTh, Sb_2S_3 and PTh/ Sb_2S_3 against RhB were calculated by below equation (2)

$$\text{Adsorption efficiency (\%)} = \frac{C_0 - C_t}{C_0} * 100\% \quad (2)$$

On the basis of the results obtained from equation (1) and (2), the thermodynamics of adsorption using Freundlich and Langmuir isotherm and the kinetics of adsorption using pseudo first and second order were studied. All the experiments performed were replicated twice.

2.4. Catalyst characterizations

The morphology, elemental composition and the particle size of the catalysts were analyzed transmission electron microscopy (TEM) and scanning electron microscopy (SEM) coupled with energy-dispersive X-ray spectroscopy (EDX) (JSM 6510 LV JEOL, Japan). The crystalline nature of the photocatalyst were determined using X-ray diffractometer (Model: MiniFlex600/600-C). Functional group analysis was done by using OPUS version (Alpha II, 210966). The absorbance of 5ml of RhB solution in concentration ranges 2-20 ppm against the photocatalysts in the aqueous solution was checked using UV-visible spectrophotometer (Agilent Technologies) at 554nm wavelength. In addition BET analysis, was carried out by using by Quantachrome Instruments version 5.21 to calculate the surface area and pore volume and pore size.

3. RESULTS AND DISCUSSION

3.1 Structural, functional groups and Microscopic studies

To assess the purity and crystalline phase of the synthesized samples, X-ray diffraction (XRD) analysis was conducted over a 2θ range of 10° to 80° . In Fig. 2a, the XRD patterns of Sb_2S_3 , PTh and PTh/ Sb_2S_3 are presented. The obtained results reveal distinct and well-defined diffraction peaks, indicative of a high level of crystallization in prepared samples. Notably, there is an absence of diffraction peaks corresponding to impurities in the XRD patterns of Sb_2S_3 nanoparticles, affirming the high purity of Sb_2S_3 . The XRD spectra for all samples consistently match the orthorhombic pure phase of crystalline stibnite- Sb_2S_3 , with a Pbnm (62) space group symmetry. The characteristic peaks at $2\theta = 28.0, 28.2, 31.1, \text{ and } 31.3^\circ$ align with the (2 3 0), (2 1 1), (3 0 1),

and (2 4 0) planes. The results revealed a partially crystalline broad peak centered on 2θ value of 22.2° . The presence of a robust diffraction peak at approximately $2\theta = 22.2^\circ$ is attributed to the amorphously arranged PTh main chain, indicative of chain-to-chain stacking distances (Hadia et al. 2019, Kalangestani et al. 2020). A small peak related to PTh was clearly seen in the XRD pattern of PTh/Sb₂S₃ sample in Fig.2a. The shifting of Sb₂S₃ peaks in the PTh/Sb₂S₃ spectra is due to the formation of heterojunction. Further Fig. 2b illustrates the Fourier transform infrared spectra of Sb₂S₃, PTh and PTh/Sb₂S₃ providing confirmation of the formation of antimony sulfide bonds. In the Fourier transform infrared (FT-IR) analysis, bonds within the 2500–4000 cm⁻¹ range are associated with O–H bond stretching vibrations, indicating the presence of water in the compound (Trivedi et al. 2015). Peaks at 612, 742, and 1639 cm⁻¹ are attributed to Sb-S symmetric stretching vibrations. Absorption bands at 1072 and 1124 cm⁻¹ are related to C–OH bond or charge delocalization (Dashariya et al. 2018, Subramanian et al. 2010). The peak at 1278 cm⁻¹ corresponds to S–C bonding (Hou et al. 2018). An absorption peak at 1383 cm⁻¹ is indicative of a metal-sulfide bond (Subramanian et al. 2010), while the peak around 1463 cm⁻¹ is assigned to C–H bond flexural vibrations (Tezel et al. 2019). The peak at 1729 cm⁻¹ is attributed to C=O stretching vibrations (Dashariya et al. 2018). Changes in peak intensity, shape, and position are attributed to the interaction between PTh and Sb₂S₃ nanorods. The spectrum of PTh polythiophene exhibits key features, including the (C-H) stretching vibration band at 2923 cm⁻¹, the (C=C) stretching band spanning 1458-1596 cm⁻¹, the (C-H) in-plane bending band at 1113 cm⁻¹, and the (C-S) bending band at 749 cm⁻¹. The absorption frequencies of the polymer undergo a shift due to increased conjugation, as supported by these results in relation to polymerization (Kalangestani et al. 2020). The Morphological properties of the photocatalyst are presented in Fig. 2 (c,d). The nanopetals of the Sb₂S₃ are clearly seen in Fig. 2c and the Sb₂S₃ nanopetals are agglomerated to the porous surface of PTh as seen in Fig. 2d. The elemental composition of PTh/Sb₂S₃ are shown in Fig. 2 (e, f) which shows the formation of the photocatalyst. TEM was employed for an in-depth investigation of the morphology and crystal structures. Fig.2g showcase a segment of the as-prepared Sb₂S₃ and PTh/Sb₂S₃ exhibiting diameters within the range of 100–180 nm and lengths spanning 3–5 μm. The Sb₂S₃ nanoparticles are agglomerated on the surface of PTh sheets. Fig.2g provides a clear indication of the successful incorporation of Sb₂S₃ nanoparticles within the PTh matrix. Furthermore, the lattice fringes, characterized by a d-spacing of 0.38 nm, align well with the (001) planes of orthorhombic Sb₂S₃ (Xiao et al. 2013). This evidence leads to the conclusion

that the Sb_2S_3 possess crystalline properties, with a preferential growth direction along (001). **Fig.2h** displays the average particles size of the PTh/ Sb_2S_3 composite. The average particle size is found to be 19.13nm.

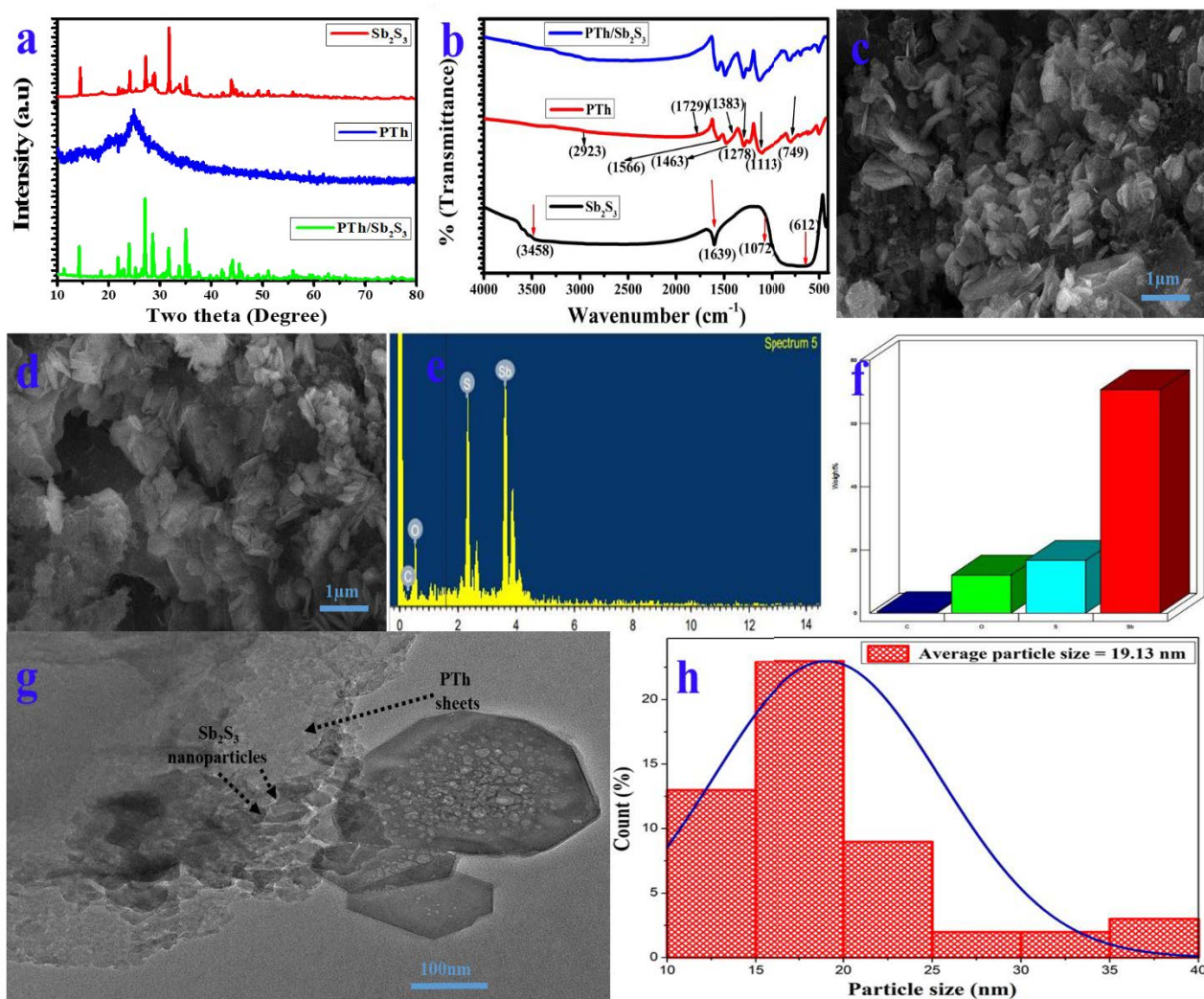


Fig.2. (a) XRD spectra and (b) FTIR spectra of Sb_2S_3 , PTh and PTh/ Sb_2S_3 (c) SEM image of Sb_2S_3 (d) SEM image of $\text{Sb}_2\text{S}_3/\text{PTh}$, (e, f) EDX image for the elemental composition, (g) TEM image of Sb_2S_3 and (h) Average particles size of nanocomposite

3.2. BET and XPS Analysis

BET analysis was carried out to determine the surface area, pore size and pore volume of the photocatalyst as shown in **Fig. 3**. The surface area, pore size and pore volume of the Sb_2S_3 are $67\text{m}^2/\text{g}$, $11.2\text{cc}/\text{g}$ and $0.0457\text{cc}/\text{g}$ and for the PTh/ Sb_2S_3 the surface area, pore size and pore volume

are $74\text{m}^2/\text{g}$, 9.24cc/g and 0.0346cc/g respectively. The BET isotherm in Fig. 3 (a, b) shows the formation of type II isotherm in which the region (0.2-0.8) of P/P_0 seems to be the flatter and is due to the formation of monolayer formation. In Fig. 3(c, d) the average pore size calculated from the spectra is found to be 4nm and 8nm which shows that the nature of the photocatalysts are mesoporous. Further it can be conclude that the surface area of $\text{Sb}_2\text{S}_3/\text{PTh}$ is higher than Sb_2S_3 because of the doping that eventually helps in the adsorption of MPs on its surface.

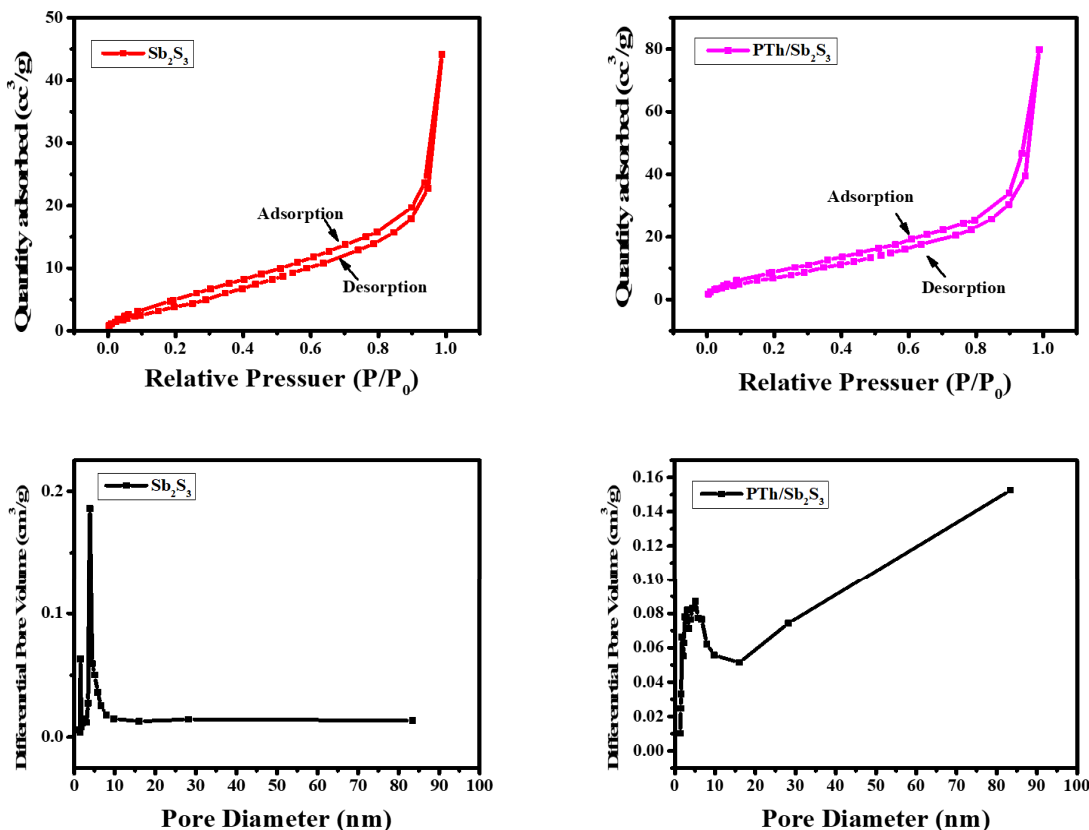


Fig.3. BET isotherm and pore size distribution of Sb_2S_3 and $\text{PTh}/\text{Sb}_2\text{S}_3$

Further, the XPS analysis was performed to characterize the chemical states, the surface elemental composition of the Sb_2S_3 and $\text{Sb}_2\text{S}_3/\text{PTh}$ catalysts and to identify any impurities present. From the Fig.4 the peaks of Sb, S and C are identified as shown in the survey scan of $\text{PTh}/\text{Sb}_2\text{S}_3$. The binding energy peaks of ($\text{Sb } 3d 5/2$) ($\text{Sb } 3d 3/2$) are located around 532 eV and 537eV respectively and the ($\text{S } 2p1/2$) are located around 154eV and 161eV and the peak around 288eV of C 1s spectrum confirmed the sp^2 hybridized carbon in the PTh.

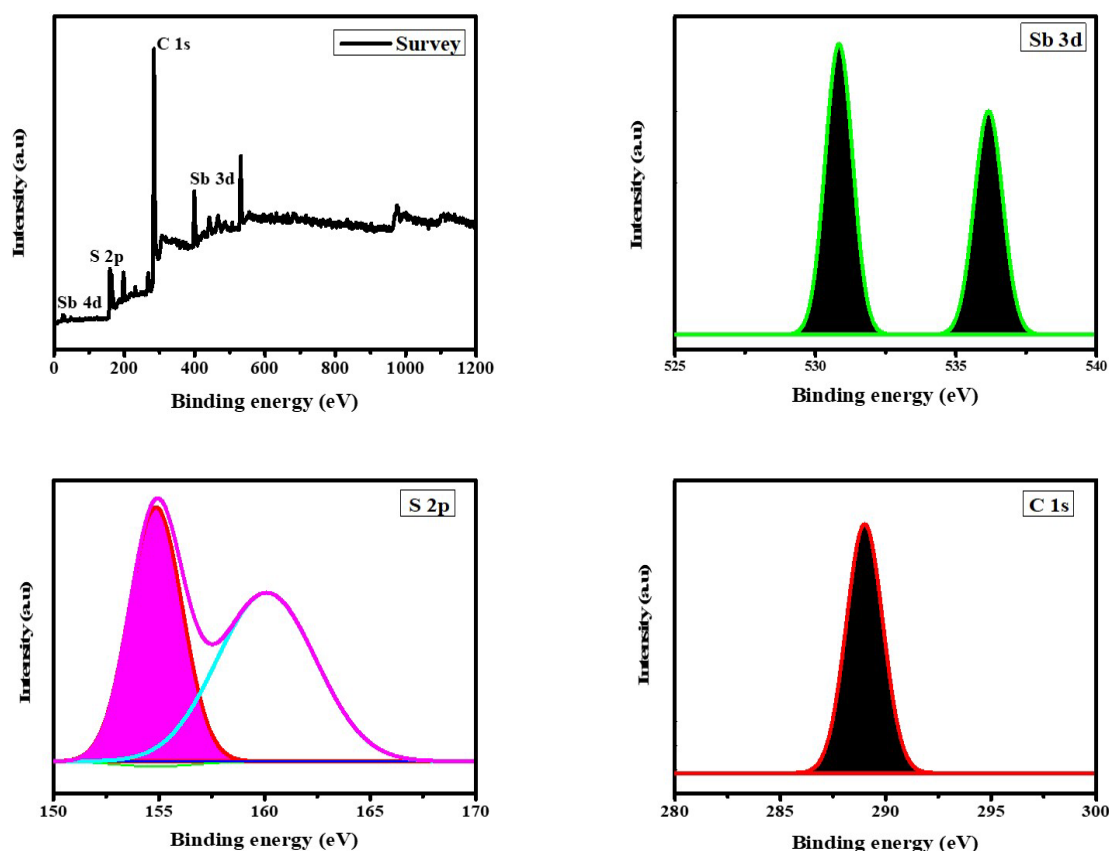


Fig.4. XPS survey of the elemental state of Sb₂S₃/PTh nanocomposite

3.4. Electrochemical Sensing of methanol Using Cyclic Voltammetry

Methanol is a highly volatile and colorless and its exposure in minute concentration in the environment caused poisoning, multi organ failure and even caused to death. Methanol poisoning leads to serious issues such as headache, allergy, fatigue, and narcosis in human beings (Bano et al. 2019). The concentration of methanol for the human intake is less than 5mg/dl is considered to be safe (Hassanian et al. 2018). Hence, there is a necessity for a straightforward and reliable approach to measure minute amounts of methanol found in human consumption. In this regards, sensing of methanol by electrochemical studies could be a viable technique and diagnose the amount of methanol present in any sample. In the present study, cyclic voltammetry (CV) technique has been used for the determination of methanol using glassy carbon electrode (GCE). CV has been proved to be a reliable technique for sensing of toxic solvents using nanomaterials and conducting polymers (Wang et al. 2018). In this technique, the reduction and the oxidation of the analyte under a given potential and the change in the current is recorded. For the detection of

methanol, oxidation peaks has been considered as the standards. In this study, the electrocatalytic property of the Sb_2S_3 and $\text{Sb}_2\text{S}_3/\text{PTh}$ against methanol were examined in 0.1 mM DMSO at room temperature using CV. The assembly for the cyclic voltammetry using working electrode (GCE) for methanol detection are presented in [Fig.S1 \(Supplementary information\)](#).

Electrochemical activity by CV of bare GCE electrode, and modified GCE electrode with Sb_2S_3 and $\text{Sb}_2\text{S}_3/\text{PTh}$ were performed. For the modification of electrode nafion binder were used for the coating of catalyst on the surface of GCE. From [Fig. 5a](#) the CV curve of GCE modified $\text{Sb}_2\text{S}_3/\text{PTh}$ GCE with and without 0.1mM of methanol solution can be clearly observed. The CV response with DMSO is almost negligible however in the presence of 0.1mM methanol, the oxidation peaks can be clearly seen that shows the presence of methanol ([Chung et al. 2016](#)). Further, the CV response of Sb_2S_3 and $\text{Sb}_2\text{S}_3/\text{PTh}$ was performed as shown in [Fig.5b](#), in case of Sb_2S_3 less redox response was recorded and in case of $\text{Sb}_2\text{S}_3/\text{PTh}$ higher current response was recorded against 0.1mM which is due to the synergistic behavior of both Sb_2S_3 and PTh which produces more catalytic sites and increases electron transfer. Further, the response of methanol with various concentration ranging from 0.1mM to 0.7mM was recorded by Sb_2S_3 and $\text{Sb}_2\text{S}_3/\text{PTh}$ in which characteristic anodic peaks in Sb_2S_3 was recorded at 0.34V and for $\text{PTh}/\text{Sb}_2\text{S}_3$ at 0.76 V and cathodic peaks around -0.2 V are observed as shown in [Fig. 5 \(c, d\)](#).

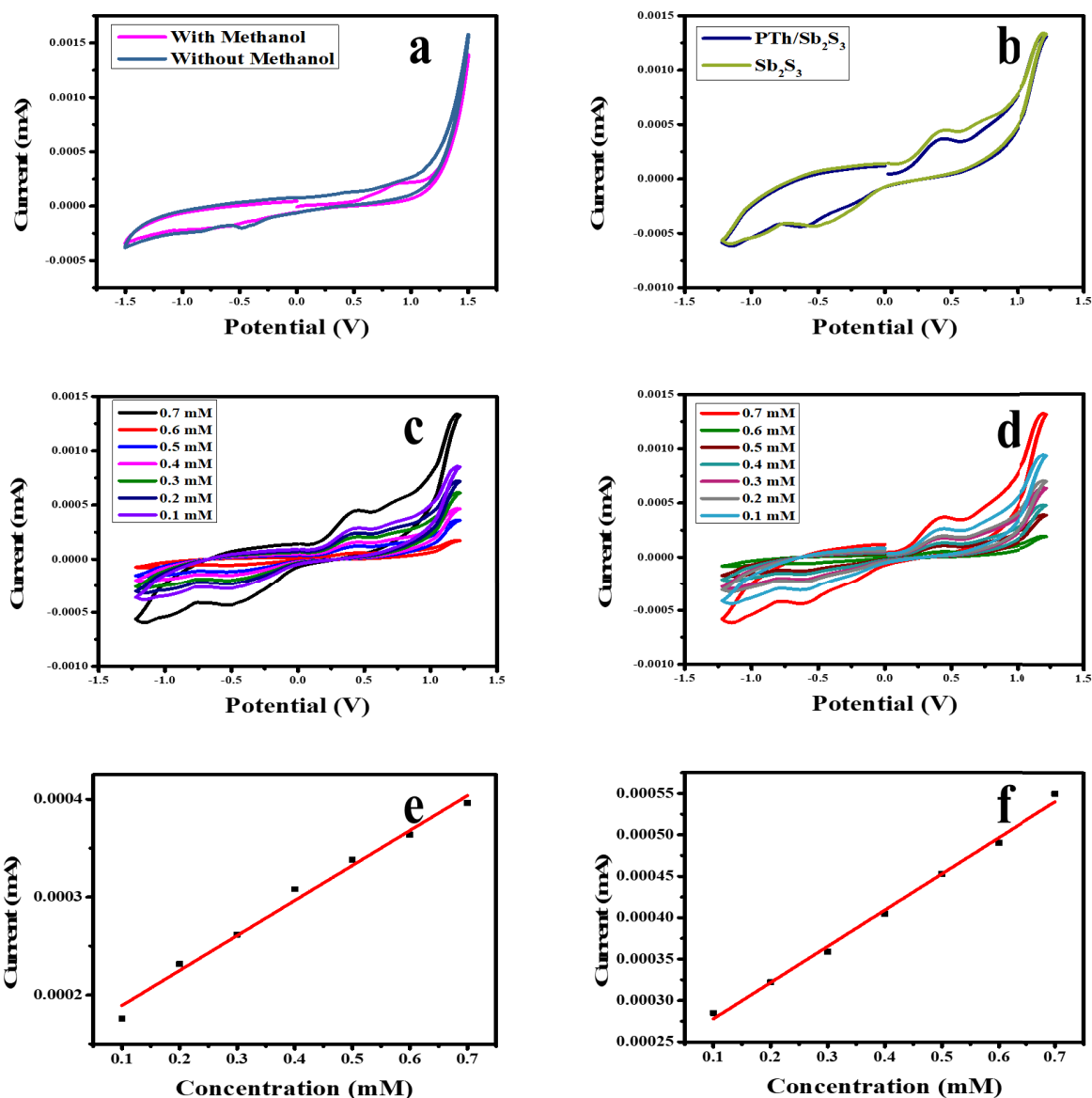


Fig.5. (a) CV curve of bare GCE ear with and without methanol (b) CV response with the modified GCE (c, d) is the CV response of methanol with range of methanol concentration and (e, f) is the calibration curve of Sb₂S₃ and PTh/Sb₂S₃

The variation of anodic peak current with the different concentration of methanol was found to be linear. From the calibration curve the analytical characteristics of Sb₂S₃ and Sb₂S₃/PTh was calculated as shown in 5 (e, f). From the curve, regression coefficient ($r^2 = 0.973$), sensitivity

(2.1025 $\mu\text{A mmol L}^{-1} \text{ cm}^{-2}$), and limit of detection (LOD: 0.046 mmol L^{-1}) were calculated at the S/N ratio of 3. The LOD was calculated using the following equation (3):

$$\text{LOD} = 3\sigma/d \quad (3)$$

Where σ is the standard deviation and the d is the detection limit of the methanol. From the results it can be clearly noted that the anodic peak current (oxidation) varies linearly with the scan rates. This variation in the peak current is due to the electrode reaction which is the surface-controlled electrochemical reaction. Further the rise in the current with varying concentration is due to the oxidation reaction of methanol. Upon continuously increasing the concentration of methanol, the surface coverage of the electrode increases that eventually leads to the oxidation of methanol. During the methanol oxidation, the electrons are liberated and leading to an increase in the current obtained.

3.5. Evaluation of adsorption thermodynamics and kinetics

The Adsorption kinetics and thermodynamics of Sb_2S_3 and $\text{Sb}_2\text{S}_3/\text{PTh}$ were examined at various concentration ranges from 2 ppm to 20 ppm of RhB dye. The adsorption experiment was performed in the acidic medium since the Rh B dye exhibits maximum adsorption in acidic medium (Kusmierek et al. 2023). The mechanism of adsorption of RhB dye at the surface of PTh/ Sb_2S_3 nanocomposite is presented in Fig.6.



Fig.6. Adsorption mechanism of RhB dye at the surface of PTh/Sb₂S₃ nanocomposite

The adsorption thermodynamics of Sb₂S₃ and Sb₂S₃/PTh were examined by using Freundlich and Langmuir adsorption isotherm. The equations for the Freundlich and Langmuir isotherm are shown below (4, 5):

$$\log q_e = \log K_f + \frac{1}{n} \log C_e \quad (4)$$

$$\frac{C_e}{q_e} = \frac{C_e}{q_m} + \frac{1}{K_L q_m} \quad (5)$$

In equation (4) K_f represents the Freundlich equilibrium constant, K_L is the Langmuir adsorption, n is a constant of Freundlich adsorption intensity. In equation (5), q_e is the equilibrium adsorption capacity of q_m is the maximum adsorption capacity of the catalysts. From the results obtained, the fitting parameters and correlation coefficients of Freundlich and Langmuir adsorption isotherm are presented in Table 1 and the plots of Freundlich and Langmuir adsorption isotherm are presented in Fig. 7 a, b.

Table 1: Parameters for the Langmuir and Freundlich model for the adsorption of RhB dye on the photocatalysts

Langmuir model		
Maximum Adsorption Capacity (q_m (mg g ⁻¹))	Adsorption constant (K_L)	Correlation coefficient R_L^2
99.8	0.029	0.97
Freundlich model		
Adsorption constant (K_F)	Adsorption intensity (n)	Correlation coefficient R_F^2
2.21	1.61	0.93

The adsorption of RhB dye onto the Sb₂S₃/PTh surface is characterized by the monolayer adsorption in which the dye molecules are in contact with PTh/Sb₂S₃ surface. The Langmuir model represented the homogenous distribution of adsorbate molecules on the adsorption sites on the adsorption's surface and this leads to monolayer adsorption while on the contrary Freundlich model is known to describe the non-ideal and reversible adsorption, which was not restricted to the formation of monolayer but leads to the multilayer adsorption. Interestingly, both models efficiently demonstrated to analyze the adsorption behavior of adsorbate molecules over the surface. It was interesting to notice that in the preceding research people used to apply both models efficiently and evaluated which one would be the best suited to discuss the adsorption behavior of adsorbate.

In our study, we have efficiently demonstrated Langmuir and Freundlich model to check which model would be best fitted to describe the adsorption of the Dye. Interestingly, it was good to observed that the Langmuir model exhibits better fitting as compared to the Freundlich model which was efficiently confirmed through correlation coefficient (Kumar et al. 2019). In the Langmuir model, the equilibrium data exhibits superior fitting as compared to the Freundlich model. The Langmuir model shows a higher correlation coefficient ($R_L^2 = 0.97$) as compared to Freundlich model ($R_F^2 = 0.93$). A maximum adsorption capacity of the photocatalysts Sb₂S₃, PTh and PTh/Sb₂S₃ is presented in Fig. S2 (Supplementary information). The study further examines into the kinetics of dye removal, employing pseudo first-order and second-order kinetics models. These models are employed to analyze the experimental data and identify the optimal fit for the adsorption of RhB dye on the Sb₂S₃/PTh surface, elucidating the mechanisms involved in the adsorption process. The adsorption process involves the interaction of RhB with the photocatalyst surface, followed by a chemical reaction. The initial diffusion process is governed by a

concentration gradient occurs between the interface and bulk driving the RhB diffusion to the Sb₂S₃/PTh surface. The diffusion process shows relation between the RhB concentration and the adsorption sites of Sb₂S₃/PTh and kinetic rate is established in the diffusion process. Consequently, the diffusion process is studied using the pseudo second order kinetic model to determine the model that best fitted with the experimental data obtained by equations (6, 7) below.

$$\frac{d\theta}{dt} = k_d^2 (\theta_e - \theta_t) \quad (6)$$

$$\ln (\theta_e - \theta_t) = \ln \theta_e - K_a t \quad (7)$$

From the equation (6, 7), θ is the coverage fraction adsorbed on the surface of the photocatalyst at time “t” and at the equilibrium “e” respectively. K_a and K_d are the rate constant for adsorption and diffusion. Moreover pseudo first and second order rate expression can be represented as given below in equations (8, 9):

$$\ln (q_e - q_t) = \ln q_e - K_1 t \quad (8)$$

$$\frac{t}{q_e} = \frac{1}{K_2 q_e^2} + \frac{1}{q_e} \quad (9)$$

Form equations (8, 9) “ q_e ” (mg g⁻¹) is the amount of RhB adsorbed at equilibrium and “ q_t ” (mg g⁻¹) is the amount of RhB adsorbed at time “t”. K_1 and K_2 (g mg⁻¹ min⁻¹) are the adsorption and diffusion rate constant for the pseudo first and second order kinetics. The plots of kinetics of pseudo-first and second order obtained from the experimental date are presented in Fig. 7 c,d. Form the plots, and the higher value “ q_t ” obtained is in case of Sb₂S₃/PTh which shows that higher adsorption of RhB on its surface.

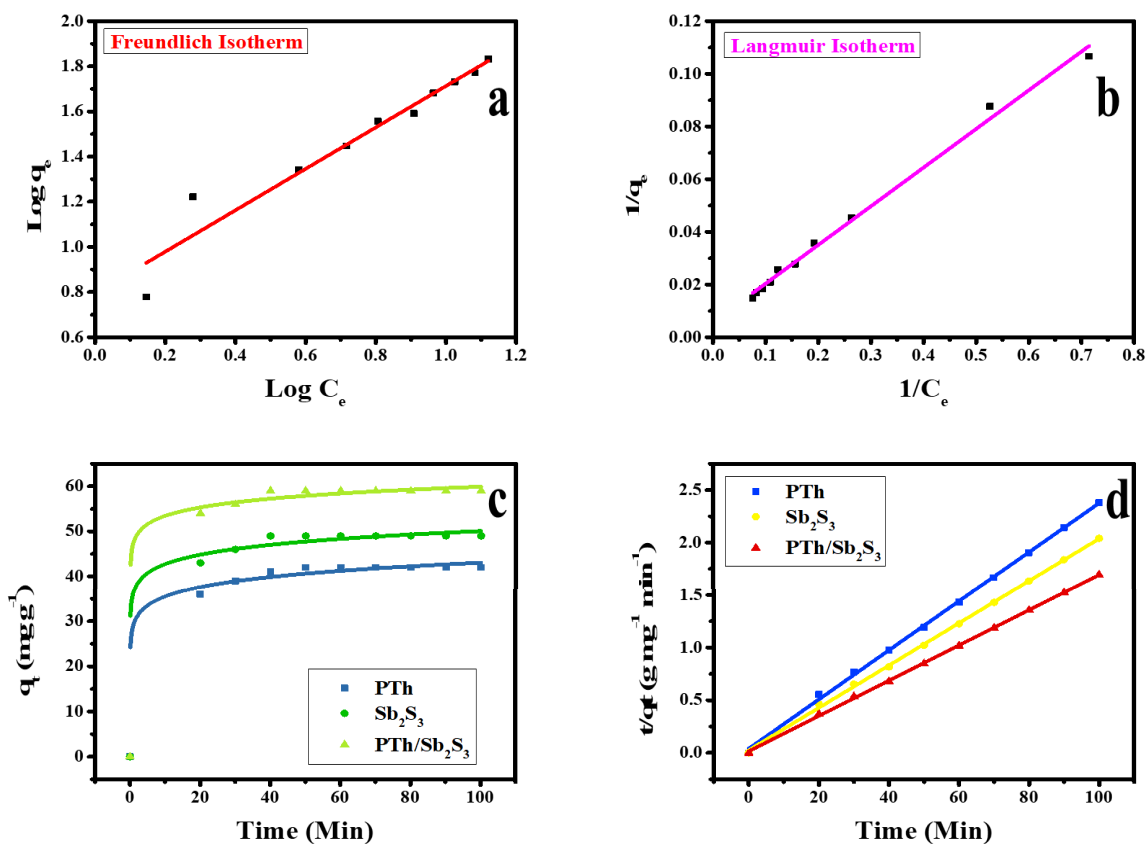


Fig.7. (a) Langmuir isotherm and (b) Freundlich adsorption isotherm of PTh/Sb₂S₃ (c) is the pseudo first order and (d) pseudo second order kinetics

The fitting of pseudo-second and first order and the rate constant obtained from the equations (8, 9) are presented in Table.2.

Table 2: A compare study of the parameters of adsorption and diffusion by PTh, Sb₂S₃ and PTh/Sb₂S₃ photocatalysts

Pseudo-second-order kinetics (diffusion)				
Catalysts	Fitting equation	Rate constant (K ₂) (g mg ⁻¹ min ⁻¹)	Correlation coefficient R _d ²	Standard Deviation
PTh	$\frac{t}{qe} = \frac{1}{K_2 qe^2} + \frac{1}{qe}$	0.0092	0.96	0.11

Sb ₂ S ₃	$\frac{t}{qe} = 0.0369t + 0.0581$	0.0181	0.98	0.10
PTh/Sb ₂ S ₃	$\frac{t}{qe} = 0.0332t + 0.0539$	0.0206	0.994	0.09
Pseudo-first-order kinetics (adsorption)				
Catalysts	Fitting equation $\ln(qe-qt) = \ln qe - K_1 t$	Rate constant (K₁) (g mg⁻¹ min⁻¹)	Correlation coefficient R_a²	Standard Deviation
PTh	=3.713-(-0.1512)t	0.15	0.74	2.23
Sb ₂ S ₃	=3.657-(-0.1452)t	0.14	0.76	1.81
PTh/Sb ₂ S ₃	=3.502-(-0.1389)t	0.13	0.76	2.23

The correlation coefficient for PTh/Sb₂S₃ ($R_d^2 = 0.99$ and $R_a^2 = 0.76$) shows that the adsorption kinetics monitored pseudo first order as well as second order kinetics which indicate that the adsorption takes place followed by diffusion of RhB molecule on the surface of photocatalysts.

4. Conclusions

To conclude, the heterojunction PTh/Sb₂S₃ was found very effective against the removal of RhB dye through adsorption. The catalyst followed both Freundlich and Langmuir isotherm model. The maximum adsorption capacity is found to be 99.8 (mg g⁻¹) when PTh/Sb₂S₃ was applied against RhB dye. The initial concentration was 20 ppm and the equilibrium concentration of 9.2ppm in 100 mins, however when 5ppm concentration was tested the equilibrium concentration was less than 1ppm which is saturation concentration for the removal of dyes. Further, the photocatalyst shows higher correlation coefficient $R^2 = 0.9983$ which indicate that the photocatalyst followed pseudo second order kinetics model in comparison to pseudo first order kinetics ($R^2 = 0.76$). Moreover, the catalysts shows sensing nature towards methanol of concentration ranging from 0.1mM to 0.7 mM. The oxidation peaks at 0.4792V shows the sensing of methanol. Therefore it can be concluded that the synthesized catalysts with their excellent adsorption property and surface area, can be applying for the sensing of toxic solvents as well as for the removal of micropollutants from the wastewater.

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Declaration of Conflict of Interest

On the behalf of all the authors, corresponding author declare no conflicts of interest.

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