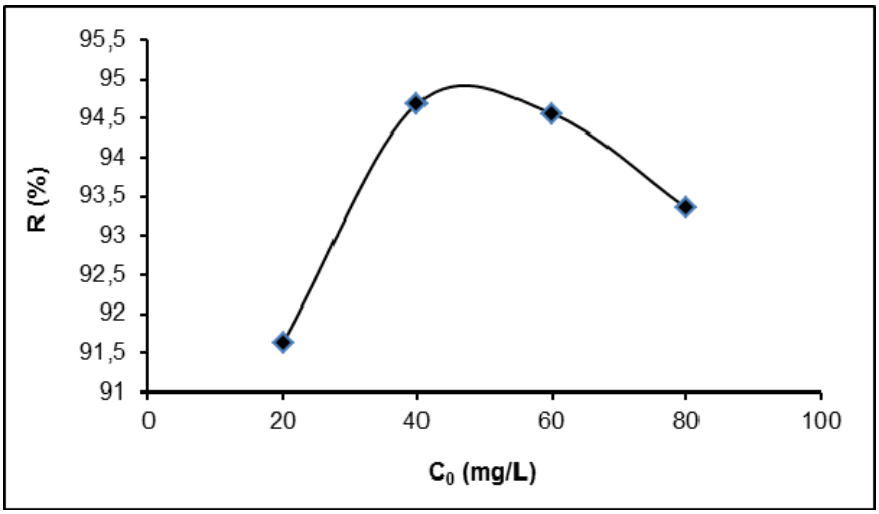

Fig. 6 – Effect of initial dye concentration of AO
(Contact time= 180 min, T=25°C, C_0 = 20 mg/L, agitation=250 rpm).

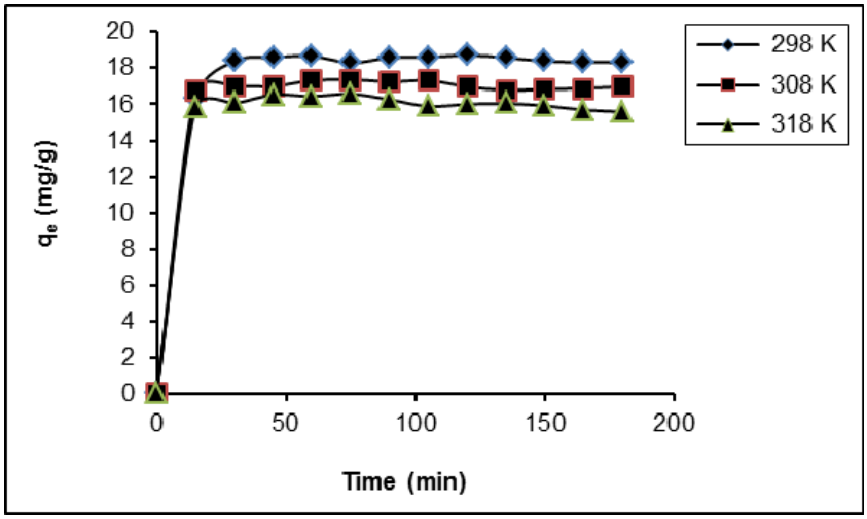

Fig. 7 – Effect of temperature on sorption of AO on GAL.

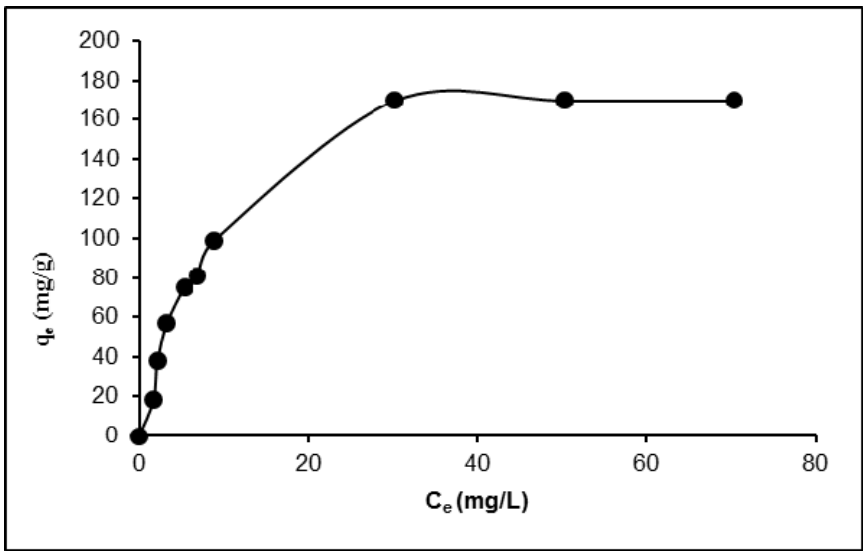

Fig. 8 – Adsorption Isotherm of AO onto GAL.

6. Biosorption isotherms

Analysis of equilibrium data is important for developing a model that can be used for the design of biosorption process. In the present study, two classical isotherm models (Langmuir and Freundlich), Temkin and Dubinin- Radushkevich were used to describe the relationship between the amount of AO adsorbed and its equilibrium concentration in solution.

The Langmuir adsorption isotherm has been successfully applied to many pollutants sorption processes and has been the most widely used sorption isotherm for the sorption of a solute from a liquid solution.[24, 25]

Langmuir isotherm equation is based on monolayer sorption onto a surface with finite number of identical sites; the model assumes uniform energies of adsorption onto the surface and no transmigration of adsorbate in the plane of the surface.[26] The linear form of Langmuir isotherm is given by equation (2):

$$1/q_e = (1/bq_{\max})(1/C_e) + (1/q_{\max}) \quad (2)$$

where, $q_{\max}$ and b are Langmuir constants denoting maximum adsorption capacity and the affinity of the binding sites, respectively. These constants can be determined from the $1/q_e$ *versus* $1/C_e$.[23] The Langmuir sorption isotherm of AO is illustrated in Figure 9. The values of $q_{\max}$ and b estimated from the plots along with the correlation coefficients (R^2) are presented in Table 3. The values $q_{\max}$ and b for the biosorption of AO with GAL biosorbent are 344.8 mg/g and 0.042 L/g, respectively. High correlation coefficient ($R^2 > 0.8518$) suggests that the Langmuir model is applicable. The essential features of a Langmuir isotherm can be expressed in terms of a dimensionless constant separation factor or equilibrium parameter, R_L which is defined by Hall *et al*. [27] as:

$$R_L = 1/(1 + bC_0) \quad (3)$$

The value of R_L indicates the shape of the isotherms to be either unfavourable ($R_L > 1$), linear ($R_L = 1$), favourable ($0 < R_L < 1$). The R_L value 0.106 at 25°C (C_0 = 20 mg/L) (Table 2). The R_L value obtained using equation (3) for AO biosorption is greater than zero and less than unity showing favorable biosorption of AO onto the GAL biosorbent.

The linearized Freundlich form based on sorption on a heterogeneous surface[28] is given below as equation (4):

$$\log q_e = \log K_f + (1/n)\log C_e \quad (4)$$

where K_f and n are Freundlich constants characteristic of the system. K_f and $1/n$ are constants related to adsorption capacity and energy or intensity of adsorption, respectively. These constants can be determined from the linear plot of log q_e *versus* log C_e. [29] The values of the Freundlich constants K_F and $1/n$ are 7.06 and 1 respectively shown in Table 3. The slope $1/n$ ranging between 0 and 1 is a measure of adsorption intensity or surface heterogeneous, becoming more heterogeneous as its value gets closer to zero.[30]

The linearized Freundlich adsorption isotherm of AO obtained is shown in Figure 9. The values of K_f and n estimated from the plots along with the correlation coefficients (R^2) are presented in Table 3.

Heat of adsorption and the adsorbent–adsorbate interaction on adsorption isotherms were studied by Temkin, its equation is given as: [31]

$$q_e = B\ln K_r + B\ln C_e \quad (5)$$

where $B_T = R_T/b$, T is the absolute temperature in K, R (J/mol) the universal gas constant, 8.314 J mol^{-1} K^{-1}, and K_T is the equilibrium binding constant (L/mg), and B is related to the heat of adsorption. The constants obtained for Temkin isotherm are shown in Table 3.

Isotherm constants and correlation coefficient (R^2) are also presented in Table 3. Temkin assumes the heat of adsorption of all the molecules in the layer decreases linearly with coverage due to adsorbent/adsorbate interactions and the adsorption is characterized by a uniform distribution of binding energies, up to a maximum binding energy.[28]

Dubinin-Radushkevich isotherm[32-34] is applied to explain the adsorption form, physical, ion exchange or chemical.[35] It is expressed as follows: [36]

$$\ln q_e = \ln q_s - \beta\varepsilon^2 \quad (6)$$

where q_e is the amount of OA ions adsorbed per unit weight of adsorbent (mg/g), q_s is the maximum adsorption capacity (mg/g), β is the activity coefficient useful in obtaining the mean sorption energy E (kJ/mol) and ε is the Polanyi potential as follows:

$$\varepsilon = RT\ln(1 + 1/C_e) \quad (7)$$

The plot of ln q_e *vs* ε^2 at different concentrations for AO is presented by Figure 9.d. The constant obtained for D–R isotherms are shown in Table 3. Energy related to adsorption can be found from the equation below: [24, 37]

$$E = \frac{\beta^{-\frac{1}{2}}}{\sqrt{2}} \quad (8)$$

The magnitude of E for the GAL adsorption was found 709.22 kJ mol^{-1} at 298K. According to these values adsorption in the present study is in the chemical nature.

The values of the parameters of these isotherms and their related correlation coefficients are shown in Table 3, the Langmuir model yields a somewhat better (R^2 = 0.8542), Temkin isotherm (R^2 = 0.8424) than the Freundlich model (R^2 = 0.6346) and Dubinin Radushkevich model (R^2 = 0.7014). AO biosorption from aqueous solutions by GAL biosorbent was better described by Langmuir model in comparison to Freundlich model since it presents higher R^2 value.

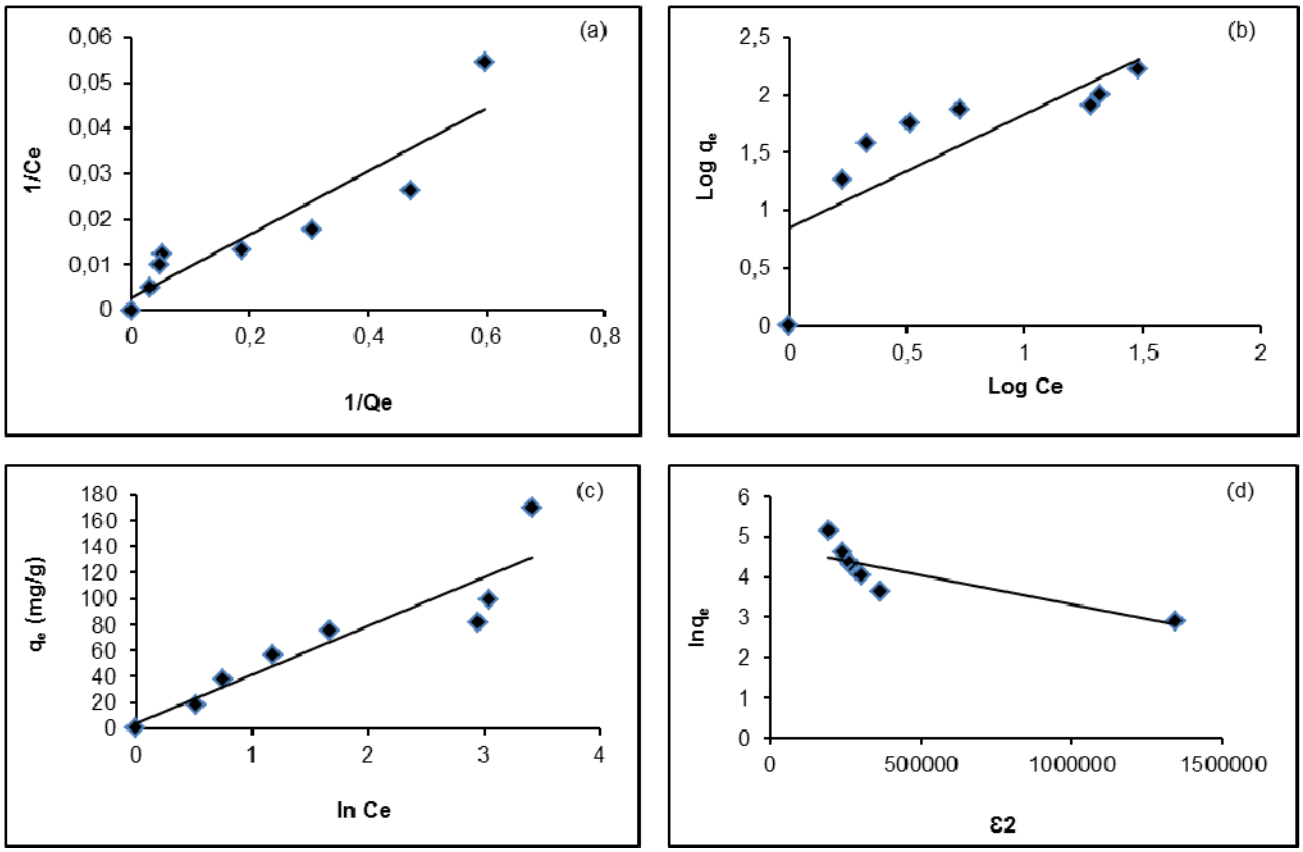

Fig. 9 – a) Langmuir isotherms b) Freundlich isotherms c) Temkin isotherms and d) Dubinin- Radushkevich isotherms obtained at 298 K.

Table 3

The coefficients Isotherm Parameters for AO dye adsorption onto GAL

Parameters	Value
Langmuir Isotherm	
q_{max} (mg/g)	344.8
b (L/mg)	0.042
R_L	0.106
R^2	0.8518
Freundlich Isotherm	
n	1
k_F (L/mg)	7.063
R^2	0.6346
Temkin Isotherm	
K_T (L.mg $^{-1}$)	1.104
R^2	0.8424
Dubinin- Radushkevich Isotherm	
E (kJ mol^{-1})	709.22
R^2	0.7014