

## A review on interaction of phenolic pollutant with other pollutants in the binary adsorption system

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### ABSTRACT

Due to the drastic industrial development, it has become evident that various harmful chemicals are released into the environment. Industrial effluent comprises pollutants of varied nature such as organic pollutants, heavy metals, dyes, and other toxic chemicals. Phenolic and its derivative pollutants are such groups of organic compounds which are widely detected in domestic wastewater. The pollutant is also associated with many different industrial effluents, making it a heterogeneous mixture. So, to abate this toxic waste many treatment methods have emerged. Adsorption is one such treatment methods which has become the best available methods to treat an effluent of this nature. However, during the process of adsorption mixture of contaminants involves complex interactions such as synergism, antagonism, non-interaction, and competition between the solute molecules for the adsorbent. In this review paper, we have tried to identify interactions in binary adsorption setup of organic pollutants (phenol and 2,4-dichlorophenol). The study also considers interaction factors present in 3 multicomponent isotherms and other factors which are mostly associated with binary system to arrive on to suitable interaction.

*Keywords:* Adsorption; Competitive; Interaction; Isotherm models; Multicomponent adsorption

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### 1. Introduction

Effluent from the industry is the source of many diversified pollutants. The effluent is mainly composed of a heterogeneous mix of contaminants such as heavy metals, organic and inorganic pollutants and is accompanied by other parameters such as total dissolved solids, colour [1–3]. Phenolic compounds are the most commonly monitored pollutants in industrial effluents, agricultural and domestic discharges [4–6]. Recently, phenol and its derivatives, such as chlorophenol, 2,4-dichlorophenol (2,4-DCP) etc., have attracted significant attention. It could be owing to their

comprehensive resources, such as effluents discharged from many industries. They are coke ovens in steel plants, petroleum refineries, petrochemical, phenolic resin, pesticide and fertiliser, pharmaceutical chemicals, dye industries, coal processing, plastics and wood products, paint and paper industries, explosives and leather treatments [7–9]. Though these compounds are present in small concentrations in frequently used items like plants, microorganisms, foods, cosmetics etc. their large-scale presence in the environment is attributed to the various human activities as these compounds are extensively used in various industries [10–13].

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There are strict regulations worldwide when the phenolic compound is considered because of its extreme toxicity. Due to their toxic effects, effluents containing phenolic compounds cannot be discharged without proper treatment. Also, the regulations on the discharge of effluents containing phenol and associated compounds, such as 2,4-DCP, chlorophenol etc., have been imposed by various environmental protection agencies and boards. Some of the important properties of phenol and 2,4-DCP are given in Table 1.

Methods such as adsorption, biodegradation, photocatalysis, etc., have been implemented to date for the remediation of such pollutants. Among them, adsorption using various adsorbents such as granular activated carbon [11], coconut husk activated carbon [18], biologically activated carbon

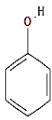
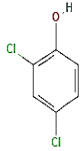
[17], rice husk ash [19], iron nanocomposites [20] etc, are investigated.

Several studies have been carried out on the adsorption of single-component pollutants [21–23]. This has happened for many decades because of the ease in conducting experiments. It is evident from the literature that, in recent two decades, studies on binary and ternary component adsorption have been advancing [24–27]. Due to the heterogeneity associated with phenol, 2-DCP and many such pollutants, it becomes challenging for an environmental engineer to abate phenolic pollutants at the lab scale using adsorption techniques [28,29]. Adding to this, difficulty is also due to complexity of interaction factors when more than one pollutant is considered for remediation using adsorption technique.

Moreover, the interaction phenomena such as synergistic (SYI), antagonistic (ANI) and non-interaction (NI) are observed depending on the adsorption capacity of the pollutants. This could be due to some inherent effects such as hydrophobic effect,  $\pi$ - $\pi$  interactions, electrostatic attraction, surface complexation, co-precipitation etc [16–19]. The interactions between adsorbents, adsorbate and between contaminants could be due to charge on pollutant, surface area, porosity of adsorbent etc. [34]. So, it is essential to understand the potential interactions occurring in the system.

A survey was made using the Scopus survey tool for the keywords “Simultaneous”, “Adsorption”, and “Interaction”. It was found that a around 2643 (from 1930–2022) different research articles have investigated the interaction factor in their respective domains. Fields such as Chemistry, Chemical Engineering, and Environmental Engineering contribute to more than 50% of the total research. From Fig. 1 it can also be concluded that there is ample scope to explore this field. Furthermore, it becomes imperative for current researchers to contribute more towards this study and investigate the interaction factors participating in adsorption process. These interaction factors will help to understand the multi-component adsorption mechanism

Table 1  
Physical and chemical properties of phenol and 2,4-dichlorophenol

Parameters	Phenol	2,4-DCP	References
Formula	C <sub>6</sub> H <sub>6</sub> O	C <sub>6</sub> H <sub>4</sub> Cl <sub>2</sub> O	
Molecular weight	94.11 g/mol	163.1 g/mol	
Solubility in water at 25°C	8.3 g/100 mL	5 g/100 mL	
Density	1.07 g/cc	1.38 g/cc	
Melting point	40.91°C	42°C–43°C	
Boiling point	181.75°C	210°C	
$\lambda_{\max}$ (nm)	270	283	[13–17]
Dipole moment	1.22 D	1.60 D	
pKa	9.89	7.9	
Structural formula			

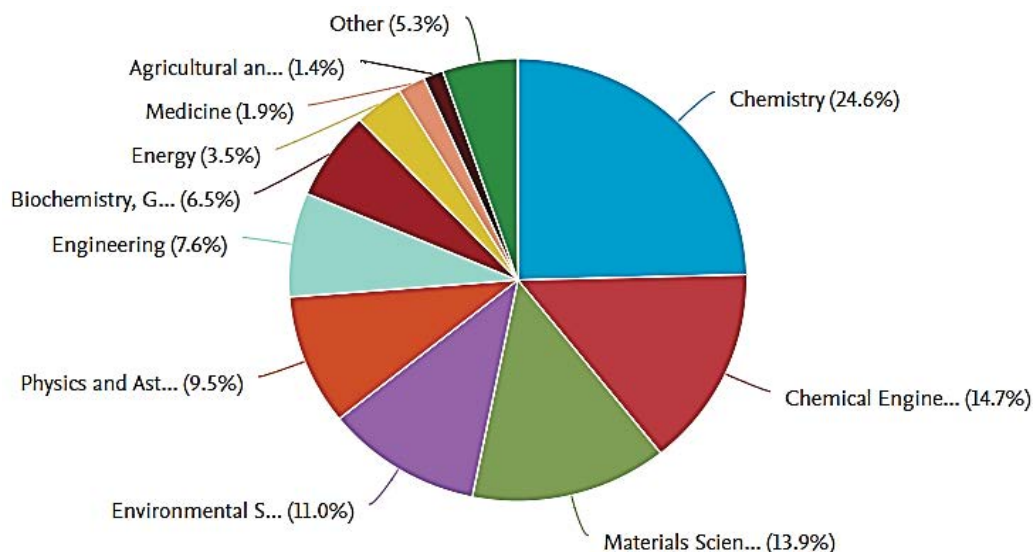


Fig. 1. Scope of the study.

better. A considerable amount of literature has been published on investigating interactions in binary adsorption system by means of adsorption capacity only. To some extent affinity, selectivity and inhibition was also discussed in some investigations. However, degree of interactions of SYI, ANI and NI are least discussed. This review looks into the simultaneous adsorption of organic components (phenols/2,4-dichlorophenol) with other components in a binary system. It is focused on (i) understanding the different interactions in binary adsorption setup by means of different factors as mentioned in section 2. (ii) Further, different possible mechanisms responsible for the interaction are discussed. (iii) Besides, an attempt to generalise the factors is carried out to arrive at specific interaction.

## 2. Types of interaction in binary system

Studies on competitive adsorption of two pollutants involve three possible mechanisms. The basic principle governing these mechanisms is by considering the adsorption capacity of the contaminants. They are adsorption capacity (i) in the binary solution  $(Q_{i,o})_b$  and the adsorption capacity adsorbate (ii) in a single-component system  $(Q_{i,o})_s$ .

### 2.1. Based on adsorption capacity

#### 2.1.1. Synergistic interaction

It is defined as a type of interaction observed in bisolute adsorption system where, presence of one solute enhances the adsorption capacity of other [35,36]. This interaction can also be depicted in terms  $(Q_m)_b$  and  $(Q_m)_s$  which represents adsorption capacity in binary and single adsorption systems, respectively. In this case, the ratio of  $(Q_m)_b$  to  $(Q_m)_s$  is always greater than 1. Mathematically, it can be represented as below:

$$\frac{(Q_m)_b}{(Q_m)_s} > 1 \tag{1}$$

The synergistic interaction is exemplified in the work undertaken by Nguyen et al. [35] and Dhandole et al. [37] wherein the former study involves simultaneous adsorption of phenol and Ni(II) and latter involves investigation on synergistic effect of heavy metals on to nanorods/nanotubes.

#### 2.1.2. Antagonistic interaction

It is defined as a type of interaction observed in binary adsorption system, in which there is decline in adsorption capacity of a pollutant when associated with another pollutant [19,33] and the ratio of  $(Q_m)_b$  to  $(Q_m)_s$  is less than 1. Mathematically it can be written as below:

$$\frac{(Q_m)_b}{(Q_m)_s} < 1 \tag{2}$$

Few examples of what is meant by antagonistic interaction can be found in research carried out by Thakur

et al. [19] and Rathore et al. [38]. The schematic representation of various interactions in bisolute adsorption system is shown in Fig. 2.

#### 2.1.3. Non-interaction

It is defined as a “type of interaction in which there is no significant change in adsorption capacity of a pollutant when associated with another pollutant” [39,40]. Mathematically, non-interaction can be represented as follows:

$$\frac{(Q_m)_b}{(Q_m)_s} \approx 1 \tag{3}$$

The above interaction has been reported in an investigation carried out by Jin et al. [41], where adsorption capacity of copper ions and 2,4-DCP did not alter in binary adsorption system. Similar interaction was communicated by Kumar et al. [42].

### 2.2. Based on multi-component isotherm model and other factors

Significant literature is available for binary adsorption systems. These studies can be modelled and validated using many modified and non-modified competitive isotherms/models. But not all of these models efficiently identify the interaction between the adsorbate molecules of a binary system. Also, in most of the cases the parameters calculated from the single-component adsorption isotherm model do not delineate the interaction between the individual components. Some models, for example, modified competitive Langmuir isotherm, modified competitive Redlich–Peterson isotherm and Sheindorf–Rebuhn–Sheintuch (SRS) equation have incorporated parameters to identify an interaction.

#### 2.2.1. Modified competitive Langmuir isotherm

In a binary system, an interaction term has to be introduced to describe the mechanism of the adsorption process. This interaction term shows the competitive effect of adsorbates in the solution. It is a characteristic parameter of a component, and it depends on the concentration of the other components present in the solution [11,18]. It is represented mathematically as below:

$$(Q_{i,e})_b = \frac{(Q_{i,o})_b \times b_i \times \frac{(C_{i,e})_b}{\eta_i}}{1 + \sum_{j=1}^N b_j \times \frac{(C_{j,e})_b}{\eta_j}} \tag{4}$$

where  $Q_{i,e}$  equilibrium adsorption capacity for component  $i$ , mg/g;  $(C_{i,e})_b$  concentration, mg/L;  $(Q_{i,o})_b$  monolayer adsorption capacity for component  $i$ , mg/g;  $b_i$  Langmuir constant for component  $i$ , L/mg.

The value of  $N$  for the binary system is 2. The notations  $\eta_i$  and  $\eta_j$  are the interaction factors for components  $i$  and  $j$ . The value of  $\eta_i$  is a function of characteristics of

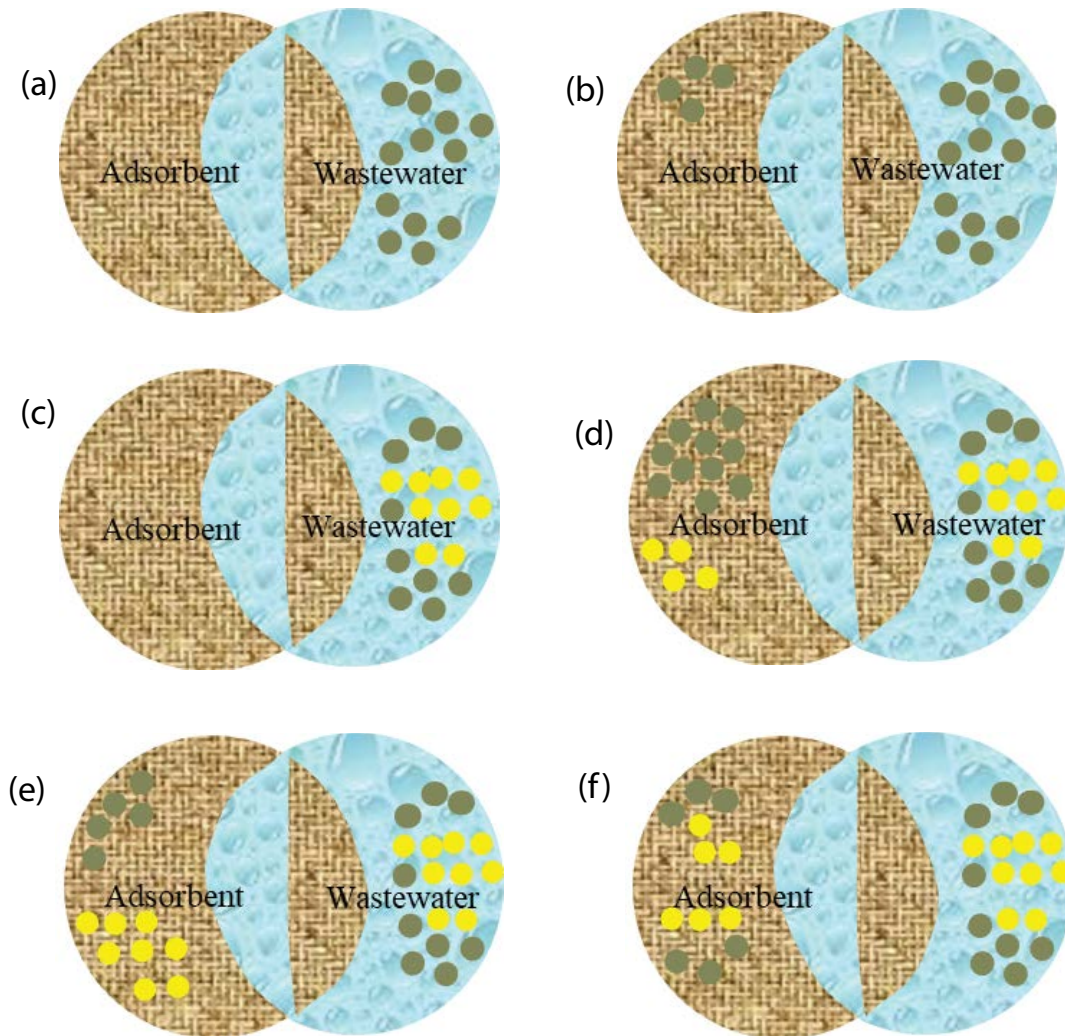


Fig. 2. Schematic representation for different interactions in binary system. (a) Single system – before adsorption, (b) single system – after adsorption, (c) binary system – before adsorption, (d) binary system – after adsorption (synergistic interaction), (e) binary system – after adsorption (antagonistic interaction) and (f) binary system – after adsorption (non-interaction).

adsorbent, concentration of component  $j$ . A higher value of  $\eta_i$  implies a lower affinity of component  $i$  to the adsorbent and vice versa.

2.2.2. Sheindorf–Rebuhn–Sheintuch equation

The interaction factor out of SRS equation has potential to investigate the inhibition of adsorption for a component in a binary solution by another component [36–38]. The equation is given as below:

$$(Q_{i,e})_b = k_i \times (C_{i,e})_b \times \left( \sum_{j=1}^N (\theta_{i,j} (C_{j,e})_b) \right)^{\left(\frac{1}{n_i}\right)-1} \tag{5}$$

where  $Q_{i,e}$  – equilibrium adsorption capacity for component  $i$ , mg/g;  $C_{e,i}$  – equilibrium concentration of an  $i$ th component, mg/L;  $k_i$  – Freundlich constant;  $n_i$  – adsorption intensity;  $\theta_{ij}$  – competition coefficient.

$\theta_{ij}$  indicates inhibition of adsorption of the  $i$ th component by adsorption intensity ( $N = 2$ ) for a binary solution. The interaction component  $\theta_{ij}$  shows inhibition of  $i$ th component on adsorption of the  $j$ th component. The higher value of  $\theta_{ij}$  than  $\theta_{ji}$  signifies that, in binary solution, the  $j$ th component has more potent inhibition. It also infers that component  $i$ th component has weaker inhibition on the adsorption of component  $j$  [25].

2.2.3. Modified competitive Redlich–Peterson isotherm

The special term ( $\eta_{PR,i}$ ) added in modified competitive Redlich–Peterson isotherm (MCRPI) shows the interaction among the components in a multi-component solution. The model can be represented as:

$$(Q_{i,e}) = \frac{(k_{PR,i} (C_{e,i} / \eta_{PR,i}))}{1 + \sum_{j=1}^N (a_{PR,j} (C_{e,j} / \eta_{PR,j})^{\beta,j})} \tag{6}$$

where  $Q_{i,e}$  – equilibrium adsorption capacity for component  $i$ , mg/g;  $C_{e,i}$  – concentration, mg/L;  $\eta_{PR,i}$  and  $\eta_{PR,j}$  – model constant, L/mg;  $\beta$  and  $a_{PR}$  – model constant, (L/mg) $^\beta$ .

The value of  $N$  for the binary system is 2. The notations  $\eta_{PR,i}$  and  $\eta_{PR,j}$  are the interaction factors for component  $i$  and  $j$  and the value of  $\eta_{PR,i}$  is dependent on the concentration of component  $j$ . A higher value of  $\eta_{PR,j}$  implies lower affinity of that component towards adsorbent and vice versa. The studies including these factors are calculated in Table 2 and the significance of each factor is explained. Further, it is important to study the interaction behaviour of the pollutant in a binary solution. It is required to investigate on how the adsorbent-components interact with each other and with adsorbate. It is moreover prominent to note that, how one adsorbent-pollutant dominates over other or gets inhibited by other pollutant in solution. Furthermore, it is also significant to understand affinity of a pollutant towards the adsorbent and how the adsorbents are attracted towards the solid surface. In the previous studies, these discussion on various interactions were investigated comparing the adsorption capacity as factor. They can also be explained based on the interaction factors namely selectivity ratio, sorption affinity, P-factor, and inhibition factor.

#### 2.2.4. Selectivity ratio ( $S_{(ij)}$ )

It is the ratio of adsorption capacity of  $i$ th solute to  $j$ th in the single/binary adsorption system. The ratio gives an idea of the affinity of an adsorbent towards a component in a binary solution. It also aids in the investigation of selective preference of the desired adsorbent for a particular pollutant. It is due to surface structure, morphology, and pore distribution [23–26]. The selectivity ratio can be represented in two forms, one each for single component and binary component adsorption system as show below:

$$S_{(ij)} = \frac{(Q_{i,o})_b}{(Q_{j,o})_b} \tag{7}$$

$$S_{(ij)} = \frac{(Q_{i,o})_s}{(Q_{j,o})_s} \tag{8}$$

where  $(Q_{i,o})_b$  – monolayer adsorption capacity for component  $i$  in binary system, mg/g;  $(Q_{j,o})_b$  – monolayer adsorption capacity for component  $j$  in binary system, mg/g;  $(Q_{i,o})_s$  – adsorption capacity for component  $i$  single system, mg/g;  $(Q_{j,o})_s$  – adsorption capacity for component  $j$  in single system, mg/g.

If the ratio  $S_{(ij)}$  is more than  $S_{(ij)'}$  it implies that the adsorbent has a stronger affinity towards component  $i$  than component  $j$  and vice versa.

#### 2.2.5. Sorption affinity ( $k_s^*$ )

It refers to an attraction of solvent to a solute molecule present in a binary solution. The factor helps compare the adsorption capabilities of different adsorbents in a binary system. It is represented by the equation as given below:

$$k_s = \frac{(C_{i,o})}{(C_{i,s})_b} \tag{9}$$

where  $(C_{i,o})$  – initial concentration of a component, mg/L;  $(C_{i,s})_b$  – concentration of solute in a solid phase in binary solution, mg/L.

The greater value of  $k_s^*$  of component  $i$  and  $j$ , indicates a weaker affinity of the adsorbent to the solute molecule in a binary system [28]. The factor can also be used to distinguish the interaction in bisolute adsorption setup. However, the formula can only be used to identify interaction when the initial concentrations of component  $i$  and  $j$  are same (say 100 mg/L).

#### 2.2.6. P-factor ( $P_f$ )

It is defined as the ratio of adsorption capacity of pollutant in mono-component to adsorption capacity in binary solution. This factor compares data about single-component equilibrium and the binary component. P-factor helps to understand the competitive adsorption of the components in a binary solution [23–28]. The factor also explains how another component in a binary solution inhibits the adsorption of a component. It is given by the expression:

$$P_{fi} = \frac{(Q_{i,o})_s}{(Q_{i,o})_b} \tag{10}$$

where  $(Q_{i,o})_s$  – adsorption capacity for component  $i$  single system, mg/g;  $(Q_{i,o})_b$  – monolayer adsorption capacity for component  $i$  in binary system, mg/g

The value of  $P_{fi}$  determines the inhibition of adsorption of a component by another component in a binary solution [23].  $P_{fi}$  greater than one, implies the adsorption of component  $i$  is inhibited in presence of component  $j$  also the component  $i$  exhibits antagonistic interaction in the presence component  $j$ . The value of  $P_{fi}$  lower than unity, implies the adsorption of component  $i$  is enhanced in presence of component  $j$  in the binary solution and the component  $i$  exhibits synergistic interaction in presence component  $j$ . For the value of  $P_{fi}$  equal to unity suggests that the adsorption of both pollutants are unaltered by other component and both components follow non-interaction.

#### 2.2.7. Inhibitory effect ( $\Delta IE$ )

The adsorption of an adsorbate may be inhibited by another component present in the binary system which can be described by the inhibitory effect ( $\Delta IE$ ). Mathematically it is represented as below:

$$\Delta IE_i = \frac{(Q_{i,o})_s - (Q_{i,o})_b}{(Q_{i,o})_s} \tag{11}$$

where  $(Q_{i,o})_s$  – adsorption capacity for component  $i$  single system, mg/g;  $(Q_{i,o})_b$  – monolayer adsorption capacity for component  $i$  in binary system, mg/g.



S. No.	Adsorbent	Pollutant	Experimental conditions				Adsorption capacity (mg/g)			Factors	Findings from factor	Interaction based on factors	Inference	References		
			Adsorbent dosage (g/L)	Temp. (K)	Initial concentration (g/L)	pH	Speed (rpm)	Pollutant ant 1 (Single)	Pollutant ant 2 (Single)						Pollutant ant 1 ant 2 (Binary)	
3.	Coconut shell-activated carbon	(1)														
		(2)	4	303	0.3/0.03	8	120	6.67	1.09	239.85	5.30	<p>Selectivity ratio: 45.3, 6.12</p> <p>Sorptive affinity: 1.39, 1.152</p> <p>P-factor: 0.028, 0.206</p> <p>Inhibitory effect: -34.96, -3.86</p> <p>Selectivity ratio: 160.5, 7.45</p>	<p>Adsorbent has a stronger affinity towards pollutant 1</p> <p>Pollutant 1 has less affinity w.r.t pollutant 2</p> <p>Adsorption of pollutant 1 is enhanced and pollutant 2 is suppressed</p> <p>Adsorption of pollutant 2 is suppressed by pollutant 1</p> <p>Adsorbent has a stronger affinity towards pollutant 1</p>	<p>Synergistic (phenol, CN)</p> <p>Synergistic (phenol, CN)</p> <p>Synergistic (phenol, CN)</p> <p>Synergistic (phenol, CN)</p>	<p>Synergistic interaction of phenol and CN was observed which can be clearly understood by negative values of inhibitory effect. Weak van der Waal forces were found to influence the adsorption process.</p>	[18]
4.	<i>Pseudomonas putida</i> on coconut shell-activated carbon	Phenol	3-4	303	0.5/0.05	7	120	18.19	2.44	349.86	2.18	<p>Sorptive affinity: 1.4, 1.13</p> <p>P-factor: 0.052, 1.12</p> <p>Inhibitory effect: -18.237, 0.107</p>	<p>Pollutant 1 has less affinity w.r.t pollutant 2</p> <p>Adsorption of pollutant 1 is enhanced and pollutant 2 is suppressed</p> <p>Adsorption of pollutant 2 is suppressed by pollutant 1</p>	<p>Synergistic (cyanide)</p> <p>Synergistic (phenol)</p> <p>Antagonistic (phenol and CN, cyanide)</p> <p>Synergistic (phenol)</p> <p>Antagonistic (CN)</p> <p>Synergistic (phenol)</p> <p>Antagonistic (CN)</p> <p>Synergistic (phenol)</p> <p>Antagonistic (CN)</p>	<p>The values of P-factor and inhibitory effect depict strong synergistic effect and a weak antagonistic effect in phenol and CN, respectively. This is due to the fact that adsorbent has stronger affinity towards phenol as observed from the values of selectivity ratio.</p>	[63]

S. No.	Adsorbent	Pollutant	Experimental conditions				Adsorption capacity (mg/g)				Factors	Findings from factor	Interaction based on factors	Inference	References		
			Adsorbent dosage (g/L)	Temp. (K)	Initial concentration (g/L)	pH	Speed (rpm)	Pollutant ant 1 (Single)	Pollutant ant 2 (Single)	Pollutant ant 1 (Binary)						Pollutant ant 2 (Binary)	
5.	Sugarcane bagasse	Phenol	CN	40	303	0.3/0.03	7	120	4.57	0.87	94.25	5.46	<p>Selectivity Ratio: 17.26, 5.253</p> <p>Sorptive affinity: 1.49, 1.26</p> <p>P-factor: 0.048, 0.159</p> <p>Inhibitory effect: -19.62, -5.3</p> <p>Selectivity ratio: 10.16, 10.8</p>	<p>Adsorbent has a stronger affinity towards pollutant 1</p> <p>Pollutant 1 has less affinity w.r.t pollutant 2</p> <p>Adsorption of pollutant 1 is enhanced and pollutant 2 is suppressed</p> <p>Adsorption of pollutant 2 is suppressed by pollutant 1</p> <p>Adsorbent has a stronger affinity towards pollutant 1</p>	<p>Synergistic (phenol, CN)</p> <p>Synergistic (phenol, CN)</p> <p>Synergistic (phenol, CN)</p> <p>Synergistic (phenol, CN)</p> <p>Synergistic (phenol, CN)</p>	<p>Filling of pores by solute molecules can be observed as one of the adsorption mechanisms as found from FE-SEM images. Higher degree of Synergism in phenol was observed as compared to CN. From the investigation, potential route of adsorption was found to be chemisorption.</p>	[58]





S. No.	Adsorbent	Pollutant		Experimental conditions				Adsorption capacity (mg/g)				Factors	Findings from factor	Interaction based on factors	Inference	References	
		(1)	(2)	Adsorbent dosage (g/L)	Temp. (K)	Initial concentration (g/L)	pH	Speed (rpm)	Pollutant 1 (Single)	Pollutant 2 (Single)	Pollutant 1 (Binary)						Pollutant 2 (Binary)
9.	<i>Bacillus</i> sp. onto tea waste biomass	Phenol	Cr(VI)	15	310	0.25–0.5	5	120	7.62	14.075	7.7608	741.389	<p>Selectivity ratio: 0.01, 0.54</p> <p>Sorptive affinity: -1.17, 1.02</p> <p>P-factor: 0.982, 0.019</p>	<p>Adsorbent has a stronger affinity towards pollutant 2</p> <p>Pollutant 1 has less affinity w.r.t pollutant 2</p> <p>Adsorption of pollutant 2 is enhanced and pollutant 1 is suppressed</p> <p>Adsorption of pollutant 1 is suppressed by pollutant 2</p>	<p>Synergistic (phenol, Cr)</p> <p>Synergistic (phenol, Cr)</p> <p>Synergistic (phenol, Cr)</p>	<p>In the presence of an organic compound, uptake of Cr(VI) increased. The values of selectivity ratio and sorption affinity suggest the same. Also, it was due to the coupling reduction of Cr(VI) with energy-yielding reactions. The significant forces such as <math>\pi-\pi</math> interactions were responsible for adsorption process. The degree of synergistic interaction in phenol was less as compared to chromium ion as observed from the values of inhibitory factor (-0.0185, -51.7).</p>	[65]
				4–5	303	0.1–1	7.2	150	25.41	24.25	25.41	24.25	24.25	<p>Selectivity ratio: 1.05, 1.05</p> <p>Sorptive affinity: 1.03, 1.02</p> <p>P-factor: 1.0, 1.0</p>	<p>Adsorbent has a equal affinity towards pollutant 1 and 2</p> <p>Pollutant 1 and pollutant 2 have same affinity</p> <p>Adsorption of pollutant 1 and 2 was neither enhanced nor inhibited</p> <p>Adsorption of pollutant 1 and 2 did not alter</p>	<p>No interaction (phenol and resorcinol)</p> <p>No interaction (phenol and resorcinol)</p> <p>No interaction (phenol and resorcinol)</p>	<p>In a binary mixture of phenol and resorcinol, the former adsorbed more. This is because the solubility of phenol is less, making it hydrophobic and favourable for adsorption. Non-interaction can be explained from the equal values of all the factors for 2 solutes.</p>
10.	GAC	Phenol	Resorcinol	4–5	303	0.1–1	7.2	150	25.41	24.25	25.41	24.25	<p>Selectivity ratio: 1.05, 1.05</p> <p>Sorptive affinity: 1.03, 1.02</p> <p>P-factor: 1.0, 1.0</p>	<p>Adsorbent has a equal affinity towards pollutant 1 and 2</p> <p>Pollutant 1 and pollutant 2 have same affinity</p> <p>Adsorption of pollutant 1 and 2 was neither enhanced nor inhibited</p> <p>Adsorption of pollutant 1 and 2 did not alter</p>	<p>No interaction (phenol and resorcinol)</p> <p>No interaction (phenol and resorcinol)</p> <p>No interaction (phenol and resorcinol)</p>	<p>In a binary mixture of phenol and resorcinol, the former adsorbed more. This is because the solubility of phenol is less, making it hydrophobic and favourable for adsorption. Non-interaction can be explained from the equal values of all the factors for 2 solutes.</p>	[42]

S. No.	Adsorbent		Pollutant	Experimental conditions				Adsorption capacity (mg/g)				Factors	Findings from factor	Interaction based on factors	Inference	References	
	(1)	(2)		Adsorbent dosage (g/L)	Temp. (K)	Initial concentration (g/L)	pH	Speed (rpm)	Pollutant ant 1 (Single)	Pollutant ant 2 (Single)	Pollutant ant 1 (Binary)						Pollutant ant 2 (Binary)
11.	Rice husk ash (RHA)	Phenol	Resorcinol	20	303	0.050-1	6	150	9.03	6.211	12.44	11.78	Selectivity ratio: 1.06, 1.454 Sorption affinity: 3.91, 1.904 P-factor: 0.726, 0.527	Adsorbent has a stronger affinity towards pollutant 1 Pollutant 1 has less affinity w.r.t pollutant 2 Adsorption of pollutant 2 is enhanced and pollutant 1 is suppressed	Synergistic (phenol, resorcinol) Synergistic (phenol, resorcinol) Synergistic (phenol, resorcinol)	The adsorption of phenol on RHA in the presence and absence of resorcinol was significant. The negative values of inhibitory effect of the solute suggest synergistic interaction. [19] The leading forces aiding adsorption and interaction were $\pi$ - $\pi$ dispersion interactions, hydrogen bonding, and donor-acceptor interactions.	[19]

S. No.	Pollutant		Experimental conditions				Adsorption capacity (mg/g)			Findings from factor	Interaction based on factors	Inference	References			
	(1)	(2)	Adsorbent dosage (g/L)	Temp. (K)	Initial concentration (g/L)	pH	Speed (rpm)	Pollutant 1 (Single)	Pollutant 2 (Single)					Pollutant 1 (Binary)	Pollutant 2 (Binary)	
13.	Sheesham sawdust	Phenol	Methylene blue (MB)	1	303	0.025	-	120	9.97	7.88	8.92	6.51	<p>Selectivity ratio: 1.37, 1.265</p> <p>Sorptive affinity: -1.23, 1.23 w.r.t pollutant 1</p> <p>P-factor: 1.12, 1.2</p> <p>Inhibitory effect: 0.105, 0.174</p>	<p>Antagonistic (phenol, MB)</p> <p>Antagonistic (phenol, MB)</p> <p>Antagonistic (phenol, MB)</p>	<p>The adsorption of phenol and MB was significantly less from the binary adsorption system than single-contaminant solutions, suggesting competition between the two for adsorption sites, both being organic molecules. The affinity of both pollutants was also most same as observed from the values of sorption affinity. Further the value of inhibitory effect suggests minimal degree of antagonistic interaction. The adsorption was due to electro-donor-acceptor mechanism and ion-exchange.</p>	[66]
14.	Spherical activated carbon	phenol	Cr(VI)	50	298	0.5	1	150	244.80	302.9	103.2	198.4	<p>Selectivity ratio: 0.52, 0.808</p> <p>Sorptive affinity: 3.0, 2.36</p> <p>P-factor: 2.4, 1.53</p> <p>Inhibitory effect: 0.58, 0.35</p>	<p>Antagonistic (phenol, Cr)</p> <p>Antagonistic (phenol, Cr)</p> <p>Antagonistic (phenol, Cr)</p>	<p>The value of P-factor (&gt; 1) for both the solute suggests antagonistic interaction. The reason for antagonistic interaction during the multi-component adsorption was competition for similar binding sites onto the adsorbent of cells and/or the screening effect by the second component. Competition on similar binding sites and screening effect was also observed.</p>	[40]

S. No.	Adsorbent		Pollutant	Experimental conditions				Adsorption capacity (mg/g)			Factors	Findings from factor	Interaction based on factors	Inference	References		
	(1)	(2)		Adsorbent dosage (g/L)	Temp. (K)	Initial concentration (g/L)	pH	Speed (rpm)	Pollutant ant 1 (Single)	Pollutant ant 2 (Single)						Pollutant ant 1 (Binary)	Pollutant ant 2 (Binary)
15.	Magnetic graphene oxide	Phenol	Cd(II)	0.5	293	0.025–0.05	7	-	270.09	85.8	209.9	87.7	<p>Selectivity ratio: 2.39, 3.148</p> <p>Sorptive affinity:</p> <p>P-factor: 1.3, 0.98</p> <p>Inhibitory effect: 0.223, -0.02214</p> <p>Selectivity ratio: 1.97, 1.32</p>	<p>Adsorbent has a stronger affinity towards pollutant 2</p> <p>Pollutant 1 has less affinity w.r.t pollutant 2</p> <p>Adsorption of pollutant 2 is enhanced and pollutant 1 is suppressed</p> <p>Adsorption of pollutant 1 is suppressed by pollutant 2</p> <p>Adsorbent has a stronger affinity towards pollutant 1</p> <p>Pollutant 2 has less affinity w.r.t pollutant 1</p> <p>Adsorption of pollutant 1 is enhanced and pollutant 2 is suppressed</p>	<p>Antagonistic (phenol)</p> <p>Synergistic (Cd)</p> <p>Antagonistic (phenol)</p> <p>Synergistic (Cd)</p> <p>Antagonistic (phenol)</p> <p>Synergistic (Cd)</p> <p>Antagonistic (phenol)</p> <p>Synergistic (Cd)</p>	<p>Adsorbent depicted stronger affinity towards cadmium ion. Significant antagonistic behaviour of phenol was observed.</p> <p>Adsorption of Cd(II) and phenol onto composites is assigned due to strong complexation, and for phenol, it is due to <math>\pi</math>-<math>\pi</math> covalent interaction between phenol and adsorbent.</p>	[54]

S. No.	Adsorbent	Pollutant		Experimental conditions					Adsorption capacity (mg/g)			Findings from factor	Interaction based on factors	Inference	References	
		(1)	(2)	Adsorbent dosage (g/L)	Temp. (K)	Initial concentration (g/L)	pH	Speed (rpm)	Pollutant 1 (Single)	Pollutant 2 (Single)	Pollutant 1 (Binary)					Pollutant 2 (Binary)
17.	Spherical activated carbon	Phenol	2-Chlorophenol (2-CP)	0.5	298	0.3	4.5	250	205	270	213	251	<p>Selectivity ratio: 0.85, 0.759</p> <p>Sorptive affinity: 1.123, 1.00</p> <p>P-factor: 0.962, 1.076</p> <p>Inhibitory effect: -0.039, 0.07</p> <p>Selectivity ratio: 1.02, 2.23</p>	<p>Synergistic (phenol)</p> <p>Antagonistic (2-CP)</p> <p>Synergistic (phenol)</p> <p>Antagonistic (2-CP)</p> <p>Synergistic (phenol)</p> <p>Antagonistic (2-CP)</p> <p>Synergistic (phenol)</p> <p>Antagonistic (2-CP)</p> <p>Synergistic (phenol)</p> <p>Antagonistic (2-CP)</p>	<p>Solubility of solutes has an important role while simultaneous adsorption of organic pollutants is investigated. Due to weak solubility of chlorophenol weak interaction with solvent is induced. The synergistic and antagonistic behaviour of phenol and chlorophenol, respectively, is very clearly portrayed by values of P-factor and inhibitory effect.</p>	[67]
															<p>Adsorbent has a stronger affinity towards pollutant 2</p> <p>Pollutant 1 has less affinity w.r.t pollutant 2</p> <p>Adsorption of pollutant 1 is enhanced and pollutant 2 is suppressed</p> <p>Adsorption of pollutant 2 is suppressed by pollutant 1</p> <p>Adsorbent has a stronger affinity towards pollutant 1</p> <p>Pollutant 2 has less affinity w.r.t pollutant 1</p> <p>Adsorption of pollutant 2 is enhanced and pollutant 1 is suppressed</p> <p>Adsorption of pollutant 1 is suppressed by pollutant 2</p>	<p>Synergistic interaction of phenol and MO was demonstrated in the study. This can also be deduced based on observation of values of adsorption capacities. Electrostatic and non-electrostatic interactions were among the governing forces of the synergistic interaction.</p>
18.	FeNP/Carbon nanocomposites	Phenol	Methyl orange (MO)	0.5-4	298	0.050	4-10	200	42.34	19.03	72.68	71.02	<p>Sorptive affinity: 1.11, 6.25</p> <p>P-factor: 0.583, 0.268</p> <p>Inhibitory effect: -0.72, -2.7</p>	<p>Synergistic (phenol, MO)</p> <p>Synergistic (phenol, MO)</p> <p>Synergistic (phenol, MO)</p> <p>Synergistic (phenol, MO)</p>	<p>Synergistic interaction of phenol and MO was demonstrated in the study. This can also be deduced based on observation of values of adsorption capacities. Electrostatic and non-electrostatic interactions were among the governing forces of the synergistic interaction.</p>	[20]







S. No.	Adsorbent	Pollutant		Experimental conditions				Adsorption capacity (mg/g)			Factors	Findings from factor	Interaction based on factors	Inference	References		
		(1)	(2)	Adsorbent dosage (g/L)	Temp. (K)	Initial concentration (g/L)	pH	Speed (rpm)	Pollutant ant 1 (Single)	Pollutant ant 2 (Single)						Pollutant ant 1 (Binary)	Pollutant ant 2 (Binary)
23.	Dry activated sludge	Phenol	Ni(II)	0.5	298	0.1	4.5	150	44.3	71.6	28.9	51.4	<p>Selectivity ratio: 0.56, 0.62</p> <p>Sorptive affinity: -1.1, 1.21</p> <p>P-factor: 1.533, 1.34</p>	<p>Adsorbent has a stronger affinity towards pollutant 2</p> <p>Pollutant 2 has less affinity w.r.t pollutant 1</p> <p>Adsorption of pollutant 2 is enhanced and pollutant 1 is suppressed</p>	<p>Antagonistic (phenol, Ni)</p> <p>Antagonistic (phenol, Ni)</p> <p>Antagonistic (phenol, Ni)</p>	<p>The presence of phenol, the adsorption was decreased.</p> <p>Competition for different sites/screening effect might have influenced the process.</p>	[69]
24.	Flower-like covalent organic framework	2,4-DCP	Bisphenol A (BPA)	0.005	298	-	9	-	36.6	56.80	36.99	58.09	<p>P-factor: 0.989, 0.978</p>	<p>Adsorption of pollutant 2 is enhanced and pollutant 1 is suppressed</p> <p>Adsorption of pollutant 1 is suppressed by pollutant 2</p>	<p>Synergistic (2,4-DCP, BPA)</p> <p>Synergistic (2,4-DCP, BPA)</p>	<p>The investigation showed no significant difference in adsorption of phenolic compounds in single and binary solute systems which resulted in no interaction. However, the values of P-factor and inhibitory effect suggest negligible synergistic interaction. The governing force in the binary adsorption process was <math>\pi</math>-<math>\pi</math> stacking interactions.</p>	[14]

S. No.	Adsorbent	Pollutant	Experimental conditions				Adsorption capacity (mg/g)				Factors	Findings from factor	Interaction based on factors	Inference	References	
			Adsorbent dosage (g/L)	Temp. (K)	Initial concentration (g/L)	pH	Speed (rpm)	Pollutant ant 1 (Single)	Pollutant ant 2 (Single)	Pollutant ant 1 (Binary)						Pollutant ant 2 (Binary)
25.	Bentonite modified with humic acid (HAB)	(1)	(2)	4	303	0.1	250	16.57	22.99	16.22	23.07	Selectivity ratio: 0.7, 0.721	Adsorbent has a stronger affinity towards pollutant 2	Non-interaction (2,4-DCP, Cu)		
		2,4-DCP	Cu(II)										Sorptive affinity: -17.7, 25	Pollutant 2 has less affinity w.r.t pollutant 1	Non-interaction (2,4-DCP, Cu)	The value selectivity ratio and P-factor show that there is no interaction in binary system when humic acid modified bentonite was used. Ion exchange depict the adsorption of copper ion and hydrophobic interaction caused adsorption of 2,4-DCP.
26.	Organo-clay	(1)	(2)	10	308	0.1	250	7.69	9.89	7.69	9.80	Selectivity ratio: 0.78	Adsorbent has a stronger affinity towards pollutant 2	Non-interaction (2,4-DCP, Pb)		
		2,4-DCP	Pb(II)										Sorptive affinity: -1.05, 1.12	Pollutant 2 has less affinity w.r.t pollutant 1	Non-interaction (2,4-DCP, Pb)	In the binary system, no competition between 2,4-DCP and lead ions was observed. This was due to sorption of pollutant occurred due to two independent mechanisms namely ion-exchange and solute partitioning.
												P-factor: 1.0, 1.009	Adsorption of pollutant 1 is enhanced and pollutant 2 is suppressed	No interaction (2,4-DCP)		
												Inhibitory effect: 00, 0.0091	Adsorption of pollutant 2 is suppressed by pollutant 1	No interaction (2,4-DCP)		
														Antagonistic (Pb)		

S. No.	Adsorbent	Pollutant	Experimental conditions				Adsorption capacity (mg/g)			Factors	Findings from factor	Interaction based on factors	Inference	References
			Temp. (K)	Initial concentration (g/L)	pH	Speed (rpm)	Pollutant 1 (Single)	Pollutant 2 (Single)	Pollutant 1 (Binary)					
27.	Activated Carbon	(1)												
		(2)	Adsorbent dosage (g/L)	Temp. (K)	Initial concentration (g/L)	pH	Speed (rpm)	Pollutant 1 (Single)	Pollutant 2 (Single)	Pollutant 1 (Binary)	Pollutant 2 (Binary)			
		Phenol	6	293	0.05/0.1	7	200	28.18	53.13	28.15	50.58			
		Cr(VI)											[71]	
28.	Rice husk ash (RHA)	Phenol	0.02	303	0.05-0.5	5.5	150	9.03	6.82	13.36	6.27			



S. No.	Adsorbent	Pollutant		Experimental conditions				Adsorption capacity (mg/g)			Factors	Findings from factor	Interaction based on factors	Inference	References	
		(1)	(2)	Adsorbent dosage (g/L)	Temp. (K)	Initial concentration (g/L)	pH	Speed (rpm)	Pollutant 1 (Single)	Pollutant 2 (Single)						Pollutant 1 (Binary)
30.	Zwitterionic adsorbents	Phenol	Pb(II)	0.05	318	0.2	150	82.2	144	121	123.3	Selectivity ratio: 0.981, 0.57  Sorption affinity: 1.72, 1.93  P-factor: 0.697, 1.168	Adsorbent has a stronger affinity towards pollutant 2  Pollutant 2 has less affinity w.r.t pollutant 1  Adsorption of pollutant 1 is enhanced and pollutant 2 is suppressed	Synergistic (phenol)  Antagonistic (Pb(II))  Synergistic (phenol)  Antagonistic (Pb(II))  Synergistic (phenol)  Antagonistic (Pb(II))	The presence of Pb(II) enhanced the adsorption of phenol and synergistic effect was observed. The adsorption mechanism of adsorbents for lead and phenol was governed by electrostatic interactions, hydrogen binding and surface complexation.	[55]
31.	HDTMA bentonite	Phenol	Phosphate(V)	0.4	293–313	0.047	7	150	–	18.82	38.5	Sorption affinity: –  P-factor: –  Inhibitory effect: –	Adsorbent has a stronger affinity towards pollutant 2  –  –	Synergistic (phenol)  Antagonistic (Pb(II))  Synergistic (phenol, phosphate)  –  –	Adsorption of phenol and phosphate ions increased in binary system. Some other factors causing increased adsorption were temperature and properties of adsorbent.	[73]

The higher or positive value of  $\Delta IE_i$  suggests the adsorption capacity of component  $i$  is suppressed in the presence of  $j$  and the antagonistic interaction is observed in component  $i$ . The lower or negative value of  $\Delta IE_i$  suggests the adsorption capacity of component  $i$  is enhanced in the presence of  $j$  and the synergistic interaction is observed in component  $i$ .

### 3. Mechanisms in adsorption system

The prominent mechanism of adsorption can be either follow physical or chemical processes. The interaction mechanism for the adsorption of the organic molecules could be due to hydrophobic effect,  $\pi$ - $\pi$  interactions, filling of pores and electron-donor reactions. Further in case of inorganic molecules electrostatic attraction, ion-exchange, surface complexation, co-precipitation etc. may be responsible for adsorption process. Some of the prominent mechanisms are shown in Fig. 3.

#### 3.1. Ion-exchange

The primary principle involved in this process is exchange of protons and ionised cations with dissolved salts on the surface of the adsorbent. A study conducted by Ru et al., on removal of organic molecules (phenol and aniline) reports that, the sorption of molecules is mainly attributed to combination of ion exchange, hydrophobic interaction [45]. Similar findings were reported by Dong et al. [46], while investigating adsorption of phenol and chromium on biochar.

#### 3.2. Surface complexation

In this adsorption mechanism, the multi-atom formation interacts with metal to create a metal complex. For example, research conducted by Zong et al. [54] on competitive removal of cadmium and phenol attributes surface complexation as interaction factor responsible for adsorption of cadmium(II) ions. Similar results were also described by Wang et al. [55].

#### 3.3. Precipitation and electrostatic interaction

It is one of the main mechanisms which is usually observed in mixture of inorganic pollutant. The mechanism involves formation of precipitate onto substrate surface. Electrostatic interaction involves attraction of organic/inorganic compounds which are ionisable to charged surface of adsorbent by means of electrostatic interaction. For example an investigation carried out by Huang et al. [56], on competitive sorption of phenol and chromium found that adsorption of former followed partition phenomena and latter followed electrostatic interaction.

#### 3.4. Partition onto uncarbonized area

Diffusion of adsorbate material into the porous uncarbonized part of adsorbent results in partition of uncarbonized area and this area is freely available to organic pollutant for interaction leads to adsorption [50]. According Zhang et al. [57], organic carbon (OC) components of biochar exhibit high sorbate partitioning of the atrazine contaminant.

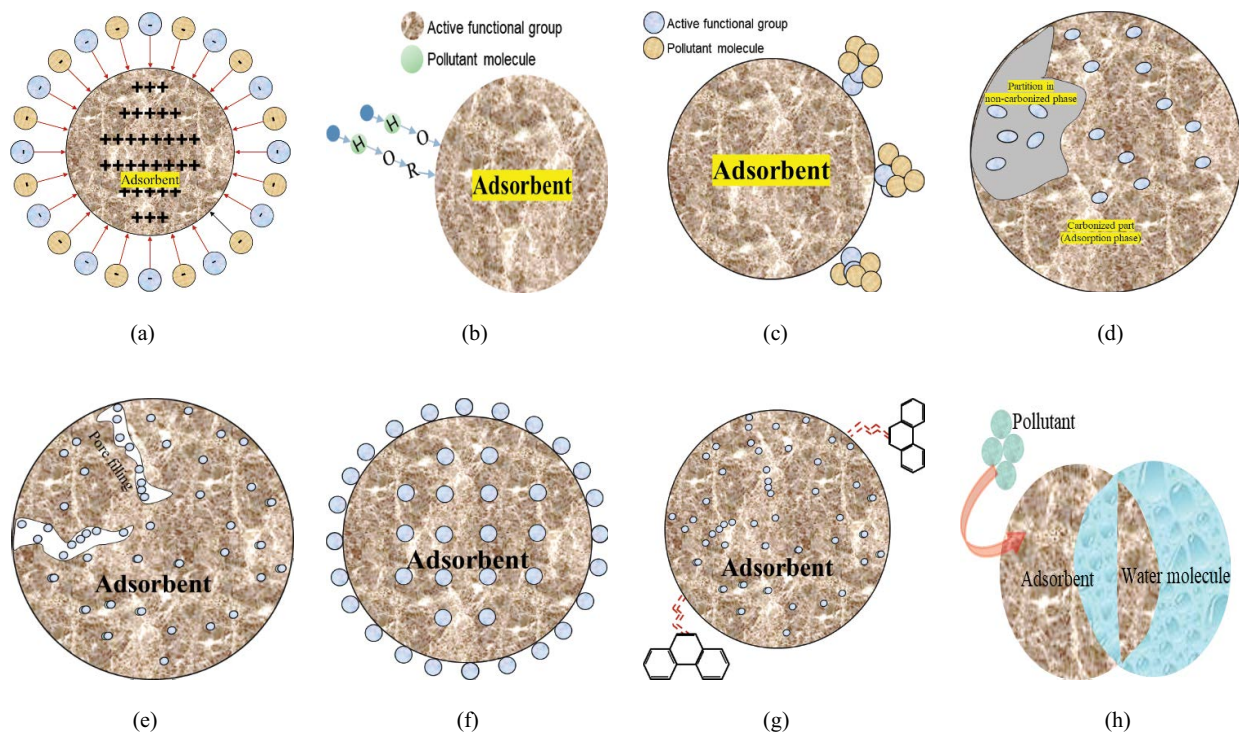


Fig. 3. Different mechanisms in adsorption. (a) Ion-exchange [47], (b) surface complexation [48], (c) precipitation [49], (d) partition onto uncarbonized area [50], (e) filling of pores [51], (f) surface sorption [52], (g) electron donor and acceptor [46], and (h) hydrophobic effect [53].

### 3.5. Filling of pores

In this mechanism the organic contaminants, based on the polarity and nature and variant of adsorbent gets attached to the surface of porous adsorbent having mesopore (2–50 nm) and micropores (<2 nm). For example a study investigated by Singh et al. [58] found that, the adsorption of phenol and cyanide was attributed to filling of pores. The same was further proved from by analysing surface morphology by means of FESEM. According to Kasozi et al., the micropore filling process for the sorption of catechol was more effective than other adsorption methods [59].

### 3.6. Surface sorption

Sorption is defined combination of physical and chemical process by means of which a pollutant molecule accumulates within another phase or on the phase boundary of two phases. The process also means accumulation of a substance onto the substrate and absorption of substrate molecule within the bulk of solid surface. The physical process which involves establishment of chemical bond as result of metal ion diffusion into porous adsorbent. The results from the study investigated by Tahermansouri et al., confirm that both the external surface sorption and intraparticle diffusion dominated in the adsorption of phenol by carbon nanotubes [60].

### 3.7. Electron donor and acceptor (EDA) interaction

The EDA interaction mechanism is mostly applied to the adsorption of aromatic compounds on biochar. For example a study carried out by Dong et al. [46] of competitive removal of phenol and chromium proposes  $\pi$ - $\pi$  interaction and electron donor-acceptor complex for phenol removal. Similar results were also reported by Al-Malack and Dauda [10], who investigated removal of phenol using activated carbon.

### 3.8. Hydrophobic effect

When organic compounds of hydrophobic and neutral nature are available, the mechanism of adsorption takes place by virtue of partitioning and hydrophobic interaction processes. In terms of energy requirement, hydrophobic interaction process works on lesser energy as compared to partition. For example, a study carried out by Rubin et al. [61], on sorption of phenolic pollutants using macro algae attributes hydrophobic effect as main interaction factor responsible for binding. Similar conclusions were drawn by Zhou et al. [8], who examined the removal of phenol using magnetic nanohybrids.

To summarise, in case of organic pollutants, the attraction of pollutant onto adsorbent was mainly dependent on the aromatic and/or unique functional groups and on the polarity of both adsorbent and the organic pollutants. The characteristic of intermolecular gravitation and electrostatic force between the adsorbent and the pollutant was the determining factor for the physical adsorption, while the chemical adsorption mainly depends on the chemical interactions between the adsorbent and the organic pollutant, which can be  $\pi$ - $\pi$  bonds, hydrogen bonds and

coordination bonds. However, for inorganic contaminants the combined effects of several interactions, such as electrostatic interaction, surface sorption, ion exchange, complexation, and precipitation, were often included in the possible adsorption process.

The mechanisms discussed above leads to furthermore interactions (SYI, ANI, NI). In Table 2 most investigations on simultaneous adsorption are identified and incorporated to discuss on interaction factors as mentioned in section 2.

Various studies on the interaction between the solute molecules in a binary solution have been published in the literature. The adsorption of molecules onto the adsorbent, the adsorption capacity of the adsorbate in single and binary solution mode, and the kind of interaction are all highlighted in this study. It also analyses the likely cause of the components' interaction. As a result, the review looks into the simultaneous adsorption of organic components (phenols/2,4-dichlorophenol) with other components in a binary system. The interaction effect among the components in the above investigation is determined from available standard relationships. The components involved in simultaneous adsorption are the adsorption capacity for each component, and the interaction mechanism are discussed below. Some of the significant findings from the literature reported in Tables 2 and 3 are discussed below.

In an investigation on multi-component adsorption, Nguyen et al. [35] used chemical and biologically modified chitosan beads (crosslinked) to remove phenol and nickel. The adsorption in binary systems increased in the second-component compared to their adsorption in single systems synergistic biosorption between phenol and Ni(II) was found. The positive value of the P-factor also imply synergism. The isotherm modelling showed that the modified Langmuir model could acceptably describe the simultaneous biosorption of phenol and Ni(II) from binary solutions, reflecting the nature of chemical adsorption. Chemical binding and coordination were found to be support mechanism for adsorption and synergism.

A study on competitive adsorption of phenol and resorcinol was carried out by Thakur et al., [19]. Lower value of  $\eta$ , of resorcinol depicts a stronger affinity towards the adsorbent. The substitution of the hydroxyl group takes place with resorcinol. Thus, the  $\pi$ - $\pi$  interaction leads to the adsorption of resorcinol with the adsorbent [19].

Aksu and Akpinar studied the performance of dried anaerobic activated sludge (DAAC) to adsorb phenol and chromium(VI) ions in a single and binary system. It was observed that the equilibrium uptakes of both the pollutants were changed due to the presence of another component. Adsorption isotherms were developed for single and binary component systems. The study also found that adsorption of phenol was inhibited in the presence of a higher concentration of Cr(VI). This could also be understood by the value of the interactions factor of modified competitive Langmuir isotherm, that is,  $\eta_{ph}$  and  $\eta_{Cr}$ , which is found to be 1.07 and 1.00, respectively. Here  $\eta_{ph}$  is greater than  $\eta_{Cr}$ , which implies Cr(IV) has a greater affinity towards sludge than phenol [76]. Positive value of inhibitory effect depicts antagonistic interaction and factors such as competition on similar binding sites and screening effect could be responsible for

such interaction. Some of the other reasons could be specific surface properties and some physicochemical properties of solution [40].

Simultaneous adsorption of phenol and cyanide on copper-infused activated carbon was carried out by Agarwal et al. [62]. It was investigated that the adsorption of phenol was increased nearly 27-fold (from 10.74 to 292.95 mg/g) in the presence of cyanide. The ratio of  $(Q_{i,o})_b/(Q_{i,o})_s$  for phenol and cyanide was calculated as 27.27 and 1.10, respectively. This relation hence establishes the fact that phenol and cyanide show synergism in the process of adsorption. The degree of synergistic effect was not prominent in cyanide; however, it can be explained with the help of an inhibitory value as calculate in Table 2. Further, this implies the adsorbent had a greater affinity towards phenol. The process can be attributed to hydrogen bonding between hydrogen atoms from phenol and a lone pair of electrons of the nitrogen atom of cyanide [62].

Agarwal and Balomajumder conducted a similar adsorption study on phenol and cyanide using granulated activated carbon (GAC) as an adsorbent. It was investigated that the adsorption of phenol was comparatively very high in the presence of cyanide. The reason could be high surface area of GAC. Further, this can be demonstrated by the value of selectivity ratio which was found to be greater than one. This implies that phenol molecule had greater affinity towards adsorbent. The interaction between cyanide and phenol could be attributed to hydrogen bonding and intraparticle diffusion [11].

Singh and Balomajumder worked on simultaneous adsorption of phenol and cyanide using coconut shells as a source of adsorbent. The adsorption of phenol was enhanced in the presence of cyanide. The adsorption of phenol in the binary state was more than its single state which is supported by negative value of inhibitory effect. Thus, indicating the interaction to be the synergistic type of interaction. The phenomena governing both solutes' adsorption were chemisorption and weak van der waal's force of attraction [18].

A similar study was investigated by Singh and Balomajumder, where *Pseudomonas putida* was immobilised on coconut shell activated carbon. The study found an increase in the adsorption of phenol from 18.19 to 349.86 mg/g in the presence of cyanide, indicating synergism. The values also suggest that phenol had a greater affinity towards the adsorbent. In addition, this can be further explained by selectivity ratio  $349.86/18.19=160.49$ , which is greater than one indicating a greater affinity of phenol than cyanide. Another reason for the higher adsorption of phenol could be initial concentration [63].

Singh and Balomajumder used sugarcane bagasse as a source of adsorbent to remove phenol and cyanide. The adsorption capacities of adsorbent were predicted and were 94.25 and 5.46 mg/g for phenol and cyanide, respectively. The greater affinity of phenol could be due to rise in temperature. This can be explained using sorption affinity  $S_{(ij)}$  factor. Here the calculated value was found greater than one [76], that is, 1.497 (phenol) and 1.26 (CN). The study shows a synergistic interaction mechanism involved in the binary adsorption process [58].

Further, a study conducted by Ha and Vinitnantharat [17] used biological activated carbon by considering phenol and 2,4-dichlorophenol (DCP) in a single and binary system. The adsorption capacity of activated carbon for both phenol and DCP decreased, indicating antagonistic behaviour. This finding can be supported by positive value of inhibitory effect. Further, the reason for such interaction could be mutual interaction and molecular size. Components in binary system were inhibited mutually. It was found that degree of inhibition was profound in DCP, which was also the reason for the fall in the adsorption capacity of DCP.

Istratie and Stoia, in their research, adsorption of methyl orange (MO) and phenol used magnetic iron oxide-based nanocomposites (MNP3). The adsorption of MO was higher compared to phenol but both components followed synergistic interaction. Electrostatic and non-electrostatic interactions were among the governing forces of the synergistic interaction. However, both electrostatic and non-electrostatic forces governed methyl orange adsorption, and phenol adsorption was due to non-electrostatic forces. Though the interaction behaviour was synergistic for both, it was found that MO had a greater affinity towards the adsorbent in the presence of phenol. This can be explained by the selectivity ratio and P-factor [20].

In work reported by Wang et al. on the adsorption of methyl red and methylene blue onto biochar, the adsorption of the molecules was governed by size and ionisation of molecules. Variation in the above factors at equilibrium and different isotherm were used to determine the interaction between the molecules. A significant rise in adsorption capacity of 2,4-DCP and Cr(VI) was observed. The synergistic interaction was due to the bridge interactions which created additional new sites for both pollutants [34].

In some of the studies, it was possible to explain the interaction behaviour of pollutants using competitive models.

In the present study, rice husk ash (RHA) was used as an adsorbent for individual and simultaneous adsorption of phenol and resorcinol. Langmuir, Freundlich and Redlich–Peterson showed a similar fit with regard to the mono-component adsorption data and Extended Langmuir best depicted the binary component experimental data. The affinity of RHA was found to be greater for phenol than that for resorcinol in both single component and binary solutions [19].

Aksu and Akpinar used dried activated sludge to abate phenol and chromium from synthetic wastewater and modelled using modified competitive Langmuir isotherm (MCLI). The model predicted the value  $\eta_i$  for phenol and was greater than that of chromium, which implies higher affinity of adsorbent towards chromium. Further, it indicates that chromium adsorption was greater than phenol in the binary state. Antagonistic pollutant behaviour during competitive removal can be proven using a modified competitive Langmuir isotherm model [40].

Research carried out by Singh and Agarwal used coconut husk-activated carbon (CHAC) as an adsorbent. It was found that phenol adsorption in the binary system was more than cyanide, implying antagonistic behaviour. It may be due to higher surface area of CHAC with active sites



Table 3  
Interaction based on multicomponent Adsorption isotherm

Sl. No	Adsorbent	Pollutant <i>i</i>	Pollutant <i>j</i>	Interaction parameter		Inference from factors	Interaction effect	References
				$\theta_{ij}$ (SRS)	$\eta_i$ (MLI) $\eta_{PRi}$ (MRP)			
1.	Dried anaerobic activated sludge	Phenol	Cr(VI)	-NA-	Phenol – 1.07 Cr(VI) – 1.00	-NA-	Lower affinity of pollutant 1 to the adsorbent	Antagonistic (phenol, Cr) [40]
2.	Copper impregnated GAC (Cu-GAC)	Phenol	CN	-NA-	Phenol – 0.71 CN – 0.76	-NA-	Lower affinity of pollutant 2 to the adsorbent	Synergistic (phenol, CN) [62]
3.	Coconut shell AC	Phenol	CN	-NA-	Phenol – 3.06 CN – 0.52	Phenol – 0.13 CN – 0.03	Lower affinity of pollutant 1 to the adsorbent	Synergistic (phenol, CN) [18]
4.	Sugarcane bagasse	Phenol	CN	-NA-	Phenol – 0.37 CN – 0.34	Phenol – 1.29 CN – 1.37	Lower affinity of pollutant 1 to the adsorbent, lower affinity of pollutant 2 to the adsorbent	Synergistic (phenol, CN) [58]
5.	Coconut husk AC	Phenol	CN	-NA-	Phenol – 0.36 CN – 0.70	Phenol – 0.20 CN – 0.23	Lower affinity of pollutant 2 to the adsorbent	Antagonistic (phenol, CN) [64]
6.	Chitosan beads (chemical and biological modified)	Phenol	Ni(II)	-NA-	Phenol – 0.11 Ni(II) – 0.27	-NA-	Lower affinity of pollutant 2 to the adsorbent	Synergistic (phenol, Ni) [35]
7.	<i>Bacillus</i> sp. immobilis onto tea waste biomass	Phenol	Cr(VI)	-NA-	Phenol – 14.14 Cr(VI) – 41.9	Phenol – 0.05 Cr(VI) – 0.82	Lower affinity of pollutant 2 to the adsorbent	Synergistic [65]
8.	Tea waste biomass	Phenol	Cr(VI)	-NA-	Phenol – 6.03 Cr(VI) – 0.25	-NA-	Lower affinity of pollutant 1 to the adsorbent	Synergistic [2]
9.	GAC	Phenol	Resorcinol	-NA-	Phenol – 0.44 Resorcinol – 0.5	-NA-	Lower affinity of pollutant 2 to the adsorbent	No interaction [42]
10.	RHA	Phenol	Resorcinol	Phenol – 1 Resorcinol – 2.11	Phenol – 1.097 Resorcinol – 1.0768	Phenol – 0.39 Resorcinol – 0.77	Pollutant 2 has weaker inhibition on the adsorption of pollutant 1, lower affinity of pollutant 1 to the adsorbent, lower affinity of pollutant 2 to the adsorbent	Synergistic (phenol, resorcinol) [19]
11.	Chitosan	Phenol	CN	-NA-	Phenol – 0.67 CN – 1	-NA-	Lower affinity of pollutant 2 to the adsorbent	Synergistic [74]
12.	Peanut shell	Phenol	Cd(II)	-NA-	Phenol – 0.63 Cd(II) – 0.68	Phenol – 1.58 Cd(II) – 1.60	Lower affinity of pollutant 2 to the adsorbent	Synergistic [75]

for phenol. The adsorption study was also modelled using a modified competitive Langmuir isotherm and modified Redlich–Peterson isotherm (MRPI). Both exemplified the interaction phenomena as antagonistic. The reason could be interaction parameter for phenol was lesser than cyanide which implies phenol showing greater affinity [64].

An investigation on the removal of chromium and phenol by using *Bacillus* sp. immobilised tea waste biomass was carried out by Gupta and Balomajumder. The study was modelled for competitive isotherms, i.e.; MCLI, extended Langmuir, extended Freundlich, non-modified competitive Redlich–Peterson etc. The extended Langmuir best fitted for phenol and non-modified competitive Redlich–Peterson best fitted for Cr(VI) sorption. It was found that chromium is synergistic in the presence of phenol, and out of all the models, MCLI can determine the interaction [65].

Tea waste activated carbon was used as an adsorbent to remove phenol and chromium from a binary solution. It was observed that the adsorption of phenol was less than chromium. The possible reason may be functional groups, the structure of the adsorbent, size, shape and molecular nature of solutes present. It was also explained that phenol gets attached to the adsorbent surface through weak van der Waals forces and p–p interaction, and chromium gets attracted to the functional groups present on the adsorbent. The synergic type of behaviour was observed in the binary system. Though the binary system experienced synergetic behaviour, phenol inhibition was higher in the presence of chromium ions. This could be explained using the interaction factor of MCLI [2].

Kumar et al. [42] investigated co-adsorption of phenol and resorcinol on GAC. Three equilibrium isotherm models, non-modified Langmuir model, modified Langmuir model and extended Freundlich, model, were considered for multi-component adsorption. The effect of low and high initial concentration was studied for different operating conditions. It was found that there was the least interaction between the pollutant in binary system. This phenomena can be understood by interaction factor  $\eta_i$  are  $\eta_j$  of MCLI, which are approximately equal to each other.

Agarwal and Sengupta, in their study, analysed the potential of modified chitosan for removal of phenol and cyanide in binary system. Modified and non-modified isotherms models were fitted to the experimental data of the binary adsorption system. It was that extended Freundlich best depicted the adsorption in a binary system. It was found that adsorption of phenol was enhanced in the presence of chromium [74].

The present study investigates the potential of peanut shells as adsorbent for the removal of phenol and cadmium(II) from a bisolute wastewater system. Langmuir–Freundlich model best fitted with regard to the mono-component adsorption data and modified Langmuir best depicted the binary component experimental data. The adsorption capacity of phenol and cadmium was almost the same in single and binary states, indicating no interaction. This may be because phenol adsorbed rapidly, making it non-interactive. And the non-interaction could also be explained from the interaction parameters present in MCLI and MRPI [75].

In one of the studies, rice husk incorporated with iron particles was used as adsorbent. Multi-component models modified, and non-modified competitive isotherms were applied to investigate the adsorption of phenol and Cr(VI) in a single and binary state. The adsorption capacity for phenol and Cr(VI) was enhanced in binary systems. This was because phenol acts as an electron donor, enhancing the Cr(VI) adsorption. Extended Freundlich for both phenol and Cr(VI) for the multi-component system was agreed better with the experimental results. The results show that, adsorption of Cr(VI) is enhanced from 7.55 mg/g in single system to 36.38 mg/g in binary system implying synergistic interaction [77].

#### 4. Discussion and conclusions

This review papers gives a brief idea of possible interaction of phenolic compounds with other pollutants which can be either organic or inorganic nature. From the studies tabulated in Table 2, it was evident that, phenol exhibited synergistic behaviour in presence of pollutants such as resorcinol, cyanide, 2,4-DCP, methyl orange, catechol, aniline, nickel, chromium, lead and cadmium. Further, in some of the studies, antagonistic interaction of phenol was observed in presence of cyanide, methylene blue, 2,4-DCP, chromium, cadmium, nitrophenol, nickel and hydroquinone. In addition, few cases of non-interaction of phenolic pollutant was observed in presence of resorcinol and mercury. The reason for such interaction could be charge on the adsorbing molecule and pH of the sample, possible overlap of surface area and many other mechanisms as discussed in section 3.

An initial objective of the review was to identify a relation between interaction and the factors. It was possible to correlate selectivity ratio, P-factor and inhibitory effect to adsorption behaviour and the interactions in simultaneous adsorption studies considered in the review but same was not convincing with sorption affinity. In case of sorption affinity, the concept of relating the interaction and factor did not hold good. However, it holds good only for same initial concentration of both the solutes.

Based on the values of selectivity ratio and sorption affinity for a binary system, a brief idea of the degree of affinity of pollutants towards the adsorbent can be understood. However, by considering P-factor and inhibitory effect for a single and binary adsorption system would aid in identifying adsorption of the prominent pollutant (inhibition/enhancement) in the binary system. Further, by analysing the values of P-factor and inhibitory effect, it was possible to generalise and distinctly arrive at interaction (synergistic, antagonistic, non-interaction) of a solute in binary adsorption system.

The relation between P-factor, inhibitory effect, and interactions (SI, AN, NI) were identified by following convention as mentioned in previous section 2. Further, it was also possible to find the interactions in the binary system using modified competitive isotherms such MCLI, MCRPI and SRS equations. The interaction factors present in MCLI and MCRP, that is,  $\eta_i$  and  $\eta_{RPj}$ , were used to depict the nature of the affinity of pollutant, and in the SRS equation the

factor  $\theta_{ij}$  was used to determine the inhibition of pollutant  $i$  on  $j$ .

Prior to this review, adsorption capacity of adsorbent in binary system was only the sole way to recognize interaction. In this review, a new understanding on interaction factors would help researchers, to improve predictions of the interaction mechanism in binary adsorption system. The findings of this review would also provide the following insights for future research. More studies on competitive adsorption of phenol and 2,4-DCP would help us to establish a greater degree of accuracy on this matter. Further research could also be conducted to determine the effectiveness of linking interaction mechanism to the factors as discussed in previous sections and this would be a fruitful area for further work. Studies involving adsorption of ternary pollutants can be investigated and modelled. Further, the parameters related to interaction can be investigated. No studies were found, which can relate Gibb's free energy, enthalpy and entropy to interaction between molecules.

## References

- [1] V.R. Kiran, B. Chandrajit, Simultaneous adsorptive removal of cyanide and phenol from industrial wastewater: optimization of process parameters, *Res. J. Chem. Sci.*, 1 (2011) 30–39.
- [2] A. Gupta, C. Balomajumder, Simultaneous adsorption of Cr(VI) and phenol onto tea waste biomass from binary mixture: multicomponent adsorption, thermodynamic and kinetic study, *J. Environ. Chem. Eng.*, 3 (2015) 785–796.
- [3] F. Banat, S. Al-Asheh, L. Abu-Aitah, Competitive adsorption of phenol, copper ions and nickel ions on to heat-treated bentonite, *Adsorpt. Sci. Technol.*, 20 (2002) 107–117.
- [4] Q. Liu, B. Yang, L. Zhang, R. Huang, Simultaneous adsorption of phenol and Cu<sup>2+</sup> from aqueous solution by activated carbon/chitosan composite, *Korean J. Chem. Eng.*, 31 (2014) 1608–1615.
- [5] Y. Gokce, Z. Aktas, Nitric acid modification of activated carbon produced from waste tea and adsorption of methylene blue and phenol, *Appl. Surf. Sci.*, 313 (2014) 352–359.
- [6] S. Ahmadi, F. Mostafapour, E. Bazrafshan, Removal of aniline and from aqueous solutions by coagulation/flocculation–flotation, *Chem. Sci. Int. J.*, 18 (2017) 1–10, doi: 10.9734/csji/2017/32016.
- [7] M. Irani, L.R. Rad, H. Pourahmad, I. Haririan, Optimization of the combined adsorption/photo-Fenton method for the simultaneous removal of phenol and paracetamol in a binary system, *Microporous Mesoporous Mater.*, 206 (2015) 1–7, doi: 10.1016/j.micromeso.2014.12.009.
- [8] K. Zhou, J. Zhang, Y. Xiao, Z. Zhao, M. Zhang, L. Wang, X. Zhang, C. Zhou, High-efficiency adsorption of and competition between phenol and hydroquinone in aqueous solution on highly cationic amino-poly(vinylamine)-functionalized GO-(o-MWCNTs) magnetic nanohybrids, *Chem. Eng. J.*, 389 (2020) 124223, doi: 10.1016/j.cej.2020.124223.
- [9] J. Li, Y. Zheng, X. Feng, C. Lv, X. Liu, Y. Zhao, L. Chen, Adsorption removal of Ni(II) and phenol from aqueous solution by modified attapulgite and its composite hydrogel, *Environ. Technol.*, 42 (2021) 2413–2427.
- [10] M.H. Al-Malack, M. Dauda, Competitive adsorption of cadmium and phenol on activated carbon produced from municipal sludge, *J. Environ. Chem. Eng.*, 5 (2017) 2718–2729.
- [11] B. Agarwal, C. Balomajumder, P.K. Thakur, Simultaneous co-adsorptive removal of phenol and cyanide from binary solution using granular activated carbon, *Chem. Eng. J.*, 228 (2013) 655–664.
- [12] C. Wu, L. Zhou, C. Zhou, Y. Zhou, S. Xia, B.E. Rittmann, Co-removal of 2,4-dichlorophenol and nitrate using a palladized biofilm: denitrification-promoted microbial mineralization following catalytic dechlorination, *J. Hazard. Mater.*, 422 (2022) 126916, doi: 10.1016/j.jhazmat.2021.126916.
- [13] K. Kuśmierk, M. Szala, A. Światkowski, Adsorption of 2,4-dichlorophenol and 2,4-dichlorophenoxyacetic acid from aqueous solutions on carbonaceous materials obtained by combustion synthesis, *J. Taiwan Inst. Chem. Eng.*, 63 (2016) 371–378.
- [14] C. Liu, J. You, R. Hu, W. Jiang, Y. Duan, J. Li, Z. Li, R. Zhu, Y. Li, Z. Liu, K. Wang, C. Chen, Removal of bisphenol A and 2,4-dichlorophenol from lake water using a flower-like covalent organic framework, *Anal. Lett.*, 54 (2021) 347–363.
- [15] A.A. Greish, P.V. Sokolovskiy, E.D. Finashina, L.M. Kustov, A.I. Vezentsev, N.D. Chien, Adsorption of phenol and 2,4-dichlorophenol on carbon-containing sorbent produced from sugar cane bagasse, *Mendeleev Commun.*, 31 (2021) 121–122.
- [16] S.-R. Ha, S. Vinitnantharat, Y. Ishibashi, A modeling approach to bioregeneration of granular activated carbon loaded with phenol and 2,4-dichlorophenol, *J. Environ. Sci. Health. Part A Toxic/Hazard. Subst. Environ. Eng.*, 36 (2001) 275–292.
- [17] S.R. Ha, S. Vinitnantharat, Competitive removal of phenol and 2,4-dichlorophenol in biological activated carbon system, *Environ. Technol.*, 21 (2000) 387–396.
- [18] N. Singh, C. Balomajumder, Simultaneous removal of phenol and cyanide from aqueous solution by adsorption onto surface modified activated carbon prepared from coconut shell, *J. Water Process Eng.*, 9 (2016) 233–245.
- [19] C. Thakur, I.D. Mall, V.C. Srivastava, Competitive adsorption of phenol and resorcinol onto rice husk ash, *Theor. Found. Chem. Eng.*, 48 (2014) 60–70.
- [20] R. Istrate, M. Stoia, C. Păcurariu, C. Locovei, Single and simultaneous adsorption of methyl orange and phenol onto magnetic iron oxide/carbon nanocomposites, *Arabian J. Chem.*, 12 (2019) 3704–3722.
- [21] H.D.S.S. Karunarathne, B.M.W.P.K. Amarasinghe, Fixed bed adsorption column studies for the removal of aqueous phenol from activated carbon prepared from sugarcane bagasse, *Energy Procedia*, 34 (2013) 83–90.
- [22] K. Lin, J. Pan, Y. Chen, R. Cheng, X. Xu, Study the adsorption of phenol from aqueous solution on hydroxyapatite nanoparticles, *J. Hazard. Mater.*, 161 (2009) 231–240.
- [23] Y. Zhou, X. Gu, R. Zhang, J. Lu, Removal of aniline from aqueous solution using pine sawdust modified with citric acid and  $\beta$ -cyclodextrin, *Ind. Eng. Chem. Res.*, 53 (2014) 887–894.
- [24] Z. Aksu, D. Akpınar, Modelling of simultaneous biosorption of phenol and nickel(II) onto dried aerobic activated sludge, *Sep. Purif. Technol.*, 21 (2000) 87–99.
- [25] S.-M. Lee, B.-J. Choi, D.-H. Kim, I.-Y. Lee, W.-G. Kim, Competitive adsorption for binary mixture of 4-nitrophenol and phenol on RSTA using GAC, *Water Sci. Technol.*, 47 (2003) 229–235.
- [26] A. Witek, A. Kołtuniewicz, B. Kurczewski, M. Radziejowska, M. Hatałski, Simultaneous removal of phenols and Cr<sup>3+</sup> using micellar-enhanced ultrafiltration process, *Desalination*, 191 (2006) 111–116.
- [27] J.W. Ma, F.Y. Wang, Z.H. Huang, H. Wang, Simultaneous removal of 2,4-dichlorophenol and Cd from soils by electrokinetic remediation combined with activated bamboo charcoal, *J. Hazard. Mater.*, 176 (2010) 715–720.
- [28] S.J. Kulkarni, J.P. Kaware, Review on research for removal of phenol from wastewater, *Int. J. Sci. Res. Publ.*, 3 (2013) 1–5.
- [29] B. Bianco, I. De Michelis, F. Vegliò, Fenton treatment of complex industrial wastewater: optimization of process conditions by surface response method, *J. Hazard. Mater.*, 186 (2011) 1733–1738.
- [30] G. Wang, S. Zhang, Y. Hua, X. Su, S. Ma, J. Wang, Q. Tao, Y. Wang, S. Komarneni, Phenol and/or Zn<sup>2+</sup> adsorption by single- or dual-cation organomontmorillonites, *Appl. Clay Sci.*, 140 (2017) 1–9, doi: 10.1016/j.clay.2017.01.023.
- [31] J.A. Arcibar-Orozco, J.R. Rangel-Mendez, P.E. Diaz-Flores, Simultaneous adsorption of Pb(II)-Cd(II), Pb(II)-phenol, and Cd(II)-phenol by activated carbon cloth in aqueous solution, *Water Air Soil Pollut.*, 226 (2015) 1–10, doi: 10.1007/s11270-014-2197-1.

- [32] W. Kamiński, K. Kuśmierk, A. Świątkowski, E. Tomczak, A.A. Witkowski, E. Tomczak, Simultaneous adsorption of phenol derivatives from water onto spherical activated carbon, *Ecol. Chem. Eng. S*, 27 (2020) 403–413.
- [33] Z. Li, L. Sellaoui, G. Luiz Dotto, A. Bonilla-Petriciolet, A. Ben Lamine, Understanding the adsorption mechanism of phenol and 2-nitrophenol on a biopolymer-based biochar in single and binary systems via advanced modeling analysis, *Chem. Eng. J.*, 371 (2019) 1–6, doi: 10.1016/j.cej.2019.04.035.
- [34] Q.S. Huang, C. Wang, W. Wei, B.J. Ni, Magnetic poly(aniline-co-5-sulfo-2-anisidine) as multifunctional adsorbent for highly effective co-removal of aqueous Cr(VI) and 2,4-dichlorophenol, *Chem. Eng. J.*, 387 (2020) 124152, doi: 10.1016/j.cej.2020.124152.
- [35] M.L. Nguyen, C. Huang, R.S. Juang, Synergistic biosorption between phenol and nickel(II) from binary mixtures on chemically and biologically modified chitosan beads, *Chem. Eng. J.*, 286 (2016) 68–75.
- [36] F. Li, Y. Dai, M. Gong, T. Yu, X. Chen, Synthesis, characterization of magnetic-sepiolite supported with TiO<sub>2</sub> and the photocatalytic performance over Cr(VI) and 2,4-dichlorophenol co-existed wastewater, *J. Alloys Compd.*, 638 (2015) 435–442.
- [37] L.K. Dhandole, S.G. Kim, H.S. Bae, H.I. Ryu, H.S. Chung, Y.S. Seo, M. Cho, P.J. Shea, J.S. Jang, Simultaneous and synergistic effect of heavy metal adsorption on the enhanced photocatalytic performance of a visible-light-driven RS-TONR/TNT composite, *Environ. Res.*, 180 (2020) 108651, doi: 10.1016/j.envres.2019.108651.
- [38] V.K. Rathore, D.K. Dohare, P. Mondal, Competitive adsorption between arsenic and fluoride from binary mixture on chemically treated laterite, *J. Environ. Chem. Eng.*, 4 (2016) 2417–2430.
- [39] T.Y. Kim, S.Y. Cho, S.J. Kim, Adsorption equilibrium and kinetics of copper ions and phenol onto modified adsorbents, *Adsorption*, 17 (2011) 135–143.
- [40] Z. Aksu, D. Akpinar, Competitive biosorption of phenol and chromium(VI) from binary mixtures onto dried anaerobic activated sludge, *Biochem. Eng. J.*, 7 (2001) 183–193.
- [41] X. Jin, M. Zheng, B. Sarkar, R. Naidu, Z. Chen, Characterization of bentonite modified with humic acid for the removal of Cu(II) and 2,4-dichlorophenol from aqueous solution, *Appl. Clay Sci.*, 134 (2016) 89–94.
- [42] S. Kumar, M. Zafar, J.K. Prajapati, S. Kumar, S. Kannepalli, Modeling studies on simultaneous adsorption of phenol and resorcinol onto granular activated carbon from simulated aqueous solution, *J. Hazard. Mater.*, 185 (2011) 287–294.
- [43] C. Leodopoulos, D. Douliu, K. Gimouhopoulos, T.M. Triantis, Single and simultaneous adsorption of methyl orange and humic acid onto bentonite, *Appl. Clay Sci.*, 70 (2012) 84–90.
- [44] R.M. Aghav, S. Kumar, S.N. Mukherjee, Artificial neural network modeling in competitive adsorption of phenol and resorcinol from water environment using some carbonaceous adsorbents, *J. Hazard. Mater.*, 188 (2011) 67–77.
- [45] R. Hu, S. Dai, D. Shao, A. Alsaedi, B. Ahmad, X. Wang, Efficient removal of phenol and aniline from aqueous solutions using graphene oxide/polypyrrole composites, *J. Mol. Liq.*, 203 (2015) 80–89.
- [46] F. Dong, L. Yan, X. Zhou, S. Huang, J. Liang, W. Zhang, Z.-W. Guo, P.-R. Guo, W. Qian, L.-J. Kong, W. Chu, Z.-H. Diao, Simultaneous adsorption of Cr(VI) and phenol by biochar-based iron oxide composites in water: performance, kinetics and mechanism, *J. Hazard. Mater.*, 416 (2021) 125930, doi: 10.1016/j.jhazmat.2021.125930.
- [47] X. Zhao, X. Bu, T. Wu, S.-T. Zheng, L. Wang, P. Feng, Selective anion exchange with nanogated isoreticular positive metal-organic frameworks, *Nat. Commun.*, 4 (2013) 2344, doi: 10.1038/ncomms3344.
- [48] H.I. Syeda, I. Sultan, K.S. Razavi, P.-S. Yap, Biosorption of heavy metals from aqueous solution by various chemically modified agricultural wastes: a review, *J. Water Process Eng.*, 46 (2022) 102446, doi: 10.1016/j.jwpe.2021.102446.
- [49] O. Perea, C. Bode-Aluko, O. Fatoba, K. Laatikainen, L. Petrik, Rare earth elements removal techniques from water/wastewater: a review, *Desal. Water Treat.*, 130 (2018) 71–86.
- [50] S. Praveen, J. Jegan, T. Bhagavathi Pushpa, R. Gokulan, L. Bulgariu, Biochar for removal of dyes in contaminated water: an overview, *Biochar*, 4 (2022) 10, doi: 10.1007/s42773-022-00131-8.
- [51] K. László, Adsorption from aqueous phenol and aniline solutions on activated carbons with different surface chemistry, *Colloids Surf., A*, 265 (2005) 32–39.
- [52] Z.F. Meng, Y.P. Zhang, Z.Q. Zhang, Simultaneous adsorption of phenol and cadmium on amphoteric modified soil, *J. Hazard. Mater.*, 159 (2008) 492–498.
- [53] W.D.W. Wang, Q. Gong, Z. Chen, W.D.W. Wang, Q. Huang, S. Song, J. Chen, X. Wang, Adsorption and competition investigation of phenolic compounds on the solid-liquid interface of three-dimensional foam-like graphene oxide, *Chem. Eng. J.*, 378 (2019) 122085, doi: 10.1016/j.cej.2019.122085.
- [54] P. Zong, Y. Cheng, S. Wang, L. Wang, Simultaneous removal of Cd(II) and phenol pollutions through magnetic graphene oxide nanocomposites coated polyaniline using low temperature plasma technique, *Int. J. Hydrogen Energy*, 45 (2020) 20106–20119.
- [55] H. Wang, D.-B. Jiang, J. Gu, L. Ouyang, Y.-X. Zhang, S. Yuan, Simultaneous removal of phenol and Pb<sup>2+</sup> from the mixed solution by zwitterionic poly(sulfobetaine methacrylate)-grafted poly(vinylbenzyl chloride) microspheres, *Ind. Eng. Chem. Res.*, 59 (2020) 6065–6077.
- [56] R. Huang, B. Wang, B. Yang, D. Zheng, Z. Zhang, Preparation and simultaneous adsorption of an organobentonite towards phenol and Cr(VI), *Desal. Water Treat.*, 52 (2014) 5923–5930.
- [57] X. Zhang, H. Wang, L. He, K. Lu, A. Sarmah, J. Li, N.S. Bolan, J. Pei, H. Huang, Using biochar for remediation of soils contaminated with heavy metals and organic pollutants, *Environ. Sci. Pollut. Res.*, 20 (2013) 8472–8483.
- [58] N. Singh, C. Balomajumder, Biosorption of phenol and cyanide from synthetic/simulated wastewater by sugarcane bagasse—equilibrium isotherm and kinetic analyses, *Water Conserv. Sci. Eng.*, 2 (2017) 1–14, doi: 10.1007/s41101-017-0019-1.
- [59] G.N. Kasozi, A.R. Zimmerman, P. Nkedi-Kizza, B. Gao, Catechol and humic acid sorption onto a range of laboratory-produced black carbons (biochars), *Environ. Sci. Technol.*, 44 (2010) 6189–6195.
- [60] H. Tahermansouri, Z. Dehghan, F. Kiani, Phenol adsorption from aqueous solutions by functionalized multiwalled carbon nanotubes with a pyrazoline derivative in the presence of ultrasound, *RSC Adv.*, 5 (2015) 44263–44273.
- [61] E. Rubin, P. Rodriguez, R. Herrero, M. Sastre de Vicente, Biosorption of phenolic compounds by the brown alga *Sargassum muticum*, *J. Chem. Technol. Biotechnol.*, 81 (2006) 1093–1099.
- [62] B. Agarwal, C. Balomajumder, Removal of phenol and cyanide in multi-substrate system using copper impregnated activated carbon (Cu-GAC), *Environ. Prog. Sustainable Energy*, 34 (2015) 1714–1723.
- [63] N. Singh, C. Balomajumder, Simultaneous biosorption and bioaccumulation of phenol and cyanide using coconut shell activated carbon immobilized *Pseudomonas putida* (MTCC 1194), *J. Environ. Chem. Eng.*, 4 (2016) 1604–1614.
- [64] N. Singh, B. Agarwal, C. Balomajumder, Simultaneous treatment of phenol and cyanide containing aqueous solution by adsorption, biotreatment and simultaneous adsorption and biotreatment (SAB) process, *J. Environ. Chem. Eng.*, 4 (2016) 564–575.
- [65] A. Gupta, C. Balomajumder, Simultaneous removal of Cr(VI) and phenol from binary solution using *Bacillus* sp. immobilized onto tea waste biomass, *J. Water Process Eng.*, 6 (2015) 1–10, doi: 10.1016/j.jwpe.2015.02.004.
- [66] S. Mubarik, A. Saeed, Z. Mehmood, M. Iqbal, Phenol adsorption by charred sawdust of sheesham (Indian rosewood; *Dalbergia sissoo*) from single, binary and ternary contaminated solutions, *J. Taiwan Inst. Chem. Eng.*, 43 (2012) 926–933.
- [67] K.-Y. Leong, S. See, J.-W. Lim, M.J.K. Bashir, C.-A. Ng, L. Tham, Effect of process variables interaction on simultaneous adsorption of phenol and 4-chlorophenol: statistical

- modeling and optimization using RSM, *Appl. Water Sci.*, 7 (2017) 2009–2020.
- [68] C. Valderrama, J.I. Barios, M. Caetano, A. Farran, J.L. Cortina, Kinetic evaluation of phenol/aniline mixtures adsorption from aqueous solutions onto activated carbon and hypercrosslinked polymeric resin (MN200), *React. Funct. Polym.*, 70 (2010) 142–150.
- [69] Z. Aksu, D. Akpınar, E. Kabasakal, B. Köse, Simultaneous biosorption of phenol and nickel(II) from binary mixtures onto dried aerobic activated sludge, *Process Biochem.*, 35 (1999) 301–308.
- [70] L. Huang, Y. Zhou, X. Guo, Z. Chen, Simultaneous removal of 2,4-dichlorophenol and Pb(II) from aqueous solution using organoclays: isotherm, kinetics and mechanism, *J. Ind. Eng. Chem.*, 22 (2015) 280–287.
- [71] R. Huang, B. Yang, Q. Liu, Y. Liu, Multifunctional activated carbon/chitosan composite preparation and its simultaneous adsorption of phenol and Cr(VI) from aqueous solutions, *Environ. Prog. Sustainable Energy*, 33 (2014) 814–823.
- [72] C. Thakur, V.C. Srivastava, I.D. Mall, A.D. Hiwarkar, Modelling of binary isotherm behaviour for the adsorption of catechol with phenol and resorcinol onto rice husk ash, *Indian Chem. Eng.*, 59 (2017) 312–334.
- [73] A. Gładysz-Plaska, Application of modified clay for removal of phenol and  $\text{PO}_4^{3-}$  ions from aqueous solutions, *Adsorpt. Sci. Technol.*, 35 (2017) 692–699.
- [74] B. Agarwal, P. Sengupta, C. Balomajumder, Equilibrium, kinetic and thermodynamic studies of simultaneous co-adsorptive removal of phenol and cyanide using chitosan, *Int. J. Chem. Nucl. Mater. Metall. Eng.*, 7 (2013) 514–521.
- [75] B.M. Villar da Gama, G. Elisandra do Nascimento, D.C. Silva Sales, J.M. Rodríguez-Díaz, C.M. Bezerra de Menezes Barbosa, M.M. Menezes Bezerra Duarte, Mono and binary component adsorption of phenol and cadmium using adsorbent derived from peanut shells, *J. Cleaner Prod.*, 201 (2018) 219–228.
- [76] C.R. Girish, Simultaneous adsorption of pollutants onto the adsorbent review of interaction mechanism between the pollutants and the adsorbent, *Int. J. Eng. Technol.*, 7 (2018) 3613–3622.
- [77] A. Gupta, C. Balomajumder, Simultaneous adsorption of Cr(VI) and phenol from binary mixture using iron incorporated rice husk: Insight to multicomponent equilibrium isotherm, *Int. J. Chem. Eng.*, 2016 (2016) 7086761, doi: 10.1155/2016/7086761.