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Usability of Rice Straw as Biosorbent for the Removal of Phosphate from Aqueous Solution: Isotherms, Kinetics and Thermodynamics

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The present study evaluated the adsorption of phosphate ions from an aqueous solution using rice straw-based adsorbents. The batch study was performed to find the effect of pH, initial ion concentration, a dose of adsorbent, contact time and temperature. The maximum adsorption capacity of raw and modified rice straw is 6.47 mg/g and 16.60 mg/g. Both adsorbents (raw rice straw and modified rice straw) showed good adsorption capacity at pH 8, adsorbent dose of 0.5 g for modified rice straw and 0.6 g for raw rice straw with an initial ion concentration of 20 ppm, contact time of 60 min at 100 rpm. Adsorption isotherm, kinetics and thermodynamic studies were also performed for adsorption data. The monolayer adsorption capacity was measured for raw rice straw at 6.21 mg/g and modified rice straw at 6.36 mg/g. Freundlich isotherm (correlation coefficient 0.91 for raw rice straw and 0.96 for modified rice straw) was best fitted to experimental data compared to Langmuir isotherm. The pseudo-second-order showed a correlation coefficient of 0.99 for both adsorbents and was perfectly fit to adsorption data. A thermodynamic adsorption study showed that the adsorption of phosphate ions is endothermic and non-spontaneous at a lower temperature. The present study revealed that modified rice straw adsorbent has good removal efficiency for phosphate ions.

Keywords: Adsorption, Phosphate, Eutrophication, Adsorbent, Rice straw.

INTRODUCTION

Phosphate is necessary for aquatic animals and plant's growth; though higher phosphate concentrations in water cause anoxic conditions and algal blooms [1]. Phosphorus concentrations in waterbodies generally exceed 0.02 mg/L to cause eutrophication and various studies indicated that even the region's groundwater quality has worsened [2]. Eutrophication is a natural phenomenon where estuaries, lakes and slowmoving streams get higher levels of nutrients due to rocks and soil weathering from the adjacent watershed [3]. The sources, as mentioned earlier, generate too many biogenic chemicals, which harm the quality of natural water resources and disrupt the ecosystems of water bodies. Phosphate percolates into groundwater *via* soil, which contaminates the groundwater and causes significant harm to the human body and environment [4]. To resolve this complex situation, it is necessary to find the significant phosphorus compound source that enter the water body and minimize the discharge of biogenic substances into water resources. Therefore, it requires removing and recovering phosphate from different water and wastewater bodies.

Several studies have been conducted on removing phosphate from wastewater utilizing physical, chemical and biological techniques [5-7]. Although advanced approaches like membrane process, electrodialysis, flocculation and reverse osmosis are found useful, which necessitate higher initial investment and continuation costs [8-10]. Most researchers look for adsorption processes as they provide practical, feasible and economical solutions for water and wastewater treatment. For the removal of phosphate, various adsorbents, including activated carbon, aluminum hydroxide, nano-alumina and nano-scale zero-valent iron, charcoal, *etc*. have been investigated [11].

Adsorbents, in general, could be considered a 'low-cost adsorbent' if they require minimal processing and are abundantly accessible or are byproducts of another industry or agricultural waste. The waste materials used for producing various economic and environment-friendly adsorbents have drawn considerable attention because of the growing interest in sustainability. Numerous research demonstrates the use of various waste materials, including Chinese medicinal herbal residue and spent *Pleurotus ostreatus* substrate [12], spent coffee grounds, pine bark and cork waste [13], polyethylene terephthalate [14], lotus seedpod waste [15], ashitaba biomass [16], cork [17], khangar [18], rice husk and rice straw [2,11,19]. Agro-waste primarily includes cellulose, hemicellulose, sugar and carbohydrates. Numerous agro-based wastes include various functional groups, including aldehyde, amine and keto groups. These qualities enhance agricultural waste's capacity to eliminate the harmful pollutants [20].

Rice straw is a significant agricultural waste produced in Haryana state of India. For 1 kg of milled rice, 0.7 to 1.4 kg of rice straw and 0.28 kg of rice husk are produced as waste material [19]. Burning rice-based waste material releases different gaseous and solid pollutants; therefore, it is necessary to find alternative ways to convert waste material into valuable products and prevent environmental pollution [21]. In recent years, the use of unmodified and modified rice straw as an adsorbent for removing different pollutants has received much interest [22].

The current study uses rice straws obatined from the agricultural waste to remove phosphate from wastewater. The adsorbent was synthesized using NaOH for chemical activation and then it was heated at 80 ºC for 24 h. Using rice straw as adsorbents, batch studies for adsorption was conducted to investigate the effects of several experimental factors such as pH, adsorbent dosage, contact period and temperature effect. The ability of rice straws to adsorb phosphate from a synthetic solution was also studied using various kinetic and isotherm models. Fourier transformed infrared spectroscopy was used to characterize the prepared adsorbent (FTIR).

EXPERIMENTAL

Preparation of adsorbent: Raw rice straw (RRS) and modified rice straw (MRS) were used as adsorbents in the present investigation. Rice straw (RS) was collected from the local agricultural field in Rohtak district, India. Washing of rice straw was performed manually with distilled water to remove impurities. Then the rice straw was dried in sunlight and an oven at 60 ºC for 14 h. The dried rice straw was transformed into a fine powder using an electric motor-driven mixer grinder. The powdered sample was sieved with the mesh size of 0.20 mm. The modi-fied rice straw adsorbent was synthesized by rice straw mixed with 0.1 N NaOH for 24 h and then the alkaline filtered adsor-bent was provided thermal treatment at 80 ºC for 24 h. Zeta potential and size distribution were analyzed using zeta analyzer using Malvern and size analyzer. Fourier transformed infrared spectroscopy was used to characterize the prepared adsorbent.

Batch studies: The batch mode was used to investigate the effects of various parameters such as adsorbent dose, initial concentration, contact time, pH and temperature. The experiment was conducted in 250 mL conical flask using 50 mL of synthetic solution with given concentrations, dosage of adsorbent and pH at ambient temperature. For batch investigations, a mechanical shaker was employed for 90 min at a speed of 100 rpm and a temperature of 25 ºC. Conical flasks were removed after the desired contact time to allow the adsorbents to settle for 2 min. The sample was filtered using Whatman filter paper No. 1 and the filtrate was examined. After the optimization of all these parameters, the obtained optimized conditions were used for the adsorption. The phosphate concentration was measured using a spectrophotometer using blank at 590 nm wavelength. The adsorption (%) was calculated using the following eqn. 1:

$$\text{Adsorption (\%)} = \frac{C_i - C_{eq}}{C_i} \times 100 \quad (1)$$

The amount of phosphate ions adsorbed on the rice straw adsorbent was determined using following eqn. 2:

$$q_e \text{ (mg/g)} = \frac{[(C_i - C_{eq}) \times V]}{M} \quad (2)$$

where q_e = adsorption capacity, C_i = initial concentration, C_{eq} = final concentration of the studied ion, V = volume of solution (L) and M = adsorbent mass (g).

Isotherm, kinetics and thermodynamics: The mechanism and interaction between the adsorbent and adsorbate were predicted using Langmuir and Freundlich isotherms based on the adsorption data. Likewise, kinetics studies were used to examine the phosphate adsorption process. Using data on phosphate adsorption onto rice straw adsorbents as a function of temperature, thermodynamics parameters such as ΔGº, ΔSº, and ΔHº were calculated.

RESULTS AND DISCUSSION

Zeta potential and size distribution: Zeta potential was performed by measuring the velocity of adsorbent particles in the electrical field [23]. The zeta potential of raw rice straw and modified rice straw were observed as -48.5 and -50.1 mV, respectively (Fig. 1a-b) at neutral pH. The particle size distribution by intensity shows the raw rice straw peak at 719 nm and modified rice straw peak at 652 nm, respectively (Fig. 2a-b).

FTIR studies: The untreated and phosphate-loaded RRS and MRS were analyzed by FTIR spectroscopy in the range of 4000 to 400 cm^{-1} wavelength. The peaks of percentage absorbance for different wavenumbers are shown in Fig. 3a-d. The significant peaks of untreated raw rice straw were observed at 1715, 1683, 1541, 1508, 1473, 1108, 1084, 725 and 643 cm^{-1} (Fig. 3a). In case of untreated modified rice straw, the peaks at 1793, 1716, 1699, 1557, 1508, 1339, 964, 839 and 785 cm^{-1} were observed (Fig. 3b). After the phosphate treatment, raw rice straw showing the peaks at 1735, 1683, 1557, 1506, 1490, 1031, 955, 747, 660 and 815 cm^{-1} (Fig. 3c). Furthermore, phosphate treated modified rice straw exibited the peaks at 3747, 3648, 1699, 1559, 1473, 1023, 991, 795, 658 and 616 cm^{-1} (Fig. 3d). The FTIR peak near 1720-1710 cm^{-1} is due to the vibration of P=O bond, while the peak at 1300-1200 cm^{-1} is due to the vibration of P=O of phosphate ether. A peak around 1650-1515 cm^{-1} represents the presence of aromatic group. Rice straw shows the adsorption peak at 1108 cm^{-1} from glycosidic bond and confirmed the presence of cellulose in rice straw adsorbent. A peak appeared near 1024 cm^{-1} after adsorption represents phosphate stretching vibration band, while the peak

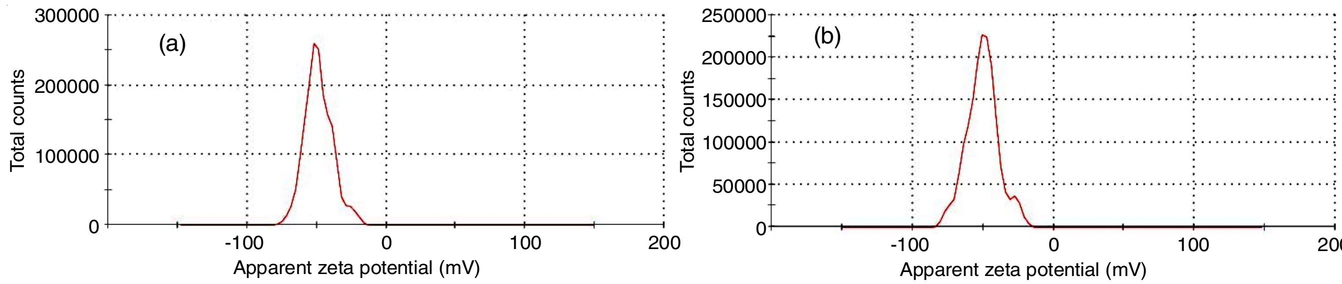

Fig. 1. Zeta potential of raw rice straw (a) and modified rice straw (b)

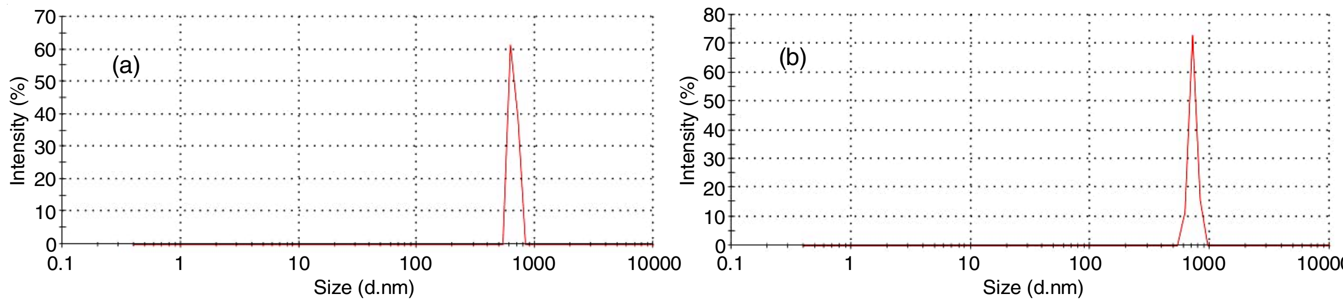

Fig. 2. Size distribution of raw rice straw (a) and modified rice straw (b)

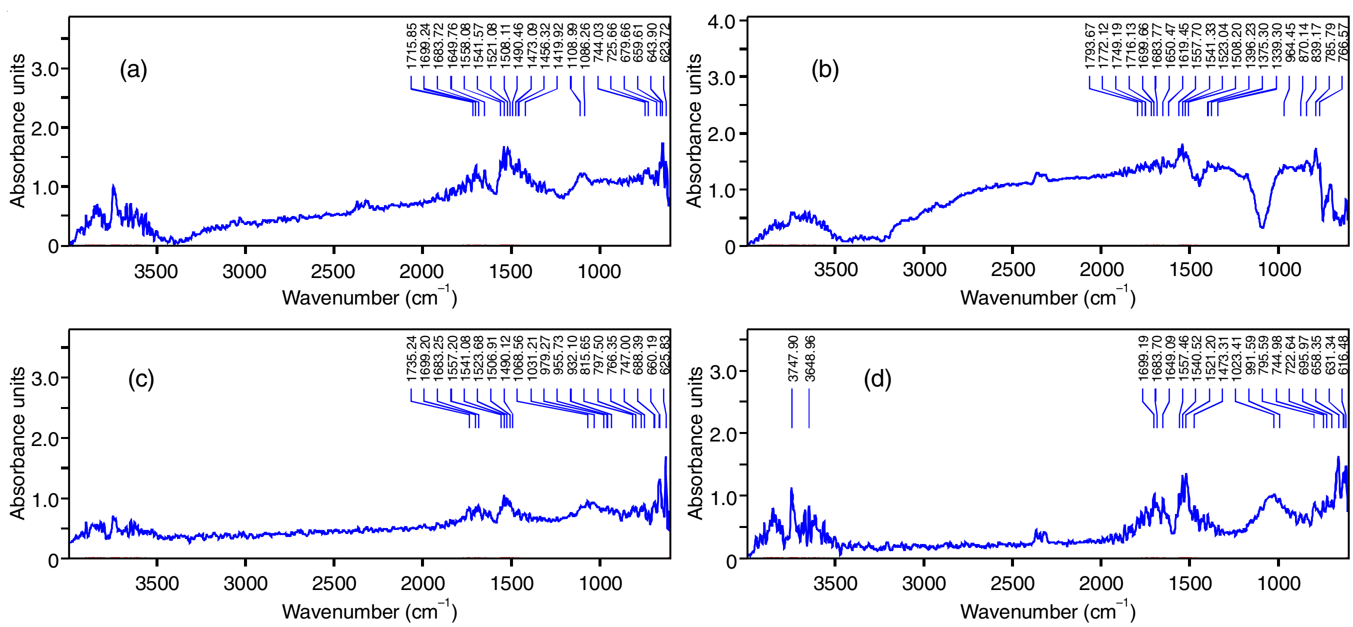

Fig. 3. FTIR absorbance plot for untreated raw rice straw (a), untreated modified rice straw (b), after treatment with phosphate raw rice straw (c), and phosphate treated modified rice straw (d)

observed at 1000-900 cm^{-1} is due to the vibration of P-OH and P-O-C bonds. Thus, it is observed that the FTIR spectra slightly changes after the phosphate treatment and indicating that phosphate adsorption due to the significant changes in the chemical composition of adsorbents, which reveals that adsorption of phosphate occurred on surface of adsorbents.

Effects of different parameters

Effect of pH: The pH effect on the adsorption study was recognized by changing pH from 2 to 8 with other parameters such as an adsorbent dose of 0.5 g and 0.2 g for raw rice straw (RRS) and modified rice straw (MRS), the initial ion concentration of 20 ppm, contact period of 90 min with 100 rpm of agitation speed and at 25 ºC (Fig. 4). The removal efficiency of phosphate was observed 85.48% and 94.84% by raw and modified rice straws at pH 8. When the pH is less than 3, the adsorption capacity of phosphate decreases, the remaining protonation is caused by the higher H^+ ions concentration [24]. Rodrigues *et al.* [25] found that phosphate can alter into many forms at various ranges of pH < 2.0, 2.0-7.0, 7.0-12.5 and > 12.5 in the form of H_3PO_4, $H_2PO_4^-$, HPO_4^{2-} and PO_4^{3-}, respectively.

Effect of adsorbent dose: The adsorbent dose effect was studied at various doses from 0.1 to 0.8 g by having another factor constant like pH 8 for both adsorbents with an initial ion concentration of 20 ppm with 90 min of contact time, agitation speed of 100 rpm and at 25 ºC. The highest phosphate removal

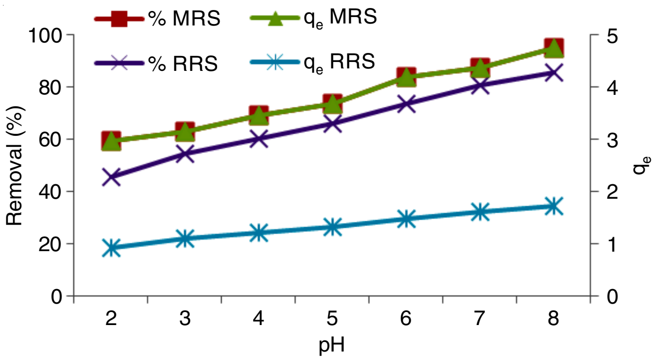

Fig. 4. Effect of pH on removal of phosphate by raw rice straw and modified rice straw

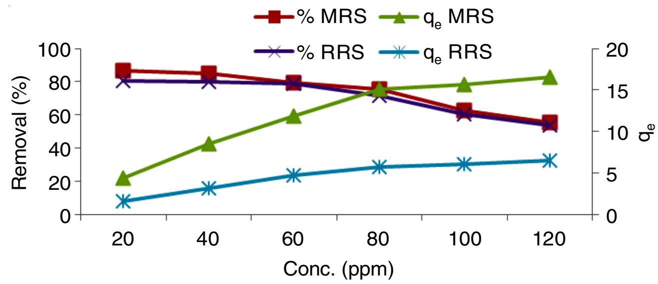

Fig. 6. Effect of initial ion concentration on removal of phosphate by raw rice straw and modified rice straw

percentage ranged from 66.01% to 90.09%, depending on the dose of raw RRS adsorbent used (0.1 g to 0.8 g), while in case of MRS with an adsorbent dose of 0.1 g to 0.8 g the removal efficiency increased from 78.06% to 93.78% (Fig. 5). The observed higher adsorption capacity was 6.6 mg/g and 7.8 mg/g for raw and modified adsorbent. The adsorption capacities were decreased with increasing adsorbent dose and removal efficiency increased with the increase in adsorbent dose. The dose dependency may be due to increased surface area and a higher number of active surface sites at a high dose [26]. The optimum considered adsorbent dose was 0.6 g for RRS and 0.5 g for MRS, with the removal of 85.57% and 91.03%, respectively. The current study demonstrated that both adsorbents were effective in removing phosphate ions at the relatively low adsorbent doses.

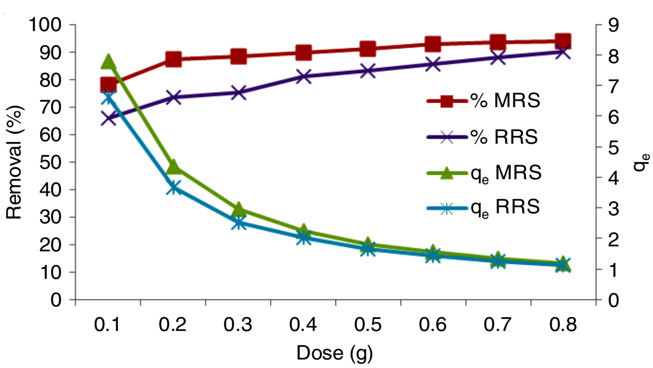

Fig. 5. Effect of adsorbent dose on removal of phosphate by raw rice straw and modified rice straw

Effect of initial phosphate concentration: The effect of the initial ion concentrations was measured at different concentrations of phosphate ions ranging from 20 to 120 ppm with pH 8 for both adsorbents, adsorbent dose of 0.2 g MRS and 0.5 g for RRS with a contact time of 90 min, agitation speed of 100 rpm and at 25 ºC. The maximum removal efficiency was observed at a lower initial concentration (20 ppm) 80.62% for raw rice straw and 86.93% modified rice straw, respectively. The higher adsorption capacities were 6.47 mg/g and 16.60 mg/g for raw and modified rice straw; it increases as the ion concentration increases (Fig. 6). Yadav *et al.* [27] reported that at a high concentration of phosphate ion in solution, some significant ions remained unadsorbed in solution to attain site saturation. Similarly, the adsorption site vacancies decrease when the concentration of phosphate increases and the uptake capacity reduces consequently.

Effect of contact time: The investigation was carried out with a 15 min break between different interaction times ranging from 15 to 120 min. However, keeping other parameters constant as pH 8 for both the rice straw adsorbents, the adsorbent dose of 0.2 g for MRS and 0.5 g for RRS, the concentration of 20 ppm, agitation speed of 100 rpm and at 25 ºC. It was revealed that as contact time increased, the absorption efficiency increased and eventually became saturated. The removal efficiency and adsorption capacity were shown to improve and become saturated as the contact time increased. The maximum removal capacity was obtained after a 60 min contact time; then, it gets saturated; raw rice straw and modified rice straw have the removal efficiency of 83.62% and 88.56% (Fig. 7). The rapid uptake of phosphate may have been facilitated by the presence of open binding sites on the surface of the adsorbent. Equilibrium following the fast ion adsorption likely depicts the entire filling of the active site on the surface of the adsorbent [28].

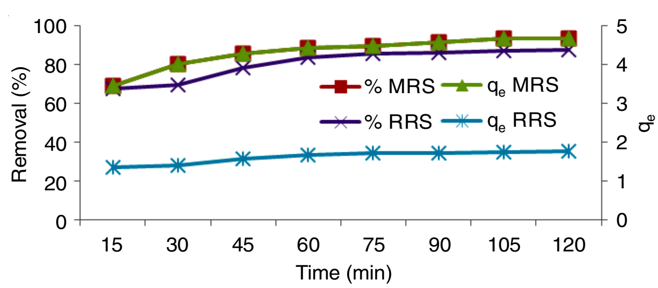

Fig. 7. Effect of contact time on removal of phosphate by raw rice straw and modified rice straw

Effect of temperature: At pH 8, with adsorbent doses of 0.2 g for MRS and 0.5 g for RRS, concentrations of 20 ppm, and agitation speeds of 100 rpm, the adsorption processes were carried out at different temperatures ranging from 5 to 45 ºC. It was found that the maximum removal efficiency of 80.71% was occured at 45 ºC for raw rice straw as adsorbent whereas the removal efficiency of modified rice straw was found to be 87.4% at 35 ºC (Fig. 8). An endothermic process is better for the adsorption at high temperatures, though exothermic leads to *vice versa* [29].

Adsorption isotherms: The adsorption isotherm models correlate the equilibrium relationship between the adsorbate concentration in the solution and the adsorbate concentration

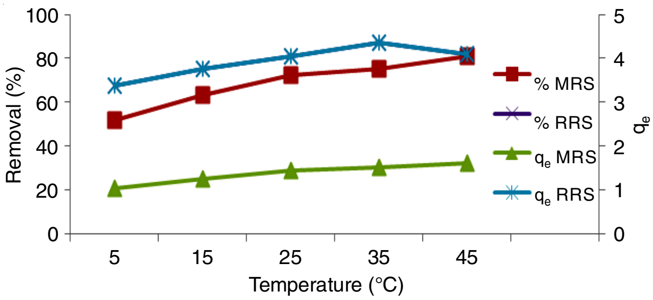

Fig. 8. Effect of temperature on removal of phosphate by raw rice straw and modified rice straw

on the surface over a range of temperatures. The mechanism of adsorption can be better understood using different adsorption isotherms. Langmuir and Freundlich isotherm models were studied to illustrate the equilibrium relationship between adsorbent and adsorbate.

Langmuir isotherm: Langmuir isotherm model, which is based on the fact that adsorbate species adsorb non-linearly to the surface of the adsorbent, shows that adsorption, occurred when adsorbate ions formed a monolayer on the heterogeneous surface of the adsorbent without interacting with one another. It assumes that there is no transmigration of adsorbate ions and that the energy of each binding site on the adsorbent surface is the same. Maximum adsorption capacities for adsorbate ion absorption by various adsorbents were calculated using a non-linear derivation of the Langmuir equation, which corresponds to the entire monolayer covering of the adsorbent surface at the establishment of equilibrium. It is extensively used two-parameter equation and usually expressed as [30]:

$$\frac{C_e}{q_e} = \frac{C_e}{q_{max}} + \frac{1}{bq_{max}} \quad (3)$$

where C_e represents the equilibrium concentration of left ion in the solution in mg/L, q_e is the quantity of the ion adsorbed per unit mass unit of adsorbent at equilibrium in mg/g, q_{max} is the sum of adsorbent at entire monolayer coverage (mg/g) and b represents the equilibrium Langmuir constant.

Separation factor: When describing the main features of the Langmuir isotherm, it is necessary for Langmuir isotherm to use the separation factor (a dimensionless constant).

$$R_L = \frac{1}{1 + bC_0} \quad (4)$$

where b belongs to Langmuir constant, C_0 is the initial ion concentration and R_L is the dimensionless constant and defined as the separation factor. When R_L is between 0 and 1, the adsorption process is favourable, while if the value of $R_L < 1$, then unfavourable adsorption take place. Moreover, if $R_L = 1$, then linear adsorption occurs, whereas the value of $R_L = 0$ means the occurance of the irreversible adsorption. In present work, the R_L value of RRS and MRS adsorbents was 0.42 and 0.27, respectively (Table-1). The correlation coefficients values of RRS and MRS adsorbents were found to be 0.56 and 0.74. A higher value of R^2 in the case of modified rice straw shows that Langmuir isotherm is ideally fitted to MRS adsorbent in comparison to RRS adsorbent.

TABLE-1
DIFFERENT ADSORPTION ISOTHERMS COMPARISON FOR PHOSPHATE REMOVAL USING RAW RICE STRAW AND MODIFIED RICE STRAW

Isotherms	Parameters	Raw rice straw	Modified rice straw
Langmuir	q_m (mg/g)	6.21	6.36
	B	0.067	0.132
	R^2	0.56	0.74
	R_L	0.42	0.27
Frendlich	N	0.73	0.66
	K_f (L/g)	2.76	1.77
	R^2	0.912	0.967

Freundlich isotherm: The assessment of the adsorption isotherm was also performed using the Freundlich adsorption isotherm, which is based on the hypothesis of heterogeneity in energy distribution of active binding sites during the interaction with the adsorbate species. The effectiveness of the adsorbents in eliminating the adsorbate species was demonstrated by this model. The Freundlich adsorption model is represented by eqn. 5 [31]:

$$\frac{x}{m} = K_f C_e \frac{1}{n} \quad (5)$$

The logarithm of this equation is:

$$\log \frac{x}{m} = \log K_f + \frac{1}{n} \log C_e \quad (6)$$

where the amount of adsorbent adsorbed (q_e), x belongs to the amount of phosphate adsorbed, C_e is equilibrium concentration (mg/L), K_f is Freundlich constant and n is the empirical constant.

Upon evaluation, the high K_f value suggests significant adsorption over the studied concentration range. The Freundlich isotherm favours modified rice straw over raw rice straw, as evidenced by the calculated correlation coefficient R^2 for raw rice straw being 0.912 and 0.967 for modified rice straw (Table-1). A correlation coefficient higher than 0.9 indicates fit agreement between the experimental and predicted value.This indicates that there was more than one layer involved in the adsorption process, as the Freundlich isotherm was a better fit for both adsorbents than the Langmuir isotherm.

Kinetics studies: Pseudo-first-order and pseudo-second-order kinetics models were used to determine the adsorption kinetics of phosphate ions onto rice straw adsorbents (RRS an MRS).

Pseudo-first-order: According to the pseudo-first-order kinetic equation of the Lagergren model, the unoccupied sites have a direct impact on the rate of adsorption. The linear form of the pseudo-first-order equation is represented as [32]:

$$\log\ (q_e - q_t) = \log\ q_e - \frac{K_1 t}{2.303} \quad (7)$$

where k_1 is the first order rate constant of pseudo-kinetic equation and q_e and q_t represent the concentration of adsorbed ion (mg g^{-1}) in the solution and at any time t (min).

The correlation coefficient (R^2) of RRS and MRS was found to be 0.97 and 0.98; the value of R^2 is significantly higher than 0.9 showing a fit agreement between experimental and measured adsorption capacity (Table-2).

TABLE-2
ADSORPTION KINETICS PARAMETERS COMPARISON FOR PHOSPHATE ION REMOVAL USING RAW RICE STRAW AND MODIFIED RICE STRAW

Kinetics models	Parameters	Raw rice straw	Modified rice straw
Experimental adsorption capacity	Q_{exp} (mg/g)	4.66	1.74
Pseudo-first-order	q_e (mg/g)	1.047	1.032
	K_1 (1/min)	0.147	0.628
	R^2	0.974	0.988
Pseudo-second-order	q_e (mg/g)	1.865	4.95
	K_2 (g/mg/min)	0.069	0.0291
	R^2	0.998	0.999

Pseudo-second-order: The pseudo-second-order equation implies the square of the number of total unoccupied sites after the adsorption rate and is represented by eqn. 8:

$$\frac{t}{q_t} = \frac{1}{K_2 q_e^2} + \frac{t}{q_e} \tag{8}$$

where k_2 is pseudo-second order rate constant at equilibrium (g mg^{-1} min^{-1}). The value of the correlation coefficient (R^2) was found to be 0.99 for both adsorbents. Table-2 shows that the estimated adsorption capacity agrees with the experimental adsorption capacity. It was found that pseudo-second-order kinetics is an excellent fit for this investigation.

Adsorption thermodynamics: The thermodynamic factors such as enthalpy (ΔH°), free Gibb's energy (ΔG°) and entropy (ΔS°) variation control the spontaneity of an adsorption process. A decrease in ΔG value with increasing temperature is indication of the ability for an effective and spontaneous adsorption process [33]. The thermodynamic studies were conducted at different temperatures of 278 K, 288 K, 298 K, 308 K and 318 K. The different parameters of thermodynamics were measured using the following equations:

$$\ln K_d = \frac{\Delta S^\circ}{R} - \frac{\Delta H^\circ}{RT} \tag{9}$$

where, $K_d = \frac{q_e}{C_e}$

$$\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ \tag{10}$$

where $K_d = q_e/C_e$ is the equilibrium constant, q_e is the adsorption capacity of phosphate at equilibrium (mg/g), C_e is the equilibrium concentration of phosphate solution (mg/L), T is the temperature (K) and R is the gas constant (8.314 J/mol/K).

The positive value of ΔH (24.31 kJ/mol for RRS and 17.93 kJ/mol for MRS) suggests that phosphate elimination from synthetic solution by both the adsorbent is endothermic [34] and chemical process. Adsorption occurs due to an internal redistribution of energy between the adsorbate and the adsorbent, as evidenced by the positive ΔS value (0.069 kJ/mol for RRS and 0.059 kJ/mol for MRS) obtained. The value of ΔG decreases as the temperature increase depicting the degree of feasibility for phosphate adsorption (Table-3).

Comparison with reported adsorbents: In Table-4, the adsorption capacity and removal efficiency rate of RRS and MRS adsorbents was compared with different reported adsor bents for phosphate ions removal. Thus, the efficiency of the prepared two adsorbants (RRS and MRS) is almost comparable to the other reported adsorbents.

Conclusion

The current investigation was carried out to determine the significant potential of rice straw adsorbents for the removal of phosphate ions. The batch study parameters were optimized with different adsorbents synthesized from rice straw, such as raw rice straw and modified rice straw. Both adsorbents of rice straw have good removal efficiency, but the modified adsorbent has superior uptake capacity as compared to raw rice straw. The modified rice straw (MRS) showed a higher uptake capacity at 8 pH, initial ion concentration of 20 ppm and a dose of adsorbent 0.5 g with a contact time of 60 min at an agitation speed of 100 rpm. Freundlich isotherm was perfectly fitted to experimental data as compared to Langmuir isotherm. The pseudo-second-order was perfectly fit as a comparison to the pseudo-first-order for adsorption data. The adsorbents adsorption process was non-spontaneous and endothermic at lower temperatures. Therefore, it was concluded that rice straw adsorbents were suitable for removing phosphate ions with a lower cost, eco-friendly and non-toxic nature.

TABLE-3
ADSORPTION THERMODYNAMIC PARAMETERS FOR PHOSPHATE UPTAKE USING RAW RICE STRAW AND MODIFIED RICE STRAW

Adsorbents	ΔH° (KJ/mol)	ΔS° (KJ/mol)	ΔG° (KJ/mol)				
			278 °C	288 °C	298 °C	308 °C	318 °C
Raw rice straw	24.31	0.069	5.16	4.43	3.74	3.05	2.36
Modified rice straw	17.93	0.059	1.31	0.71	0.11	-0.48	-0.125

TABLE-4
REMOVAL RATE OF VARIOUS ADSORBENTS FOR PHOSPHATE IONS

Adsorbent	Dosage (g/L)	Initial conc. (ppm)	Adsorption capacity	Removal rate (%)	Ref.
Rice husk	2	–	–	89	[1]
Fruit juice residue	3	–	–	95.85	[27]
Sugercane bagasse	30	30	0.33	99.2	[35]
Corn stalks	4	50	20.04	96.03	[36]
Wheat straw	–	–	16.58	–	[37]
Raw rice straw (RRS)	0.6	20	6.47	90.03	Present study
Modified rice straw (MRS)	0.5	20	16.60	93.78	

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

REFERENCES

1. D.W. Schindler, S.R. Carpenter, S.C. Chapra, R.E. Hecky and D.M. Orihel, *Environ. Sci. Technol*., **50**, 8923 (2016); https://doi.org/10.1021/acs.est.6b02204
2. S. Mor, K. Chhoden and K. Ravindra, *J. Clean. Prod.*, **129**, 673 (2016); https://doi.org/10.1016/j.jclepro.2016.03.088
3. F.A. Khan and Abid Ali Ansari, *Botanical Rev.*, **71**, 449 (2005).
4. B. Singh and E. Craswell, *SN Appl. Sci*., **3**, 518 (2021); https://doi.org/10.1007/s42452-021-04521-8
5. J.T. Bunce, E. Ndam, I.D. Ofiteru, A. Moore and D.W. Graham, *Front. Environ. Sci.*, **6**, 8 (2018); https://doi.org/10.3389/fenvs.2018.00008
6. O. Ruzhitskaya and E. Gogina, *MATEC Web Conf.*, **106**, 07006 (2017); https://doi.org/10.1051/matecconf/20171060
7. K. Nobaharan, S.B. Novair, B.A. Lajayer and E.D. van Hullebusch, *Water*, **13**, 517 (2021); https://doi.org/10.3390/w13040517
8. A. Sperlich, D. Warschke, C. Wegmann, M. Ernst and M. Jekel, *Water Sci Technol.*, **61**, 301 (2010); https://doi.org/10.2166/wst.2010.800
9. Y. Tian, W. He, D. Liang, W. Yang, B.E. Logan and N. Ren, *Water Res.*, **138**, 129 (2018); https://doi.org/10.1016/j.watres.2018.03.037
10. K. Velusamy, S. Periyasamy, P.S. Kumar, D.-V.N. Vo, J. Sindhu, D. Sneka and B. Subhashini, *Environ. Chem. Lett.*, **19**, 3165 (2021); https://doi.org/10.1007/s10311-021-01239-2
11. S. Hamzah, N.A. Razali, N.I. Yatim, M. Alias, A. Ali, N.S. Zaini and A.A. Abuhabib, *J. Water Supply*, **67**, 766 (2018); https://doi.org/10.2166/aqua.2018.087
12. C. Feng, S. Zhang, Y. Wang, G. Wang, X. Pan, Q. Zhong, X. Xu, L. Luo, L. Long and P. Yao, *Bioresour. Technol.*, **307**, 123231 (2020); https://doi.org/10.1016/j.biortech.2020.123231
13. B. Silva, M. Martins, M. Rosca, V. Rocha, A. Lago, I.C. Neves and T. Tavares, *Sep. Purif. Technol.*, **235**, 116139 (2020); https://doi.org/10.1016/j.seppur.2019.116139
14. O.I. Ungureanu, D. Bulgariu, A.M. Mocanu and L. Bulgariu, *Water*, **12**, 2624 (2020); https://doi.org/10.3390/w12092624
15. Y. Liu, Q. Gao, S. Pu, H. Wang, K. Xia, B. Han and C. Zhou, *Colloids Surf. A Physicochem. Eng. Asp.*, **568**, 391 (2019); https://doi.org/10.1016/j.colsurfa.2019.02.017
16. H. Xue, X. Wang, Q. Xu, F. Dhaouadi, L. Sellaoui, M.K. Seliem, A. Ben Lamine, H. Belmabrouk, A. Bajahzar, A. Bonilla-Petriciolet, Z. Li and Q. Li, *Chem. Eng. J.*, **430**, 132801 (2022); https://doi.org/10.1016/j.cej.2021.132801
17. Q. Wang, Z. Lai, J. Mu, D. Chu and X. Zang, *Waste Manag.*, **105**, 102 (2020); https://doi.org/10.1016/j.wasman.2020.01.041
18. G. Nagpal, A. Bhattacharya and N.B. Singh, *Asian J. Chem.*, **28**, 814 (2016); https://doi.org/10.14233/ajchem.2016.19526
19. K.E. Motlagh, N. Asasian-Kolur and S. Sharifian, *Biomass Conv. Bioref.*, **12**, 5729 (2020); https://doi.org/10.1007/s13399-020-01145-7
20. R. Jain, D. Dominic, N. Jordan, E.R. Rene, S. Weiss, E.D. van Hullebusch, R. Hübner and P.N.L. Lens, *Environ. Chem. Lett.*, **14**, 381 (2016); https://doi.org/10.1007/s10311-016-0560-8
21. E. Sanchis, M. Ferrer, S. Calvet, C. Coscollà, V. Yusà and M. Cambra-López, *Atmos. Environ.*, **98**, 25 (2014); https://doi.org/10.1016/j.atmosenv.2014.07.062
22. B.A. Goodman, *J. Bioresour. Bioprod.*, **5**, 143 (2020); https://doi.org/10.1016/j.jobab.2020.07.001
23. V. Boonamnuayvitaya, C. Chaiya, W. Tanthapanichakoon and S. Jarudilokkul, *Sep. Purif. Technol.*, **35**, 11 (2004); https://doi.org/10.1016/S1383-5866(03)00110-2
24. H. Qiao, L. Mei, G. Chen, H. Liu, C. Peng, F. Ke, R. Hou, X. Wan and H. Cai, *Appl. Surf. Sci.*, **483**, 114 (2019); https://doi.org/10.1016/j.apsusc.2019.03.147
25. L.A. Rodrigues and M.L.C.P. da Silva, *Desalination*, **263**, 29 (2010); https://doi.org/10.1016/j.desal.2010.06.030
26. H.T. Banu and S. Meenakshi, *Int. J. Biol. Macromol.*, **104**, 1517 (2017); https://doi.org/10.1016/j.ijbiomac.2017.03.043
27. D. Yadav, M. Kapur, P. Kumar and M.K. Mondal, *Process Saf. Environ. Prot.*, **94**, 402 (2015); https://doi.org/10.1016/j.psep.2014.09.005
28. M.W. Golie and S. Upadhyayula, *Int. J. Biol. Macromol.*, **97**, 489 (2017); https://doi.org/10.1016/j.ijbiomac.2017.01.066
29. P.S. Kumar, L. Korving, M.C.M. van Loosdrecht and G.-J. Witkamp, *Water Res. X*, **4**, 100029 (2019); https://doi.org/10.1016/j.wroa.2019.100029
30. I. Langmuir, *J. Am. Chem. Soc.*, **40**, 1361 (1918); https://doi.org/10.1021/ja02242a004
31. H. Freundlich, *J. Phys. Chem.*, **57**, 385 (1906).
32. S.K. Lagergren, *Sven Vetenskapsakad Handingarl*, **24**, 1 (1898).
33. W.S. Wan Ngah and M.A.K.M. Hanafiah, *Biochem. Eng. J.*, **39**, 521 (2008); https://doi.org/10.1016/j.bej.2007.11.006
34. C. Rudram, L.P. Praveen and P.D. Sankar Reddy, *Asian J. Chem.*, **34**, 2597 (2022); https://doi.org/10.14233/ajchem.2022.23836
35. P. Ganesan, R. Kamaraj and S. Vasudevan, *J. Taiwan Inst. Chem. Eng.*, **44**, 808 (2013); https://doi.org/10.1016/j.jtice.2013.01.029
36. L. Wang, Z. Xu, Y. Fu, Y. Chen, Z. Pan, R. Wang and Z. Tan, *RSC Adv.*, **8**, 36468 (2018); https://doi.org/10.1039/C8RA06617E
37. J.H. Li, G.H. Lv, W.B. Bai, Q. Liu, Y.C. Zhang and J.Q. Song, *Desalination Water Treat.*, **57**, 4681 (2016); https://doi.org/10.1080/19443994.2014.994104