

Adsorptive Separation of Nitrate from Water Using Rice Dust Biochar: Performance at 5-10 ppm Concentration

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ABSTRACT

Nitrate contamination of groundwater threatens public health, yet most adsorption studies are conducted at concentrations far above those found in many supplies. This study evaluated rice dust biochar (RDB), a low-cost residue-derived sorbent, for nitrate removal at 5-10 mg L⁻¹. The biochar was produced by oxygen-limited pyrolysis at 500 °C and characterized by SEM-EDS, FTIR, BET, XRD and pH_{pzc} analysis. Batch experiments examined pH, dose, contact time, initial concentration and temperature, and the data were interpreted with isotherm, kinetic and thermodynamic models. RDB was a mesoporous material (86.4 m² g⁻¹) with a pH_{pzc} of 6.8. Removal peaked at pH 4 (83.4%), the optimum dose was 2.0 g L⁻¹, and equilibrium was reached in about 90 min. Kinetics followed the pseudo-second-order model (R² = 1.000), and the Freundlich isotherm gave the best fit (R² = 0.999). Across 5-10 mg L⁻¹, removal was 82.8-86.8%, and adsorption was spontaneous and endothermic, with evidence pointing to electrostatic attraction, anion exchange and pore filling. After five regeneration cycles, 88% of the initial efficiency was retained; phosphate was the most inhibitory coexisting anion, and removal in a real water sample was 74.0%. These findings indicate that RDB is a promising candidate for trace-level nitrate polishing, pending column and leaching studies.

Keywords- nitrate removal; rice dust biochar; adsorption; low concentration; isotherm; kinetics.

I. INTRODUCTION

1.1 Nitrate contamination: sources, health effects and regulatory limits

Nitrate (NO₃⁻) is among the most pervasive chemical contaminants of terrestrial water systems, and its prevalence has escalated in step with the intensification of agriculture, the proliferation of synthetic nitrogenous fertilizers, and the inadequate management of livestock effluent and domestic sewage [1,2]. Owing to its high solubility and negligible affinity for soil particles, nitrate migrates readily through the vadose zone and accumulates in groundwater, where its residence time may extend over decades [3]. Consequently, nitrate loading in aquifers frequently persists long after the original anthropogenic input has ceased.

The toxicological significance of nitrate is well established. In the gastrointestinal tract, nitrate is reduced to nitrite, which oxidizes haemoglobin to methaemoglobin and thereby impairs oxygen transport, a

condition of particular gravity in bottle-fed infants (methaemoglobinaemia, or "blue baby syndrome") [4]. Moreover, endogenous nitrosation of nitrite with secondary amines may yield N-nitroso compounds, and long-term ingestion of nitrate under such conditions has been classified by the International Agency for Research on Cancer as probably carcinogenic to humans [5]. Beyond human health, nitrate enrichment drives eutrophication, hypoxia and loss of biodiversity in receiving water bodies [6]. To mitigate these risks, the World Health Organization recommends a guideline value of 50 mg L⁻¹ as NO₃⁻, while the Bureau of Indian Standards (IS 10500) prescribes an acceptable limit of 45 mg L⁻¹ with no relaxation in the absence of an alternative source [7,8].

1.2 Conventional remediation technologies and their constraints

A diverse repertoire of technologies has been proposed for nitrate abatement, including ion exchange, reverse osmosis, electrodialysis, chemical reduction, and

biological denitrification [9,10]. Each, however, is encumbered by intrinsic limitations. Ion-exchange resins are costly, display imperfect selectivity in the presence of sulfate and chloride, and generate concentrated brines that pose a secondary disposal challenge. Membrane-based processes demand substantial capital and energy expenditure, as well as rigorous maintenance to counter fouling. Biological denitrification, although economical at scale, is sensitive to temperature and carbon availability and carries a risk of residual organic carbon and microbial contamination in the treated effluent [11]. These shortcomings are especially consequential for decentralized and resource-constrained settings, where simplicity, affordability and operational robustness are paramount.

1.3 Biochar as a sustainable adsorbent

Adsorption is widely regarded as an attractive alternative by virtue of its operational simplicity, modularity, and capacity for regeneration [12]. Within this domain, biochar, the carbon-rich solid obtained through the oxygen-limited pyrolysis of biomass, has emerged as a promising and economically viable sorbent [13]. Its appeal derives from a porous architecture, tunable surface chemistry, and the circularity afforded by valorizing agricultural residues that would otherwise be burned in the field or discarded [14]. Rice, a staple crop cultivated extensively across Asia, generates voluminous by-products, including husk, straw and milling dust, whose disposal remains an environmental concern in agrarian economies [15]. The siliceous and lignocellulosic composition of these residues renders them suitable precursors for biochar production, and their abundance and negligible cost enhance the prospects of scalable deployment [16].

Nevertheless, pristine biochar typically carries a net negative surface charge at near-neutral pH, which disfavours the uptake of anionic species such as nitrate through electrostatic repulsion [17]. Sorption of nitrate on biochar is therefore governed by a subtler interplay of pore filling, surface protonation, anion exchange and weaker interfacial interactions, whose relative contributions depend on feedstock, pyrolysis conditions and solution chemistry [18]. Elucidating these mechanisms for rice-derived dust biochar, a feedstock that has received comparatively scant attention, constitutes a meaningful scientific undertaking.

1.4 Research gap

A substantial proportion of the extant literature on nitrate adsorption has been conducted at initial concentrations spanning tens to several hundred mg L⁻¹, conditions that favour the assessment of maximum adsorption capacity but seldom resemble the realities of contemporary water supplies [19]. Many groundwater and surface sources, as well as the effluents of upstream treatment units, contain nitrate at single-digit mg L⁻¹ levels. Within this trace regime, adsorbent performance cannot be extrapolated reliably from high-concentration data, because the driving force for mass transfer, the

occupancy of heterogeneous binding sites, and the competitive influence of co-existing anions differ markedly. Systematic evidence on the behaviour of rice dust biochar in the 5-10 mg L⁻¹ window is, to the best of our knowledge, lacking. Addressing this deficit is pertinent to polishing applications, to the establishment of performance benchmarks, and to the design of point-of-use systems.

1.5 Objectives

In this context, the present investigation aims to evaluate the efficacy of rice dust biochar for the adsorptive separation of nitrate from aqueous solution at initial concentrations of 5-10 mg L⁻¹. The specific objectives are: (i) to prepare and physicochemically characterize the biochar; (ii) to optimize operational parameters, namely solution pH, adsorbent dosage, contact time and temperature; (iii) to interpret equilibrium and kinetic behaviour through established isotherm and kinetic models; (iv) to delineate the governing adsorption mechanism and thermodynamic feasibility; and (v) to appraise regeneration potential, selectivity in the presence of competing ions, and performance in real water matrices.

II. MATERIALS AND METHODS

2.1 Feedstock collection and biochar preparation

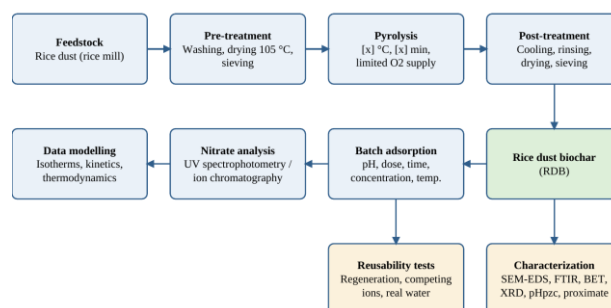


Figure 1. Schematic workflow of biochar preparation, characterization, batch adsorption experiments, analysis and modelling.

Rice dust, the fine particulate by-product generated during milling and handling of paddy, was procured from [location/mill]. The feedstock was washed repeatedly with deionized water to eliminate adhering soluble salts and extraneous particulates, oven-dried at 105 °C to constant mass, and homogenized by sieving to a uniform particle-size fraction of [x] µm. Carbonization was conducted in a muffle furnace under oxygen-limited conditions, with the biomass loaded in a covered crucible and heated at a ramp rate of [x] °C min⁻¹ to a peak temperature of [x] °C, held for [x] min. After cooling to ambient temperature within the furnace, the resulting biochar was gently ground, re-sieved, rinsed with deionized water until the filtrate attained a stable pH, dried at 105 °C, and stored in an airtight desiccator until

use. [If applicable: Chemical modification was performed by impregnating the biochar with (agent, concentration) at a solid-to-liquid ratio of (x), followed by thermal activation at (x) °C.] The material is hereafter designated RDB, and the complete experimental workflow is summarized in Figure 1.

2.2 Characterization of the biochar

Table 1. Characterization techniques and the parameters derived from each.

Technique	Parameter obtained	Relevance to nitrate uptake
SEM-EDS	Surface morphology; elemental composition	Pore accessibility; elemental surface distribution
FTIR	Surface functional groups	Sites for protonation, ion exchange and complexation
BET / BJH (N ₂ , 77 K)	Surface area; pore volume; pore size	Physical capacity for pore filling
XRD	Crystalline and mineral phases	Silica and ash-derived phases
pH _{pzc} (pH-drift)	Surface charge behaviour vs. pH	Electrostatic attraction or repulsion of NO ₃ ⁻
Proximate analysis	Moisture, volatile matter, ash, fixed carbon; yield	Degree of carbonization; stability

Surface morphology and elemental distribution were examined by scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM-EDS). Surface functional groups were identified by Fourier-transform infrared spectroscopy (FTIR) over the range 4000-400 cm⁻¹. Specific surface area, pore volume and pore-size distribution were derived from N₂ adsorption-desorption isotherms at 77 K using the Brunauer-Emmett-Teller (BET) and Barrett-Joyner-Halenda (BJH) methods, respectively. Crystallographic and mineral phases were assessed by X-ray diffraction (XRD). The point of zero charge (pH_{pzc}) was established by the pH-drift method [19], in which the final pH of 0.01 M NaCl solutions with initial pH values of 2-12 was recorded after 24 h of equilibration with the adsorbent. Proximate analysis (moisture, volatile matter, ash and fixed carbon) was performed in accordance with the relevant ASTM protocol, and the product yield was calculated on a dry-weight basis. The techniques employed and the parameters derived from each are listed in Table 1.

2.3 Reagents and preparation of nitrate solutions

All reagents were of analytical grade, and ultrapure water was used throughout. A stock solution of 1000 mg L⁻¹ nitrate was prepared by dissolving a precisely

weighed quantity of oven-dried potassium nitrate (KNO₃) in deionized water [expressed as NO₃⁻ / NO₃⁻-N]. Working solutions of 5, 6, 7, 8, 9 and 10 mg L⁻¹ were obtained by serial dilution immediately prior to each experiment. The pH was adjusted with 0.1 M HCl or 0.1 M NaOH, as appropriate.

2.4 Batch adsorption experiments

Table 2. Operating windows of the batch adsorption experiments (agitation [x] rpm; volume [x] mL).

Parameter	Range studied	Fixed conditions
Solution pH	2 - 10	Dose [x] g L ⁻¹ ; C ₀ [x] mg L ⁻¹ ; [x] min; [x] K
Adsorbent dose (g L ⁻¹)	[0.1 - 2.0]	Optimum pH; C ₀ [x] mg L ⁻¹ ; [x] min; [x] K
Contact time (min)	0 - [x]	Optimum pH and dose; C ₀ [x] mg L ⁻¹ ; [x] K
Initial concentration (mg L ⁻¹)	5, 6, 7, 8, 9, 10	Optimum pH, dose and time; [x] K
Temperature (K)	[288, 298, 308, 318]	Optimum pH, dose and time; C ₀ [x] mg L ⁻¹

Batch experiments were executed in [100/250] mL stoppered conical flasks containing [50] mL of nitrate solution, agitated on a temperature-controlled orbital shaker at [x] rpm. Each operational parameter was varied in turn while the others were held constant: solution pH (2-10), adsorbent dosage ([0.1-2.0] g L⁻¹), contact time (0-[x] min, with sampling at predetermined intervals), initial concentration (5-10 mg L⁻¹) and temperature ([288, 298, 308, 318] K). Upon completion, suspensions were separated by centrifugation and/or filtration through a 0.45 µm membrane, and the filtrate was retained for analysis. The operating windows are summarized in Table 2. The removal efficiency and the equilibrium and time-dependent adsorption capacities were computed as:

$$\text{Removal (\%)} = [(C_0 - C_e) / C_0] \times 100 \quad (1)$$

$$q_e = (C_0 - C_e)V / m \quad (2)$$

$$q_t = (C_0 - C_t)V / m \quad (3)$$

where C₀, C_t and C_e (mg L⁻¹) denote the initial, time-t and equilibrium concentrations, V (L) is the solution volume, and m (g) is the adsorbent mass.

2.5 Analytical determination

Residual nitrate was quantified by [ultraviolet spectrophotometry at 220 nm, with correction for dissolved organic matter by absorbance at 275 nm, following APHA Standard Method 4500-NO₃⁻ B / ion chromatography with suppressed conductivity detection]. Calibration was established with at least five standards spanning the working range, with a coefficient of determination (R²) exceeding 0.999. The method

detection and quantification limits were determined from replicate blank measurements, and a mid-range check standard was analysed periodically to verify instrumental stability. Because dissolved organic leachates from biochar may absorb in the ultraviolet region, biochar-only blanks were processed in parallel to correct for any interference.

2.6 Isotherm, kinetic and thermodynamic modelling

Equilibrium data were fitted to the Langmuir, Freundlich and Temkin isotherms:

$$\text{Langmuir: } q_e = q_m K_L C_e / (1 + K_L C_e) \quad (4)$$

$$\text{Freundlich: } q_e = K_F C_e^{1/n} \quad (5)$$

$$\text{Temkin: } q_e = (RT / b_T) \ln(K_T C_e) \quad (6)$$

in which q_m is the monolayer capacity, K_L , K_F and K_T are the respective affinity constants, n is the heterogeneity factor, and b_T is related to the heat of adsorption. The favourability of Langmuir adsorption was judged from the dimensionless separation factor $R_L = 1 / (1 + K_L C_0)$. Kinetic behaviour was interrogated with the pseudo-first-order, pseudo-second-order and intraparticle diffusion models:

$$q_t = q_e [1 - \exp(-k_1 t)] \quad (7)$$

$$t / q_t = 1 / (k_2 q_e^2) + t / q_e \quad (8)$$

$$q_t = k_{id} t^{1/2} + C \quad (9)$$

For the temperature series, the thermodynamic parameters were evaluated from:

$$K_d = q_e / C_e; \quad \Delta G^\circ = -RT \ln K_d; \quad \ln K_d = \Delta S^\circ / R - \Delta H^\circ / RT \quad (10)$$

where R is the universal gas constant and T the absolute temperature. Non-linear regression was preferred over linearized transformations to avoid error distortion, and model adequacy was assessed jointly through the coefficient of determination (R^2), the reduced chi-square (χ^2) and the root-mean-square error (RMSE).

2.7 Regeneration and reusability

Spent RDB was recovered after saturation and contacted with [x M NaCl / NaOH / other eluent] for [x] min, rinsed to neutral pH, dried, and redeployed under identical conditions. The adsorption-desorption sequence was repeated for [five] consecutive cycles, and the retention of removal efficiency was taken as the index of reusability. The influence of coexisting anions (Cl^- , SO_4^{2-} , HCO_3^- , PO_4^{3-}) at [x] mg L^{-1} were evaluated using the optimized conditions.

2.8 Quality assurance and statistical treatment

All experiments were performed in triplicate, and the results are presented as mean $\pm$ standard deviation, represented by error bars. Procedural blanks (without adsorbent) and adsorbent controls (without nitrate) were included in every run to account for nitrate loss to the container walls and for leachable interferents. Glassware was acid-washed and rinsed with ultrapure water. Statistical significance among treatments was verified by one-way analysis of variance (ANOVA) at a confidence level of 95% ($p < 0.05$), and model fitting was carried out with [Origin / Python (SciPy)].

III. RESULTS AND DISCUSSION

3.1 Characterization of the biochar

Table 3. Physicochemical properties of rice dust biochar (RDB) (dummy values).

Property	Value
Yield (%)	31.4
Moisture / volatile matter / ash / fixed carbon (%)	4.2 / 18.6 / 36.8 / 40.4
BET surface area ($\text{m}^2 \text{g}^{-1}$)	86.4
Total pore volume ($\text{cm}^3 \text{g}^{-1}$); mean pore diameter (nm)	0.071; 3.3
pH_{pzc}	6.8
Elemental composition by EDS (wt%): C / O / Si / K / other	58.1 / 24.3 / 11.6 / 3.2 / 2.8

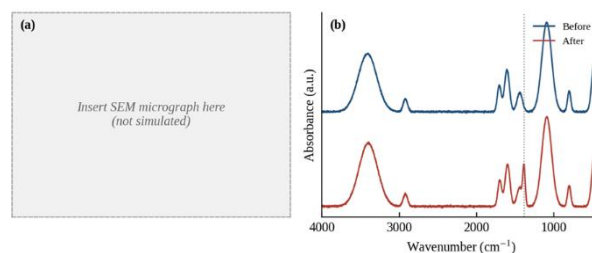


Figure 2. (a) SEM micrograph of RDB (to be inserted); (b) FTIR spectra of RDB before and after nitrate adsorption.

The physicochemical attributes of RDB are collated in Table 3. Scanning electron micrographs (Figure 2a) disclosed a [heterogeneous, irregularly porous] surface texture, consistent with the release of volatiles during carbonization at 500 $^\circ\text{C}$ [describe your own micrographs]. The BET surface area of 86.4 $\text{m}^2 \text{g}^{-1}$ and total pore volume of 0.071 $\text{cm}^3 \text{g}^{-1}$ indicate a predominantly mesoporous framework (mean pore diameter 3.3 nm) capable of accommodating a hydrated anion of the dimensions of nitrate. EDS analysis confirmed that carbon and oxygen predominate, accompanied by silicon (11.6 wt%) and potassium (3.2 wt%), an elemental signature characteristic of rice-derived residues. The high ash content (36.8%) is likewise consistent with the siliceous nature of the feedstock.

The FTIR spectrum (Figure 2b) exhibited bands at approximately 3410 cm^{-1} (O-H stretching), 1705 cm^{-1} (C=O), 1605 cm^{-1} (aromatic C=C) and 1090 cm^{-1} (Si-O-Si/C-O), attesting to the persistence of oxygenated and siliceous functionalities that may serve as sites for protonation and anion interaction. The pH_{pzc} of 6.8 implies that the surface bears a net positive charge at pH values below this threshold, thereby favouring electrostatic attraction of NO_3^- under acidic to near-neutral conditions.

3.2 Effect of solution pH

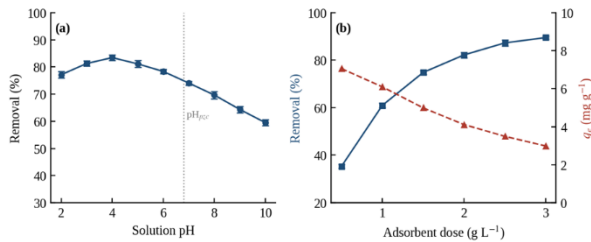


Figure 3. Effect of (a) solution pH and (b) adsorbent dose on nitrate removal by RDB ($C_0 = 10 \text{ mg L}^{-1}$, 298 K, 120 min; mean $\pm$ SD, $n = 3$).

Solution pH exerted a pronounced influence on nitrate uptake (Figure 3a). Removal efficiency rose from 77.1% at pH 2 to a maximum of 83.4% at pH 4, and subsequently declined to 59.5% at pH 10. Under acidic conditions, protonation of surface functional groups generates positively charged sites that attract the anionic adsorbate, whereas at alkaline pH the deprotonated surface repels NO_3^- and hydroxyl ions compete for the remaining sites. The attenuation at pH 2 may be ascribed to competition from Cl^- introduced during acidification with HCl. The optimum pH of 4 was adopted for all subsequent experiments.

3.3 Effect of adsorbent dose

As shown in Figure 3b, increasing the dose from 0.5 to 3.0 g L^{-1} raised the removal efficiency from 35.3% to 89.5%, reflecting the greater availability of surface area and binding sites. Conversely, the equilibrium capacity q_e diminished from 7.06 to 2.98 mg g^{-1} , a trend attributable to the incomplete saturation of sites at higher dosages and to possible particle aggregation that curtails the effective surface. Beyond 2.0 g L^{-1} the gain in removal was marginal (82.2% versus 87.3% at 2.5 g L^{-1}), and a dose of 2.0 g L^{-1} therefore represented the most judicious compromise between removal and capacity.

3.4 Effect of contact time and adsorption kinetics

Table 4. Kinetic parameters for nitrate adsorption on RDB at 10 mg L^{-1} (dummy values).

Model	Parameters	R^2	χ^2 / RMSE
Pseudo-first-order	$q_e = 3.93 \text{ mg g}^{-1}$; $k_1 = 0.118 \text{ min}^{-1}$	0.983	0.101 / 0.151
Pseudo-second-order	$q_e = 4.23 \text{ mg g}^{-1}$; $k_2 = 0.044 \text{ g mg}^{-1} \text{ min}^{-1}$	1.000	0.002 / 0.021
Intraparticle diffusion	$k_{id,1} = 0.598$, $C_1 = 0.77$; $k_{id,2} = 0.059$, $C_2 = 3.38$	0.983 / 0.863	-

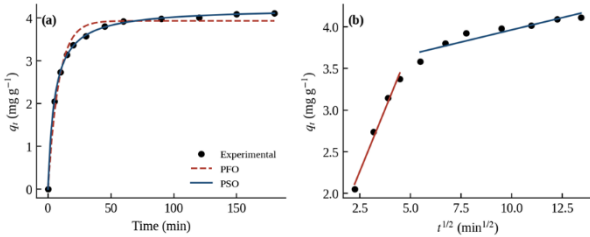


Figure 4. (a) Kinetic profiles with non-linear pseudo-first-order (PFO) and pseudo-second-order (PSO) fits; (b) intraparticle diffusion plot ($C_0 = 10 \text{ mg L}^{-1}$, pH 4, 2 g L^{-1} , 298 K).

Uptake proceeded in two discernible stages (Figure 4a): a rapid initial phase, during which approximately 83% of the equilibrium capacity was attained within 20 min, followed by a gradual approach to equilibrium at about 90 min. The initial rapidity reflects the abundance of vacant, readily accessible sites, while the subsequent deceleration signals progressive site occupancy and increasing diffusional resistance.

Comparison of the model fits (Table 4) revealed that the pseudo-second-order model afforded the superior description of the data, with the highest R^2 (1.000), the lowest error functions, and a calculated q_e (4.23 mg g^{-1}) within 4% of the experimental value (4.07 mg g^{-1}). This outcome is commonly interpreted as indicative of a rate-limiting step involving surface interaction, although agreement with this model alone does not constitute proof of chemisorption. The intraparticle diffusion plot (Figure 4b) was bilinear, and neither segment passed through the origin ($C_1 = 0.77$, $C_2 = 3.38$), implying that pore diffusion contributes to, but is not the sole determinant of, the overall rate.

3.5 Effect of initial concentration and adsorption isotherms

Table 5. Isotherm parameters for nitrate adsorption on RDB (298 K, pH 4, 2 g L^{-1}) (dummy values).

Isotherm	Parameters	R^2	χ^2 / RMSE
Langmuir	$q_m = 9.30 \text{ mg g}^{-1}$; $K_L = 0.457 \text{ L mg}^{-1}$; $R_L = 0.18$ -0.30	0.997	0.002 / 0.034
Freundlich	$K_F = 2.89$; $1/n = 0.66$	0.999	0.001 / 0.018
Temkin	$K_T = 4.36 \text{ L mg}^{-1}$; $b_T = 1233 \text{ J mol}^{-1}$	0.992	0.007 / 0.060

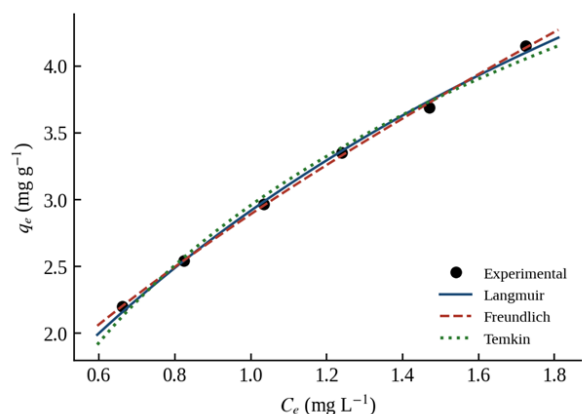


Figure 5. Equilibrium data for nitrate adsorption on RDB with non-linear isotherm fits (pH 4, 2 g L⁻¹, 298 K).

Across the examined range of 5–10 mg L⁻¹, the equilibrium capacity increased from 2.20 to 4.15 mg g⁻¹, whereas the percentage removal decreased modestly from 86.8% to 82.8%, a pattern expected when a fixed number of sites is exposed to a progressively greater solute load. The isotherm parameters are summarized in Table 5 and the fits are displayed in Figure 5. The Freundlich model correlated best with the data ($R^2 = 0.999$), suggesting heterogeneous binding on a surface of non-uniform energy. The separation factor R_L of 0.18–0.30 lies between 0 and 1, and $1/n$ of 0.66 is below unity, both denoting favourable adsorption.

It must be emphasised that the concentration window is deliberately narrow; model discrimination within such a range is inherently limited, as the R^2 values of the Langmuir and Freundlich fits differ only marginally, and the q_m derived from the Langmuir fit should be treated as an empirical descriptor rather than a true saturation capacity.

3.6 Thermodynamic analysis

Table 6. Thermodynamic parameters for nitrate adsorption on RDB (dummy values).

T (K)	ln K_d	ΔG° (kJ mol ⁻¹)	ΔH° (kJ mol ⁻¹)	ΔS° (J mol ⁻¹ K ⁻¹)
288	0.76	-1.81	9.9	40.5
298	0.87	-2.15		
308	1.02	-2.61		
318	1.14	-3.01		

The thermodynamic parameters derived from the van't Hoff relation are presented in Table 6, with K_d taken as q_e/C_e in L g⁻¹. The negative values of ΔG° (-1.81 to -3.01 kJ mol⁻¹) denote a spontaneous process, and the increasing magnitude with temperature indicates that adsorption is more favourable at elevated temperature. The positive ΔH° of 9.9 kJ mol⁻¹ signifies an endothermic process, and its modest magnitude lies below the range

generally associated with strong chemical bonding, pointing towards weak interactions such as electrostatic attraction and ion exchange. The positive ΔS° of 40.5 J mol⁻¹ K⁻¹ reflects increased randomness at the solid-solution interface, plausibly owing to the displacement of hydration water and previously bound ions.

3.7 Adsorption mechanism

The collective evidence points to a multi-faceted mechanism. First, the strong dependence on pH and the pH_{pzc} of 6.8 implicate electrostatic attraction between protonated surface sites and NO₃⁻. Second, FTIR spectra recorded after adsorption (Figure 2b) show a new band near 1384 cm⁻¹, typical of nitrate, and small shifts of the C=O (1705 to 1698 cm⁻¹) and aromatic C=C (1605 to 1598 cm⁻¹) bands, suggesting involvement of surface groups. Third, the low magnitude of ΔH° and the mesoporous texture are compatible with contributions from anion exchange with Cl⁻/OH⁻ and from pore filling. The relative weight of each pathway cannot be apportioned from batch data alone, and post-adsorption EDS or XPS would furnish more decisive confirmation.

3.8 Regeneration and reusability

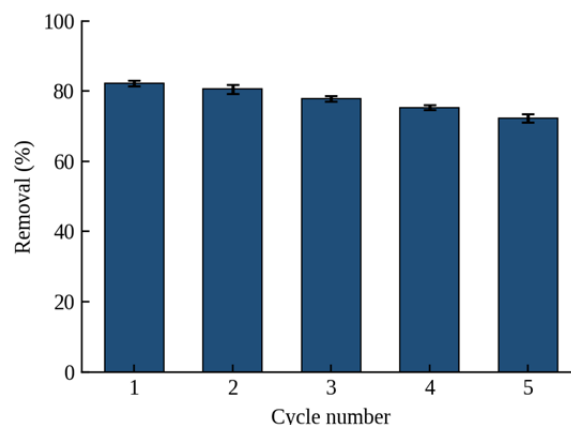


Figure 6. Removal efficiency of RDB over five successive adsorption-desorption cycles using 0.1 M NaCl as eluent (mean $\pm$ SD, $n = 3$).

RDB retained 88% of its initial removal efficiency after five adsorption-desorption cycles (Figure 6), the progressive decline from 82.3% in cycle 1 to 72.3% in cycle 5 being attributable to incomplete desorption, loss of mass during handling and partial site blockage. Such performance supports the prospect of repeated deployment, although the benefit of regeneration must be weighed against the volume of eluent consumed and the nitrate-laden regenerant that results.

3.9 Influence of coexisting ions and real water testing

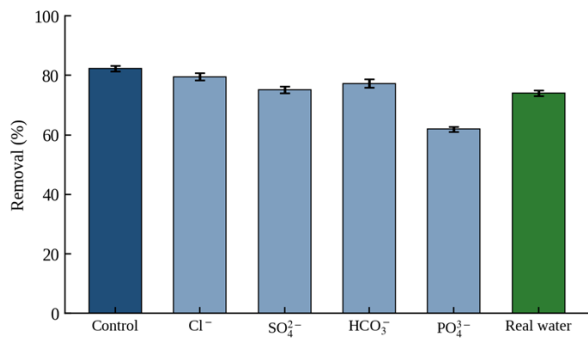


Figure 7. Effect of coexisting anions (50 mg L⁻¹ each) and of a real water matrix on nitrate removal by RDB (mean ± SD, n = 3).

In the presence of 50 mg L⁻¹ of Cl⁻, SO₄²⁻, HCO₃⁻ and PO₄³⁻, nitrate removal fell from 82.3% to 79.6%, 75.1%, 77.3% and 61.9%, respectively (Figure 7). Phosphate exerted the most deleterious effect, consistent with its higher charge density and greater affinity for protonated sites. When applied containing 10 mg L⁻¹ nitrate, RDB achieved 74.0% removal, lower than in synthetic solution, a difference ascribed to the complex matrix, including dissolved organic matter and competing anions.

3.10 Comparison with other adsorbents

Table 7. Comparison of RDB with other carbon-based adsorbents reported for nitrate removal (n/r = not reported in the abstract consulted).

Adsorbent	C ₀ (mg L ⁻¹)	pH	q _m or removal	Ref.
RDB (this study, dummy)	5-10	4	82.8-86.8% removal; q _m 9.3 mg g ⁻¹	This work
Rice husk biochar (OM5451)	50	4	12.84 mg g ⁻¹	Hue Univ. J. Sci., 2021
Mg-impregnated rice husk biochar (fixed bed)	20-100	n/r	9.4 mg g ⁻¹	Biomass Conv. Bioref., 2026
Granular activated carbon	50	6	81.07 mg g ⁻¹	Aman et al., 2023
Chemically modified coconut husk GAC	n/r	7.6	6.0 ± 1.3 mg g ⁻¹	See DOI 10.1007/s43393-022-00108-5
Orange peel activated carbon / Fe-impregnated	n/r	n/r	16.23 / 41.32 mg g ⁻¹	Mohammadiyan Fard et al., 2017

Sources (values taken from abstracts; verify against the full texts before citing): Adsorption of nitrate by biochar prepared from rice husks (*O. sativa* L., OM5451), Hue Univ. J. Sci. Nat. Sci. 130(1A), 31-39, 2021. Mg-impregnated rice husk biochar in fixed-bed columns, Biomass Convers. Biorefin., DOI 10.1007/s13399-026-07093-y. Aman N. et al., Facile fabrication of nano zerovalent iron and granular activated carbon for enhanced nitrate removal from water, Geol. Ecol. Landscapes, 2023, DOI 10.1080/24749508.2023.2167626. Nitrate removal from groundwater using chemically modified coconut husk based granular activated carbon, DOI 10.1007/s43393-022-00108-5. Mohammadiyan Fard Z. et al., Fe/activated carbon from orange peel for nitrate removal, Applied Chemistry Today 12(45), 41-50, 2017, DOI 10.22075/chem.2017.2618.

Table 7 situates RDB among other nitrate adsorbents. Direct comparison is confounded by differences in initial concentration, pH, dose and the manner in which capacity is reported: the literature values were mostly obtained at around 50 mg L⁻¹ or higher, where q_m is naturally larger, so they are not like-for-like

with data collected at 5-10 mg L⁻¹. Nevertheless, RDB attains 82.8-86.8% removal in the trace-level regime while deriving from an abundant, negligible-cost residue. These attributes position it as a credible candidate for trace-level polishing rather than bulk nitrate removal.

IV. PRACTICAL IMPLICATIONS AND LIMITATIONS

4.1 Practical implications

The performance of RDB in the trace-concentration regime carries several implications for water treatment. First, rice milling dust is generated continuously and in considerable volume wherever paddy is processed, so the feedstock is geographically proximate to many of the rural and peri-urban communities that depend on nitrate-affected groundwater. Valorizing this residue offsets disposal burdens while furnishing an adsorbent whose raw material cost is negligible. Second, because RDB was effective at 5-10 mg L⁻¹, its most realistic role is as a polishing stage downstream of, or in tandem with, a primary process, or as a point-of-use

medium where source water sits close to the permissible limit, rather than as a substitute for ion exchange or membranes in heavily contaminated supplies.

Regarding scalability, translating batch behaviour into a continuous process will require fixed-bed column trials, in which empty-bed contact time, bed depth and flow rate govern breakthrough and must be optimised. The modest regeneration performance observed here (Section 3.8) indicates that reuse is feasible, yet the regenerant becomes a nitrate-enriched stream whose handling must be planned. A comprehensive techno-economic appraisal, encompassing pyrolysis energy, labour, transport and eluent consumption, is needed before cost advantages can be asserted quantitatively.

The disposal of spent biochar also merits deliberate attention. Nitrate-laden biochar may find a secondary use as a soil amendment or slow-release nutrient carrier, an option that has been explored for related biochars; however, this presupposes that the material is free of leachable contaminants, that its high ash content does not adversely alter soil chemistry, and that local regulations permit such reuse. Where those conditions are not met, controlled landfilling or co-processing should be considered.

4.2 Limitations

Several limitations circumscribe the present findings. (i) The experiments were conducted in batch mode at laboratory scale; dynamic column behaviour, mass-transfer zones and long-term stability were not examined. (ii) The initial concentration was confined to 5–10 mg L⁻¹, which limits discrimination among isotherm models and precludes reliable extrapolation of the fitted capacities to higher loadings. (iii) Most experiments employed synthetic KNO₃ solutions; only a single real water sample was tested, and its composition may not represent the variability of natural sources. (iv) Competing anions, particularly phosphate, suppressed uptake appreciably, signalling reduced suitability for waters rich in such species. (v) The mechanistic interpretation rests on indirect evidence (pH dependence, p*H*_{pzc}, FTIR and thermodynamics); direct confirmation by XPS or post-adsorption elemental mapping was not undertaken. (vi) Possible leaching of ash-derived constituents (for example silicon and potassium) and of dissolved organic matter into treated water was not quantified, although it bears directly on drinking-water suitability. (vii) Concentrations were expressed as [NO₃⁻ / NO₃⁻-N], and comparisons with guideline limits must respect that basis.

V. CONCLUSIONS

The present study evaluated the adsorption performance of rice dust biochar (RDB) for nitrate removal from aqueous solutions at low initial concentrations of 5–10 mg L⁻¹. The findings demonstrate that RDB possesses physicochemical characteristics suitable for nitrate adsorption, including a mesoporous

structure, a specific surface area of 86.4 m² g⁻¹, and a point of zero charge (p*H*_{pzc}) of 6.8. The presence of oxygen-containing functional groups and siliceous surface constituents further indicates the potential involvement of surface interactions in nitrate uptake. The utilization of rice dust as a biochar precursor also offers an opportunity to convert an agricultural processing residue into a value-added material for water treatment.

The adsorption performance of RDB was strongly influenced by solution pH, adsorbent dosage, and contact time. Maximum nitrate removal of 83.4% was obtained at pH 4, indicating that acidic conditions favoured interactions between nitrate ions and the biochar surface. An adsorbent dosage of 2.0 g L⁻¹ was identified as a practical operating condition, providing a balance between removal efficiency and adsorbent utilization. The adsorption process approached equilibrium within approximately 90 min, reflecting rapid initial uptake followed by a gradual reduction in the adsorption rate as available binding sites became occupied. These findings establish the importance of optimizing operating conditions when applying RDB to low-concentration nitrate treatment.

The pseudo-second-order kinetic model provided the best fit to the experimental data, with a coefficient of determination of $(R^2 = 1.000)$. Intraparticle diffusion contributed to the overall adsorption process but did not independently control the adsorption rate. Among the evaluated equilibrium models, the Freundlich isotherm exhibited the highest goodness of fit $(R^2 = 0.999)$, suggesting adsorption across a heterogeneous distribution of surface sites. However, because the initial nitrate concentration range was limited to 5–10 mg L⁻¹, the fitted Langmuir maximum adsorption capacity of 9.3 mg g⁻¹ should be interpreted as an empirical parameter rather than a definitive saturation capacity. Thermodynamic analysis indicated spontaneous and endothermic adsorption, with standard Gibbs free-energy changes ranging from -1.81 to -3.01 kJ mol⁻¹ and an enthalpy change of 9.9 kJ mol⁻¹. Collectively, the results support the probable contribution of electrostatic attraction, anion exchange, and pore filling, although further surface-specific investigations are required to establish the relative importance of these mechanisms.

The regeneration experiments demonstrated that RDB retained 88% of its initial nitrate-removal efficiency after five adsorption-desorption cycles, indicating potential for repeated use. Nevertheless, the decline in performance over successive cycles highlights the need to improve regeneration efficiency and assess the long-term stability of the adsorbent. The presence of competing anions adversely affected nitrate uptake, with phosphate producing the strongest inhibitory effect and reducing removal efficiency to 61.9%. Furthermore, nitrate removal in a real water sample reached 74.0%, which was lower than the performance observed in synthetic solutions. This difference emphasizes the influence of

competing ions and other water-matrix constituents on adsorption efficiency. Therefore, the applicability of RDB will depend partly on the chemical composition of the target water and the selectivity of the adsorption process under practical operating conditions.

The results identify rice dust biochar as a promising, potentially low-cost adsorbent for trace-level nitrate polishing rather than a proven replacement for established treatment technologies used for heavily contaminated water. Its practical advantages include the utilization of an agricultural residue, relatively effective nitrate removal at low initial concentrations, and the possibility of regeneration. However, the present findings are limited by the batch-scale experimental design, the narrow concentration range, the restricted assessment of real water matrices, and the indirect nature of the proposed adsorption mechanism. Further research should investigate continuous-flow fixed-bed performance, breakthrough behaviour, and mass-transfer characteristics under different hydraulic conditions. Surface modification using suitable metal-based or amine-containing functionalities could also be explored to improve nitrate affinity and selectivity in the presence of competing anions. In addition, systematic evaluation of constituent leaching, dissolved organic matter release, spent-adsorbent management, and potential toxicity is necessary before drinking-water applications can be considered. Finally, a comprehensive techno-economic and life-cycle assessment should be conducted to determine the environmental and economic feasibility of producing, regenerating, and deploying RDB at larger scales.

In conclusion, rice dust biochar demonstrated encouraging performance for nitrate removal within the investigated concentration range of 5–10 mg L⁻¹, achieving removal efficiencies of 82.8–86.8% under the reported experimental conditions. Its adsorption behaviour, favourable regeneration performance, and agricultural-residue origin support further investigation as a material for low-concentration water treatment. Nevertheless, the effects of competing anions, the reduction in efficiency observed in real water, and the absence of continuous-flow and leaching assessments indicate that additional validation is essential. Accordingly, RDB should be regarded as a promising candidate for nitrate-polishing applications whose suitability for practical deployment remains contingent on performance optimization, environmental safety assessment, and full-scale process evaluation.

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