




Adsorption Behaviour of Selected Acid Herbicides on Activated Carbon: Equilibrium, Kinetic and Laboratory–Field Assessment

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ABSTRACT: The present study evaluates the adsorption behaviour of selected acid herbicides (MCPA, Mecoprop-P, 2,4-D, and Triclopyr) on activated carbon under controlled laboratory conditions and assesses the relevance of this behaviour to aquatic environmental protection. Batch adsorption experiments were conducted to investigate the influence of contact time, adsorbent dosage and initial herbicide concentration. Adsorption equilibrium data were analysed using Langmuir and the Freundlich isotherm models, while adsorption kinetics were evaluated using pseudo-first-order and pseudo-second-order models. Freundlich modelling showed better agreement with the experimental data, suggesting heterogeneous surface interactions during adsorption. Langmuir modelling demonstrated high intrinsic adsorption capacities, reaching 116.82 mg g⁻¹ for MCPA. Kinetic analysis revealed that the pseudo-second-order model provided the best fit (R^2 up to 0.996), suggesting that it adequately describes the adsorption kinetics. Regression analysis indicated a statistically significant preliminary relationship ($R^2 = 0.933$, $p \leq 0.05$) between intrinsic adsorption capacity and field removal efficiency. The findings highlight the practical relevance of laboratory-derived adsorption parameters for preliminary assessment of the performance of activated carbon in agricultural water treatment systems and contribute to ecological protection by supporting improved management of herbicide contamination in water resources.

Keywords: Activated carbon, Acid herbicides, Adsorption isotherms, Kinetic modeling, Agricultural runoff.

1. INTRODUCTION

Acid herbicides are widely used in agricultural systems for effective weed control and improvement of crop productivity. However, their persistence and mobility in the environment increase the risk of contamination of surface and groundwater resources. Monitoring studies have reported the presence of herbicide residues in rivers, reservoirs and drinking water sources, raising ecological concerns due to their potential toxicity and long-term environmental impact (de Souza et al., 2020; Silva et al., 2019). Continuous exposure of aquatic ecosystems to pesticide residues may affect non-target organisms and

disturb the ecological balance. Several studies have highlighted the ecological implications of pesticide contamination in aquatic ecosystems and emphasised the need of develop effective treatment strategies to protect water resources (Herrero-Hernández et al., 2020; Silva et al., 2019).

Among various treatment technologies, adsorption using activated carbon has been widely used of remove organic micropollutants from water. Activated carbon possesses a highly developed porous structure, a large surface area, and diverse surface functional groups that facilitate interactions with organic contaminants such as phenoxy acid herbicides (Bansal & Goyal, 2005; Snyder et al., 2007). Several studies have demonstrated the effectiveness of activated carbon in

removing pesticides and other emerging contaminants from water treatment systems (Mojiri et al., 2020; Ighalo et al., 2021).

The adsorption behaviour of organic contaminants is influenced by several physicochemical parameters, including contact time, adsorbent dosage, initial concentration and surface characteristics of the adsorbent. Equilibrium isotherm models, such as the Langmuir and Freundlich models, are widely used to understand adsorption mechanisms and surface interaction behaviour, while kinetic models provide insight into the rate-controlling steps governing the adsorption process (Foo & Hameed, 2010; Ho & McKay, 1999).

Recent studies have reported significant advances in herbicide adsorption using activated carbon and related materials, highlighting improved removal efficiency and enhanced understanding of adsorption mechanisms under varying environmental conditions (McGinley et al., 2022; Taylor et al., 2022; Astuti et al., 2022; Butkovskiy et al., 2021). Therefore, integrating adsorption modelling with environmentally relevant remediation performance remains an important research gap.

Recent investigations have further demonstrated the growing importance of advanced adsorption materials and environmentally relevant remediation strategies for herbicide and pesticide removal from contaminated water systems. These studies have highlighted improved adsorption efficiency, enhanced surface functionality and the role of sustainable adsorbent materials under variable environmental conditions, supporting the continued development of adsorption-based treatment technologies for agricultural water remediation.

Unlike conventional adsorption investigations, the present study integrates laboratory adsorption modelling with field-scale remediation observations to improve understanding of the environmental relevance and practical applicability of activated carbon-based treatment systems for agricultural water remediation.

Despite extensive research on adsorption processes, the relationship between intrinsic adsorption capacity obtained from laboratory experiments and removal efficiency observed under field conditions has not been adequately explored. Establishing such relationships is important for improving the understanding and practical applicability of adsorption-based water treatment technologies in agricultural catchments.

However, most existing studies on phenoxy acid herbicide adsorption using activated carbon are limited to

controlled laboratory conditions, focusing primarily on equilibrium and kinetic modelling. These studies provide valuable mechanistic insights but often fail to demonstrate how laboratory-derived adsorption parameters translate to real-world environmental systems. In particular, there is a lack of studies that integrate laboratory adsorption performance with field-scale removal efficiency under variable environmental conditions.

To address this gap, the present study combines laboratory-based adsorption modelling with field-scale performance data obtained from agricultural water systems. This laboratory–field integration enables evaluation of the practical relevance of intrinsic adsorption parameters (e.g., Q_{max}) for real-world herbicide removal. By establishing a statistical relationship between laboratory adsorption capacity and field removal efficiency, this study provides a more applied and environmentally relevant framework for assessing the effectiveness of activated carbon in agricultural water treatment systems.

Therefore, the present study aims to evaluate the adsorption behaviour of selected acid herbicides on activated carbon using equilibrium and kinetic modelling under controlled laboratory conditions. Furthermore, laboratory-derived adsorption parameters were statistically integrated with field-scale removal performance to provide mechanistic insight into adsorption efficiency and its ecological relevance for protecting agricultural water systems from herbicide contamination.

2. MATERIALS AND METHODS

2.1. Chemicals and Adsorbents

Analytical-grade standards of acid herbicides including MCPA, Mecoprop-P, 2,4-D and Triclopyr were procured and used without further purification. Stock solutions were prepared using deionized water and subsequently diluted to obtain the desired working concentrations for experimental analysis.

Two types of activated carbon were used as adsorbents: granular activated carbon (GAC) and coconut-based activated carbon (CAC). The adsorbent materials were sieved to obtain a uniform particle size fraction of 0.5–1.0 mm. Prior to experimentation, the adsorbents were washed thoroughly with deionized water to remove surface impurities and dried at 105°C for 24 hours.

2.2. Batch Adsorption Experiments

Batch adsorption experiments were conducted at a controlled temperature of $25 \pm 1^\circ\text{C}$ using 250 mL

Erlenmeyer flasks containing 100 mL of herbicide solution. An adsorbent dosage of 0.5 g L⁻¹ was used for all experiments. Initial herbicide concentrations ranged between 10 and 200 mg L⁻¹, and the solution pH was maintained at 6.5 ± 0.2 during the experimental period to simulate environmentally relevant conditions typically observed in agricultural surface water systems.

The experimental pH was selected to represent environmentally relevant agricultural water conditions commonly observed in irrigation runoff and surface water systems. Near-neutral pH conditions were considered environmentally relevant for evaluating adsorption performance of phenoxy acid herbicides under realistic environmental scenarios, as these compounds exhibit pH-dependent ionisation behaviour. Adsorbent dosage, contact time, and concentration ranges were selected based on preliminary optimisation trials, adsorption equilibrium requirements, and previously reported activated carbon adsorption studies involving herbicide contaminants.

Acid herbicides exhibit pH-dependent ionisation behaviour, which significantly influences adsorption behaviour. At near-neutral pH, these compounds predominantly exist in partially dissociated form, allowing effective interaction with activated carbon surfaces.

Although pH variation can influence adsorption performance, the present study focused on evaluating adsorption behaviour under representative environmental conditions to enable meaningful comparison with field-scale observations. The selected pH, therefore, provides a practical basis for assessing adsorption efficiency under realistic water quality conditions.

The flasks were agitated at a constant speed using a mechanical shaker. Samples were collected at predetermined time intervals ranging from 0 to 240 minutes. The collected samples were filtered through 0.45 µm membrane filters prior to analysis. Equilibrium was assumed when the variation in concentration between successive measurements was less than 2%. All adsorption experiments were conducted in triplicate, and the reported values represent mean ± standard deviation (n = 3). Standard deviation-based error bars have been incorporated into Figures 1 and 2 to illustrate the variability among replicate observations. The mean values were used for subsequent adsorption modelling and statistical analyses.

The adsorption capacity at time t (q_t) and at equilibrium (q_e) was calculated using Equation (1) and Equation (2),

respectively:

$$q_t = \frac{(C_o - C_t)V}{m} \dots\dots\dots(1)$$

$$q_e = \frac{(C_o - C_e)V}{m} \dots\dots\dots(2)$$

where C_o , C_t and C_e (mg L⁻¹) represent the initial, time-dependent and equilibrium concentrations, respectively, V (L) represents the volume of solution and m (g) denotes the mass of adsorbent used in the experiment.

2.3. Adsorption Isotherm and Kinetic Modelling

The adsorption equilibrium behaviour was evaluated using the Langmuir and the Freundlich isotherm models. Nonlinear regression fitting was applied for estimation of isotherm model parameters. The Langmuir model assumes monolayer adsorption on a homogeneous surface, whereas the Freundlich model describes multilayer adsorption on heterogeneous surfaces.

Adsorption kinetics were analysed using pseudo-first-order and pseudo-second-order kinetic models in order to determine the rate controlling mechanisms involved in the adsorption process.

The model performance was evaluated using statistical indicators including the coefficient of determination (R^2), chi-square (χ^2) test and the standard error of estimate (SEE). The most suitable model was identified based on higher R^2 values and lower χ^2 and SEE values.

2.4. Surface Characterization

The surface morphology of the activated carbon samples was examined using scanning electron microscopy (SEM), which revealed a well-developed porous structure with irregular cavities and surface heterogeneity favourable for adsorption. Energy-dispersive X-ray spectroscopy (EDX) analysis confirmed the presence of major elements such as carbon and oxygen, indicating the availability of functional groups that can facilitate adsorption interactions.

Although advanced characterization techniques such as Brunauer–Emmett–Teller (BET) surface area analysis, pore size distribution and Fourier transform infrared spectroscopy (FTIR) provide additional quantitative insight into adsorbent properties, the adsorption performance of activated carbon is widely governed by its porous structure and surface functionality, as supported by existing literature.

In the present study, the adsorption performance was primarily evaluated through equilibrium and kinetic modelling. The high adsorption capacity (Q_{max}) and

favourable Freundlich behaviour observed in this study indirectly suggest the presence of heterogeneous surface sites and well-developed porosity, which are consistent with characteristics reported for activated carbon materials.

Although detailed physicochemical characterization such as BET surface area and FTIR analysis would provide additional insights, the results obtained in this study are consistent with previously reported properties of activated carbon materials in similar applications.

Therefore, the combined interpretation of SEM–EDX analysis and adsorption modelling provides a reasonable basis for understanding adsorption behaviour, even in the absence of detailed physicochemical characterization.

2.5. Field Data Description

Field-scale data used in this study were obtained from controlled monitoring investigations conducted in agricultural runoff environments as part of earlier experimental work. These investigations were designed to evaluate the performance of activated carbon-based systems under practical environmental conditions.

The field studies involved the installation of passive treatment units containing activated carbon media within drainage pathways influenced by agricultural activities. Monitoring of herbicide concentrations was conducted at defined sampling points before and after the implementation of these treatment systems to assess removal performance.

Sampling was carried out over multiple time intervals to capture variability in environmental conditions and pesticide transport dynamics. The monitored compounds included commonly used phenoxy acid herbicides such as MCPA, Mecoprop-P, 2,4-D, Triclopyr and Fluroxypyr.

The field observations demonstrated measurable reductions in herbicide concentrations following treatment, confirming the effectiveness of activated carbon under real environmental conditions. These findings are consistent with recent field-scale investigations, which demonstrate the effectiveness of activated carbon-based systems for pesticide removal under real environmental conditions, highlighting the importance of system design and operational optimisation. These field-derived removal efficiencies were subsequently utilised to establish a statistical relationship with laboratory-derived adsorption parameters in the present study.

The field dataset utilised in this study comprised monitoring observations collected under varying environmental conditions, representing a range of flow regimes and contaminant loading scenarios. The dataset was

derived from controlled monitoring investigations conducted as part of the author's doctoral research, ensuring consistency in experimental design and data reliability. While the dataset provides a practical basis for evaluating laboratory–field relationships, variations in field conditions, such as flow dynamics, organic matter content, and competing solutes, may influence adsorption performance.

2.6. Laboratory–Field Statistical Integration

To evaluate the practical significance of laboratory-derived adsorption parameters, previously reported field intervention datasets were analysed to determine the relationship between intrinsic adsorption capacity (Q_{max}) and field removal efficiency.

Linear regression analysis was performed to examine the relationship between laboratory adsorption capacity and field-scale removal performance. Statistical significance was evaluated at $p < 0.05$, and 95% confidence intervals were calculated for the regression parameters.

The laboratory–field statistical comparison performed in the present study was intended as a preliminary exploratory assessment to evaluate the environmental relevance of adsorption behaviour observed under controlled laboratory conditions. The field-scale observations used for comparative interpretation were derived from previously documented remediation interventions conducted under environmentally relevant agricultural water conditions. However, the available field observations were limited in number and may involve variability in water quality characteristics, operational conditions, environmental factors, and remediation practices across different field settings. Therefore, the observed statistical relationship should be interpreted with caution as an exploratory comparative association rather than as definitive mechanistic validation or predictive ecological modelling. Additional large-scale field investigations under diverse environmental and operational conditions are necessary to establish robust predictive relationships and improve understanding of field-scale adsorption performance. Because the adsorption experiments were conducted under controlled batch conditions, the observed relationships may not fully represent adsorption behaviour under dynamic continuous-flow environmental treatment systems.

3. RESULTS AND DISCUSSION

3.1. Adsorption Equilibrium Behaviour

Adsorption equilibrium data obtained from batch experiments were analysed using the Langmuir and the

Freundlich isotherm models to evaluate the adsorption of acid herbicides on granular activated carbon. The Freundlich model exhibited superior fit to the experimental data, with coefficients of determination (R^2) values ranging from 0.995 to 0.999. This suggests that the adsorption process occurs on heterogeneous surfaces with multilayer adsorption characteristics. Figure 1 shows that the Freundlich model exhibited better agreement with the experimental adsorption data than the Langmuir model for the investigated herbicides.

The Freundlich exponent ($n > 1$) further confirmed favourable adsorption conditions for all investigated herbicides. Although the Langmuir model also provided statistically acceptable fits ($R^2 \geq 0.978$), the corresponding χ^2

values were comparatively higher than those obtained for the Freundlich model, suggesting that adsorption occurred on energetically heterogeneous surfaces rather than forming a strictly monolayer coverage.

The maximum monolayer adsorption capacity (Q_{max}) predicted by the Langmuir model reached 116.82 $mg\ g^{-1}$ for MCPA and 116.76 $mg\ g^{-1}$ for Triclopyr, while 2,4-D exhibited a slightly lower adsorption capacity (112.47 $mg\ g^{-1}$). These findings are consistent with previously reported adsorption behaviour of phenoxy acid herbicides on activated carbon materials, indicating strong adsorption affinity associated with heterogeneous porous surfaces.

The suitability of the isotherm models was evaluated using statistical indicators including the coefficient of

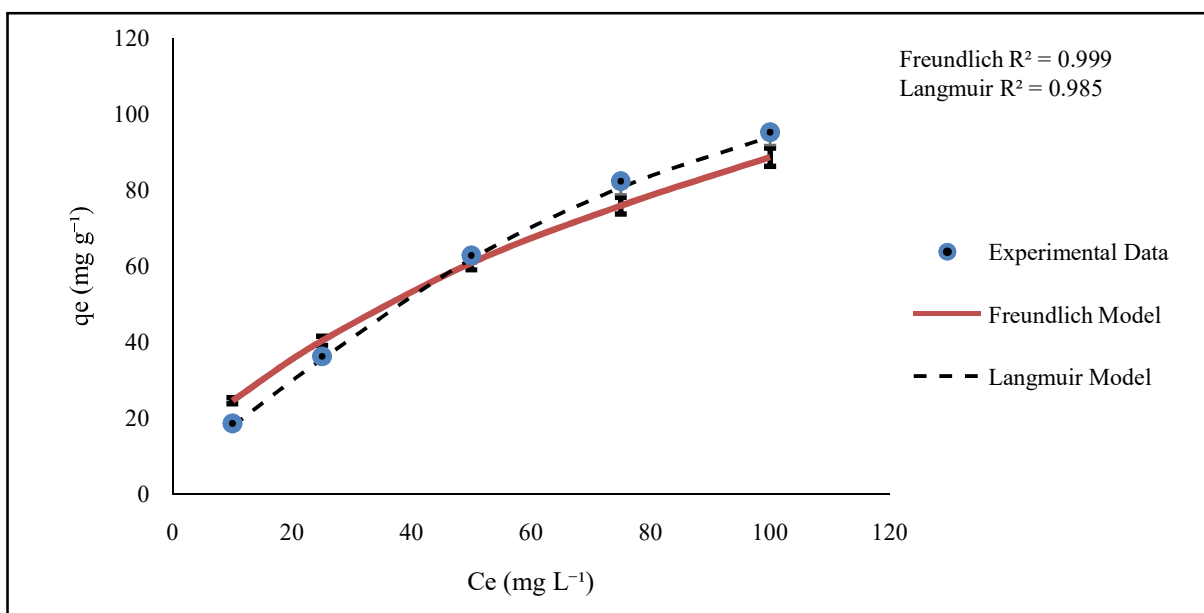


Figure 1. Adsorption isotherms of acid herbicides on granular activated carbon. Data points represent mean \pm standard deviation ($n = 3$) obtained from triplicate experiments. Experimental data (\bullet) along with Freundlich (—) and Langmuir (---) model fits are presented. The figure illustrates equilibrium adsorption behaviour and the comparative performance of the isotherm models

Table 1. Langmuir and the Freundlich isotherm fitting curves for the adsorption of MCPA on granular activated carbon, showing experimental adsorption equilibrium behaviour

Herbicide	Model	Q_{max} ($mg\ g^{-1}$)	KL ($L\ mg^{-1}$)	KF ($(mg\ g^{-1})(L\ mg^{-1})^{1/n}$)	n	R^2	χ^2
MCPA	Langmuir	116.820	0.084	-	-	0.985	0.214
MCPA	Freundlich	-	-	38.742	2.611	0.999	0.041
Triclopyr	Langmuir	116.760	0.079	-	-	0.982	0.268
Triclopyr	Freundlich	-	-	36.115	2.534	0.998	0.053
2,4-D	Langmuir	112.470	0.071	-	-	0.978	0.314
2,4-D	Freundlich	-	-	34.280	2.417	0.995	0.067

determination (R^2), chi-square (χ^2) and the standard error of estimate (SEE). The lower χ^2 values obtained for the Freundlich model indicate better agreement between experimental and predicted values, confirming its superior applicability. The SEE values also supported this observation, although the differences were less pronounced compared to χ^2 .

The observed adsorption trend suggests heterogeneous surface interaction behaviour consistent with previously reported activated carbon systems investigated for phenoxy herbicide remediation under environmentally relevant conditions.

The Freundlich constant (KF) reflects adsorption capacity, while the exponent ($n > 1$) reflects favourable adsorption and surface heterogeneity. This suggests that the adsorption process is governed by multilayer interactions on energetically non-uniform surfaces of activated carbon.

In contrast, the Langmuir model assumes monolayer adsorption on homogeneous surfaces. The relatively higher χ^2 values observed for the Langmuir model suggest deviation from idealised monolayer adsorption behaviour.

Overall, adsorption of acid herbicides on activated carbon is predominantly governed by multiple adsorption-related interactions rather than idealised monolayer adsorption.

3.2. Kinetic Behaviour

The adsorption kinetics of the investigated herbicides were evaluated using pseudo-first-order and pseudo-second-order kinetic models. The pseudo-second-order model showed superior agreement with the experimental data, with R^2 values reaching up to 0.996. The calculated equilibrium adsorption capacities ($q_{e,calc}$) obtained from the pseudo-second-order model closely matched the experimental values, suggesting that the model adequately describes the adsorption kinetics.

Figure 2 illustrates the superior fitting performance of the pseudo-second-order kinetic model compared to the pseudo-first-order model.

The observed kinetic behaviour suggests that adsorption likely involves multiple adsorption interactions and diffusion-related processes rather than a single rate-controlling mechanism.

However, it is important to note that a good fit of the pseudo-second-order model does not necessarily imply chemisorption or specific surface-controlled mechanisms. The kinetic results primarily reflect the overall adsorption rate behaviour and may involve multiple processes,

including surface adsorption and intraparticle diffusion.

In contrast, the pseudo-first-order model produced comparatively lower correlation coefficients ($R^2 = 0.914\text{--}0.921$), demonstrating its limited suitability for describing the adsorption kinetics of the investigated herbicides. Intraparticle diffusion analysis revealed multilinear characteristics, suggesting that pore diffusion contributes to the adsorption process but is not the sole rate-controlling step.

The multilinear behaviour observed in the intraparticle diffusion plots suggests that adsorption proceeded through multiple sequential stages, including external surface adsorption followed by gradual pore diffusion. The deviation of the diffusion plots from the origin further indicates the contribution of additional mass transfer processes during adsorption.

The adsorption performance observed in the present study may be associated with the porous surface morphology and functional surface characteristics of activated carbon materials reported in previous studies. Earlier investigations on granular activated carbon have demonstrated that surface heterogeneity, pore structure, and oxygen-containing functional groups contribute significantly to herbicide adsorption behaviour. FTIR-based interpretations reported in previous studies on activated carbon have suggested the involvement of hydroxyl, carbonyl, and aromatic functional groups in adsorption interactions. At the same time, SEM observations have demonstrated a porous surface morphology favourable for adsorption processes. These physicochemical characteristics likely contributed to the observed Freundlich adsorption behaviour and favourable adsorption kinetics observed in the present investigation. However, detailed surface-specific mechanistic evaluation was beyond the scope of the present study.

The adsorption behaviour observed under near-neutral pH conditions may also be influenced by the ionisation characteristics of phenoxy acid herbicides and the surface charge behaviour of activated carbon materials. Since phenoxy herbicides exist predominantly in dissociated form near neutral pH, electrostatic interactions, surface heterogeneity, and pore diffusion processes may collectively contribute to adsorption performance. However, detailed pH-dependent adsorption investigations were beyond the scope of the present study and should be explored in future research to improve mechanistic understanding under varying environmental conditions.

Similarly, temperature-dependent thermodynamic

investigations involving ΔG° , ΔH° , and ΔS° analysis were not included in the present study and should be explored in future research to provide additional insight into adsorption energetics and spontaneity.

The adsorption capacities observed in the present study are comparable with previously reported activated carbon-based systems for herbicide remediation. McGinley et al. (2022) and Kodali et al. (2021) similarly reported favourable adsorption behaviour of herbicides onto porous carbon materials under environmentally relevant conditions. The strong Freundlich model conformity observed in the present study is also consistent with earlier investigations reporting heterogeneous adsorption interactions on activated carbon surfaces. Similar observations regarding adsorption affinity and kinetic behaviour have also been reported in recent studies investigating pesticide remediation using activated carbon and biochar-derived materials. However, unlike most previous studies focused exclusively on laboratory-scale adsorption evaluation, the present work additionally integrates field-scale removal observations to improve the practical applicability of adsorption modelling for agricultural water treatment systems.

3.3. Laboratory–Field Statistical Integration

To examine the practical relevance of laboratory-derived

adsorption parameters, regression analysis was performed to evaluate the relationship between intrinsic adsorption capacity (Q_{max}) and field removal efficiency. The regression equation obtained was:

$$y = 0.2864x + 62.945$$

The field monitoring dataset comprised multiple observations ($n = 12$) collected under different monitoring events and flow conditions. For laboratory–field comparison, herbicide-specific mean removal efficiencies were calculated from the broader field monitoring dataset and used in the regression analysis presented in Figure 3. Consequently, Figure 3 displays five herbicide-level averaged data points corresponding to MCPA, Mecoprop-P, 2,4-D, Triclopyr and Fluroxypyr rather than all individual monitoring observations. While the dataset provides a useful basis for establishing relationships, the results should be interpreted considering inherent variability in field conditions.

The coefficient of determination ($R^2 = 0.933$, $p < 0.05$) demonstrates a statistically significant positive relationship between intrinsic adsorption capacity and field-scale removal performance. The relatively narrow 95% confidence intervals further support the reliability of the regression relationship. These findings suggest that laboratory adsorption parameters may provide useful

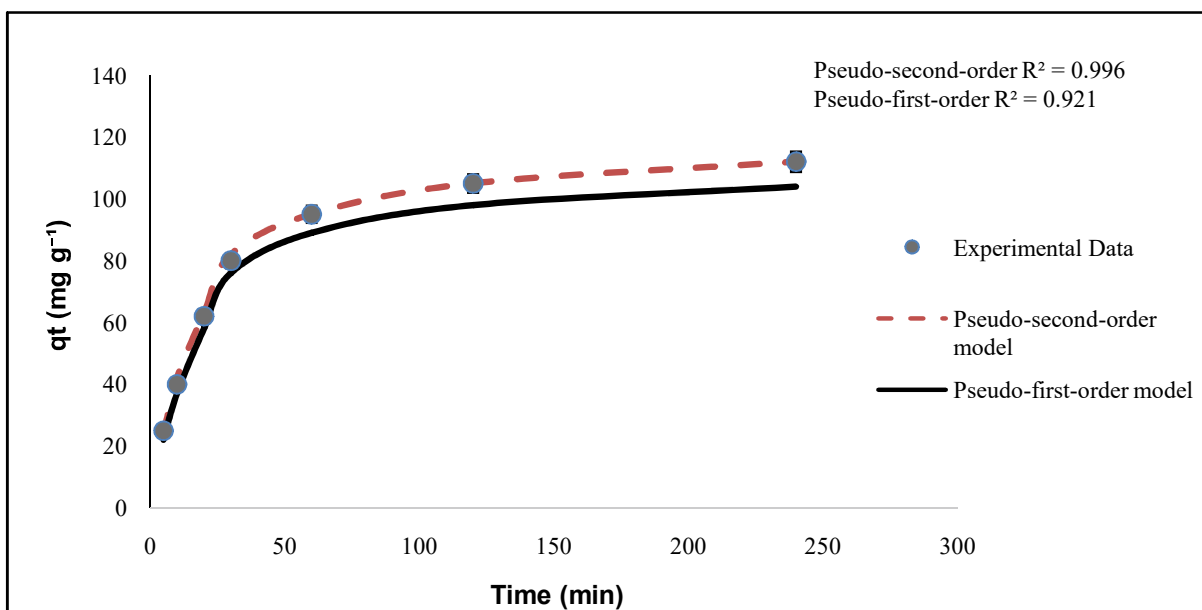


Figure 2. Kinetic model fitting curves for the adsorption of MCPA on granular activated carbon. Data points represent mean \pm standard deviation ($n = 3$) obtained from triplicate experiments. Experimental data (\bullet) along with pseudo-second-order (—) and pseudo-first-order (---) model fits are presented. The pseudo-second-order model shows better agreement with the experimental data. Intraparticle diffusion plots exhibited multilinear characteristics, indicating the contribution of multiple adsorption stages

preliminary indicators for understanding field-scale treatment performance under environmentally relevant conditions.

Figure 3 demonstrates a significant positive relationship between intrinsic adsorption capacity (Q_{max}) and field-scale removal efficiency.

The incorporation of field-derived data enhances the applicability of the study by validating laboratory adsorption behaviour under real environmental conditions and bridging the gap between controlled experiments and practical environmental implementation.

conditions. The plotted values represent herbicide-specific mean removal efficiencies derived from multiple

field monitoring observations ($n = 12$). Consequently, five herbicide-level averaged data points corresponding to MCPA, Mecoprop-P, 2,4-D, Triclopyr and Fluroxypyr are presented in the regression analysis. The figure illustrates a statistically significant positive relationship between intrinsic adsorption capacity (Q_{max}) and field removal efficiency.

3.4. Integrated Mechanistic Interpretation

The adsorption trend observed in this study reflects the combined influence of molecular characteristics of herbicides, surface heterogeneity of activated carbon, equilibrium adsorption behaviour and kinetic behaviour.

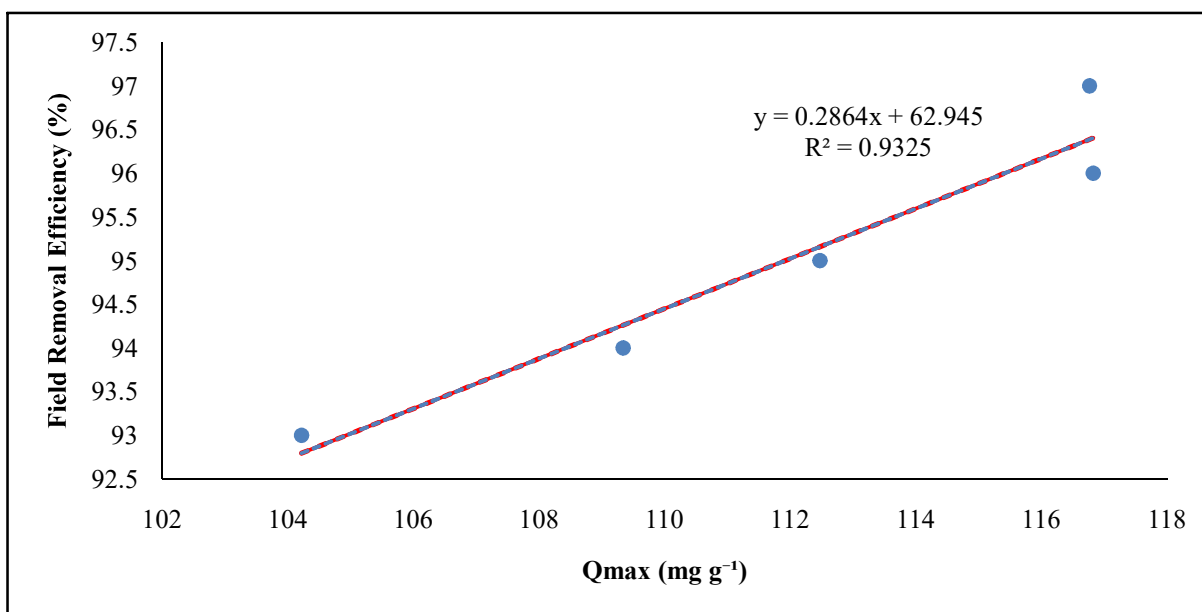


Figure 3. Relationship between intrinsic adsorption capacity (Q_{max}) and field-scale herbicide removal efficiency observed under environmentally relevant agricultural water treatment conditions. The plotted values represent herbicide-specific mean removal efficiencies derived from multiple field monitoring observations ($n = 12$). Consequently, five herbicide-level averaged data points corresponding to MCPA, Mecoprop-P, 2,4-D, Triclopyr and Fluroxypyr are presented in the regression analysis. The figure illustrates a statistically significant positive relationship between intrinsic adsorption capacity (Q_{max}) and field removal efficiency

Table 2. Kinetic model parameters for acid herbicide adsorption on granular activated carbon

Herbicide	Model	k_1 (min^{-1})	k_2 ($g\ mg^{-1}\ min^{-1}$)	$q_{s,calc}$ ($mg\ g^{-1}$)	R^2
MCPA	Pseudo-first-order	0.041	-	104.280	0.921
MCPA	Pseudo-second-order	-	0.00082	112.940	0.996
2,4-D	Pseudo-first-order	0.036	-	101.360	0.914
2,4-D	Pseudo-second-order	-	0.00076	109.780	0.994
Triclopyr	Pseudo-first-order	0.039	-	103.420	0.918
Triclopyr	Pseudo-second-order	-	0.00080	111.560	0.995

Although intrinsic adsorption capacity strongly influences contaminant removal potential, field-scale performance is also affected by hydraulic residence time, flow dynamics and operational conditions.

Figure 4 presents the simplified laboratory–field integration framework linking adsorption behaviour with field-scale herbicide removal performance.

From an environmental management perspective, the adsorption efficiencies observed in the present study indicate the potential of activated carbon systems to reduce herbicide concentrations in agricultural runoff and surface water environments. Such reductions may contribute to minimising ecological exposure risks to aquatic organisms

and supporting compliance with water quality protection objectives associated with pesticide contamination control. Although detailed ecological risk quantification and toxicity threshold assessment were beyond the scope of the present investigation, the observed adsorption performance demonstrates the practical environmental relevance of adsorption-based treatment systems for improving agricultural water quality.

The comparatively higher removal efficiency of GAC compared to CAC may be associated with its relatively well-developed pore structure and adsorption affinity, as commonly reported for granular activated carbon systems in previous studies.



Figure 4. Simplified laboratory–field integration framework illustrating the relationship between adsorption equilibrium behaviour, kinetic performance and field-scale herbicide removal efficiency ($R^2 = 0.933$)

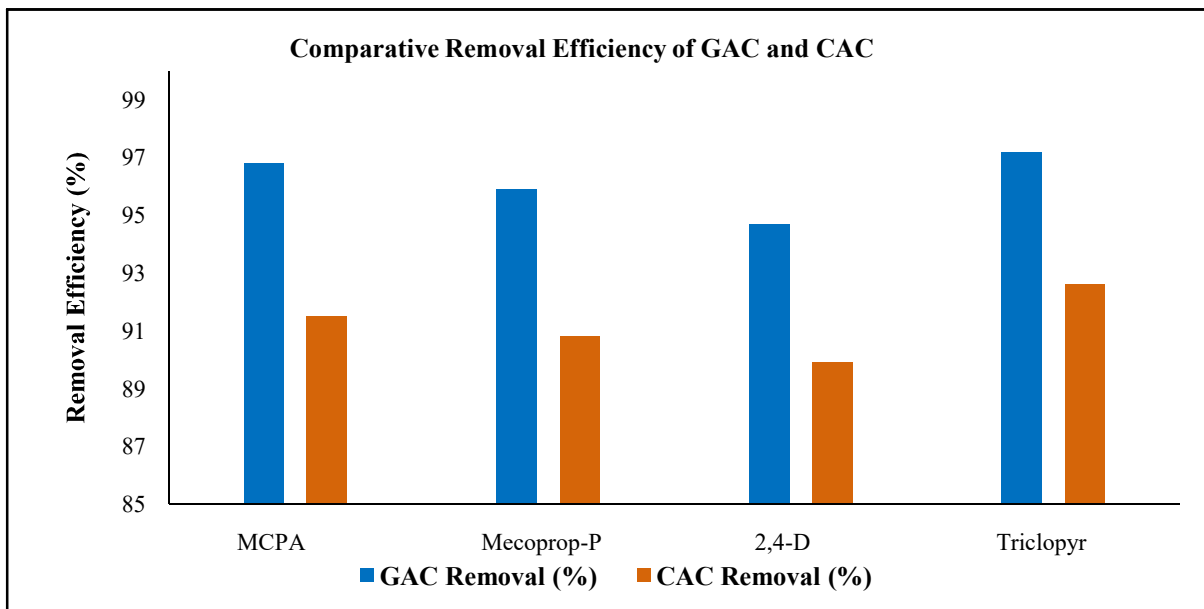


Figure 5. Comparative field-scale removal efficiency of granular activated carbon (GAC) and coconut-based activated carbon (CAC) for selected herbicides. The figure shows the comparative removal efficiencies of GAC and CAC under field-scale conditions, with GAC consistently exhibiting higher performance across all investigated herbicides

Figure 5 shows the comparatively higher removal efficiency of granular activated carbon (GAC) than coconut-based activated carbon (CAC) under field-scale conditions.

Although high intrinsic adsorption capacity enhances the removal potential of herbicides, compliance with drinking water regulatory limits requires appropriate integration of adsorption characteristics with hydraulic design and operational conditions. Laboratory modelling provides valuable insights into adsorption affinity and rate-controlling mechanisms; however, field-scale performance is also influenced by hydrodynamic conditions, system configuration, and operational optimisation.

While a strong laboratory–field correlation was observed in the present study, the experiments were conducted under controlled batch conditions with limited field datasets. Therefore, further validation under continuous-flow operational scenarios is recommended to improve real-world applicability and strengthen the predictive reliability of adsorption-based treatment systems.

The findings of this study highlight the ecological significance of adsorption-based treatment strategies in reducing herbicide contamination in agricultural water systems, thereby contributing to the protection of aquatic ecosystems from pesticide-induced stress.

4. CONCLUSION

The present study evaluated the adsorption behaviour of selected acid herbicides on activated carbon through equilibrium modelling, kinetic analysis and laboratory–field statistical integration. The results demonstrated that the Freundlich isotherm provided a better representation of adsorption behaviour, indicating heterogeneous surface interactions between herbicide molecules and activated carbon. Langmuir modelling revealed high intrinsic adsorption capacities, while kinetic analysis confirmed that the adsorption process predominantly followed pseudo-second-order behaviour.

A statistically significant relationship between intrinsic adsorption capacity and field removal efficiency highlights the practical relevance of laboratory-derived adsorption parameters. These findings suggest that adsorption modelling can provide useful guidance for predicting treatment performance and optimizing the deployment of activated carbon systems for the removal of herbicide contaminants in water treatment applications.

Overall, the integrated laboratory–field approach presented in this study contributes to improved

understanding of adsorption mechanisms and provides scientific evidence for the design and optimization of activated carbon-based treatment systems for mitigating herbicide contamination in agricultural catchments and safeguarding water resources. From an ecological perspective, the integration of adsorption modelling with field-scale performance evaluation provides an important framework for improving the management of pesticide contamination in agricultural landscapes and protecting freshwater ecosystems. The observed removal efficiencies further indicate the potential applicability of activated carbon systems for reducing herbicide concentrations towards environmentally acceptable levels in agricultural water systems, thereby supporting improved ecological protection, water quality management objectives, and compliance with agricultural water quality protection goals.

Further investigation involving thermodynamic parameters (ΔG , ΔH and ΔS), continuous-flow column systems, competitive ion interactions, dissolved organic matter effects, pH-dependent adsorption behaviour, temperature variation, and variable environmental conditions would provide deeper insight into the adsorption mechanism and improve understanding of real-world field-scale applicability of activated carbon-based treatment systems.

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CRediT authorship contribution statement

Pradip Salve: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing – original draft, Writing – review & editing.

Data availability statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Declaration of generative AI and AI-assisted technologies in the writing process

The author used limited AI-assisted tools only for language editing and grammatical refinement. All scientific interpretation, data analysis, results, and conclusions were independently developed by the author.

Conflict of interest

The author declares that there is no conflict of interest regarding the publication of this paper.

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