Sustainable Removal of Methyl Orange from Wastewater Using *Cyperus rotundus*: A Low-cost Natural Adsorbent

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Abstract*–*Synthetic* dyes found in wastewater create substantial environmental hazards and health risks, which require effective and sustainable wastewater treatment methods. The present study investigates using *Cyperus rotundus* as a natural adsorbent so that methyl orange is removed from aqueous solutions under a batch system. A total of 71 experimental runs were conducted in this study so that the impacts of varying dye concentration between (5 and 100) ppm, pH range between (3 and 11), a contact time increasing at discrete steps between (10 and 90 min), and finally a varying temperature from (25 to 45°C) on the adsorption process were assessed. A 97% dye removal efficiency was obtained at a dye concentration of 10 ppm, pH of 4, and contact time of 90 min. Isotherm analysis revealed that the Langmuir model best fits the data with 2.25 mg/g adsorption capacity and a coefficient of determination (R^2 = 0.657). The kinetic data followed a pseudo-second-order model, indicating that chemisorption is the governing process (R^2 > 0.95). Thermodynamic analysis proved that this adsorption is both spontaneous (with a standard Gibbs free energy change ranging from $\Delta G°$ = −4.76 to −5.69 kJ/mol) and endothermic (enthalpy change $\Delta H°$ = 9.10 kJ/mol). Both scanning electron microscopy and Fourier transform infrared spectroscopy confirmed the presence of dye adsorbent interactions when both structural and functional changes of the groups that occurred after adsorption were tested. The results show that *C. rotundus* is a low-cost biosorbent in methyl orange removal and can serve as a sustainable wastewater treatment material.

***Index Terms*–Adsorption, *Cyperus rotundus,* Methyl orange, Natural adsorbent and wastewater treatment.**

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I. Introduction

The presence of dyes in water resources poses a significant environmental concern because of their adverse effects on aquatic life and human health. Methyl orange, a widely deployed anionic dye, has become a major pollutant of concern with its discharge into water resources, imposing detrimental consequences. Recent studies have confirmed that methyl orange is toxic to the environment and to people's health. *In silico* toxicological assessments indicate that methyl orange can penetrate the skin, cross the blood–brain barrier, affect foetal development, and show compatibility with human colon carcinoma cells, with a high intestinal absorption rate, highlighting its potential risk to human health when released into water systems. It was also found that the addition of methyl orange into aquatic ecosystems affects the structure of microbial communities in water-sediment systems, which attributes in blocking crucial ecological processes like cycling of nutrients and organic matter decomposition, thereby threatening biodiversity and ecosystem stability (Ibrahim, Ahmed and Abduljabbar, 2024).

Conventional methods such as coagulation, precipitation, and biological treatment have proven largely ineffective in the removal of methyl orange, especially when there is a high concentration of the dye. In contrast, adsorption is widely considered as one of the most effective dye removal techniques because of its high efficiency, affordability, and simplicity of use (Agarwala and Mulky, 2023; Hambisa, et al., 2023). The adsorption process is significantly affected by various factors such as temperature, adsorbent dose, solution pH, and initial dye concentration (Dutta, et al., 2021). Several materials, such as carbon-based materials (Kuyucu, et al., 2025), metal oxides (Kramer, et al., 2025), and biopolymers (Bellaj, et al., 2026), have been tested for dye removal through adsorption processes using different techniques including coagulation (Rahmoun, et al., 2025; Mohamed, et al., 2026), biological degradation (Kassa, Engida and Endaye, 2025; Malik, Janiad and Ng, 2025), and advanced oxidation processes (Kivrak, et al., 2022;

Ziembowicz and Kida, 2025). The potential of *Cyperus rotundus* as a biological adsorbent for wastewater treatment has not been extensively studied. The significance of pH level, adsorbent dosage, and contact time is emphasized by an optimization work (WARSE, 2021), but to the best of the authors' knowledge, no extensive investigation has been conducted on methyl orange adsorption with *C. rotundus* under various operating conditions.

The present study used *C. rotundus* as a natural biological adsorbent to adsorb methyl orange from contaminated wastewater. In this context, the present study investigates the adsorption potential of *C. rotundus* as a naturally available biosorbent for the removal of methyl orange from aqueous solutions. The adsorption mechanism and adsorption performance are investigated using scanning electron microscopy (SEM) and Fourier transform infrared spectroscopy (FTIR) under multiple controlled parameters. The main contributions of this research are a novel extensive investigation of adsorbing methyl orange using *C. rotundus*, deployment of a naturally growing plant to act as a biological adsorbent at no financial cost, and promoting practical wastewater treatment methods using sustainable and eco-friendly alternatives.

II. Materials and Methods

A. Adsorbent Material

C. rotundus has its name derived from both Greek and Latin origins. *Cyperus* comes from the Greek word (*Kyperos*) which refers to rush or sedge plants while *Rotundus* is from Latin which means round. It is also known as Java grass, nut grass, purple nut sedge, and purple nut sedge (Abbas, Saleh Alsaade and Yousif Almashhdan, 2019). *C. rotundus* is a *Cyperaceae* species native to India that has spread to parts of Africa, America, Asia, and Europe. The plant is available in abundance in large quantities in Erbil and other parts of Iraq. It has a perennial life cycle with plants growing to 7–40 cm and generating both rhizomes and tubers that have several valuable therapeutic characteristics. This species' subsurface system is made up of tubers, bulbs, and rhizomes that can propagate even at unfavorable settings. Research reports that roots, rhizomes, tubers, leaves, and even the entire plant are used in developing homemade medications (Bezerra and Vieira, 2022). The plant contains essential oils, alkaloids, flavonoids, and terpenes and poses potential adsorption capabilities (Zhang, et al., 2017).

B. Chemicals and Apparatus

Methyl orange (with a chemical formula of $C_{14}H_{14}N_3NaO_3S$, a molecular weight or molar mass of 327.33 g/mol) was used as the dye in the batch adsorption process. *C. rotundus*, collected from Erbil, Iraq, served as the adsorbent. Dye solution pH and oxidation–reduction potential were monitored using an HI 2211 Benchtop pH meter (HANNA Instruments, USA). Adsorption experiments were performed with continuous stirring on an LMS-2003D hot plate magnetic stirrer (Lab Tech, Korea). After adsorption, the solid adsorbent was separated from the solution using a UNIVERSAL 320 R centrifuge (Hettich Zentrifugen, Germany). A Cary series UV-Vis spectrophotometer (Agilent Technologies, Malaysia) was deployed to determine the methyl orange concentration. A Denver Instrument scale (Germany) was used to weigh the solid adsorbent, while drying procedures were conducted in an LDO-060E oven (Lab Tech, Korea). Surface morphology was examined using a field-emission scanning electron microscope (TESCAN, Czech). Functional groups present on the adsorbent's surface were identified using an FTIR spectrometer (Explorer, Austria). The adsorbent was finely ground and then sieved using a 120-µm sieve (Edibon, Spain).

C. Preparation of the Adsorbent

C. rotundus as a natural adsorbent was harvested from Erbil, Iraq. To remove dirt and contaminants, the sample was thoroughly rinsed using distilled water and oven dried at 50°C for a duration of 24 h. The dried biomass was ground with an electrical grinder until all particles reached a size below 60 microns. The final particle size was standardized by sieving the ground biomass through a 60-µm stainless steel laboratory sieve to ensure uniform granulometry for batch tests. Particle size distribution was verified by sieve analysis and optical microscopy; the material passing the 60-µm sieve was retained for all adsorption experiments. This preparation procedure follows the standard biosorbent preparation method reported for *C. rotundus* in dye adsorption studies (Ahmad and Kumar, 2013).

D. Preparation of the Dye Solution

The chemical properties of methyl orange were obtained from (Flinn Scientific, 2014) and are presented in Table I. A 25 mL aliquot of 5 mg/L methyl orange was transferred into a 100 mL Erlenmeyer flask. This solution was used as the working standard for calibration and adsorption experiments.

E. Experimental Procedure

The methyl orange solution (having concentration levels of 5, 10, 25, 50, and 100 ppm) had its pH set to (3, 5, 9, and 11) using 0.1 M of hydrochloric acid and 0.1 M of sodium hydroxide and that was verified using a pH meter. A precisely weighed 0.3 g of *C. rotundus* was mixed as an adsorbent with a solution volume of 25 mL to initiate adsorption. A magnetic stirrer was used to stir the mixture

TABLE I
Chemical Properties of Methyl Orange

Properties	Description
Name	Methyl Orange
CAS Registry Number	547-58-0
Formula	$C_{14}H_{15}N_3O_3SNa$
Molecular weight	327.334
Synonyms	Sodium p-dimethylaminoazobenzene sulfonate; C.I. 13025

at 225 rpm, with contact times of (10, 20, 30, 60, and 90 min) and (25, 35, and 45°C) temperatures. The sample was later centrifuged at 4000 rpm for 20 min, and the supernatant was analyzed using a UV-Vis spectrophotometer at 465 nm, with distilled water as a blank reference. The adsorption efficiency (removal percentage) was calculated based on a standard calibration curve. This procedure was repeated for all experimental runs using predefined values for each parameter. All experiments were conducted under controlled laboratory conditions, with the testing carried out over 71 runs during a period of 75 working days. All absorbance values were converted to concentrations using the calibration curve while SEM and FTIR characterizations were performed on the samples before and after adsorption to confirm structural changes. All adsorption experiments were conducted in duplicate under identical conditions, and the average values were reported. Experimental measurements were performed using calibrated laboratory instruments, and variations between repeated experiments were within acceptable laboratory limits. All experiments were conducted under controlled laboratory conditions.

III. Results And Discussion

A. Adsorption Isotherm Modeling Results Analysis

Langmuir, Freundlich, Temkin, and Harkins–Jura isotherm models were applied to analyze the experimental data of adsorbing methyl orange onto *C. rotundus*.

Monolayer adsorption on a homogeneous surface exists in the Langmuir model which describes a maximum adsorption capacity (q_m) of 2.25 mg/g with an acceptable fit. Adsorption of methyl orange onto *C. rotundus* followed the Freundlich model. Although the obtained adsorption capacity is moderate because heterogeneous adsorption sites exist compared to some chemically modified or engineered biosorbents reported in the literature, the use of *C. rotundus* offers several important advantages. The material is naturally abundant, inexpensive, and requires minimal processing before use. These characteristics enhance its practical value as a sustainable and environmentally friendly adsorbent for wastewater treatment applications. The Temkin model which includes adsorbate–adsorbent bond effects displayed a negative BT value of −2.10 kJ/mol to indicate a weak adsorption force between the molecules. Adsorption on heterogeneous and porous surfaces according to the Harkins–Jura model did not show that the experimental data and the theoretical predictions are strongly correlated, suggesting that heterogeneous surface interactions or multilayer adsorption were less significant under the studied conditions. Therefore, the adsorption behavior of methyl orange on *C. rotundus* is best described by the monolayer adsorption assumption inherent in the Langmuir model. Table II provides a detailed summary of the corresponding isotherm parameters. The Langmuir isotherm model provided a reasonable description of the adsorption behavior, indicating the formation of a monolayer of methyl orange molecules on the surface of *C. rotundus*. The relatively good fit suggests that the adsorption process occurs on a finite number of energetically equivalent active sites on the adsorbent surface. It should be noted that the present work focuses on laboratory-scale batch adsorption experiments using synthetic dye solutions. Further studies involving regeneration performance, reuse cycles, and real wastewater systems are required to fully evaluate the practical applicability of the adsorbent.

B. Adsorption Kinetics and Thermodynamics Study

The rate and mechanism of methyl orange dye adsorption onto *C. rotundus* were investigated using different kinetic models applied to experimental data at varying contact times. Pseudo-first and pseudo-second-order models were applied to evaluate the adsorption kinetics.

The linear form of the pseudo first-order model is (Chakraborty, et al., 2020; Adnan and Thanasupsin, 2016):

$$\log\left(q_e - q_t\right) = \log q_e - \frac{k_1}{2.303} \quad (1)$$

Eqn. (2) resembles the pseudo-second-order model:

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e} \quad (2)$$

- q_e and q_t in (mg/g): Quantity of the dye adsorbed at equilibrium and at a given time t, respectively
- k_1 (L/min): Pseudo-first-order rate constant
- k_2 (g/mg/min): Pseudo-second-order rate constant.

To assess the feasibility and nature of the adsorption process, thermodynamic parameters were calculated at different temperatures (25°C, 35°C, and 45°C). The standard Gibbs free energy change (ΔG°), enthalpy change (ΔH°), and entropy change (ΔS°) were determined using the following equations (Chakraborty et al. 2020):

$$K_c = \frac{C_A}{C_B} \quad (3)$$

$$\ln K_c = \frac{-\Delta H^\circ}{RT} + \frac{\Delta S^\circ}{R} \quad (4)$$

$$\Delta G^\circ = \Delta H^\circ - T\,\Delta S^\circ \quad (5)$$

Where:

- K_c: thermodynamic equilibrium constant
- C_A in (mg/L): concentration of methyl orange adsorbed per liter onto *C. rotundus* at equilibrium

TABLE II
Adsorption Isotherm Model Parameters of Methyl Orange onto *Cyperus rotundus*

Langmuir			Freundlich			Temkin			Harkins–Jura		
q_m mg/g	K_L L/g	R^2	K_f L/g	n^{-1}	R^2	B_T kJ/mol	K_T L/g	R^2	A_{HJ} mg/g	B_{HJ}	R^2
2.25	0.434	0.6574	1.33	0.123	0.0403	−0.089	−2.10	0.0728	2.213	0.703	0.039

- C_B in (mg/L): equilibrium methyl orange concentration
- R: universal gas constant (8.314 J/moL·K)
- T: absolute temperature in Kelvin.

The Van't Hoff plot, shown in Fig. 1, illustrates the relationship between ln K_c versus 1/T for methyl orange adsorption onto *C. rotundus*. The slope and intercept method was used to determine ΔH° and ΔS° as illustrated in Table III which confirms that adsorption is endothermic (ΔH° = 9.10 kJ/mol) and spontaneous at all temperatures tested, as indicated by negative ΔG° values (−4.76–−5.69 kJ/mol). The negative ΔS° (−46.23 J/mol/K) suggests low randomness at the solid–liquid interface as dye molecules become more organized on the adsorbent surface.

Experimental data fit the pseudo-second-order model, indicating that chemisorption is the dominant mechanism, implying the existence of valency forces or electron sharing between the adsorbent and methyl orange molecules. This is consistent with the interactions suggested by FTIR analysis (e.g., hydroxyl and carbonyl group involvement). These results confirm that *C. rotundus* exhibits high affinity and rapid uptake capacity for methyl orange, particularly under optimized conditions.

The calculated thermodynamic parameters in Table III show that:

- ΔG° exhibits negative values at all tested temperatures, indicating that adsorption is spontaneous
- The value of ΔH° was positive, suggesting an endothermic process, which implies that adsorption efficiency is directly proportional to temperature
- ΔS° was negative, indicating a low stochasticity at the solid–to–liquid interface during the adsorption of methyl orange.

TABLE III
Thermodynamic Parameters of Methyl Orange Adsorption onto *Cyperus rotundus*

Temperature (K)	Kd	ΔG° (kJ/mol)	ΔH° (kJ/mol)	ΔS° (J/mol/K)
298	0.12	−4.76	9.10	−46.23
308	0.14	−5.00	-	-
318	0.15	−5.69	-	-

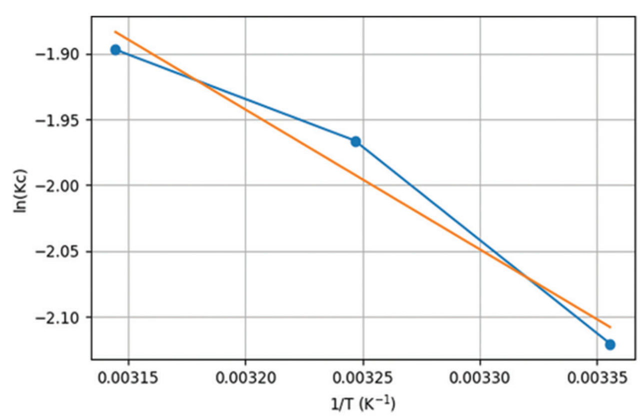


Fig. 1. Van't Hoff Plot for methyl orange adsorption onto *Cyperus rotundus*.

Although the adsorption kinetics were best described by the pseudo-second-order model, this does not necessarily imply that the process is governed solely by chemisorption. The relatively low ΔG° values suggest that physical interactions, such as electrostatic attraction, hydrogen bonding, and van der Waals forces, also contribute to the adsorption process. Therefore, the adsorption of methyl orange onto *C. rotundus* is likely controlled by a combination of surface interactions rather than purely chemical bonding. This interpretation is consistent with the FTIR results, which indicate involvement of surface functional groups without evidence of strong covalent bond formation.

C. Quantitative Analysis

UV-Vis spectrophotometry was used to determine the methyl orange concentration. The specimens were placed into a UV spectrometer device to analyze methyl orange and compared to distilled water.

For different initial methyl orange concentrations (5, 10, 25, 50, and 100 ppm), Fig. 2. shows that the adsorption process reaches equilibrium rapidly at low dye concentrations. However, at high initial dye concentration (i.e., 100 ppm), the adsorption process shows detectable instability, implying that desorption or equilibrium shifts happen during extended exposure.

Fig. 3 shows the percentage of methyl orange dye removed under different initial concentrations and temperatures of 25, 35, and 45°C. The adsorption behavior shows significant differences in accordance with the temperature variation. For example, the adsorption process at 45°C shows an initial increase followed by a rapid drop until it reaches equilibrium. The observed adsorption-desorption pattern, together with surface saturation phenomena, explains these results at elevated temperatures. The removal percentage was higher at low initial dye concentrations and gradually decreased as the initial dye concentration increased at all tested temperatures, due to the progressive saturation of available adsorption sites on the adsorbent surface.

The pH of the solution significantly affects methyl orange adsorption, since it is an anionic dye and

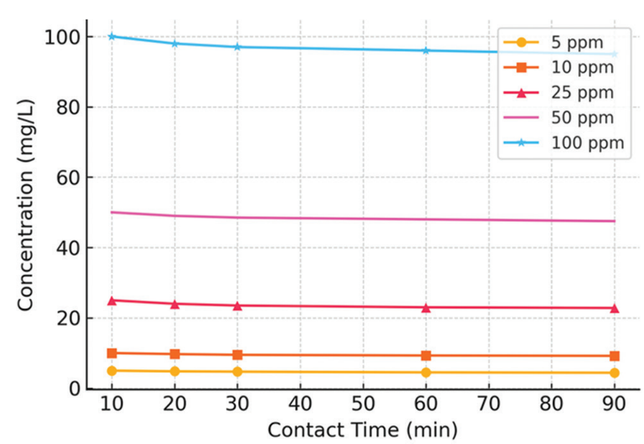


Fig. 2. Concentration of methyl orange over different contact times.

C. rotundus possesses functional groups (−OH, −COOH) that are subject to protonation and deprotonation. Fig. 4 implies that at low pH (e.g., pH 3–4), the functional groups of *C. rotundus* become positively charged on the adsorbent surface by protonation. This increases the electrostatic attraction between the surface of methyl orange dye (which has negative charges) and the sulfonate groups (being positively charged), thereby leading to increased adsorption efficiency.

With the increase in pH, the adsorbent surface becomes increasingly deprotonated and negatively charged. The anionic dye molecules are repelled on the negatively charged surface by electrostatic repulsions that cause adsorption to be significantly reduced at alkaline pH. Thus, the highest removal at acidic pH is explained by the existence of a favorable electrostatic interaction, and less adsorption at high pH is caused by the presence of repulsions.

D. Methyl Orange Adsorption Capacity Using Different Natural Adsorbents

A comparison of methyl orange adsorption capacity obtained using different plant-based adsorbents is presented in Table IV. Under the relatively specified model of adsorption isotherm, Table IV clearly shows that the capacity of *C. rotundus* is moderate as compared to other adsorbents such as the populous leaves dust, lemon peel, and the sugar scum. However, its natural availability in abundance and cheap price renders it an affordable and eco-friendly adsorbent for wastewater treatment. In recent years, numerous natural biosorbents derived from agricultural residues and plant biomass have been investigated for dye removal from wastewater. These materials are attractive due to their low cost, environmental compatibility, and simple preparation methods. However, adsorption performance varies depending on the physicochemical properties of the biomass and the presence of active surface functional groups. Therefore, the investigation of locally available natural materials remains an important approach for developing accessible and sustainable wastewater treatment solutions.

It should be noted that many higher-capacity adsorbents involve chemical modification or activation processes that increase preparation complexity and cost. In contrast, the adsorbent used in this study was applied without chemical treatment, highlighting its potential as a simple and naturally available material for preliminary dye removal applications.

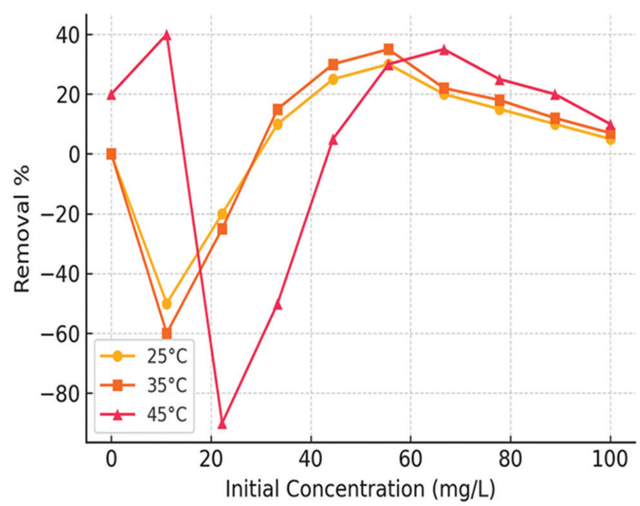


Fig. 3. Removal percentage of methyl orange at various temperatures.

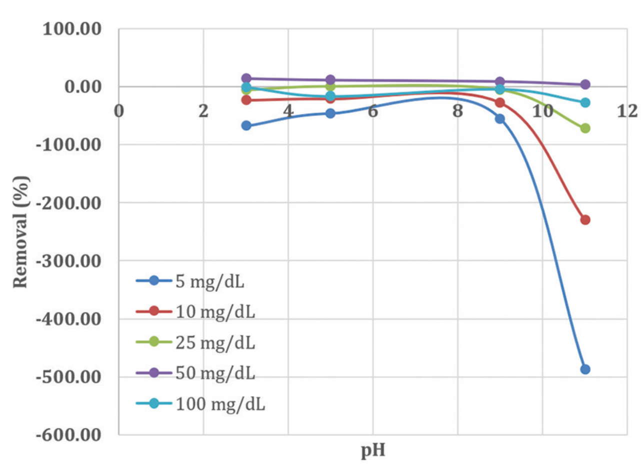


Fig. 4. Effect of pH level on methyl orange removal percentage.

E. Characterization Results

FTIR results

The FTIR spectrum of *C. rotundus* before adsorption, illustrated in Fig. 5, shows the presence of some functional groups in the chemical structure that are important in the study of the batch adsorption of methyl orange dye. A wide absorption band at 3419.89 cm^{-1} is indicative of O-H stretching vibrations, which are characteristic of hydroxyl groups that can form hydrogen bonds or electrostatic interactions with the dye molecules. The first sharp peak at 2929 cm^{-1} can be attributed to the C-H stretching vibrations which demonstrate the potential of existing aliphatic hydrocarbons in the structure of the material. A peak at 1650 cm^{-1} has been observed with greater intensity and corresponds to the C=O stretching frequency, which suggests that carbonyl groups are present in the adsorbed species that may interact with the sulfonate groups of methyl orange. Furthermore, the range of 1000–1300 cm^{-1} contains multiple peaks corresponding to C-O stretching, which might be attributed to ether or ester. These two different peaks prove that the natural material is chemically complex with many functional groups that could have a chance to interact with methyl orange dye, which is essential for evaluating the changes before and after the adsorption process.

The peaks around 1459 cm^{-1} and 1381 cm^{-1} indicate the presence of C-H bending vibrations in alkyl groups which confirms that organic material is present in the sample. The functional groups found in the *C. rotundus* (including hydroxyl, carbonyl, and alkyl) are essential for the adsorption process since they can offer hydrogen bonding, van der Waals forces, or electrostatic interaction with dye molecules. One of the possible active sites for dye adsorption is the broad O-H stretching band, which suggests that the material is able to interact with polar dye molecules.

After adding the adsorbent, several changes in the peak positions are observed as can be seen in Fig. 6. It is noticed that the reduction occurring in the O-H stretching peak implies that some of the hydroxyl groups are involved in the

TABLE IV
Methyl Orange Adsorption Capacity Using Different Bio-adsorbents

Adsorbent	Adsorption capacity (mg/g) 5+6	Isotherm model	References
Corn leaves	0.24	Langmuir	(Al-Kazragi, et al., 2024; Fadhil and Eisa, 2019)
Sugar scum	15.24	Langmuir	(Al-Kazragi, et al., 2024; El Maguana, et al., 2020)
Populous leaves dust	39.85	Langmuir	(Al-Kazragi, et al., 2024; Shah, et al., 2021)
Coal fly ash	0.42	Freundlich	(Al-Kazragi, et al., 2024; Potgieter, Pardesi and Pearson, 2021)
Lemon peel	33	Langmuir	(Potgieter, Pardesi and Pearson, 2021)
Mahagoni	6.071	Freundlich	(Ramutshatsha-Makhwedzha, et al., 2022)
Cyperus rotundus	2.25	Langmuir	Present study

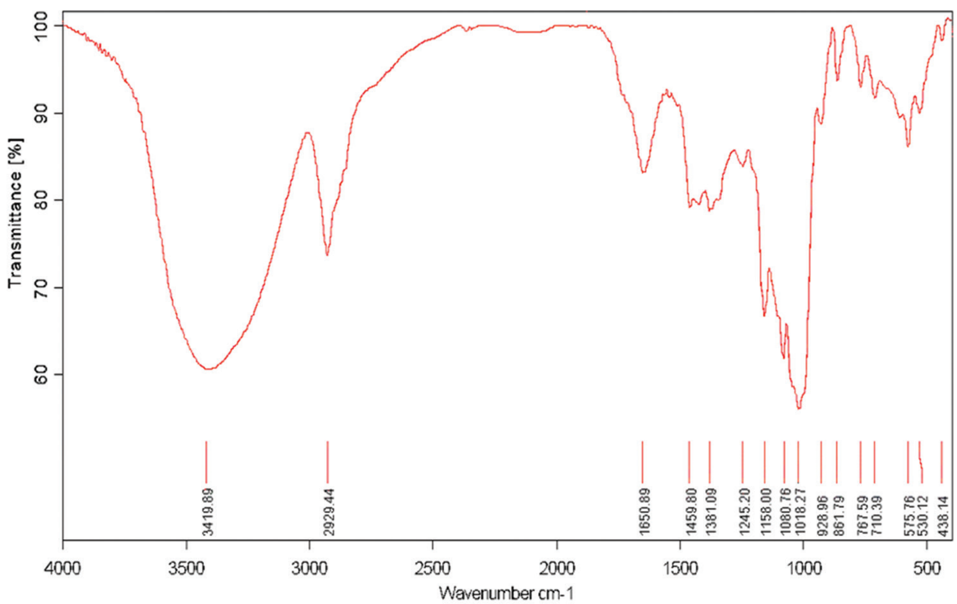


Fig. 5. Fourier transform infrared spectrum of *Cyperus rotundus* before adsorption of methyl orange dye.

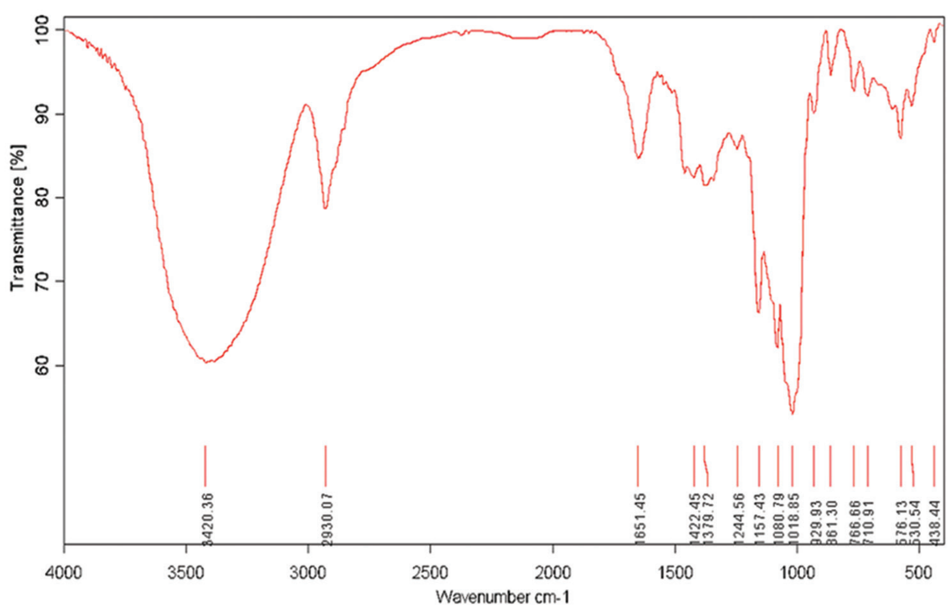


Fig. 6. Fourier transform infrared spectroscopy spectrum of *Cyperus rotundus* after adsorption of methyl orange dye.

interaction with the dye molecules. Similarly, the changes in the C=O stretching peak indicate interactions between the carbonyl groups of *C. rotundus* and the dye.

After the adsorption process, new or changes in the peaks that can be seen in Fig. 6 indicate the formation of new chemical bonds between *C. rotundus* and methyl orange. For instance, shifts or reductions in the O-H stretching region (3200–3600 cm^{-1}) and C=O stretching region (1600–1750 cm^{-1}) show that these functional groups are active participants in the adsorption process. In addition, new peaks in the C-O stretching range (1000–1300 cm^{-1}) indicate the formation of new bonds. On the other hand, the disappearance of or decrease in some peaks is caused by the saturation of functional groups, confirming their engagement in binding the dye molecules.

TABLE V
Summary of the Quantitative Results of SEM Analysis before Adding *Cyperus rotundus*

Element	Weight percentage
Carbon	45.85
Oxygen	48.16
Chlorine	2.02
Potassium	3.97

SEM: Scanning electron microscopy

TABLE VI
Summary of the quantitative results of SEM analysis after adding *Cyperus rotundus*

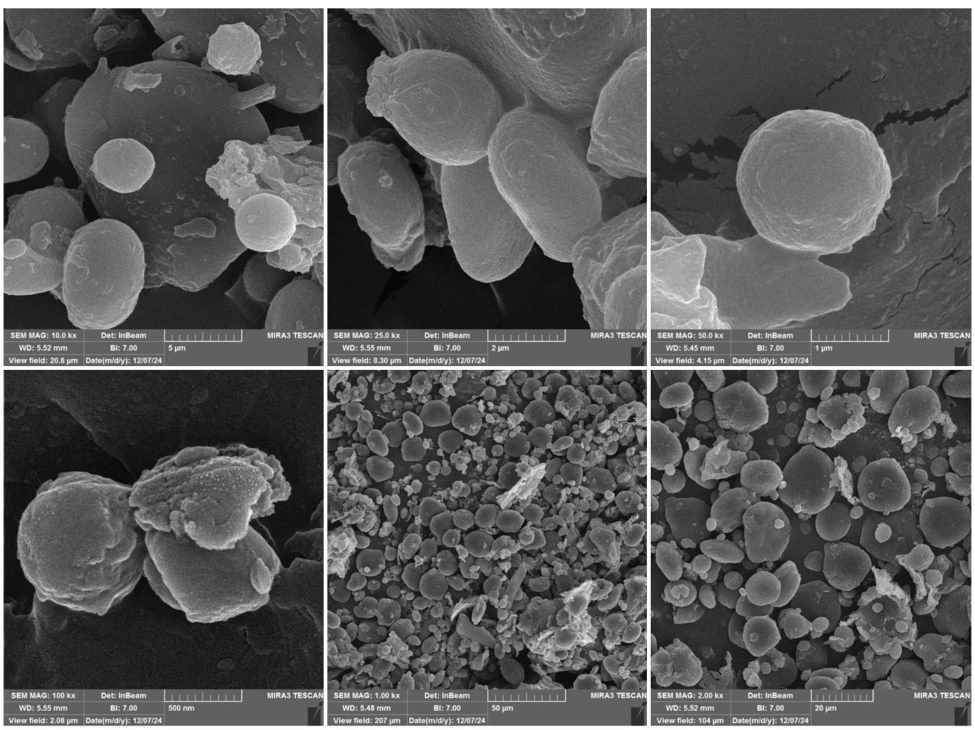
Element	Weight percentage
Carbon	38.69
Oxygen	59.54
Nitrogen	1.77

SEM: Scanning electron microscopy

SEM results

The SEM analysis operating parameters for the sample without *C. rotundus* consisted of an accelerating voltage of 20.0 kV at a magnification level of ×2500. It was found that the sample contains 45.85 W% carbon (C), 48.16 W% oxygen (O), 2.02 W% chlorine (Cl), and 3.97 W% potassium (K) in its quantitative elemental composition as can be seen in Fig. 7 and Table V.

When *C. rotundus* was applied to the solution, it was found that the proportion of carbon decreased to 38.69 W% while that of oxygen increased to 59.54 W%. It was also



Quantitative Results

Elt	Line	Int	Error	K	Kr	W%	A%	ZAF	Formula	Ox%	Pk/Bg	Class	LConf	HConf	Cat#
C	Ka	619.8	111.5133	0.5901	0.1950	45.85	54.64	0.4253		0.00	2897.40	A	45.37	46.32	0.00
O	Ka	264.4	29.4739	0.2558	0.0845	48.16	43.09	0.1755		0.00	1302.62	A	47.40	48.93	0.00
Cl	Ka	46.9	60.8107	0.0515	0.0170	2.02	0.82	0.8412		0.00	26.39	A	1.95	2.10	0.00
K	Ka	89.8	31.5897	0.1026	0.0339	3.97	1.45	0.8551		0.00	42.21	A	3.86	4.07	0.00
				1.0000	0.3305	100.00	100.00			0.00					0.00

Fig. 7. Scanning electron microscopy images before adding *Cyperus rotundus*.

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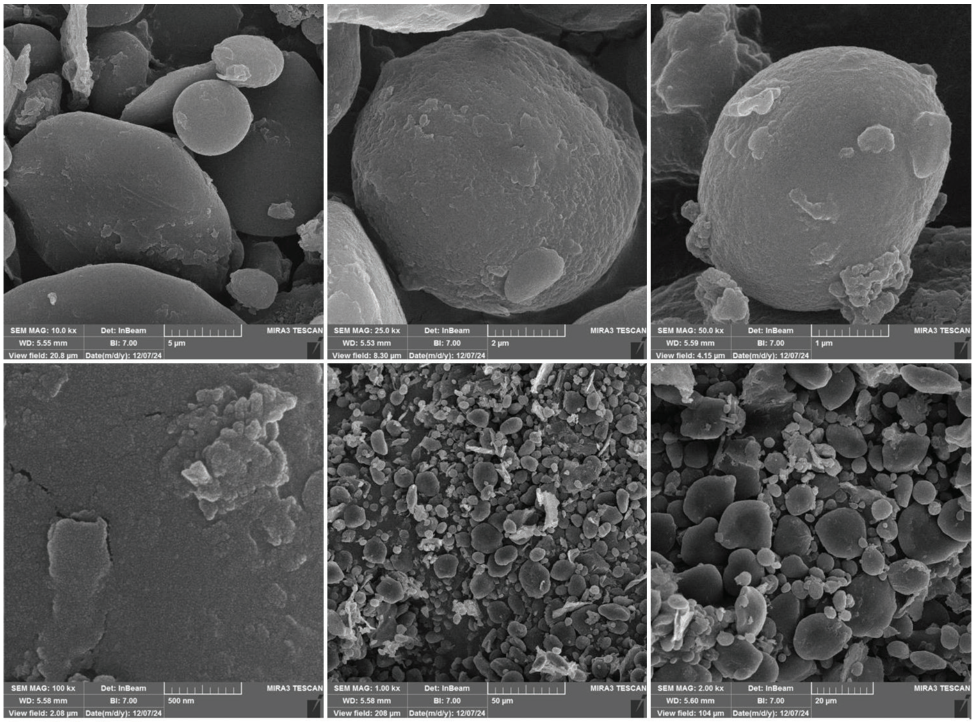

Quantitative Results

Elt	Line	Int	Error	K	Kr	W%	A%	ZAF	Formula	Ox%	Pk/Bg	Class	LConf	HConf	Cat#
C	Ka	276.7	16.0385	0.5799	0.1896	38.69	45.57	0.4899		0.00	2228.75	A	38.09	39.29	0.00
N	Ka	3.3	16.0385	0.0069	0.0022	1.77	1.79	0.1269		0.00	34.36	A	1.52	2.02	0.00
O	Ka	194.1	16.0385	0.4132	0.1351	59.54	52.64	0.2268		0.00	1830.75	A	58.44	60.64	0.00
				1.0000	0.3269	100.00	100.00			0.00					0.00

Fig. 8. Scanning electron microscopy images after adding *Cyperus rotundus*.

TABLE VII
Summary of Quantitative SEM Results Before and After Adding Cyperus rotundus

Element	Weight % Before	Weight % After	Observation
Carbon	45.85	38.69	Decrease in carbon content, attributed to the adsorption of methyl orange and changes in surface composition
Oxygen	48.16	59.54	Significant increase in oxygen, suggesting enhanced functional groups (e.g., hydroxyl and carboxyl)
Chlorine	2.02	Not detected	Indicates removal or dilution post adsorption
Potassium	3.97	Not detected	Suggests an alteration in mineral composition after interaction
Nitrogen	Not detected	1.77	New detection implies the introduction of nitrogen-containing compounds, likely from the dye or adsorption process.

SEM: Scanning electron microscopy

found that nitrogen (N) could be detected at 1.77 W% following the addition of *C. rotundus* as illustrated in Fig. 8 and Table VI.

SEM results demonstrate the ability of *C. rotundus* to add functional groups that enhance methyl orange interaction and enable better adsorption based on the increased amount of oxygen content. The amount of nitrogen introduced during the process directly relates to dye molecule adsorption since methyl orange primarily contains nitrogen. The decrease in carbon alongside other elements indicates surface cleaning activities and changes how elements distribute because of dye adsorption. A summary of the SEM quantitative results is presented in Table VII.

IV. Conclusions

In the present study, the deployment of *C. rotundus* as a natural adsorbent to remove methyl orange in aqueous solutions was investigated. Several experimental runs were conducted to assess how dye concentration (in ppm), pH, contact time (in minutes), and temperature (in °C) affect the adsorption process. In addition, the adsorption isotherm model, kinetics, and thermodynamics were studied.

An extensive analysis of the experimental results highlighted the following findings:

- *C. rotundus* was found to achieve a maximum removal efficiency of 97% of methyl orange from the solution

- A Langmuir maximum adsorption capacity of 2.25 mg/g in optimized operating conditions (pH 4, 10 ppm, 90 min, and 25–45°C) was obtained which suggests monolayer adsorption on relatively homogeneous active sites
- Kinetics of adsorption were pseudo-second order ($R^2 > 0.95$), indicating that the rate-controlling process is chemisorption
- Thermodynamic analysis showed that the reaction is endothermic ($\Delta H° = 9.10$ kJ/mol) and spontaneous ($\Delta G° = -4.76$ to -5.69 kJ/mol), with lower interfacial randomness of dye attachment.

Further analysis of the SEM results showed that:

- The O-H and C=O functional groups shifted because of hydrogen bonding and electrostatic interactions with the sulfonate groups of methyl orange
- A shift in surface morphology and elemental composition was observed following the addition of *C. rotundus* as a methyl orange dye adsorbent
- *C. rotundus* has functional groups and surface properties to bind dyes using a combination of synergistic physical and chemical interactions.

In conclusion, this research has shown the potential of using *C. rotundus* as a cost-effective and sustainable natural adsorbent that is easy to process without any chemical modification. *C. rotundus* was found to achieve significant methyl orange dye removal and its performance during diverse operating conditions indicates a high potential for being incorporated in green wastewater treatment approaches.

Although the results demonstrate the adsorption potential of *C. rotundus* as a natural adsorbent, further investigations are required to assess its practical implementation. Future work should include regeneration and reuse studies, evaluation using real wastewater samples, and preliminary economic assessment to determine the feasibility of large-scale applications. In addition, future research plans need to assess regeneration performance in continuous flow or column systems to evaluate its suitability, adsorption capacity when using multi-contaminant systems, and the ability to scale up this adsorbent to be used in continuous or large-scale systems.

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