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RESEARCH ARTICLE

Multipurpose use of *Colocasia esculenta* for COD and iron leachate treatment in constructed wetlands optimized by response surface methodology

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Abstract

This study explores the versatile application of *Colocasia esculenta* (L.) Schott (taro) in the treatment of contaminated water, focusing on its dual role as a natural component of constructed wetlands and as an adsorbent for the removal of chemical oxygen demand (COD) and iron (Fe) from landfill leachate. Constructed wetlands (CW) planted with *C. esculenta* achieved an Fe removal efficiency of 77.97 % (from 0.59 mg/L to 0.13 mg/L), while COD removal was limited to 33.37 % (from 1531 mg/L to 1020 mg/L). To improve pollutant reduction, activated carbon derived from *C. esculenta* was tested using batch adsorption experiments. Response surface methodology (RSM) was employed to optimize key parameters, including pH 6 and a contact time of 53 min, resulting in 46.37 % COD removal and 84.62 % Fe removal. These findings demonstrate the promising potential of *C. esculenta* as both a phytoremediator and a bio adsorbent, providing an eco-friendly and sustainable solution for leachate treatment in agricultural, industrial and municipal wastewater applications. This research contributes to the development of low-cost, environmentally sound strategies for pollutant removal and resource recovery in sustainable water management.

Keywords: bio adsorbent; enhance efficiency; sustainability; taro

Introduction

Leachate is a polluted liquid that results from the degradation of solid waste in landfills. It is contaminated with organic and inorganic chemicals, heavy metals and hazardous compounds. Treatment of leachate is critical for preventing pollution of groundwater and surface water bodies (1). Several strategies for leachate treatment have recently been proposed, including biological, physical, chemical and physicochemical procedures (2).

Biological treatment is often favoured because of its dependability, simplicity and cost-effectiveness (3). One of the biological treatments that has succeeded in processing raw leachate as a pre-treatment with phytotechnology uses a combination of *Typha angustifolia* plants and bioaugmentation. Excellent pollution removal capabilities can be achieved with several plants such as *Phragmites australis* (common reed), *Typha* spp. (cattails), *Colocasia* spp. (taro) and *Scirpus* spp. (bulrushes) are frequently used (4). *C. esculenta* have a strong pollution absorption capability and resistance to leachate conditions and was chosen (5).

Some chemicals, however, such as ammonia, are difficult to biodegrade due to their toxicity to microorganisms at high concentrations (6). Several studies have found that physicochemical procedures are appealing pre- or post-treatment approaches for lowering effluent toxicity (7). Adsorption is a popular approach for removing toxins from a variety of environmental matrices, including air, water and soil. Because of its high adsorption capacity, vast surface area and versatility, activated carbon has attracted substantial attention among the many adsorbents available (8). Because of their renewable and sustainable nature, adsorbents are often generated from a variety of carbonaceous sources, including plant materials (9).

Plant-based activated carbon (AC) has emerged as a viable alternative to non-renewable activated carbons made from coal or petroleum. Plants have various benefits as raw materials for the synthesis of activated carbon, including abundant availability, low cost and environmentally friendly properties (10). Furthermore, the utilization of plant-based activated carbon helps to valorize agricultural wastes and biomass waste, decreasing reliance on fossil fuels and creating a circular economy (11, 12). Carbonization, activation and purification are three critical processes in the manufacture of AC from plant sources. Carbonization is the process of heating plant material in an oxygen-depleted atmosphere to eliminate volatile components and convert it to carbon. The carbon is then activated to improve its adsorption characteristics by forming a porous structure (13). This is usually accomplished by physical or chemical means, such as steam activation or chemical activation with activating agents such as phosphoric acid or zinc chloride.

Finally, purifying operations are performed to eliminate any remaining impurities or activating agents, ensuring that the finished product fulfils the specified quality criteria (14).

The selection of plant material for AC manufacture is critical because it has a large impact on the adsorption performance and characteristics of the resultant material. Agricultural leftovers (e.g., rice husk, coconut shell, sugarcane bagasse), wood-based materials (e.g., sawdust, wood chips) and other biomass waste (e.g., bamboo, fruit peels) have all been investigated for their potential as activated carbon precursors (15). The plant material chosen is determined by criteria such as availability, cost, carbon content and particular adsorption needs (16). The adsorption capacity and effectiveness of plant-based activated carbon are determined not only by the carbonaceous material's intrinsic qualities, but also by the surface functional groups and chemical composition. Surface modifications and post-treatments can be used to improve adsorption performance and customize the material for specific purposes (17). To increase the adsorption capacity and selectivity of plant-based activated carbon, techniques such as chemical functionalization, thermal treatments and impregnation with metal nanoparticles have been studied (18).

Furthermore, research efforts have concentrated on the development of new adsorbent materials and modifications to improve leachate adsorption performance (19). To increase adsorbent selectivity, adsorption capacity and regeneration potential, advanced approaches such as chemical modification, surface functionalization and hybrid adsorbents have been investigated. Adsorption has also been combined with other treatment technologies, such as biological processes or membrane filtration, to produce better removal efficiencies and comprehensive leachate treatment (20). However, the process's performance depends on variables such as starting pollutant concentration, chitosan dose, pH, sedimentation duration and their optimisation to maximise the adsorption process. Finally, the use of plant-based AC from constructed wetland (CW) is abundant and their regenerative nature makes them an appealing alternative to standard activated carbons.

More research and development in this area hold strong potential to expand the applications and enhance the performance of plant-based activated carbon materials for environmental remediation, water treatment and air purification. Continued efforts are essential to improve the leachate treatment process using CW and adsorption, explore novel adsorbents and integrate adsorption with other treatment technologies to achieve sustainable and environmentally friendly leachate management strategies. Traditionally, the one-variable-at-a-time (OVAT) method has been widely applied for developing media composition during the initial phases of experimental design (21). However, this method has limitations in identifying interactions among variables. In this study, RSM was employed to examine the combined effects of pH and contact time and to optimize the adsorption process for reducing COD in leachate. This approach builds on earlier research highlighting the efficiency of RSM in optimizing adsorption conditions for complex wastewater systems (22, 23).

Materials and Methods

Collection of leachates

Leachate samples were collected from Jeram Sanitary landfill in appropriate containers to retain their original composition and avoid additional contamination (Fig. 1).

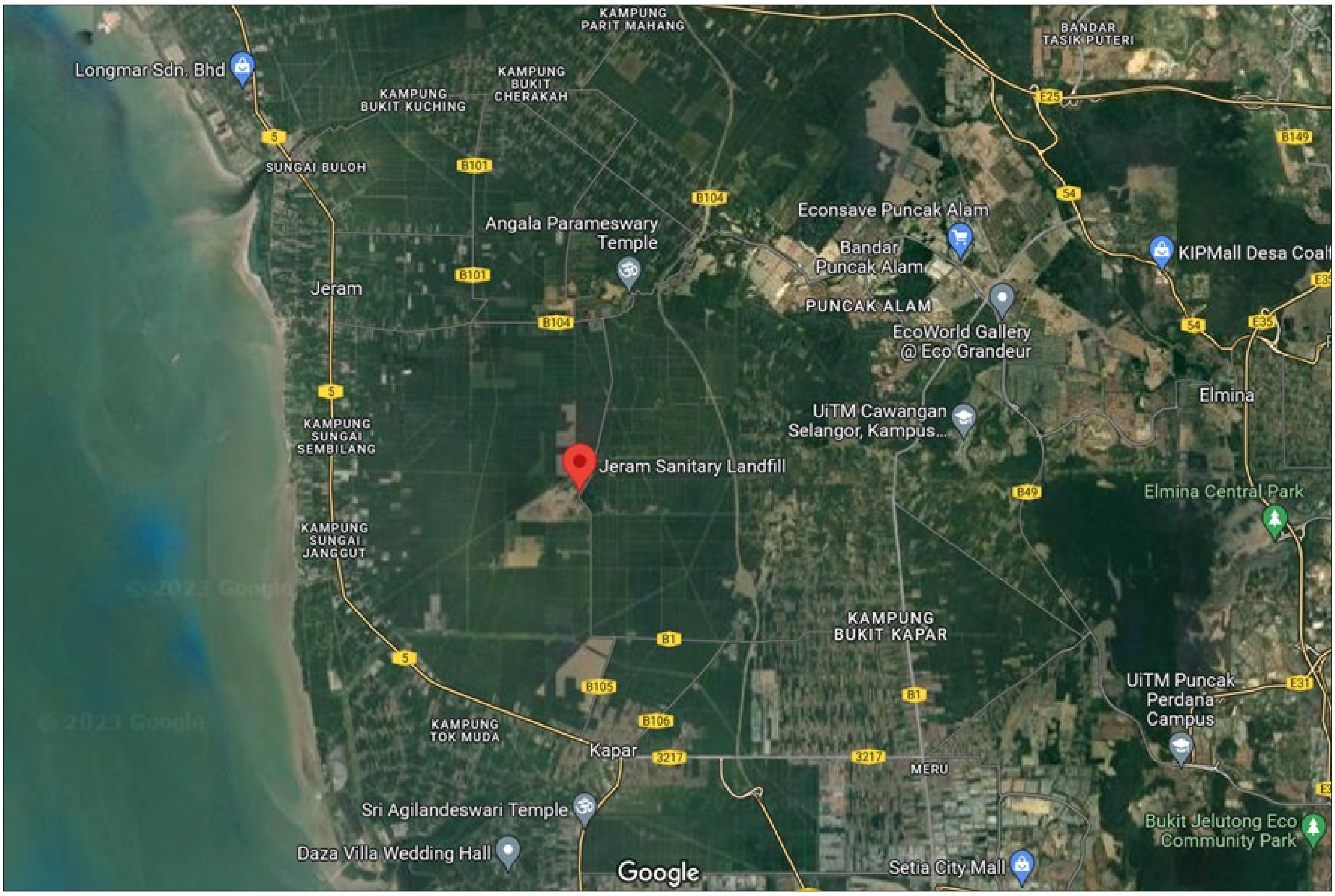


Fig. 1. Leachate sampling location.

Leachate characterization

The physicochemical parameters and pollutant concentrations of the collected leachate samples were determined. pH, COD and Fe concentrations were assessed (Table 1).

Plant selection and culture

C. esculenta plants were collected from Taman Tasik Metropolitan Kepong, Malaysia. The samples were taken by digging around the plant using a scoop. Following that, the plant samples were carefully extracted from the soil medium to ensure that the plant's roots were not harmed (21). The plant samples were gathered and acclimatised in the nursery tank for three days. Throughout the research period, healthy plant samples with nearly the same plant size and number of leaves (2 to 3) were chosen and utilised for research purposes to ensure the accuracy of the experimental results.

Preparation of plant-adsorbent

A carbonization and activation technique were used to create adsorbents from plant-based resources. The old *C. esculenta* plants were taken from CW tank, rinsed and dried at 100 °C for 12 hr in an oven. Physical activation entailed heating the carbonized material to high temperatures in the presence of steam or carbon dioxide and then, griding it to a sufficient particle size to pass a 63 µm mesh (22). The sequence of making CAC can be seen in Fig. 2.

Table 1. Leachate characteristics

Parameter	Unit	Result 1 (external lab)	Result 2 (internal lab)	Method
pH		7	8	ASTM D1293
COD	mg/L	3840	4784	APHA 5220 C/ HACH
Cadmium (Cd)	mg/L	ND (< 0.01)	-	APHA 3030 F b & APHA 3120 B
Nickel (Ni)	mg/L	ND (< 0.01)	-	APHA 3030 F b & APHA 3120 B
Iron (Fe)	mg/L	13.9	-	APHA 3030 F b & APHA 3120 B

Constructed wetland design and installation

For leachate treatment, a CW system was planned and installed in a 10 L tank size. The substrate material was chosen because it acts as a medium for plant development and as a surface for microbial adhesion. Substrates used include gravel 3-5 cm (3 cm), gravel 1-2 cm (3 cm) and biochar soil (5 cm). Constructed wetland reactor can be seen in Fig. 3.

Results and Discussion

Experiments with adsorption

In this study, *C. esculenta* var. *antiquorum* was selected. This variety, locally known as "keladi pulut" in Malaysia, is commonly found in wetland areas and is known for its high biomass production and tolerance to polluted water. The specimens were collected from Taman Tasik Metropolitan Kepong, Selangor, Malaysia, where they naturally grow in moist, nutrient-rich soils. *C. esculenta* activated carbon (CAC) was used in adsorption studies. To generate standard solutions for ad-sorption testing, leachate samples were collected from the CW effluent. In batch adsorption tests, a 100 mL volume of leachate was mixed with 1 g of CAC. The containers were agitated or mixed (120 rpm) to ensure appropriate contact between the leachate and the CAC and the adsorption process was allowed to run for a predetermined amount of time (15-60 min) and a pH of 5-7 (11, 23). Samples were collected at regular intervals and examined to determine the residual pollutant concentrations in the leachate. By comparing the initial and final pollutant concentrations and the efficiency of plant-activated carbon were assessed (Fig. 4).

Fig. 2. Stages of CAC process.

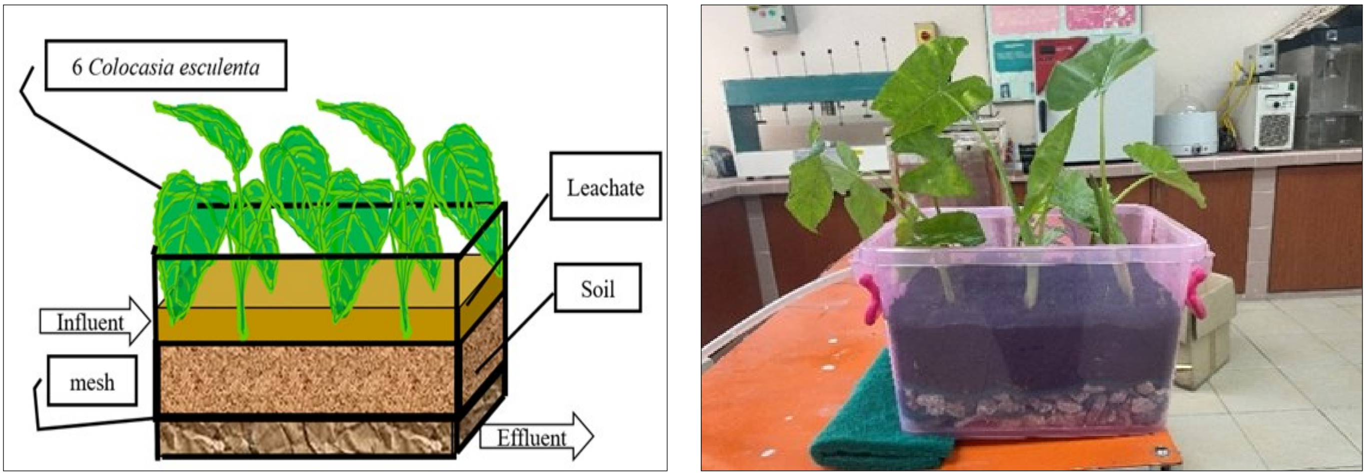


Fig. 3. Constructed wetland reactor.

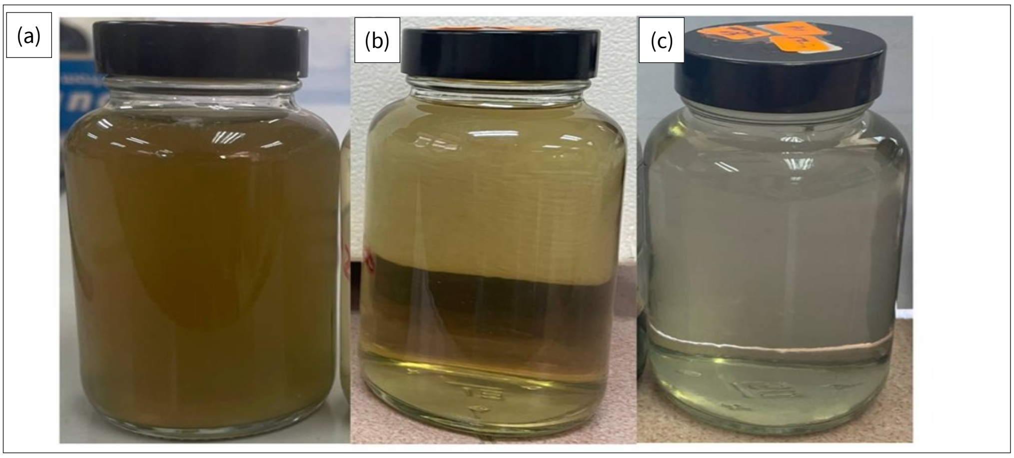


Fig. 4. Leachate visualization (a) raw leachate; (b) after treatment using constructed wetland; (c) after adsorption process.

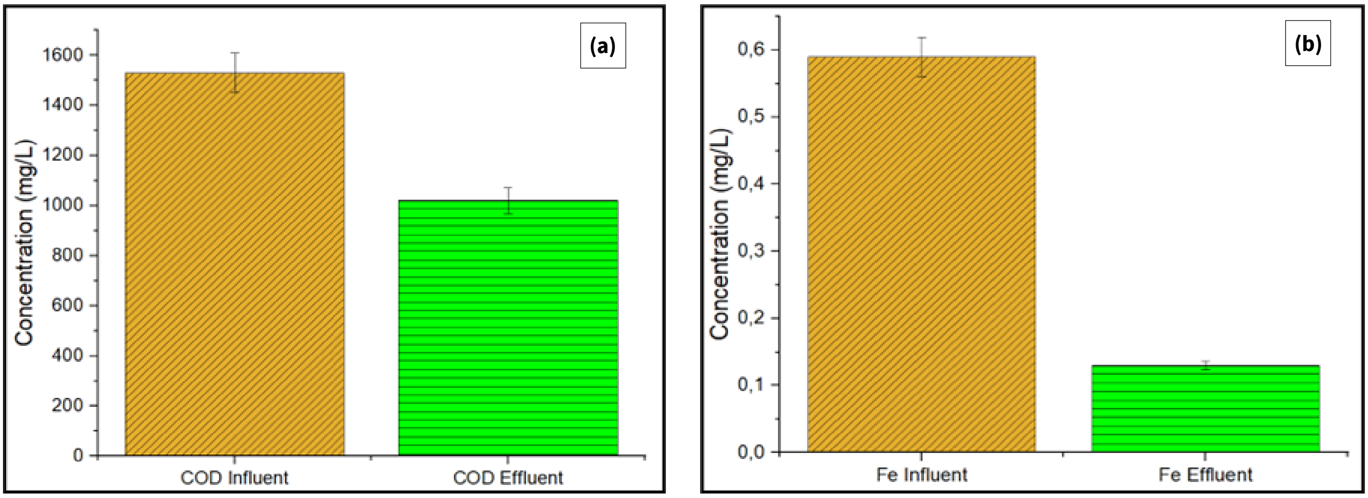


Fig. 5. Leachate treatment result using CW.

Constructed wetland

C. esculenta was assessed for its performance in leachate treatment in a constructed wetland. CW is a treatment that is commonly used for leachate (25). Leachate was tested in CW for pre-treatment of COD and Fe (Fig. 5).

C. esculenta exhibited a low concentration reduction from 1531 mg/L to 1020 mg/L, whereas Fe was reduction from 0.59 mg/L to 0.13 mg/L (Fig. 5). However, *C. esculenta* did not significantly contribute to COD removal. This result is consistent with previous studies, which have reported that constructed wetland shows greater heavy metal reduction (26). However, the effluent still retained a yellowish colour and high COD concentration. The adsorption process has the potential to purify the water colour and COD by using an adsorbent (27). This finding suggests that the CW is better suited for further treatment or modification with AC to reduce the yellowish colour and increase COD removal.

Response surface methodology

OVAT analysis for primary screening of medium components

Based on the previous research screened and optimised the major influencing factors (pH and contact time) for the adsorption process were screened and optimised. Different pH and contact time were then chosen for an OVAT study to discover the most optimal leachate treatment. The factor con-centration ranges were established based on current literature data and publications (24). Subsequently, RSM based on central composite design (CCD) was used to model and optimise the parameters that impact the adsorption process for effective COD removal in leachate. The

Table 2. Central composite experimental design matrix on adsorption processes

Std	Run	Factor 1	Factor 2	Response 1	Response 2
		A: pH	B: contact time	COD	Fe
			min	%	%
11	1	6	37.5	46.37	84.62
5	2	4	37.5	2.06	69.23
1	3	5	15	12.65	69.23
12	4	6	37.5	46.37	84.62
7	5	6	5.68	17.65	53.85
3	6	5	60	11.57	61.54
4	7	7	60	12.65	61.54
2	8	7	15	26.57	53.85
6	9	7	37.5	45.98	84.62
10	10	6	37.5	46.37	84.62
8	11	6	69.32	28.33	69.23
9	12	6	37.5	46.37	84.62
13	13	6	37.5	46.37	84.62

parameters of the adsorption process, namely contact time (A) and pH of leachate (B) were examined. The range and magnitude of the process variables are shown in Table 2.

Assessment of COD and Fe using OVAT analysis in adsorption treatment (pH versus contact time)

The effect of pH and contact time in the adsorption process wase chosen for an OVAT study. The contact time and pH ranges were selected based on existing literature data and available reports (28). Based on the previous study, contact time (15-60 min) and pH (5-7) were chosen as the variable for the subsequent OVAT analysis (29). Table 3 displays the results of the experimental vs projected values for all 13 experimental runs. ANOVA was used to assess the statistical

Table 3. Design matrix and CCD experimental and predicted results for COD removal in leachate treatment

Source			Sum of squares	df	Mean square	F-value	*p*-value	
Model			2977.02	5	595.40	8.21	0.0076	significant
A-pH			743.29	1	743.29	10.25	0.0150	
B-contact time			0.0013	1	0.0013	0.0000	0.9967	
AB			41.22	1	41.22	0.5684	0.4755	
A^2			1191.30	1	1191.30	16.43	0.0049	
B^2			1286.91	1	1286.91	17.75	0.0040	
Residual			507.62	7	72.52			
Lack of fit			507.62	3	169.21			
Pure error			0.0000	4	0.0000			
Cor total			3484.64	12				
Std. Dev.	8.52	R^2	0.8543					
Mean	29.95	**Adjusted R^2**	0.7503					
C.V. %	28.44	**Predicted R^2**	-0.0359					
		Adeq Precision	6.8803					

Table 4. Design matrix and CCD experimental and predicted results for Fe removal in leachate treatment

Source	Sum of squares	df	Mean Square	F-value	*p*-value	
Model	1498.33	5	299.67	5.99	0.0181	significant
A-pH	5.10	1	5.10	0.1019	0.7588	
B-contact time	59.14	1	59.14	1.18	0.3128	
AB	59.14	1	59.14	1.18	0.3128	
A^2	231.65	1	231.65	4.63	0.0684	
B^2	1260.91	1	1260.91	25.22	0.0015	
Residual	349.95	7	49.99			
Lack of fit	349.95	3	116.65			
Pure error	0.0000	4	0.0000			
Cor total	1848.29	12				
Std. Dev.	7.07	R^2	0.8107			
Mean	72.78	**Adjusted R^2**	0.6754			
C.V. %	9.71	**Predicted R^2**	-0.3464			
		Adeq Precision	6.4060			

significance of the quadratic model (Table 3, 4). Eq. 1 and Eq. 2 show the quadratic equation derived from ANOVA for COD and Fe.

$$Y = +15.73 + 23.41A + 0.02B - 5.08AB - 1.97A^2 - 0.0002B^2 \quad (1)$$

$$Y = -225.79 + 98.00A + 0.14B - 5.15AB - 8.1A^2 - 0.0019B^2 \quad (2)$$

Model terms were evaluated by the highest value of coefficient of determination (R^2), F-test, *p*-value and lack of fit. *P*-values less than 0.05 indicate that model terms are significant. In this case B^2 was a significant model term. Values greater than 0.10 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve the model (30). Table F-test values of 8.21 and 5.99, indicating that the developed models are significant (Table 3 & 4). The predicted R^2 value for COD and Fe (0.8543 and 0.8107, respectively) is in reasonable agreement with the adjusted R^2 values (0.7503 and 0.6754, respectively), with a difference of less than 0.2 (31). In this study, the adequate precision was less than 15 for the two responses, proving the model can be used to navigate the design space. Additionally, the adequate precision ratio, with a value of 6.88 and 6.41, are higher than 4, which indicates an adequate signal (30).

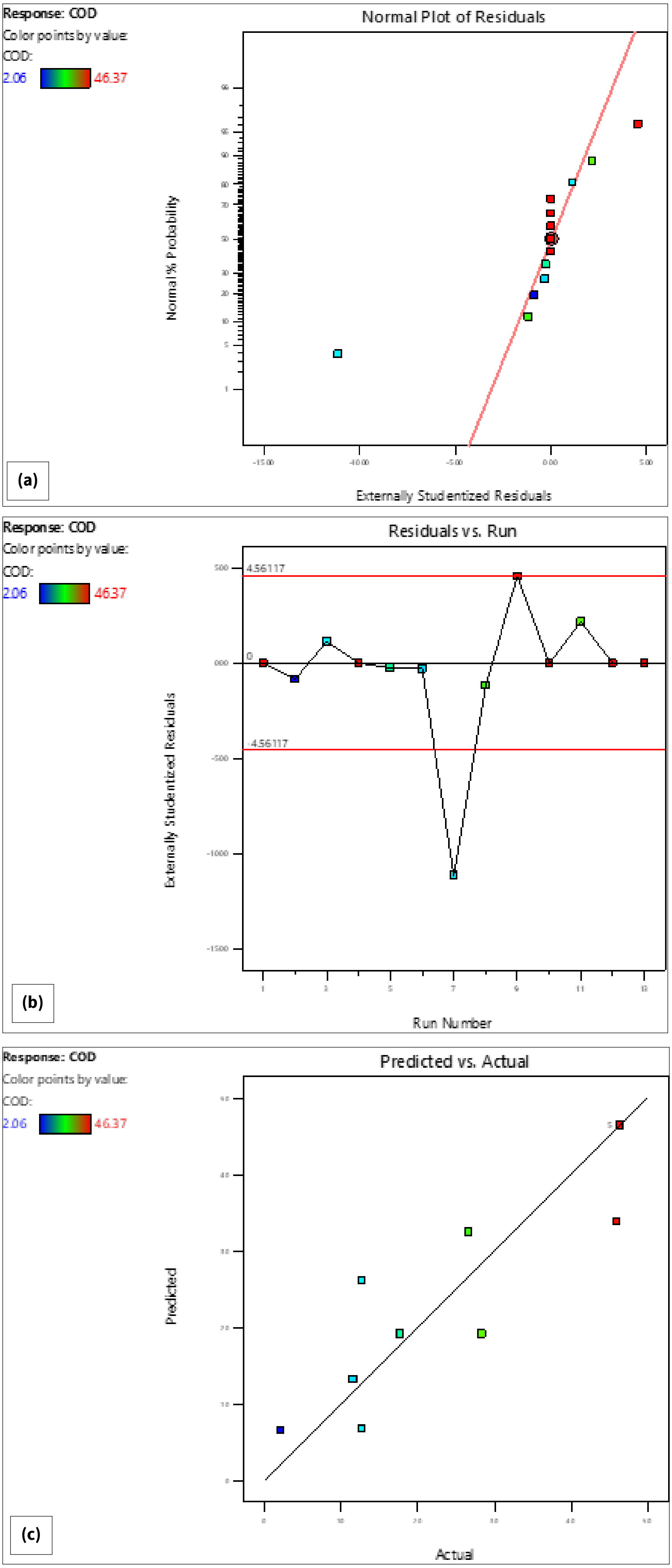
RSM model analysis

The RSM model was utilized to fit the experimental data and the relationship between normal and residual plots, actual and predicted values and surface of interactive effect between contact time and pH was analysed (Fig. 6 & 7). The normal plot residual showed that the data points closely followed the straight line, indicating that the model is a reliable tool for predicting responses from independent input data points. Although some data points deviated from the normal distribution, the deviation was not significant.

The residual versus run number plot showed that the data points were randomly scattered within the red line boundaries, while one point exceeded the redline (Fig. 6). A somilar condition observed in previous study showed that the residuals are normally distributed and the variance equations do not appear to be violated (32). Furthermore, the predicted vs. actual plot revealed that the distribution points were closely matched along the 45 ° line, implying that the model can reliably predicting COD and Fe reduction (Fig. 4c & 5c). The 3D response surface plots highlighting the interaction impacts of each factor's response and experimental levels (Fig. 6d & 7d). According to the response surface plots, the highest turbidity reduction is located within the design limit.

The interaction influence of pH and contact time throughout a 60-min adsorption time (Fig. 6d & 7d). The pH increases the COD and Fe removal rise gradually in line with the increase in contact time. In contrast, when the pH approaches alkaline levels, COD and Fe removal reduces at a higher time of 40 min. The resulting graphic appearance is like what has been done in previous studies, which found that a high pH and a longer contact time can reduce the performance efficiency of the adsorption process (33, 34).

Overall, the results show that *C. esculenta* in the constructed wetland effectively removed certain pollutants (notably Fe) but gave only limited COD reduction. Integrating a subsequent adsorption step using CAC markedly improved COD and colour removal, supporting the value of combining phytotechnology and plant-



Response: COD
Color points by value:
COD:
2.06
46.37
Normal Plot of Residuals
Normal % Probability
Externally Studentized Residuals
(a)
Response: COD
Color points by value:
COD:
2.06
46.37
Residuals vs. Run
4.56117
0
-4.56117
Externally Studentized Residuals
Run Number
(b)
Response: COD
Color points by value:
COD:
2.06
46.37
Predicted vs. Actual
Predicted
Actual
(c)

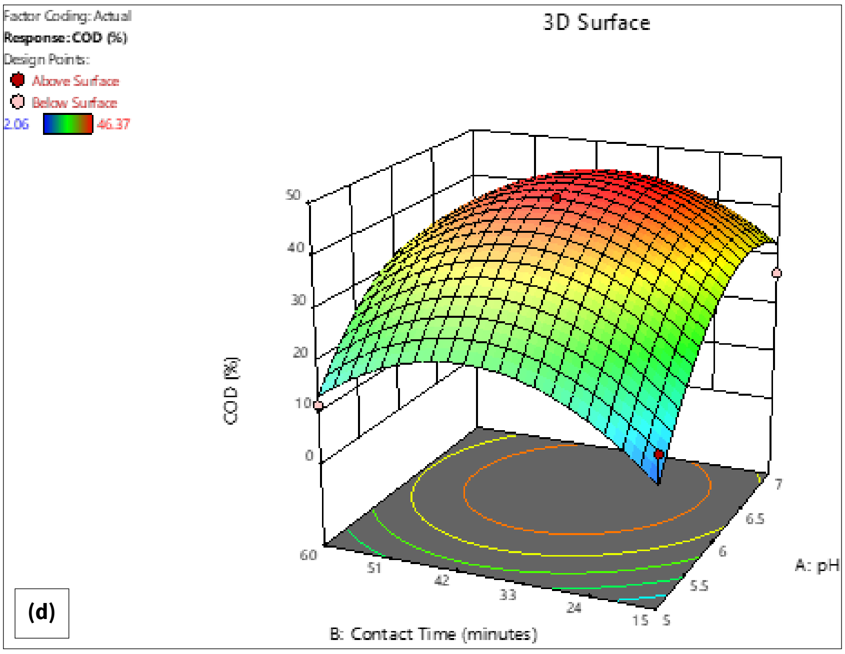
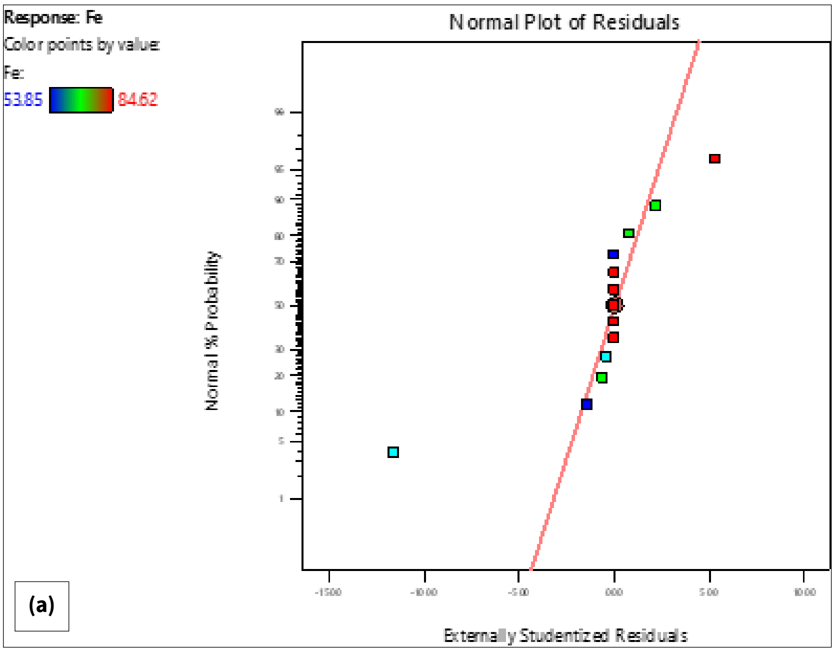
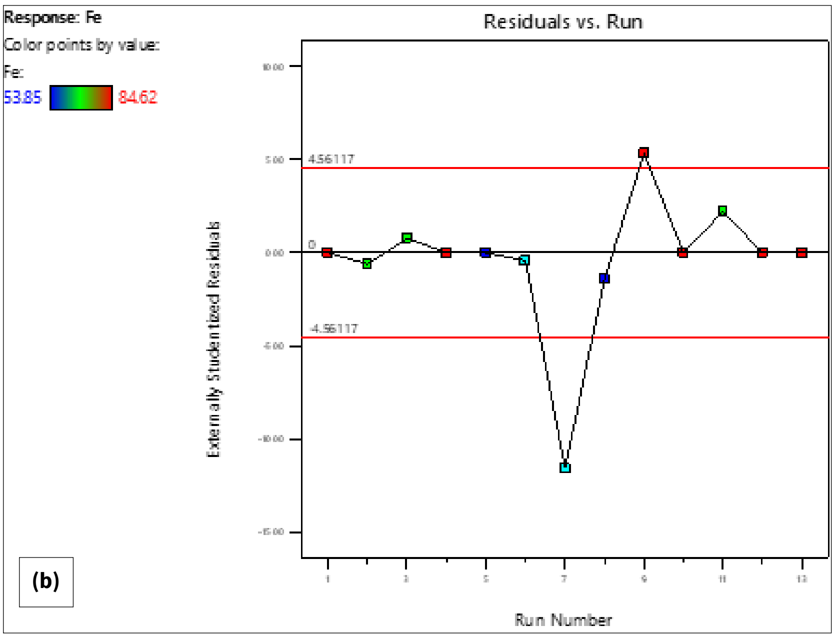


Fig. 6. Plot of (a) normal plot of residuals; (b) residuals versus run number; (c) predicted versus actual; (d) surface of interactive effect between a contact time and pH for COD removal in leachate treatment using CAC as adsorbent.





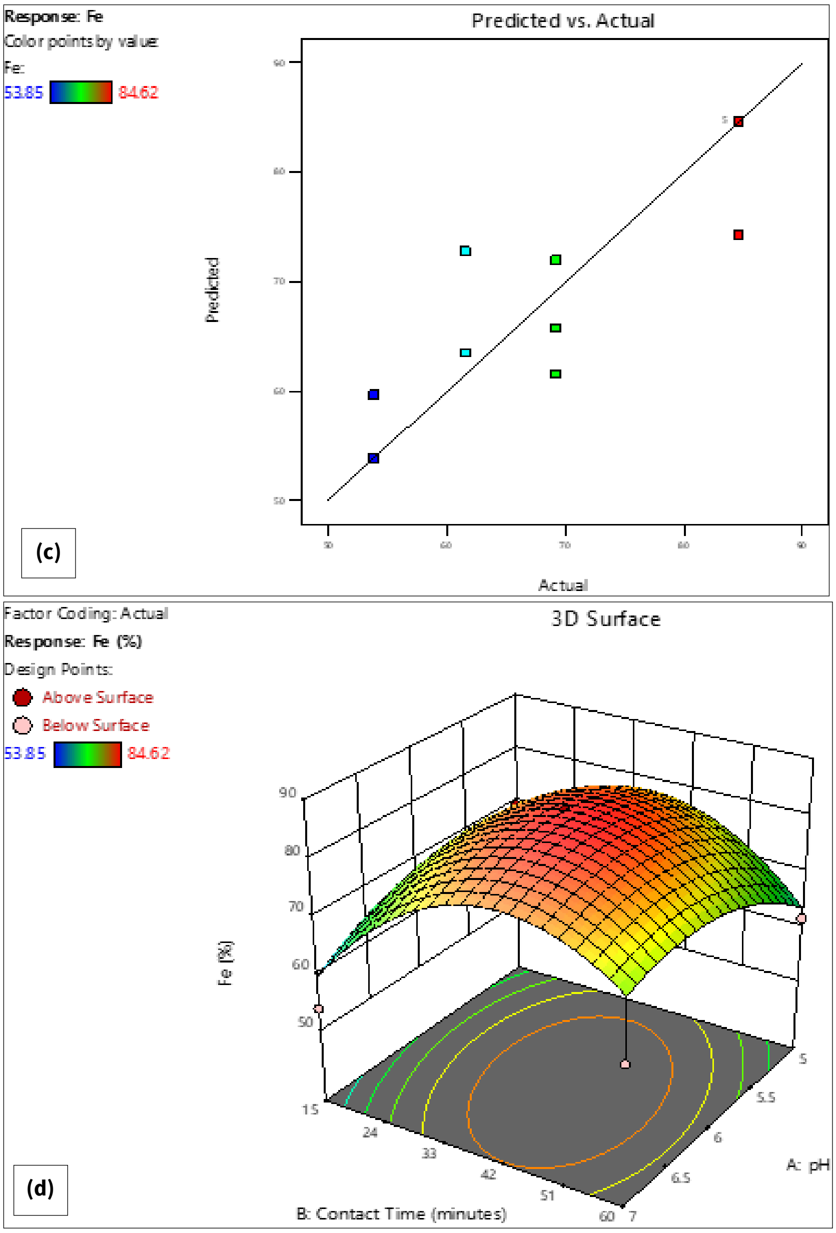


Fig. 7. Plot of (a) normal plot of residuals; (b) residuals versus run number; (c) predicted versus actual; (d) surface of interactive effect between a contact time and pH for Fe removal in leachate treatment using CAC as adsorbent.

based adsorbents for leachate polishing (35, 36). Optimization using RSM confirmed that pH and contact time are key parameters for adsorption efficiency and the developed quadratic models had acceptable predictive performance within the experimental domain (37, 38).

Conclusion

The research undertaken in this study explored the multifaceted utility of *C. esculenta* in two distinct applications: as a constituent of constructed wetlands and as an adsorbent for the treatment of COD and iron in leachate. Through the systematic application of RSM, the results provided valuable insights into the optimization of these applications. The predicted R^2 values for COD and Fe (0.8543 and 0.8107, respectively) are in reasonable agreement with the adjusted R^2 values (0.7503 and 0.6754, respectively). The combination of multipurpose *C. esculenta*, constructed wetlands and RSM optimization represents a promising approach for the sustainable and cost-effective treatment of COD and iron in wastewater. This innovative method aligns with the principles of green and eco-friendly wastewater treatment, offering a viable solution for addressing water pollution challenges.

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Authors' contributions

IA conducted the experimental research, performed data collection and contributed to drafting the manuscript. SC provided the overall research guidance, designed the study and performed the statistical analysis using response surface methodology (RSM). BVT contributed to the analysis and interpretation of the data and helped in manuscript preparation. SM participated in the study design, provided expert advice on the treatment process and supported the experimental setup. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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