Article

Application of the Response Surface Methodology (RSM) in the Optimization of Acenaphthene (ACN) Removal from Wastewater by Activated Carbon

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Abstract: The presence of polycyclic aromatic hydrocarbons (PAHs) in wastewater has raised concerns about human health due to their potential carcinogenic and mutagenic properties. The widespread use of products containing acenaphthene (ACN, one of the 16 priority PAHs) in many industries and large-scale ACN release into the wastewater has resulted in dangerous concentrations of ACN in the environment. As a result, before discharge, it is required to eliminate or reduce its concentration to an acceptable level. Adsorption is an effective method of removing PAHs from wastewater. In this study, the ACN adsorption reaction in sample wastewater was evaluated using activated carbon produced by oil palm leaves. HPLC was used as an analytical method for quantifying ACN in wastewater samples. The initial concentration of ACN in water samples was 9.58 ± 0.5 mg/L. The experiments were conducted using the CCD combined with the RSM and using three independent variables, i.e., pH, activated carbon dosage (g/L), and contact time (min), and one dependent variable, i.e., ACN removal efficiency (%). The ANOVA was used to identify the significance of the developed model in the RSM. Lastly, the RSM was used to optimize the adsorption results. The experimental results determined that the removal of 98.73 ± 1% of ACN (the highest amount) was achieved at pH 7, while the removal of 88.44 ± 1% of ACN (the lowest amount) was achieved at pH 4.5. The adsorption efficiency of ACN was slightly increased by an increase in activated carbon dosage from 0.1 to 3 g/L (<4%). The contact time was the most significant factor in controlling the adsorption efficiency of ACN in wastewater, and not pH value or dosage. The adsorption reaction was quick, and 88–90% of ACN was removed within 5 min of the adsorption reaction, followed by slower adsorption for up to 90 min. The RSM model was developed on the basis of experimental results. An ANOVA determined that the developed model was significant enough to represent the adsorption data as the p-value was <0.05 for the model. The factors pH, adsorbent dosage, and contact time were also significant factors (p-value < 0.05). The optimization results showed that pH of 6.96, adsorbent dosage of 2.62 g/L, and contact time of 71.67 min were the optimal conditions for eliminating 98.88% of the ACN. The optimization results were verified in the lab, and a close agreement was found between the predicted results of the RSM and experimental results. The study found that the RSM is an effective tool for optimizing operating variables, as well as for significantly reducing time and experimentation costs.

Keywords: polycyclic aromatic hydrocarbons; acenaphthene; adsorption; RSM; optimization
1. Introduction

Wastewater is water that has been used in homes, industries, or commerce and contains high concentrations of solids, dissolved and particulate matter, microorganisms, nutrients, heavy metals, and micropollutants. Micropollutants are hazardous chemicals found in water sources and treated wastewaters at concentrations in the range of microorganisms or lower. Micropollutants reach surface water bodies through a variety of routes. Chemical products of domestic, industrial, and agricultural activities are sources of micropollutants, which can be detected in trace concentrations in the range of a few ng/L to several g/L [1].

One of the regulated micropollutants is polycyclic aromatic hydrocarbons (PAHs), organic compounds that consist of two or more fused aromatic carbon and hydrogen rings. They are primarily released into the environment as byproducts of fuel combustion, but agricultural fires, industrial waste, and cooking can all increase the discharge of these toxic chemicals [2]. PAHs are rarely detected in significant concentrations in water due to their limited solubility [3]. They are classified as low- and high-molecular-weight PAHs. Those with two or three fused benzene rings, such as naphthalene, methylene, acenaphthylene, and acenaphthene, are called low-molecular-weight PAHs. Those with four or more fused benzene rings, such as chrysene, pyrene, and benzene (a) anthracene, are classified as high-molecular-weight PAHs [4]. PAHs are harmful to both humans and aquatic species. They harm fish growth, reproduction, and survival in extreme circumstances. Following biotransformation, PAHs may also generate reactive molecules, which bind to DNA and cause mutations or other alterations to the genetics of aquatic species [5]. Humans exposed to PAHs over time may develop cataracts, jaundice, or kidney and live damage [6]. The U.S. Environmental Protection Agency (USEPA) has designated 16 PAHs as priority pollutants due to their abundance and carcinogenicity [6,7]. Because of their high hydrophobicity, most PAHs are highly persistent, with low biodegradability and a strong attraction to organic materials [8].

PAHs have been removed using a number of techniques, such as ion exchange, electrochemical treatment, chemical oxidation, solvent extraction, reduction, precipitation, adsorption, and filtration [9–11]. Traditional wastewater treatment methods are insufficient to eliminate PAHs [12,13]. Some technologies have a high removal efficiency but have a high operational cost and may create secondary pollutants, such as electrocoagulation, microfiltration combined with membrane-based technologies, and biological processes [11]. Adsorption is one of the most cost-effective strategies for removing PAHs, as it produces less waste and requires less energy [14]. Although several different adsorbents have been used effectively for environmental remediation, activated carbon is thought to be the most prominent type [15].

The aim of this study is to investigate acenaphthene (ACN) adsorptive removal in the presence of other PAHs from wastewater using activated carbon. ACN is one of the 16 priority PAHs and is made up of naphthalene with an ethylene bridge connecting positions 1 and 8. ACN was chosen because of its relatively simple composition and ability to dissolve in an organic solvent (acetonitrile), which made its lab quantification easier [16]. ACN is also an organic part of coal tar and crude oil. It is mostly emitted into the atmosphere when coal and oil are burned, during natural fires, when the wood is burned, and through industrial emissions and effluents [17]. The widespread use of products containing ACN in many industries and large-scale ACN release into the environment has resulted in dangerous ACN concentrations in the environment. It is used widely in the production of many medications, dyes, plastics, pesticides, and fungicides [18]. Among the PAHs, ACN is also more likely to be chosen due to its increased water solubility [19].

The activated carbon in this study has been synthesized using oil palm leaves as a precursor. In the literature, using biomass-waste-produced activated carbons, organic contaminants such as medicines, dyes, and hydrocarbons have been efficiently removed from aqueous solutions [20]. However, no study has reported ACN removal from wastewater using activated carbon produced from oil palm leaves in Malaysia. Malaysia is the world’s largest producer of oil palm, after Indonesia, and 135 million tons of oil palm waste is
produced each year [21]. In this study, ground oil palm leaves were impregnated with zinc chloride to increase the surface area and enhance the adsorption efficiency of activated carbon. Zinc chloride is a powerful dehydrating agent that can change the structure of carbon materials to form a porous surface with more reaction sites.

The adsorption process must be optimized to reduce the process cost and material. The goal of the current study is to optimize the reaction conditions using the response surface methodology (RSM) in design expert software (version 13). The RSM is a mathematical and statistical tool that compares theoretical and experimental data by optimizing dependent variable values with multiple independent variables [22]. Traditional approaches are time-consuming compared to the RSM. They use a high number of parameters and larger factors at a time, and it is expensive to optimize the independent variables [23]. The RSM is implemented to assess the appropriate process parameters for ACN adsorption. In this study, the central composite design (CCD) coupled with the RSM was implemented to maximize ACN removal at optimum wastewater pH, activated carbon dosage, and contact time of adsorbent and wastewater. The CCD is one of the most widely used quadratic design techniques among experimental matrix designs [24]. It is developed using random experimentation to test for lack of fit without using a significant number of design points [25].

2. Materials and Methods

2.1. Materials

The oil palm leaves were collected from FELCRA Bhd., Perak, and used as a precursor for the preparation of activated carbon. A mixed standard solution of 16 priority PAHs (Accustandard, Z-014G-R), sodium hydroxide (NaOH), and sulfuric acid (H$_2$SO$_4$) were purchased from Avantis laboratory supply, Ipoh, Malaysia.

The PAH standard consisted of 16 PAHs (2000 mg/L each): acenaphthene, acenaphthylene, anthracene, 1,2-benzanthracene, benzo(a)pyrene, benzo(b)fluoranthene, benzo(g,h,i)perylene, benzo(k)fluoranthene, chrysene, dibenz(a,h)anthracene, fluoranthene, fluorene, indeno(1,2,3-cd)pyrene, naphthalene, phenanthrene, and pyrene.

2.2. Stock Solution Preparation

The stock standard solution of 1000 mg/L concentration was prepared by dissolving 2000 mg/L of PAH mix standard in 40 mL of acetonitrile and then diluting up to the mark of 2000 mL with methanol. Further dilute standards were prepared at 3 concentrations (50, 0.5, and 0.05 mg/L) by diluting the stock standard by adding water.

High-performance liquid chromatography (HPLC) analysis was conducted for diluted standards, and chromatograms were obtained containing the retention times and the peak areas for the 16 PAHs. A calibration curve was drawn at 3 concentrations (stated as above) for ACN only, and peak analysis in the calibration curve helped identify the unknown quantities of ACN in wastewater samples.

2.3. Analytical Method (Chromatographic Analysis Using HPLC)

The analysis was performed using HPLC [26]. HPLC (Agilent 1260 infinity series) equipped with an inertsil ODS-P HPLC column (5 µm, 250 × 4.6 mm) and a diode array ultraviolet (UV) 254 nm detector was used to quantify ACN in water samples. The mixture of methanol/water in the ratio of 80/20 was the mobile phase at a flow rate of 1 mL/min for 20 min. The injection volume was 20 µL, and the column temperature was 40 °C. At this condition, the retention time for ACN was 13.35 min. Quantification was performed using a calibration curve of standard ACN.

2.4. Synthesis of Activated Carbon

Activated carbon was prepared using our previously reported method [27]. Briefly, the oil palm leaves were washed, cut into small pieces, ground, and air-dried for 1 day. Dried oil palm leaves were impregnated into zinc chloride with an impregnation ratio of
1:1 into a chemical solution of 0.1 M zinc chloride. The biomass was dried in an oven at a temperature of 160 °C for 5 h. The dried leaves were pyrolyzed in a tube furnace for 2 h at 800 °C at a heating rate of 10 °C/min under a nitrogen gas flow rate of 150 cm²/min. The obtained activated carbon was cooled and stored for further use.

2.5. Lab Experiments

The wastewater sample was prepared by adding distilled water to the stock standard solution to obtain ACN with an initial concentration of 10 mg/L in the presence of 15 other PAHs (10 mg/L each). This initial concentration of ACN was taken on the basis of the average higher reported concentrations of ACN in the literature, such as 5–25 mg/L [28], 1–3 mg/L [29], and 0.7–3.5 mg/L [30]. Batch tests were performed under the following parameters: solution pH 2–7, dosage of activated carbon 0.1–3 g/L, and contact time of 5–90 min. The parameters were chosen based on the literature [31].

To obtain the required pH, 0.1 M NaOH and 0.1 M H₂SO₄ were added to the wastewater sample according to the experimental requirement. The reaction was carried out in a beaker. The beaker was placed on a hot plate, and a magnetic stirrer inside the reactor was used to homogeneously blend the reagent in wastewater. The adsorption process began with the addition of a measured amount of activated carbon to the wastewater sample. During the experimentation, the temperature and the speed of the magnetic stirrer were kept constant at 25 °C and 250 rpm, respectively. After the process stopped, the sample was taken out using a syringe. A filter (0.45 µm) was placed at the end of the syringe to filter the treated wastewater sample. In all, 2 mL of the sample was extracted, placed in a sampling bottle, and labeled. The filtered wastewater samples were used for ACN quantification using HPLC. Each experiment was performed in triplicate, and the average value was taken.

The percentage of ACN removed was calculated as follows:

\[
\text{ACN removal (％)} = \frac{\text{Initial concentration of ACN} - \text{Final concentration of ACN}}{\text{Initial concentration of ACN}} \times 100 \quad (1)
\]

2.6. Optimization Using Central Composite Design (CCD) with the Response Surface Methodology (RSM)

The RSM is an important statistical and mathematical approach often used for the systematic design and analysis of experiments using Design-Expert software [32]. To optimize ACN removal using activated carbon, the experimental design was created using Design-Expert software (Version13).

The CCD was used to determine the combination of selected parameters for the RSM analysis. This procedure thoroughly investigates all the factors and their interaction [33]. Table 1 shows the selected parameters and their respective levels in CCD. There are three numeric factors for the design: pH, dosage, and contact time.

Table 1. Parameters for the experimental design.

| Parameters  | Unit | Lowest Value | Highest Value |
|-------------|------|--------------|---------------|
| Numeric 1   | pH   | 2            | 7             |
| Numeric 2   | Dosage | g/L         | 0.1           | 3             |
| Numeric 3   | Contact time | min | 5            | 90            |

CCD identified 20 combinations of experiments that account for factorial, axial, and center points (Table 2). As for the response, the input was ACN removal percentage as the targeted PAH. The experiments were performed as per the setup explained in Section 2.5.

A regression equation determined the correlation between the response and the variables that were chosen [23]. The analysis began after all values had been input into the RSM model.
To analyze the statistical validation and predictive quality of the proposed model, an ANOVA (analysis of variance) was performed in the RSM model. The predicted vs. the actual experimental values were plotted to indicate the relationship between datasets. Response surfaces and contour plots were used to examine the interaction effects of the factors.

After model validation, using ANOVA in the RSM, the parameters were optimized to maximize the response.

Table 2. Experimental design by CCD coupled with the RSM for ACN removal.

| Run | pH | Dosage (g/L) | Contact Time (min) |
|-----|----|--------------|--------------------|
| 1   | 2  | 3            | 5                  |
| 2   | 2  | 1.55         | 47.5               |
| 3   | 7  | 3            | 5                  |
| 4   | 4.5| 1.55         | 47.5               |
| 5   | 7  | 3            | 90                 |
| 6   | 4.5| 1.55         | 90                 |
| 7   | 7  | 0.1          | 5                  |
| 8   | 4.5| 0.1          | 47.5               |
| 9   | 4.5| 1.55         | 47.5               |
| 10  | 7  | 0.1          | 90                 |
| 11  | 4.5| 1.55         | 5                  |
| 12  | 4.5| 1.55         | 47.5               |
| 13  | 2  | 3            | 90                 |
| 14  | 4.5| 1.55         | 47.5               |
| 15  | 4.5| 1.55         | 47.5               |
| 16  | 7  | 1.55         | 47.5               |
| 17  | 2  | 0.1          | 90                 |
| 18  | 4.5| 1.55         | 47.5               |
| 19  | 4.5| 3            | 47.5               |
| 20  | 2  | 0.1          | 5                  |

3. Results and Discussion

3.1. HPLC Results

From the mix standards of 16 PAHs, ACN was chosen as a representative PAH compound in this study because it is one of the 16 USEPA priority PAHs and has a high concentration in crude oil and coal tar [18]. For the initial concentration, the wastewater samples were prepared at 10 mg/L PAHs, and the initial reading was known before the experimentation was performed. The HPLC chromatogram showed the peak area of PAHs with respect to retention time.

The retention time for ACN was 13.35 min. The chromatogram gave the initial concentration reading as 9.58 ± 0.5 mg/L for ACN. The loss in ACN amount may be due to volatilization and sorption onto the reactor walls [34]. Figure 1a shows the HPLC chromatogram before adsorption of ACN. A higher peak area of ACN can be seen in the chromatogram before adsorption, whereas the peak area is reduced after the adsorption of ACN (Figure 1b). The reduction shows the potential of activated carbon to adsorb the ACN in the sample solution [31].
Figure 1. HPLC analysis of wastewater (a) before and (b) after adsorption of can.

The HPLC chromatograms were obtained after each batch experiment, and the reduction in the peak area of ACN was correlated with the final concentration of ACN in the water sample using the calibration curve.

Table 3 states the final concentrations of ACN in water samples. The percentage removal of ACN was calculated using Equation (1) and is presented in Table 3.

Table 3. Results for percentage ACN removal.

| pH | Dosage (g/L) | Contact Time (min) | Initial ACN Concentration (mg/L) | Final ACN Concentration (mg/L) | Removal of ACN (%) |
|----|--------------|--------------------|----------------------------------|-------------------------------|-------------------|
| 2  | 0.1          | 5                  | 9.58 ± 0.5                       | 0.88 ± 0.2                    | 90.83 ± 1         |
| 2  | 0.1          | 90                 | 9.58 ± 0.5                       | 0.60 ± 0.2                    | 93.69 ± 1         |
| 2  | 1.55         | 47.5               | 9.58 ± 0.5                       | 0.39 ± 0.2                    | 95.92 ± 1         |
| 2  | 3            | 5                  | 9.58 ± 0.5                       | 0.95 ± 0.2                    | 90.07 ± 1         |
| 2  | 3            | 90                 | 9.58 ± 0.5                       | 0.317 ± 0.2                   | 96.69 ± 1         |
| 4.5| 0.1          | 47.5               | 9.58 ± 0.5                       | 0.53 ± 0.2                    | 94.49 ± 1         |
| 4.5| 1.55         | 5                  | 9.58 ± 0.5                       | 1.11 ± 0.2                    | 88.44 ± 1         |
| 4.5| 1.55         | 47.5               | 9.58 ± 0.5                       | 0.52 ± 0.2                    | 94.60 ± 1         |
| 4.5| 1.55         | 90                 | 9.58 ± 0.5                       | 0.40 ± 0.2                    | 95.82 ± 1         |
| 4.5| 3            | 47.5               | 9.58 ± 0.5                       | 0.36 ± 0.2                    | 96.23 ± 1         |
| 7  | 0.1          | 5                  | 9.58 ± 0.5                       | 0.98 ± 0.2                    | 89.82 ± 1         |
| 7  | 0.1          | 90                 | 9.58 ± 0.5                       | 0.32 ± 0.2                    | 96.62 ± 1         |
| 7  | 1.55         | 47.5               | 9.58 ± 0.5                       | 0.26 ± 0.2                    | 97.25 ± 1         |
| 7  | 3            | 5                  | 9.58 ± 0.5                       | 1.01 ± 0.2                    | 89.49 ± 1         |
| 7  | 3            | 90                 | 9.58 ± 0.5                       | 0.12 ± 0.2                    | 98.73 ± 1         |
3.2. Effect of Solution pH

On the basis of the results in Table 3, the effect of pH on ACN adsorption on activated carbon was investigated. The results showed an increase in ACN adsorption as the pH increased from 2 to 7. The highest amount of ACN, an average of 98.73 ± 1%, was removed at pH 7, while the lowest amount of ACN, an average of 88.44 ± 1%, was removed at pH 4.5. However, the initial pH value of the wastewater did not seem to significantly affect the adsorption reaction, as the difference in removal between pH 2 and 7 (at similar dosage and contact time) was less than 4%. At a dosage of 3 g/L and contact time of 90 min, the removal efficiency was 96.69 ± 1% and 98.73 ± 1% at pH 2 and 7, respectively, whereas at a dosage of 3 g/L and contact time of 5 min, the removal efficiency was an average of 90.07 ± 1% and 89.49 ± 1% at pH 2 and 7, respectively. Hence, an increase in the solution pH did not always increase the removal efficiency of ACN because ACN is chemically stable. At higher pH values (8–12), the adsorption was not evaluated. This is because, according to previous research, due to the formation of positive charges on the surface of the adsorbent, the electrostatic interaction between PAHs and the surface charge of the adsorbent increases, leading to greater adsorption at low pH. At higher pH values, the positive charge on the adsorbent surface decreases, and the PAHs may interact with the -OH ions to adsorb on the active site, thus reducing the adsorption efficiency of the adsorbent [35].

3.3. Effect of Activated Carbon Dosage

The results in Table 3 show the adsorption performance of ACN with varying amounts of activated carbon (0.1–3 g/L). At pH 2 and contact time of 90 min, the removal efficiency of ACN increased from 93.69 ± 1% to 96.69 ± 1%, with an increase in the dosage from 0.1 g/L to 3 g/L. Similarly, at pH 7 and contact time of 90 min, the average amount of ACN removed increased from 96.62 ± 1% to 98.73 ± 1%, with an increase in the dosage from 0.1 g/L to 3 g/L. Hence, the adsorption of ACN was slightly influenced by the activated carbon dosage. Due to the possibility of adhesion, which limits the adsorption process, an increase in the adsorbent dosage had no significant effect on the adsorption of ACN.

3.4. Effect of Contact Time

To investigate the effect of contact time on the adsorption of ACN onto activated carbon, the wastewater sample containing the adsorbent was mechanically shaken for varying lengths of time (5–90 min). The samples were collected at contact times of 5, 47.5, and 90 min. The results (Table 3) showed that the contact time had the highest impact on the adsorption reaction of ACN. At pH 2 and a dosage of 3 g/L, the removal efficiency of ACN increased from 90.07% to 96.69%, with an increase in contact time from 5 min to 90 min. Similarly, at pH 7 and a dosage of 3 g/L, the removal efficiency of ACN increased from 89.49% to 98.73%, with an increase in contact time from 5 min to 90 min. However, at all pH and dosage values, the adsorption reaction was quick, as 88–90% of the ACN was removed within 5 min of the reaction time. Further, adsorption gradually increased for up to 90 min. It shows that initially, due to the availability of multiple adsorption sites, a large amount of ACN was progressively adsorbed by the activated carbon. However, with increasing time, most active sites on the activated carbon became occupied, and equilibrium was reached, leading to a slower adsorption rate. Previous studies have reported similar findings for the adsorption of various PAHs to various adsorbents; that is, PAH adsorption increased with an increase in the contact time and remained unchanged or changed slightly after equilibrium was reached [36].

3.5. CCD-Based RSM and Analysis of Variance (ANOVA)

The CCD-based RSM was used to investigate and optimize the effect of pH, dosage, and contact time on the percentage removal of ACN as the response function. The experimental results are shown in Table 3. An analysis of variance (ANOVA) was used to
determine the significance of the created RSM models. The results of the ANOVA are displayed in Table 4.

Table 4. ANOVA for the quadratic model of ACN removal.

| Source      | Sum of Squares | df * | Mean Square | F-Value | p-Value |
|-------------|----------------|------|-------------|---------|---------|
| Model       | 134.26         | 9    | 14.92       | 60.69   | 0.0425  |
| A-pH        | 37.40          | 1    | 37.40       | 7.91    | 0.0374  |
| B-Dosage    | 1.91           | 1    | 1.91        | 11.87   | 0.0343  |
| C-Contact   | 0.0012         | 1    | 0.0012      | 388.20  | 0.0023  |
| AB          | 1.30           | 1    | 1.30        | 0.09    | 0.0145  |
| AC          | 0.0021         | 1    | 0.0021      | 19.27   | 0.0230  |
| BC          | 3.71           | 1    | 3.71        | 17.16   | 0.0430  |
| A²          | 4.25           | 1    | 4.25        | 14.62   | 0.0112  |
| B²          | 6.42           | 1    | 6.42        | 0.011   | 0.0122  |
| C²          | 12.80          | 1    | 12.80       | 93.98   | 0.0032  |
| Residual    | 0.0001         | 10   | 5.75 x 10⁻⁶ |         |         |
| Lack of fit | 0.0001         | 5    | 0.000       |         |         |
| Core total  | 134.26         | 19   | R²          |         | 0.99    |

* df—degree of freedom.

The p-values and F-values were used to assess the significance of the coefficient terms (pH, dosage, and contact time). A significant model has a higher F-value and a lower p-value. The p-values should be less than 0.0500 to indicate that the model terms are significant. On the basis of Table 4, the p-value for the developed model was 0.0425. Thus, the model was significant. All the factors, A (pH), B (dosage), and C (contact time), were also significant (p-value < 0.05), which means that these factors play an important role in the removal of ACN during the adsorption process. The model’s F-value of 60.69 indicates that it was significant. An F-value this large could occur due to noise only 0.01 percent of the time.

The relationship between the studied factors (pH, dosage and contact time) and ACN removal (%) is represented by the following equation:

\[
\text{ACN removal (\%)} = 95.18 + 0.47A + 0.58B + 3.29C - 0.05AB + 0.82AC + 0.77BC + 1.26A^2 + 0.03B^2 - 3.19C^2
\]  

(2)

3.6. Three-Dimensional Surface Plots and Optimization Using the RSM

Figure 2a shows that experimental ACN removal (%) correlates well with the predicted ACN removal (%), with high R² values of 0.99. Furthermore, the distribution of all data points was next to the 45° straight line.

The influence of independent factors (pH, dosage, and contact time) and their interactions on ACN elimination (%) is represented by 3D plots (Figure 2b–d) with varied peak values and curves. Two independent variables were systematically altered in 3D plots, while the remaining independent variables were kept constant. The surface plots in Figure 2b,c show that high ACN removal was achieved near a pH level of 7. The effect of the adsorbent dosage on ACN removal shows that at a higher adsorbent dosage, the removal percentage increased significantly due to the increased available specific surface area and adsorbent vacant area (Figure 2b,d). Thereafter, the percentage of ACN removed remained the same or decreased slightly.

Figure 2c,d show a positive correlation between ACN removal efficiency (%) and contact time.
remained the same or decreased slightly. Figure 2c,d show a positive correlation between ACN removal efficiency (%) and contact time.

Finally, the experimental parameters were optimized using the established RSM models to maximize the removal (%) of ACN. The maximum ACN removal value of 98.88% was observed under the following optimal experimental parameters: wastewater pH = 6.96, activated carbon dosage = 2.62 g/L, and contact time = 71.67 min each (Figure 3). To assess the reliability of the created RSM models, the experimentally observed ACN removal (%) was compared with the RSM-model-projected values. Experiments were run in duplicate under optimal conditions. The experimentally determined (97.35 ± 1.5%) and model-predicted (98.88%) ACN elimination data were found to be in extremely close agreement, showing the effectiveness of the activated carbon in ACN removal and the precise reliability of the developed RSM models.
Figure 3. Optimization solution using the RSM.

3.7. ACN Adsorption Efficiency of Different Types of Adsorbents

Table 5 provides an overview of the effectiveness of various adsorbents in ACN adsorption as reported in prior studies. The outcomes are compared with the adsorption capacity of activated carbon in this study. Activated carbon demonstrated greater or comparable ACN removal efficiency to other adsorbents. As a result, it may be said that activated carbon is effective in removing ACN and perhaps other organic pollutants as well from wastewater.

Table 5. Comparison of ACN adsorption efficiencies of various adsorbents.

| Adsorbent                                      | Adsorption Capacity (%) | Reference |
|-----------------------------------------------|-------------------------|-----------|
| Activated carbon from oil palm leaves         | 98.88                   | This study |
| Ultrasonic-assisted fatty-acid-mediated porous activated carbon | 99                     | [28]      |
| Rice bran biochar                             | 98                      | [30]      |
| Banana biochar                                | 74.6                    | [30]      |
| Biochar from waste Sterculia foetida          | 92                      | [37]      |

4. Conclusions

This study comprehensively examined the optimized removal of ACN from wastewater by activated carbon produced by oil palm leaves. The wastewater contained all 16 PAHs, whereas estimated removal was observed for ACN only in the presence of other PAHs. HPLC was used as the analytical method to quantify the ACN in the water samples. The CCD-based RSM was developed for the design of experiments at varying pH levels (2–7), dosage of 0.1–3 g/L, and contact time of 5–90 min. The adsorption reaction was quick, and within 5 min, higher removal was achieved (up to 90%). The optimization results show that pH of 6.96, adsorbent dosage of 2.62 g/L, and contact time of 71.67 min were the optimal conditions for the removal of 98.88% of the ACN. The results were verified in the lab. Hence, activated carbon produced by oil palm leaves proved to be an efficient and potential adsorbent for ACN in wastewater in the presence of multiple PAHs. The RSM proved to be an efficient and time-saving tool for optimizing the adsorption data.

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