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Optimization of Batch Extraction of Aromatics from Reformed Heavy Naphtha by Response Surface Methodology

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Keywords:
Reformed Heavy Naphtha (RHN); Box-Behnken Design (BBD); Optimization; Extraction by Furfural Solvent; Batch Extraction.

Highlights:

- *An optimization approach for batch extraction of aromatics from reformed heavy naphtha.*
- *Response Surface Methodology (RSM) based on Box–Behnken design (BBD).*
- *Extraction by Furfural Solvent.*
- *Analysis of variance (ANOVA).*

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Abstract: This study presents an optimization approach for batch extraction of aromatics from reformed heavy naphtha, provided by Al-Dora refinery in Iraq, using furfural solvent. Response Surface Methodology (RSM) based on Box–Behnken design (BBD) was employed to design the experiments to optimize the extraction efficiency and reduce energy consumption in the range of study. The effects of such variables as solvent-to-feed (S/F) ratio (0.5-2.5 vol/vol), stirring speed (200-1000 rpm), and contact time (1-5 h) at an ambient temperature of 20 °C were investigated. Following a (BBD), fifteen experimental runs systematically optimized the extraction efficiency and determined the interactive effects of these variables on extraction efficiency. Experimentally, the percentage efficiency of extraction ranged between 42.77% and 98.01%, pointing to an effective extraction process using furfural solvent. The maximum experimental extraction efficiency of 98.0127% was achieved at an S/F ratio of 0.5, a stirring speed of 1000 rpm, and a contact time of 3 hours. The resulting model was a quadratic polynomial that accurately captured the relationship between process variables and the extraction concentration of aromatics. Statistical analysis demonstrated that the S/F ratio and its squared term significantly influenced the actual concentration. Analysis of variance (ANOVA) showed excellent agreement between experimental and predicted aromatics concentrations. The results obtained by batch experiments will be used later in an intensified continuous extraction operation.

تحسين عملية الاستخلاص الدفعية للمواد الاروماتية من النفثا الثقيلة المهذبة بواسطة منهجية استجابة السطح (RSM)

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الخلاصة

تقدم هذه الدراسة نهج التحسين للاستخلاص الدفعي للمواد الاروماتية من النفثا الثقيلة المهذبة (المجهزة من مصفى الدورة في العراق) باستخدام مذيب الفورفورال. استخدمت منهجية استجابة السطح (RSM) مستندة الى تصميم بوكس - بيهنكن (BBD) لتصميم التجارب بهدف تحسين كفاءة الاستخلاص وتقليل استهلاك الطاقة في نطاق الدراسة. تم البحث في تأثير متغيرات مثل نسبة المذيب إلى اللقيم (S/F) (٠,٥-٢,٥ حجم/حجم) وسرعة المزج (٢٠٠-١٠٠٠ دورة في الدقيقة) وزمن المزج (١-٥ ساعات) عند درجة حرارة الجو ٢٠ درجة مئوية. ما مجموعه ١٥ تجربة عملية متبعة تصميم بوكس– بيهنكين (BBD) حسنت بشكل منهجي كفاءة الاستخلاص وحددت التأثيرات التفاعلية لهذه المتغيرات على كفاءة الاستخلاص. عمليا، تراوحت النسبة المئوية لكفاءة الاستخلاص بين ٤٢,٧٧٪ و ٩٨,٠١٪، مما يشير إلى فعالية عملية الاستخلاص باستخدام مذيب الفورفورال. ان اعلى كفاءة استخلاص عملية ٩٨,٠١٢٧٪ تم تحقيقها عند S/F ٠,٥، وسرعة مزج ١٠٠٠ دورة في الدقيقة، وزمن مزج ٣ ساعات. ان النموذج الناتج كان متعدد حدود من الدرجة الثانية عبر بشكل دقيق عن العلاقة بين متغيرات العملية والتركيز المستخلص للمواد الاروماتية. برهن التحليل الاحصائي ان نسبة S/F والحد التربيعي لها اثرتا بشكل كبير على التركيز الفعلي. أظهر تحليل التباين (ANOVA) توافقا ممتازًا بين تراكيز المواد الاروماتية العملية والمتوقعة. ان النتائج التي تم الحصول عليها بواسطة التجارب الدفعية سيتم استخدامها لاحقا في عملية استخلاص مستمرة مكثفة.

الكلمات الدالة: النفثا الثقيلة المهذبة (RHN)، تصميم بوكس - بيهنكن (BBD)، تحسين، الاستخلاص باستخدام الفورفورال، استخلاص دفعي.

1.INTRODUCTION

Extracting aromatics hydrocarbons, namely benzene, toluene, and xylene, is an essential process in the petrochemical industry. These compounds are widely used in producing chemicals and polymers [1,2]. However, the extraction process is intricate with efficiency, influenced by various operation conditions, such as temperature, pressure, and solvent content. Given the significant economic and environmental implications, the optimization of this process holds paramount importance. Catalyst reforming is a crucial chemical process that converts low-octane naphtha into high-octane reformed gasoline. Catalyst advancements have greatly influenced this process, which is the fastest-growing in refining [3]. Additionally, catalyst reforming is pivotal in supplying aromatics compounds extensively used in the petrochemical sector [4]. Lubricating oils are predominantly derived from the atmospheric distillation residue of crude oil through vacuum distillation. These oils encompass naphthenic, aromatic, and paraffinic components. For product enhancement and specification compliance, extracting aromatics from the lube oil cut is vital. This separation mainly employs liquid-liquid extraction [5]. Desired lubricant attributes are achieved by strategic material selection and additive use, with around 80% of oil base stocks providing viscosity, stability, and pour point [6]. Liquid-liquid extraction is commonly employed for aromatic separation from petroleum streams. A selective solvent, maximizing liquid phase differences, is used to reduce aromatics effectively [7, 8]. This method is widely used in lubricating oil production to meet requirements and enhance quality. It is also effective in recycling waste lubricant oil [9]. The procedure includes blending previously used oil with an appropriate solvent to reclaim base oil and isolate contaminants, frequently enabling solvent reuse [10]. Various solvents, additives, heating, and dilution are utilized to lower viscosity and process heavy crude oil. Recovery methods involve steam and solvent application [11]. Selecting the solvent is crucial for aromatic separation based on solubility characteristics. Furfural, known for being sticky and colorless, darkens when exposed to air. It is widely used as a solvent to extract dyes from hydrocarbons and separate saturated and unsaturated components to extract lubricating oils, gas oils, and diesel fuel [12]. Furthermore, due to its notable selectivity towards aromatics, furfural has been the subject of extensive research [13-16]. Furfural extracts from the lubricating oil unit are transformed into valuable products like high-octane gasoline, light and heavy naphtha, kerosene, gas oil, and lubricating oil [17]. Furthermore, the decline in furfural selectivity is less pronounced with increasing temperature than other solvents, adapting it to suit lighter and heavier lube oil fractions [18]. Izza and Korichi [19] experimentally assessed the impact of incorporating a surfactant, specifically sodium lauryl ether sulfate, for extracting aromatic compounds from lube oil using furfural. The results showed that adding this surfactant improved the selectivity of furfural towards aromatic components during the extraction process. In another study [20], different solvents, including furfural, methanol, and sulfolane, were used to compare the effectiveness of different solvents in separating aromatic components from cracked gas oil. The results revealed that using furfural as the solvent in a batch of liquid-liquid extraction systems led to a higher yield of aromatic components than sulfolane and methanol. However, sulfolane demonstrated greater selectivity in separating aromatics

from alkanes than the other solvents. Efficient extraction design requires an accurate model describing factors influencing high extraction efficiency and product purity [21-23]. RSM statistically examines relationships between multiple variables and response variables, aiming to determine optimal outcomes via regression analysis of well-designed experiments [24,25]. RSM blends stats and math to enhance processes like building or refining products. It assesses the impact of factors, alone or combined, on processes, examining independent variables to simulate chemical or biological processes [26,27]. Optimizing these factors can be achieved through the statistical optimization technique known as Response Surface Methodology (RSM). Marcos et al. [28] defined RSM as a set of mathematical and statistical methods that involve fitting a polynomial equation to experimental data. This equation should accurately represent the dataset behavior, aiming to establish a statistical correlation [29-31]. The present study devoted to optimizing naphtha aromatics extraction in Iraq aligns with several relevant national and international policies and agendas, demonstrating its potential impact beyond technological advancements: Sustainable Development Goal 7 (SDG 7): Affordable and clean energy. This study optimizes energy use in the extraction process, leading to potential fuel savings and reduced greenhouse gas emissions. SDG 9: Industry, Innovation, and Infrastructure: Focuses on building sustainable and resilient infrastructure [32,33]. This study is a private application of RSM using Box–Behnken design (BBD) for furfural/ reformed heavy naphtha to optimize the process, contributing to technological advancement and improved industrial practices. The design experiments involved the effects of solvent/feed ratio, stirring speed, and contact time on aromatics extraction in a batch process using furfural solvent. Describing the process by a model based on experimental data is crucial for designing a complete continuous system based on the effects of these parameters to improve extraction efficiency and decrease energy consumption. Therefore, exploring its benefits, discussing its limitations, and providing insights into potential solutions and strategies to address these limitations were of first place in this research. Generally, oil processes involve modeling and optimization to enhance system performance and improve process efficiency without escalating the number of experiments, costs, and time [34].

2.Methodology

2.1.Materials and Methods

Materials were used as they were delivered without any further treatment. The reformed heavy naphtha feedstock for the extraction process was provided by Al-Dora Refinery/ Iraq. Furfural (98.5% purity), a commonly used solvent, was also provided by the same refinery. The measured properties of reformed heavy naphtha are as follows: the density and viscosity values were 0.731 (g/ml) and 1.03 cSt, respectively. Furfural, characterized by its adhesive and transparent nature, undergoes darkening upon exposure to air. Possessing a density of 1.155 (g/ml) and viscosity of 2.09 cSt. The aromatic concentrations in various samples were assessed based on ASTM D-3238 (Agilent 7890A Gas Chromatography Device).

2.2.The Design of Experiment

Applying Response Surface Methodology (RSM) involves a set of mathematical and statistical methods for modeling and examining situations where multiple variables impact a desired outcome to optimize that outcome. The Box-Behnken Design (BBD), a form of response surface design, visually depicts the connections between measured responses and crucial input factors [35]. The BBD was utilized to consider solvent-to-feed volume ratio, stirring speed (in rpm), and contact time (in hours) as the primary process variables. Each of these independent factors was assessed at three distinct levels (-1, 0, +1) across 15 experimental runs. Selecting these levels was guided by preliminary studies, past experiences, and information gathered from existing literature. The process parameters optimized included contact time, ranging from 1 to 5 hours, stirring speed, set between 200 and 1000 rpm, and solvent/feed ratio, regulated between 0.5 and 2.5. The detailed specifications of these variables are tabulated in Table 1. The factors and levels utilized in the experimental design, in coded and uncoded forms, are displayed in Table 2. The empirical data derived from the liquid-liquid equilibrium was scrutinized using the BBD regression, as represented by the polynomial equation in Eq. (1) [35]. The general equation for a response surface model is:

$$Y = \beta 0 + \Sigma \beta i Xi + \Sigma \beta ii Xi^2 + \Sigma \beta ij Xi Xj + \varepsilon \quad (1)$$

Table 1 Experimental Range and the Levels of the Variables for Box-Behnken Design.

	Factors	High level (+1)	Medium level (0)	Low level (-1)
A	Solvent/Feed ratio	2.5	1.5	0.5
B	Stirring Speed (rpm)	1000	600	200
C	Contact Time (hours)	5	3	1

where Y is the predicted response (concentration of aromatic compounds in the extract phase), β0, βi, βii, and βij are the regression coefficients, Xi and Xj are input variables, and ε is the random error component. The β coefficients are determined

through the least squares estimation method using the experimental data obtained from the experiments. These coefficients provide information about the variables' impact and interaction on the response. Once these coefficients are determined, the equation can be used to predict the response for given values of the variables and to identify the optimal values of the variables for maximizing or minimizing the response.

2.3.Procedure

In the experimental study, various ratios of furfural and reformed heavy naphtha were combined (0.5-2.5 vol/vol ratio) at different stirring speeds (ranging from 200 to 1000 rpm) and contact times (1 to 5 hours), as illustrated previously in Table 2. The temperature was at 20 °C during all experiments representing the room temperature. After each run, when two immiscible phases formed, furfural was separated as the extract phase and naphtha as the raffinate phase using a separating funnel for a settling time of 24 hours.

2.4.Extraction Efficiency

The efficiency and capacity of mass transfer in liquid-liquid extractions are influenced by various factors, including the chemical systems, their physical properties, and additional variables. The efficiency of aromatics extraction can be defined as the ratio of the amount of aromatics extracted to the total amount of aromatics present in the feed. It can be expressed as [36, 37]:

$$\text{Extraction Efficiency (E)} = \frac{(C_R)_i - (C_R)_f}{(C_R)_i} * 100 \quad (2)$$

where C_R refers to the concentration of aromatics in the raffinate phase, and the subscripts i and f refer to initial and final concentrations, respectively. By applying mass balance principles:

$$(C_R)_i - (C_R)_f = (C_E)_f \quad (3)$$

where C_E represents the aromatic concentration in the extract phase. As the initial concentration of aromatics in the extract was regarded as zero (pure solvent), the final concentration was the only term in the equation. Therefore, Eq. (2) can be reformulated as follows:

$$\text{Extraction Efficiency (E)} = \frac{(C_E)_f}{(C_R)_i} * 100 \quad (4)$$

Table 2 Experimental Design for the Aromatic's Extraction.

Run	Factor 1 (A) Solvent/Feed Ratio		Factor 2 (B) Stirring Speed (rpm)		Factor 3 (C) Contact Time (hours)	
	Coded Value	Actual Value	Coded Value	Actual Value	Coded Value	Actual Value
1	-1	0.5	-1	200	0	3
2	1	2.5	-1	200	0	3
3	-1	0.5	1	1000	0	3
4	1	2.5	1	1000	0	3
5	-1	0.5	0	600	-1	1
6	1	2.5	0	600	-1	1
7	-1	0.5	0	600	1	5
8	1	2.5	0	600	1	5
9	0	1.5	-1	200	-1	1
10	0	1.5	1	1000	-1	1
11	0	1.5	-1	200	1	5
12	0	1.5	1	1000	1	5
13	0	1.5	0	600	0	3
14	0	1.5	0	600	0	3
15	0	1.5	0	600	0	3

3.RESULTS AND DISCUSSION

3.1.RSM Model

RSM model using the BBD method was predicted and tested using (Design Expert 13). The model's statistical significance was assessed using analysis of variance (ANOVA) and the coefficient of determination (R2). ANOVA was employed to assess the significance of individual terms in the model equation. A reliable model would demonstrate high significance in its ANOVA outcomes. The analysis was performed with a significance threshold of $P < 0.05$ to ascertain the relevance of each term in the model equation. Table 3 shows the analysis of variance (ANOVA) data obtained from the design of experiment (DOE) and demonstrates the validation of the quadratic model to represent the batch extraction process.

Table 3 Examination of Variance Related to Quadratic Terms in the Response Surface Model.

Parameter	Value	Parameter	Value
Std. Dev [a]	1.08	R^2	0.9951
Mean	29.63	Adjusted R^2	0.9864
C.V. % [b]	3.64	Predicted R^2	0.9222

[a] Standard Deviation
[b] Percentage Coefficient of Variation

A model equation predicted by the BBD regression was as follows:

$$\begin{aligned}\text{Response (Y)} = {} & 26.97 - 11.6054\,A \\ & + 0.468125\,B \\ & + 0.7635\,C - 0.8005\,AB \\ & - 1.20875\,AC \\ & - 0.18925\,BC \\ & + 5.10125\,A\text{^}2 \\ & + 0.32175\,B\text{^}2 \\ & - 0.434\,C\text{^}2 \end{aligned} \quad (5)$$

where Y denotes the anticipated concentration of the extracted aromatics in the extract phase, A represents the solvent/feed ratio, B signifies the stirring speed, and C represents the contact time. Utilizing ANOVA analysis, as outlined in Table 4, the statistical significance, fitness, and importance of individual and interacting terms within the model were evaluated. Notably, the coefficient of determination R2 (0.9951) and the adjusted coefficient of determination Adj R^2 (0.9864) were close enough to pronounce the significance of the model. Also, an F-value of 113.65 and a P-value below 0.0001 underscored the model's strong relevance. Assessment of individual terms within the model involved scrutinizing the F-value and the p-value. The present findings highlighted that the most influential term in the model was (A), corresponding to the ratio (S/F), which exhibited a substantial F-value of 925.33. Following closely was the term (A2), reflecting the ratio squared, with an F-value of 82.52. The two variables were significant, as their p-values were less than 0.05 (the threshold for significance). However, their levels of significance varied. On the other hand, the variables B and C, as well as all interacting terms, i.e., AB, AC, and BC, were insignificant, as their p-values, i.e., 0.2744, 0.1018, 0.1980, 0.0752, and 0.7401, respectively, were greater than 0.05. Therefore, A and A2 were deemed significant model terms. The model equation in terms of significant factors affecting the process can be presented by Eq. (6), yielding the actual concentrations of extracted aromatics.

$$\textbf{Actual (Y)} = \mathbf{48.8093} - \mathbf{23.8953\ A} + \mathbf{2.08125\ C} + \mathbf{5.10125\ A^2} \quad \textbf{(6)}$$

Table 4 ANOVA Outcomes for the Quadratic Model.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	1191.07	9	132.34	113.65	< 0.0001	significant
A-ratio	1077.48	1	1077.48	925.33	< 0.0001	
B-stirring	1.75	1	1.75	1.51	0.2744	
C-time	4.66	1	4.66	4.00	0.1018	
AB	2.56	1	2.56	2.20	0.1980	
AC	5.84	1	5.84	5.02	0.0752	
BC	0.1433	1	0.1433	0.1230	0.7401	
A^2	96.08	1	96.08	82.52	0.0003	
B^2	0.3822	1	0.3822	0.3283	0.5915	
C^2	0.6955	1	0.6955	0.5973	0.4746	
Residual	5.82	5	1.16			
Lack of Fit	5.82	3	1.94			
Pure Error	0.0000	2	0.0000			
Cor Total	1196.89	14				

It is obvious from Table 5 that all the extraction experiments are feasible, and the maximum obtained percentage efficiency was 98.0127, corresponding to the conditions: S/F 0.5, stirring speed 1000 rpm, and contact time 3h. This excellent result revealed that aromatic compounds could be extracted almost completely from reformate by furfural in batch mode. Notably, a percentage efficiency of 97 corresponding to 0.5 S/F, 600 rpm, and 5 h set of conditions signifies the insignificant effect of stirring speed and contact time, meaning that the process was not controlled by mass transfer. In other words, the process was believed to be controlled by the feed and the solvent's chemical properties and the ratio in which they are present in the system. Table 5 presents the predicted and actual concentrations of the aromatics in the extract phase and the percentage efficiency. It is obvious from Table 5 that good compatibility between the predicted and experimental values is confirmed by the residuals. The extraction efficiency is an important criterion to assess the feasibility of the extraction process. In Table 5, residual 0 means the actual and the predicted values are approximately identical. These results indicate a perfect prediction for this specific data point. In some experiments, there are disparities between actual and predicted values. The residuals for these experiments indicated whether the predictions were lower (underpredictions, i.e., negative values) or higher (overpredictions, i.e., positive values) than the actual values.

3.2.Effect of Solvent/Feed Ratio, Stirring Speed, and Contact Time on the Extracted Aromatics Efficiency

Figure 1 displays a graph illustrating the predicted concentrations of aromatics in the extract phase against their actual concentrations based on the provided actual values, predicted values, and residuals. The excellent matching between the actual and predicted values is obvious from Figure 1 due to the complete accumulation of approximately all points on the 45-degree line.

Table 5 The Predicted and Actual Extracted Aromatic Concentrations and Percentage Efficiency for the Aromatic Extraction.

Run	Solvent/Feed ratio	Stirring Speed (rpm)	Contact Time (hours)	Actual Concentration (wt.%)	Predicted Concentration (wt.%)	Residual	Efficiency %
1	1.5	600	3	26.97	26.97	0.0000	57.383
2	2.5	600	1	20.10	20.48	-0.3751	42.77
3	0.5	600	1	40.51	41.27	-0.7644	86.183
4	1.5	200	1	26.61	25.44	1.17	56.619
5	1.5	1000	5	26.73	27.90	-1.17	56.8638
6	2.5	200	3	20.32	21.12	-0.7990	43.236
7	2.5	1000	3	20.86	20.46	0.4097	44.393
8	1.5	600	3	26.97	26.97	0.0000	57.383
9	1.5	200	5	27.38	27.34	0.0346	58.248
10	0.5	200	3	42.32	42.73	-0.4098	90.04
11	0.5	1000	3	46.07	45.27	0.7990	98.0127
12	0.5	600	5	45.59	45.21	0.3751	97
13	1.5	600	3	26.97	26.97	0.0000	57.383
14	2.5	600	5	20.35	19.59	0.7644	43.3
15	1.5	1000	1	26.72	26.75	-0.0346	56.844

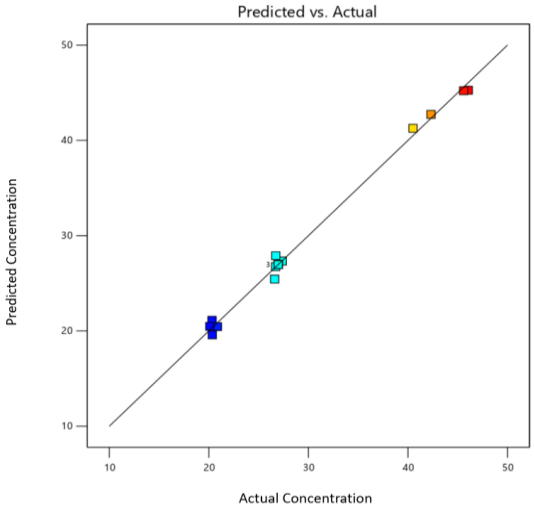

Fig. 1 Actual Response from Experiments Versus Predicted Response.

Figure 2 presents three-dimensional surface response plots illustrating how changes in two independent variables affect the response. The third variable was kept constant at its midpoint. This visualization demonstrates a strong interplay between independent variables in aromatics extraction. Notably, the impact of solvent-to-feed ratio and stirring speed (rpm) on extraction efficiency is highlighted. Interestingly, agitation intensity represented by stirring speed insignificantly influenced extraction efficiency, interpreted by good mass transfer between small amounts of liquids in batch modes. Increasing the solvent/feed ratio means that a larger amount of solvent is added to the extraction process relative to the feed, hindering the access of the accumulated solvent particles to the naphtha particles for extraction, resulting in lower efficiency of extracted aromatics. Consequently, adjusting the solvent–to–feed ratio is crucial in achieving high efficiency and saving resources. This result is in agreement with [38]. As the solvent-to-feed ratio increased, the solubility of hydrocarbons in the extract phase decreased. The effectiveness of extracting aromatics using a solvent relies on its selectivity and capacity, referring to its ability to selectively extract the target components and its capacity to hold a significant amount of the extracted aromatics [39]. Compared to [40] that studied the efficiency of FCC gasoline desulfurization through liquid extraction with sulfolane in a batch system using Response Surface Methodology (RSM), the statistical analysis revealed that the solvent-to-feed ratio exerted the greatest impact on efficiency within the researched parameter range, with the highest desulfurization efficiency, reaching 65.34%. Moreover, the extraction of aromatics from naphtha reformate utilizing a mixed solvent system comprising propylene carbonate (PC) and diethylene glycol (DEG) in a batch system [41] resulted in a yield of 0.6 at a solvent-to-feed ratio of 3. Removing BTEX in a batch system enriched with mineral salts and employing a mixed culture of five bacteria employing Response Surface Methodology (RSM) [42] reached an efficiency of 99%. According to the ANOVA results (Table 4), the model holds significance (p-value < 0.0001), signifying that the combined influence of the independent variables on the response variable is noteworthy. The substantial F-value of 113.65 reflects substantial variation among different groups in the model. The A-ratio factor exhibits high significance (p-value < 0.0001), indicating its pronounced effect on the response. The notable F-value of 925.33 underscores substantial mean differences across A-ratio factor levels. Statistical scrutiny affirms a meaningful alignment between experimental and predicted values, affirming the model's adequacy. Moreover, Figure 3 illustrates the insignificant effect of contact time on efficiency. The contact time refers to the duration of contact between the feed and solvent phases. The duration of contact influences the efficiency and effectiveness of mass transfer, ultimately affecting the

efficiency of extracted aromatics. Increasing the contact time allows for a longer interaction between the feed and solvent, facilitating the transfer of aromatics from the feed phase to the solvent phase. This extended contact time promotes greater solute-solvent interaction, enhancing the mass transfer rate and improving extraction efficiency [30,31]. If the system reached equilibrium, increasing the contact time would be ineffective, which is likely to occur in the experiments.

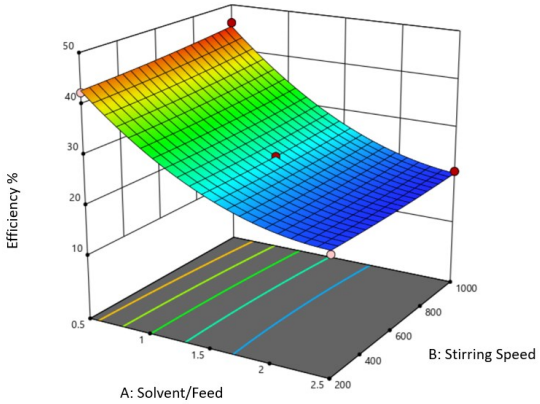

Fig. 2 3-D Response Surface Plot for the Efficiency as a Function of Solvent/Feed Ratio and Stirring Speed.

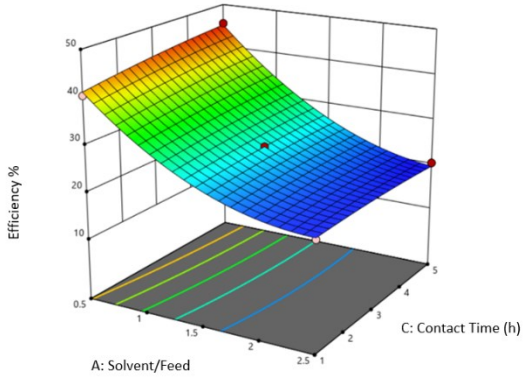

Fig. 3 3-D Response Surface Plot for the Efficiency as a Function of Solvent/Feed Ratio and Contact Time.

Factor C, i.e., contact time, appears in Eq. (6) because it was included as an independent variable during regression analysis to explore its potential influence on the response variable (aromatics concentration). Although factor C showed no statistical significance in predicting the actual concentration based on the p-value, it was still included in Eq. (6). However, factor C included in the equation with a coefficient value of (2.08125) suggests a small contribution to the prediction of the actual concentration compared to the other significant factors in the model, such as A and A^2.

4.CONCLUSIONS

In the present study, batch experiments were conducted to investigate the influence of some factors on the extraction efficiency of aromatic compounds from reformated heavy naphtha using furfural solvent. The experiments were designed using Box-Behnken Design to assess the impact of solvent/feed ratio, stirring speed, contact time, and their interactions on the concentration of the extracted aromatic compounds. The maximum experimental extraction efficiency of 98.0127% was achieved at an S/F ratio of 0.5, stirring speed of 1000 rpm, and contact time of 3 hours. A regression model was developed, and the predicted concentration was computed and compared with the actual concentration to evaluate the model's effectiveness. The analysis of variance (ANOVA) indicated that the predicted concentration closely approximated the actual concentration, showing that R^2 values and Adj R^2 values were very close. The solvent/feed ratio substantially impacted the extracted concentration. On the other hand, the stirring speed and contact time, demonstrated unclear influence in the process. A higher A-ratio resulted in a lower extracted concentration, indicating an inverse relationship. The results of this study are regarded as a base to apply the extraction process in an intensified continuous process.

REFERENCES

[1] Humid SH, Ali MA. **Comparative Study of Solvents for the Extraction of Aromatics from Naphtha.** *Energy Sources* 2007; **18**(1): 65–84.

[2] Speight JG. **Handbook of Industrial Hydrocarbon Processes.** 2nd ed.; Elsevier: Amsterdam, The Netherlands, 2019.

[3] Ahmedzeki NS, Al-Tabbakh BA, Antwan MB, Yilmaz S. **Heavy Naphtha Upgrading by Catalytic Reforming Over Novel Bi-Functional Zeolite Catalyst.** *Reaction Kinetics, Mechanisms and Catalysis* 2018; **125**: 1127–1138.

[4] Rodríguez MA, Ancheyta J. **Detailed Description of Kinetic and Reactor Modeling for Naphtha Catalytic Reforming.** *Fuel* 2011; **90**(12): 3492–3508.

[5] Espada JJ, Rodríguez R. **Prediction of Density and Refractive Index in Furfural+Lubricating Oil Systems.** *Fluid Phase Equilibria* 2017; **438**: 29–36.

[6] Fahad MR, Abdulmajeed BA. **Experimental Investigation of Base Oil Properties Containing Modified TiO_2/CuO Nanoparticles Additives.** *Journal of Physics: Conference Series* 2021; **1973**: 012089.

[7] Coto B, Van Grieken R, Pena JL, Espada JJ. **A Model to Predict Physical Properties for Light Lubricating Oils and Its Application to the Extraction Process by Furfural.**

Chemical Engineering Science 2006; **61**(13): 4381–4392.

[8] Montahaie A, Hatamipour MS, Tavakkoli T, Aghamiri S. **Liquid-Liquid Equilibrium of (Lube-Oil Cut + Furfural) in Several Solvent/Feed Ratios and at Different Temperatures.** *Journal of Chemical and Engineering Data* 2009; **54**(6): 1871–1875.

[9] Naife TM, Rashid SA, Abdul Jabbar MF. **Treatment of Used Lubricant Oil by Solvent Extraction.** *Iraqi Journal of Chemical and Petroleum Engineering* 2022; **23**(1): 43–50.

[10] Hussein HQ, Abdulkarim AL. **Investigation of Binary Solvents Performance for Regeneration of Iraqi 15W-40 Waste Lubricant.** *Iraqi Journal of Chemical and Petroleum Engineering* 2016; **17**(4): 83–94.

[11] Majeed EM, Naife TM. **Viscosity Reduction of Iraqi Crude Oil by Different Additives.** *AIP Conference Proceedings* 2020; **2213**: 020142.

[12] Ghosh S, Falyouna O, Malloum A, Othmani A, Bornman C, Beda H, Onyeaka H, Al-Sharify ZT, Jacob AO, Miri T, Osagie C, Ahmadi S. **A General Review on the Use of Advance Oxidation and Adsorption Processes for the Removal of Furfural from Industrial Effluents.** *Microporous and Mesoporous Materials* 2022; **331**: 111638.

[13] Espada JJ, Coto B, Pena JL. **Liquid-Liquid Equilibrium in the Systems Furfural + Light Lubricating Oils Using UNIFAC.** *Fluid Phase Equilibria* 2007; **259**(2): 201–209.

[14] Mohammed A-K A-H, Hussain KH, Sadiq RJ. **The Effect of Solvent Extraction of Light Lubricating Oil on Viscosity Index and Chemical Composition.** *Iraqi Journal of Chemical and Petroleum Engineering* 2007; **8**(4): 1–12.

[15] Shakir IK, Qasim MA. **Extraction of Aromatic Hydrocarbons from Lube Oil Using Different Co-Solvent.** *Iraqi Journal of Chemical and Petroleum Engineering* 2015; **16**(1): 79–90.

[16] Huasong CUI, Qing NI, Dongyue P, Cuishi G. **Mechanism of Binary Solvent Extraction and Separation of Aromatics from Heavy Oils.** *Acta Petrolei Sinica* 2022; **38**(6): 1414–1422.

[17] Hummadi KK, Mohammed A-K A-H, Elaibi AI, Ali SM, Heeres HJ, He S. **Catalytic Conversion of Furfural Extract from Lubricating Oil Extraction Unit Over the Shaped and Promoted HY Catalysts to Valuable Petroleum Products.** *Catalysis Communications* 2020; **134**: 105834.

[18] Kumar UKA, Mohan R. **Liquid-Liquid Equilibria Measurement of Systems Involving Alkanes (Heptane and Dodecane), Aromatics (Benzene or Toluene), and Furfural.** *Journal of Chemical & Engineering Data* 2011; **56**: 485–490.

[19] Izza H, Korichi M. **Extraction of Aromatic from Lube Oil Using a Surfactant as an Additive.** *Petroleum Science and Technology* 2017; **35**: 201–205.

[20] Habaki H, Yoshimura Y, Egashira R. **Separation of Aromatic Components from Light Cycle Oil by Solvent Extraction.** *Separation Science and Technology* 2019; **54**: 1159–1166.

[21] Rappel R, Nelson de Gois LM, Mattedi S. **Liquid–Liquid Equilibria Data for Systems Containing Aromatic + Nonaromatic + Sulfolane at 308.15 and 323.15 K.** *Fluid Phase Equilibria* 2002; **202**(2): 263–276.

[22] Uemasu I, Kushiyama S. **Selective Separation of Benzene from Hydrocarbon Mixtures via Liquid–Liquid Extraction Method Using Aqueous Solutions of Substituted Cyclodextrins.** *Fuel Processing Technology* 2004; **85**(13): 1519–1526.

[23] Fazlali A, Askari-Mehrabadi M, Mohammadi MH. **Extraction of Aromatics from Petroleum Naphtha Reformate by Solvent: UNIFAC Modelling and Optimization of Solvent Consumption.** *The Journal of Chemical Thermodynamics* 2012; **53**: 30–35.

[24] Jo MS, Rene ER, Kim SH, Park HS. **An Analysis of Synergistic and Antagonistic Behavior During BTEX Removal in Batch System Using Response Surface Methodology.** *Journal of Hazardous Materials* 2008; **152**(3): 1276–1284.

[25] Pereira LMS, Milan TM, Tapia-Blácido DR. **Using Response Surface Methodology (RSM) to Optimize 2G Bioethanol Production: A Review.** *Biomass & Bioenergy* 2021; **151**: 106166.

[26] Myers RH, Montgomery DC, Anderson-Cook CM. **Response Surface Methodology: Process and Product Optimization Using Designed Experiments.** 4th ed.; John Wiley & Sons: New York, 1995.

[27] Ong TH, Hamzah MH, Che Man H. **Optimization of Palm Oil Extraction from Decanter Cake Using Soxhlet Extraction and Effects of Microwaves Pre-Treatment on Extraction Yield and Physicochemical Properties of Palm Oil.** *Food Research* 2021; **5**(1): 525–532.

[28] Marcos AB, Ricardo ES, Eliane PO, Leonardo SV, Luciane AE. **Rapid Surface Methodology (RSM) as a Tool for Optimization in Analytical Chemistry.** *Talanta* 2008; **76**: 965–977.

[29] Myers RH, Montgomery DC. **Response Surface Methodology: Process and Product Optimization Using Designed Experiments.** 2nd ed.; John Wiley & Sons: New York, 2002.

[30] Owolabi RU, Usman MA, Anuoluwapo AD, Oguamanam OP. **Modelling, Optimization and Green Metrics Evaluation of Bio-Catalytic Synthesis of Biodiesel.** *Tikrit Journal of Engineering Sciences* 2020; **27**(3): 17–30.

[31] Jarullah A, Mohammed HJ. **Experimental Design of Oxidative Desulfurization of Kerosene Through Response Surface Methodology (RSM).** *Tikrit Journal of Engineering Sciences* 2023; **30**(2): 130–141.

[32] United Nations, Department of Economic and Social Affairs. **Sustainable Development. The Sustainable Development Goals Report 2023: Special Edition.** 10 July 2023.

[33] United Nations, Department of Economic and Social Affairs. **Sustainable Development. The Sustainable Development Goals Report 2023: Special Edition.** 10 July 2023.

[34] Zaid H, Al-Sharify Z, Hamzah MH, Rushdi S. **Optimization of Different Chemical Processes Using Response Surface Methodology- A Review: Response Surface Methodology.** *Journal of Engineering and Sustainable Development* 2022; **26**(6): 1–12.

[35] Montgomery DC. **Handbook of Design and Analysis of Experiments.** 9th ed.; John Wiley & Sons: Arizona State University, 2017.

[36] Tang J, Zhang X, Cai W, Wang F. **Liquid–Liquid Extraction Based on Droplet Flow in a Vertical Microchannel.** *Experimental Thermal and Fluid Science* 2013; **49**: 185–192.

[37] Kumar UK, Mohan R. **Liquid-Liquid Extraction of Aromatics from Hydrocarbon Mixtures in Capillaries.** *Brazilian Journal of Chemical Engineering* 2018; **35**(2): 605–614.

[38] El-Bassuoni AA, Esmael KK. **Extraction of Aromatics from Heavy Naphtha Using Different Solvents.** *TESCE* 2004; **30**(2).

[39] Saha M, Rawat BS, Khanna MK, Nautiyal BR, Raghuram MV. **Extraction of Aromatics from Naphtha Reformate Using Combination Solvents.** *Indian Journal of Chemical Technology* 1999; **6**: 85–89.

[40] Adžamić T, Sertić-Bionda K, Marcec-Rahelic N. **Modeling of the FCC Gasoline Desulfurization Process by Liquid Extraction with Sulfolane.** *Petroleum Science and Technology* 2010; **28**(18): 1936–1945.

[41] Lababidi HMS, Ali SH, Fahim MA. **Optimization of Aromatics Extraction of Naphtha Reformate by Propylene Carbonate/ Diethylene Glycol Mixed Solvent.** *Industrial & Engineering Chemistry Research* 2006; **45**(14): 5086–5097.

[42] Jo M-S, Rene ER, Kim S-H, Park H-S. **An Analysis of Synergistic and Antagonistic Behavior During BTEX Removal in Batch System Using Response Surface Methodology.** *Journal of Hazardous Materials* 2008; **152**(3): 1276–1284.