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Comparative Analysis of Levulinic Acid Adsorption by Amberlite IRA-96 and IRA-400 Ion Exchange Resin

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Graphical/Tabular Abstract (Grafik Özet)

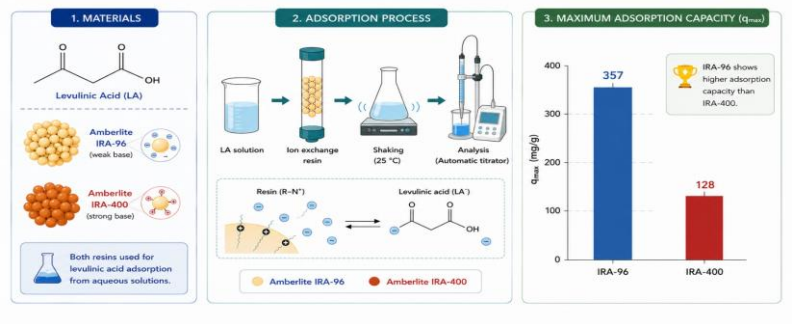

Figure A: Levulinic Acid Adsorption Process/ **Şekil A:** Levulinik Asit Adsorpsiyonu

This study investigated levulinic acid adsorption using Amberlite IRA-96 and IRA-400 resins. IRA-96 exhibited a higher adsorption capacity (357 mg/g) than IRA-400 (128 mg/g).

Bu çalışmada levulinik asidin Amberlite IRA-96 ve IRA-400 reçineleri üzerindeki adsorpsiyonu incelenmiştir. IRA-96, 357 mg/g kapasite ile IRA-400'den (128 mg/g) daha yüksek performans göstermiştir.

Highligts (Önemli noktalar)

- *IRA-96 showed higher adsorption capacity than IRA-400 resin.*
- *Insights support sustainable separation of levulinic acid from water.*
- *IRA-96, IRA-400 reçinesine göre daha yüksek adsorpsiyon kapasitesi gösterdi.*
- *Elde edilen bulgular, levulinik asidin sudan sürdürülebilir bir şekilde ayrılmasını desteklemektedir.*

Aim (Amaç): *Investigation of levulinic acid adsorption with Amberlite IRA- 96 and Amberlite IRA- 400 ion- exchange resins /Amberlite IRA- 96 ve Amberlite IRA- 400 iyon değiştirici reçineleri ile levulinik asit adsorpsiyonunun incelenmesi*

Originality (Özgünlük): *This study compares levulinic acid adsorption using Amberlite IRA-96 and IRA-400 resins. The adsorption performance, equilibrium, and kinetics were evaluated, revealing the superior capacity of Amberlite IRA-96 for efficient levulinic acid recovery/ Bu çalışmada, Amberlite IRA-96 ve Amberlite IRA- 400 reçinelerinin adsorpsiyon performansı, denge özellikleri ve kinetiği değerlendirilmiş; Amberlite IRA-96' nın levulinik asidin etkin geri kazanımı için daha yüksek adsorpsiyon kapasitesi sunduğu ortaya konmuştur.*

Results (Bulgular): *The maximum adsorption capacities of AIRA-96 and AIRA-400 for LA uptake has been obtained to be 357 and 128 mg/g. q_e value has been obtained 259,65 mg/ g for AIRA-96 and 228,69 mg/g for AIRA- 400 according to pseudo- first- order kinetic model. Also q_e value has been calculated regarding pseudo- second- order kinetic model and found 400 mg/g for AIRA- 96 and 315 mg/g for AIRA- 400./ AIRA-96 ve AIRA- 400 için maksimum adsorpsiyon kapasiteleri 357 ve 128 mg/ g bulunmuştur. Birinci derece kinetic modele göre q_e değerleri ise sırasıyla 259, 65 mg/ g ve 228,69 mg/ g olarak hesaplanmıştır.*

Conclusion (Sonuç): *The outcomes were shown that AIRA-96 and AIRA-400 are high selectivity for LA. Adsorption isotherm modelling study specified that the adsorption of LA on both adsorbents were a heterogenous processes and multilayers. Kinetic modelling outcomes have been defined as appropriate fitting the pseudo-second order model for AIRA-96 while fitting the pseudo-first order model for AIRA-400./ Elde edilen sonuçlar, AIRA-96 ve AIRA-400'ün LA'ya karşı yüksek seçiciliğe sahip olduğunu göstermiştir. Adsorpsiyon izoterm modelleme çalışması, LA'nın her iki adsorban üzerine adsorpsiyonunun heterojen bir süreç olduğunu ve çok katmanlı adsorpsiyon gerçekleştiğini ortaya koymuştur. Kinetik modelleme sonuçları, AIRA-96 için yalancı ikinci derece modelin, AIRA-400 için ise yalancı birinci derece modelin uygun olduğunu göstermiştir.*

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Abstract

Levulinic acid (LA) is a multi- purpose platform chemical derived from lignocellulosic biomass, widely utilized in pharmaceuticals, polymers, and fuel additives. However, the efficient recovery of LA from aqueous solutions constitutes a significant challenge because of its high solubility and the presence of various by-products. This study systematically examines the adsorption performance of two ion exchange resins: Amberlite IRA-96 (AIRA-96) and Amberlite IRA-400 (AIRA-400). Batch adsorption trials have been realized to appraise the influences of equilibrium contact time, temperature, adsorbent dosage, and initial LA concentration. The maximum adsorption capacities for AIRA-96 and AIRA-400 were found to be 357 mg/g and 128 mg/g, respectively. The outcomes emphasize the potential of ion exchange resins as effective materials for the recovery of levulinic acid and provide valuable understanding for their practical application in downstream biorefinery processes.

Amberlite IRA-96 ve IRA-400 İyon Değişim Reçineleri ile Levulinik Asit Adsorpsiyonunun Karşılaştırmalı Analizi

Makale Bilgisi

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Öz

Levulinik asit (LA), ilaçlarda, polimerlerde ve yakıt katkı maddelerinde yaygın olarak kullanılan lignoselülozik biyokütleden elde edilen çok yönlü bir kimyasaldır. Aynı zamanda LA' nın yüksek çözünürlüğü ve istenmeyen yan ürünlerin varlığı nedeniyle, sulu çözeltilerden verimli bir şekilde geri kazanılması ciddi bir zorluğa yol açmaktadır. Bu çalışmada, Amberlite IRA-96 (AIRA-96) ve Amberlite IRA-400 (AIRA-400) iyon değişim reçinelerinin adsorpsiyon performansı sistematik olarak incelenmiştir. Denge temas süresi, sıcaklık, adsorban dozu ve başlangıç LA konsantrasyonunun etkilerini değerlendirmek için adsorpsiyon denemeleri gerçekleştirilmiştir. AIRA-96 ve AIRA-400 için maksimum adsorpsiyon kapasiteleri sırasıyla 357 mg/g ve 128 mg/g olarak bulunmuştur. Sonuçlar, iyon değişim reçinelerinin levulinik asidin geri kazanımı için etkili malzemeler olarak potansiyelini vurgulamakta ve biyorafinasyon süreçlerinde pratik uygulamaları için değerli bilgiler sağlamaktadır**.**

1. INTRODUCTION (GİRİŞ)

Levulinic acid (LA) is an organic intermediate that serves as a key raw material in the synthesis of a several chemicals, including fuel additives, solvents, coatings, plasticizers, flavorings, fragrances, and pharmaceuticals [1, 2]. This biomass-derived compound has garnered remarkable attention in the chemical industry because of its versatility as a raw material in the production of infinite chemicals and fuel [3, 4]. LA can be efficiently produced at a low cost by converting renewable biomass into sugars, which are then transformed into levulinic acid through processes such as acid hydrolysis or degradation [5]. Also referred to as 4-oxopentanoic acid, levulinic acid is a water-soluble organic compound that boasts extensive functionality and reactivity, attributed to various functional groups, including a ketone carbonyl group (C=O) and a carboxyl group

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(COOH) [6]. Levulinate esters hold a prominent position in the fuel additive, cosmetics, and food industries, owing to their flavoring and emulsifying properties [4]. As a fundamental chemical raw material, levulinic acid can react with a diverse array of chemicals to synthesize various products. It can be converted into methyltetrahydrofuran (MTHF), which serves as both a solvent and fuel additive, aminolevulinic acid (DALA), a biodegradable herbicide, and diphenolic acid (DPA), a monomer used in the synthesis of polymer resins [5, 7].

Due to LA used in processes must be of high purity, and the recovery of LA from aqueous solutions by low-cost and environmentally friendly methods poses a challenge. Therefore, recovery and purification of levulinic acid is required, including aqueous solutions, wastewater and chemical industries. Various separation methods such as adsorption [8], extraction [9], distillation [10], ultrafiltration [11], electrodialysis [12] and membrane separation [13] are used for the separation of LA from aqueous solutions and wastewater. When considering all these methods, adsorption is one of the most preferred methods owing to its low cost, ease of application, high recovery efficiency and variety of low-cost adsorbents [14–16]. The removal of LA from aqueous solutions by adsorption method with various adsorbents has been investigated and reported in the literature [17–19]. There are a few studies LA adsorption by Amberlite XAD-4 [5], LA-2 [9], IRA-67 [20] in the literature. However, LA adsorption via AIRA-96 and AIRA-400 have not been researched yet.

Ion exchange resins are composed of water-insoluble polymers. They play a notable role in the exchange of ions, which can be composed of positively or negatively charged functional groups. A positively charged ion exchanger attracts negatively charged anions, while a negatively charged ion exchanger attracts positively charged cations [21]. These polymeric resins have garnered attention for their high adsorption capacity and selectivity in removing various pollutants. Their flexible molecular structure allows for the design of resins that target an array of contaminants, including heavy metals, organic toxins, and hazardous chemicals [22]. Among the different types of resins, Amberlite resins stand out as a promising alternative adsorbent group due to their favorable physical-chemical properties and diverse pore structures [23]. The adsorption process using ion exchange resins is particularly beneficial because of its selectivity, durability, higher adsorption performance, and comparatively low cost. It has been reported that Amberlite resins are effective adsorbents for dyes, phenols, and organic acids. Specifically, AIRA-400 is a macroporous, strongly basic anion-exchange resin in gel form [24]. Meanwhile, AIRA-96 features a styrene-divinyl benzene matrix with polyamine functional groups and sulfonic acid as the active group, exhibiting a macroreticular structure that offers greater maximum porosity compared to other gel-matrix resins [25].

In this study, the adsorption of LA was investigated using AIRA-96 and AIRA-400 polymeric resins as adsorbents. The optimum time required for the adsorption to reach equilibrium was calculated and the impacts of the initial acid concentration, the amount of adsorbent, temperature affecting the adsorption were examined by changing the parameters. The adsorption mechanism was explained utilizing adsorption isotherm and kinetic modelling.

2. MATERIALS AND METHODS (MALZEME VE METOT)

2.1. Materials (Malzemeler)

Levulinic acid was supplied by ACROS Organics. AIRA-96 and AIRA-400 were provided from Merck.

2.2. Experimental Design (Deney Tasarımı)

Batch adsorption trials have been realized to investigate the adsorption of LA by AIRA-96 and AIRA-400. Firstly, equilibrium contact time was specified at 25 ºC by utilizing Amberlite dosage of 0.1 g, LA concentration of 10% w/w Then, at initial concentrations ranging from 2 to 10% acid solutions have been prepared by dissolving LA in distilled water and the initial LA concentration effect on adsorption has been defined. After that, the adsorbent dosage influence on the adsorption has been investigated and various quantities in the range of 0.05 to 0.30 g have been utilized. Finally, to examine the effect of temperature on adsorption, the experiments has been studied at temperatures of 25 to 55 ºC. All adsorption trials have been performed out by shaking in a thermostatic water shaker bath (Core ST 30) at 150 rpm. After the adsorption, Amberlite resins have been separated by filtration technique from the solution. The concentration of LA in the solutions prior to and following the adsorption step has been defined by employing automatic titrator (Schott Titroline Easy Module 2) using 0.1 N NaOH. Adsorption capacity, adsorption (%) values, which express the adsorption performance of adsorbent and q_e (mg/g) have been calculated using the following equations:

$$\text{Adsorption\%} = \left(1 - \frac{C_e}{C_0}\right) * 100 \quad (1)$$

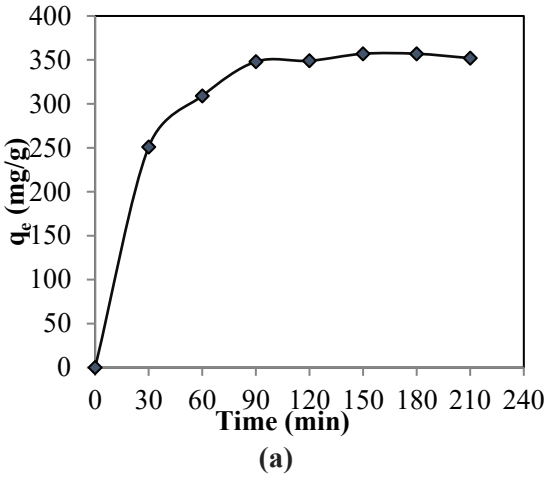
$$q_e = \left[\frac{(C_0 - C_e)}{M}\right] * V \quad (2)$$

In the equation, C_0 indicates initial concentrations of the acid solution and C_e indicates equilibrium concentrations of the acid solution, respectively. M is the quantity of adsorbent and V is the volume of acid solution.

3. RESULTS (BULGULAR)

Adsorption optimum time *(Optimum süre denemeleri)*

In order to determine the equilibrium time of LA, trials have been conducted in the range of 30-210 minutes. For this purpose, samples were prepared by utilizing 0.1 g of AIRA-96 and AIRA-400 adsorbents separately into a 10% LA solution. The results are shown in the graphs in Figure 1, where the adsorption increased rapidly in the first 60 minutes for both adsorbents and reached equilibrium at 120 minutes.



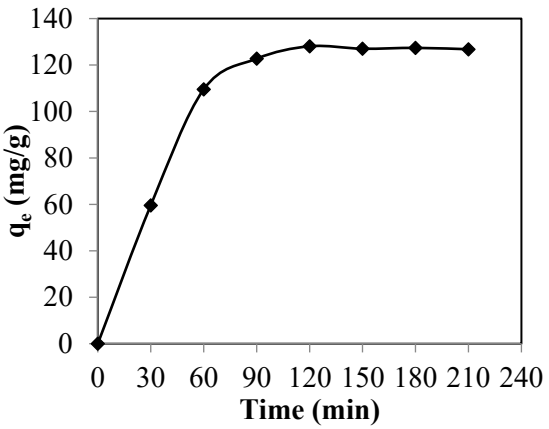
(a)

Initial acid concentration *(Başlangıç asit konsantrasyonu etkisi)*

To investigate the influence of initial acid concentration on the adsorption of LA, solutions with a concentration range of 2-10% were adsorbed using 0.1 g of adsorbent in 120 minutes, which is the optimum time and, at temperature of 25 °C. The outcomes are shown in Figure 2, and it was observed that the amount of adsorbed acid enhanced as the initial LA concentration raised. The molecules in the adsorbate solution obtain greater impetus to the adsorbent, facilitating diffusion. This results in more frequent collisions between the active sites on the adsorbent and the molecules in the adsorbate [26].

Adsorbent dosage *(Adsorban miktarı etkisi)*

AIRA- 96 and AIRA- 400 resins were utilized in the range of 0.1-0.5 g to research the influence of the amount of adsorbent on adsorption. The trials were carried out with an initial LA concentration of 10%, at temperature of 25 °C and equilibrium time of 120 minutes. The outcomes are shown in Figure 3 and it is seen in the graphs that as the amount of adsorbent increases, the q_e decreases. Here, q_e refers to the amount of adsorbate retained per unit mass of adsorbent, meaning that a higher quantity of adsorbent corresponds to a lower q_e.



(b)

Figure 1. The outcomes of adsorption processes: The influence of contact time for the LA adsorption by (a) AIRA-96 and (b) AIRA-400 (AIRA-96 (a) ve AIRA-400 (b) ile gerçekleştirilen LA denemelerine ait temas süresi grafikleri)

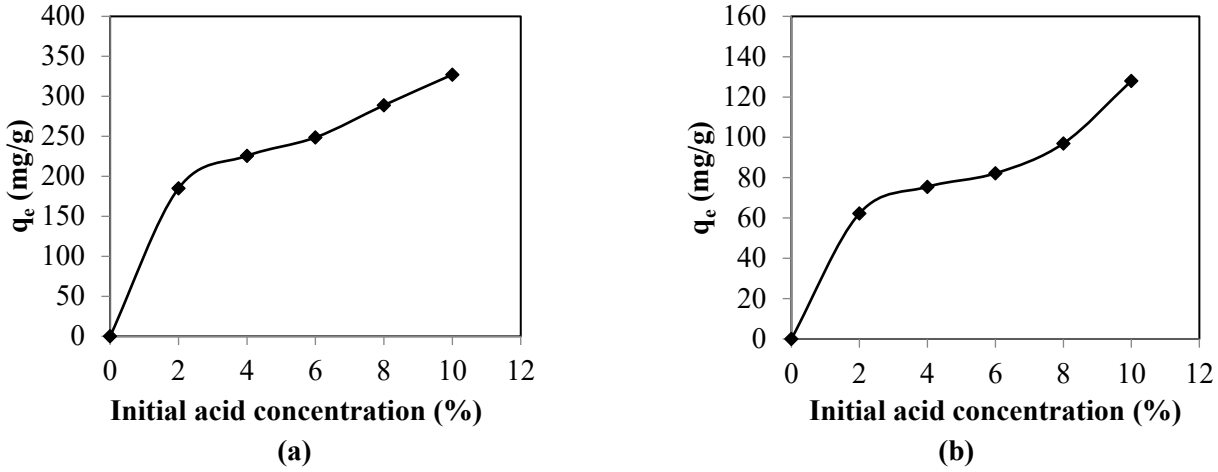


Figure 2. The outcomes of adsorption processes: The influence of initial acid concentration for the LA adsorption by (a) AIRA-96 and (b) AIRA-400 (AIRA- 96 (a) ve AIRA- 400 (b) ile LA adsorpsiyonuna başlangıç asit konsantrasyonu etkisi)

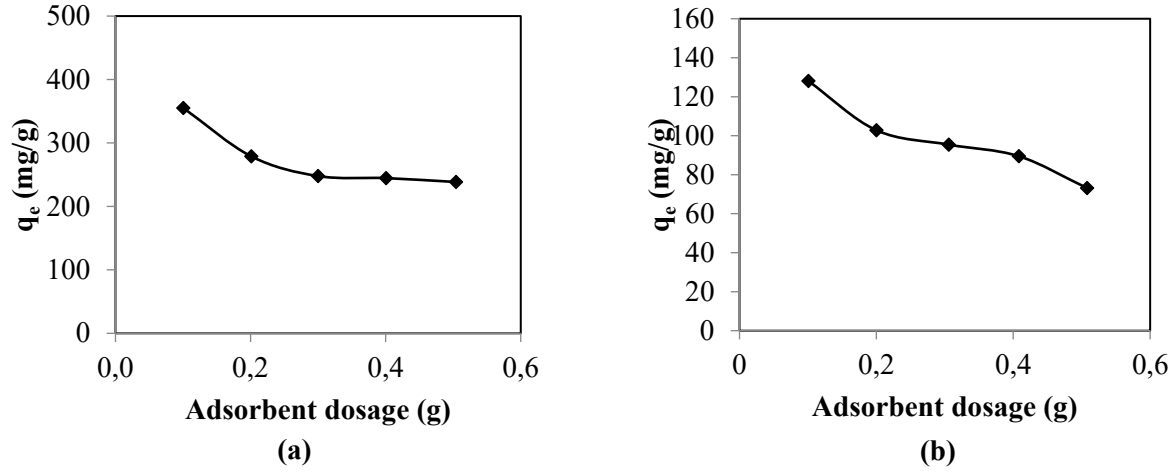


Figure 3. The outcomes of adsorption processes: The influence of adsorbent dosage for the LA adsorption by (a) AIRA-96 and (b) AIRA-400 (AIRA- 96 (a) ve AIRA- 400 (b) ile LA adsorpsiyonuna adsorban miktarı etkisi)

Temperature (Sıcaklık)

Adsorption experiments were executed utilizing 10% LA solution, 0.1 g adsorbent, and temperatures ranging from 25-55 °C to research the effect of temperature on the adsorption of LA with AIRA-96 and AIRA-400. The experimental outcomes, illustrated in Figure 4, indicate that the q_e declines as the temperature rises. The results show that the adsorption of LA by AIRA-96 and AIRA-400 are exothermic processes. These results are confirmed by previous studies in the literature [18, 20].

Isotherm models (İzoterm modelleri)

Isotherm models have been developed using equilibrium data from the adsorption process to assess the mechanism of LA adsorption by AIRA-96 and AIRA-400. The Freundlich, Temkin, and Langmuir isotherm models are abstracted in Table 1 [27]. The linear fitting plots for these adsorption isotherms have been presented in Table 2, with the outcomes depicted in Figures 5 and 6. The highest R^2 values for both AIRA-96 and AIRA-400 have been found for the Freundlich isotherm model, 0.9623 and 0.8761, respectively. This suggests that it is the most proper model for characterizing adsorption of LA. This model supposes that active adsorption sites consist of heterogeneous surfaces, resulting in multilayer adsorption on the adsorbent surface [28].

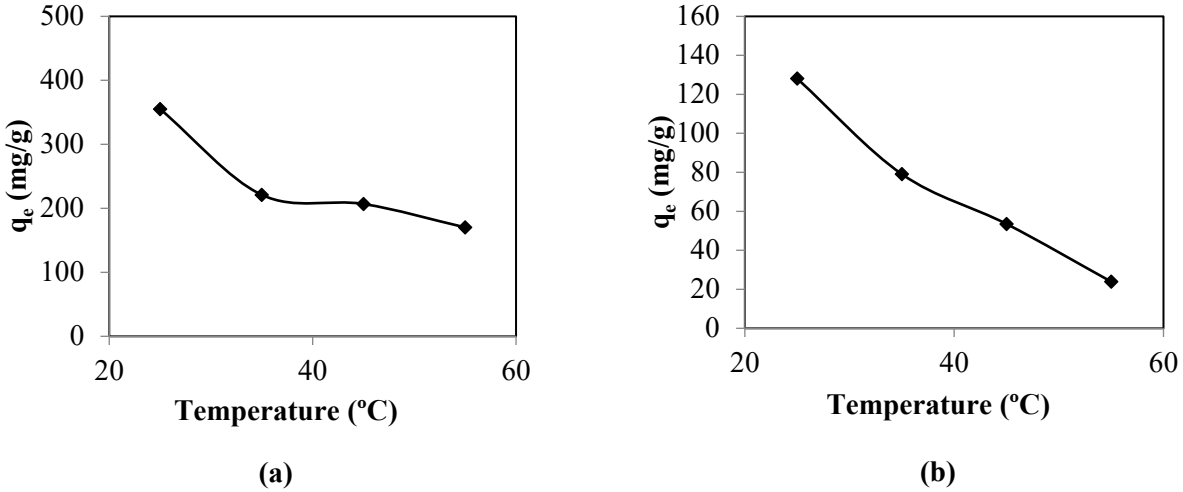


Figure 4. The outcomes of adsorption processes: The influence of temperature for the LA adsorption by (a) AIRA-96 and (b) AIRA-400 (AIRA- 96 (a) ve AIRA-400 (b) ile LA adsorpsiyonuna sıcaklık etkisi).

Table 1. Equations of Isotherm Models (İzoterm model denklemleri)

Langmuir isotherm model	
$\boldsymbol{Non-linear\ form}$: $\boldsymbol{q_e = \frac{Q_0 b C_e}{1 + bC_e}}$	(3)
$\boldsymbol{Linear\ form}$: $\boldsymbol{\frac{1}{q_e} = \frac{1}{Q_0} + \left(\frac{1}{b * Q_0}\right) * \left(\frac{1}{C_e}\right)}$	(4)
$\boldsymbol{Plot}$: $\boldsymbol{\frac{1}{q_e}\ vs. \frac{1}{C_e}}$	
$\boldsymbol{Q_0}$: Maximum adsorption capacity (mg/g)	
$\boldsymbol{b}$: Langmuir isotherm constant (L/mg)	
Freundlich isotherm model	
$\boldsymbol{Non-linear\ form}$: $\boldsymbol{q_e = K_f C_e^{\frac{1}{n}}}$	(5)
$\boldsymbol{Linear\ form}$: $\boldsymbol{\log q_e = \log K_f + \frac{1}{n} \log C_e}$	(6)
$\boldsymbol{Plot}$: $\boldsymbol{\log q_e\ vs.\ \log C_e}$	
n: Freundlich isotherm constant regarding adsorption intensity	
$\boldsymbol{K_f}$: Freundlich isotherm constant regarding adsorption capacity (mg/g).(L/mg)^n	
Temkin isotherm model	
$\boldsymbol{Non\ linear\ form}$: $\boldsymbol{q_e = B \ln(K_t C_e)}$; $\boldsymbol{B = \frac{RT}{b_t}}$	(7)
$\boldsymbol{Linear\ form}$: $\boldsymbol{q_e = \mathrm{B} \ln K_t + B \ln C_e}$	(8)
$\boldsymbol{Plot}$: $\boldsymbol{q_e\ vs.\ \ln C_e}$	

$\boldsymbol{b_t}$: Temkin isotherm constant relating to adsorption heat (J/mol)

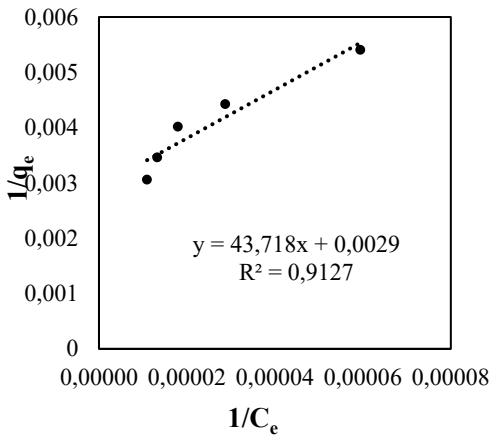
$\boldsymbol{K_t}$: Temkin isotherm constant (L/g)

R: Universal gas constant (8.314 J/mol.K)

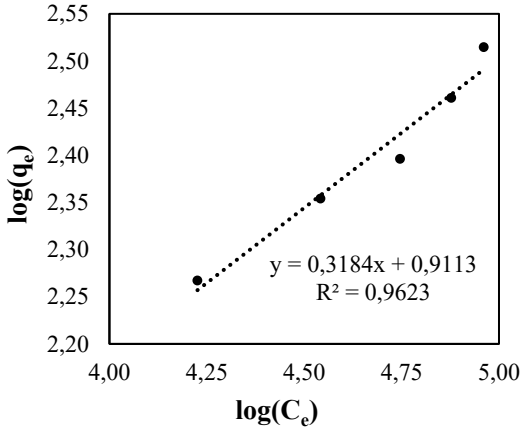
T: Temperature (K)

Table 1. The parameters of isotherm models for the LA adsorption by AIRA-96 and AIRA-400 (AIRA- 96 ve AIRA-400 ile LA adsorpsiyonuna ait izoterm model parametreleri)

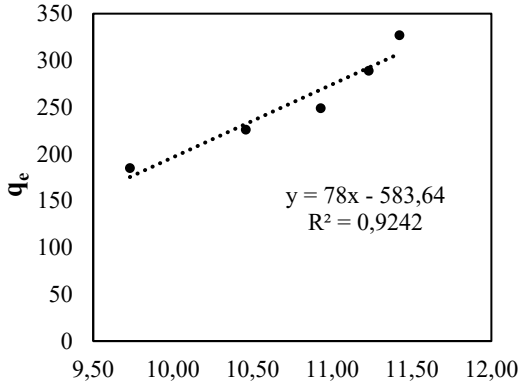
Isotherm models	Parameters	AIRA-96	AIRA-400
Langmuir	b (L/mg)	$6.63*10^{-5}$	$4.69*10^{-5}$
	Q_0 (mg/g)	344.82	126.58
	R^2	0.9127	0.8371
Freundlich	n	3.14	2.53
	K_f (mg/g).(L/mg)^n	8.15	1.20
	R^2	0.9623	0.8761
Temkin	K_t (L/g)	$5.62*10^{-4}$	$2.57*10^{-4}$
	b_t (J/mol)	31.76	71.43
	R^2	0.9242	0.7944



(a)



(b)



(c)

Figure 5. (a) Langmuir, (b) Freundlich, and (c) Temkin isotherm models for LA adsorption by AIRA-96 (AIRA-96 ile LA adsorpsiyonuna ait (a) Langmuir, (b) Freundlich, (c) Temkin izoterm modelleri)

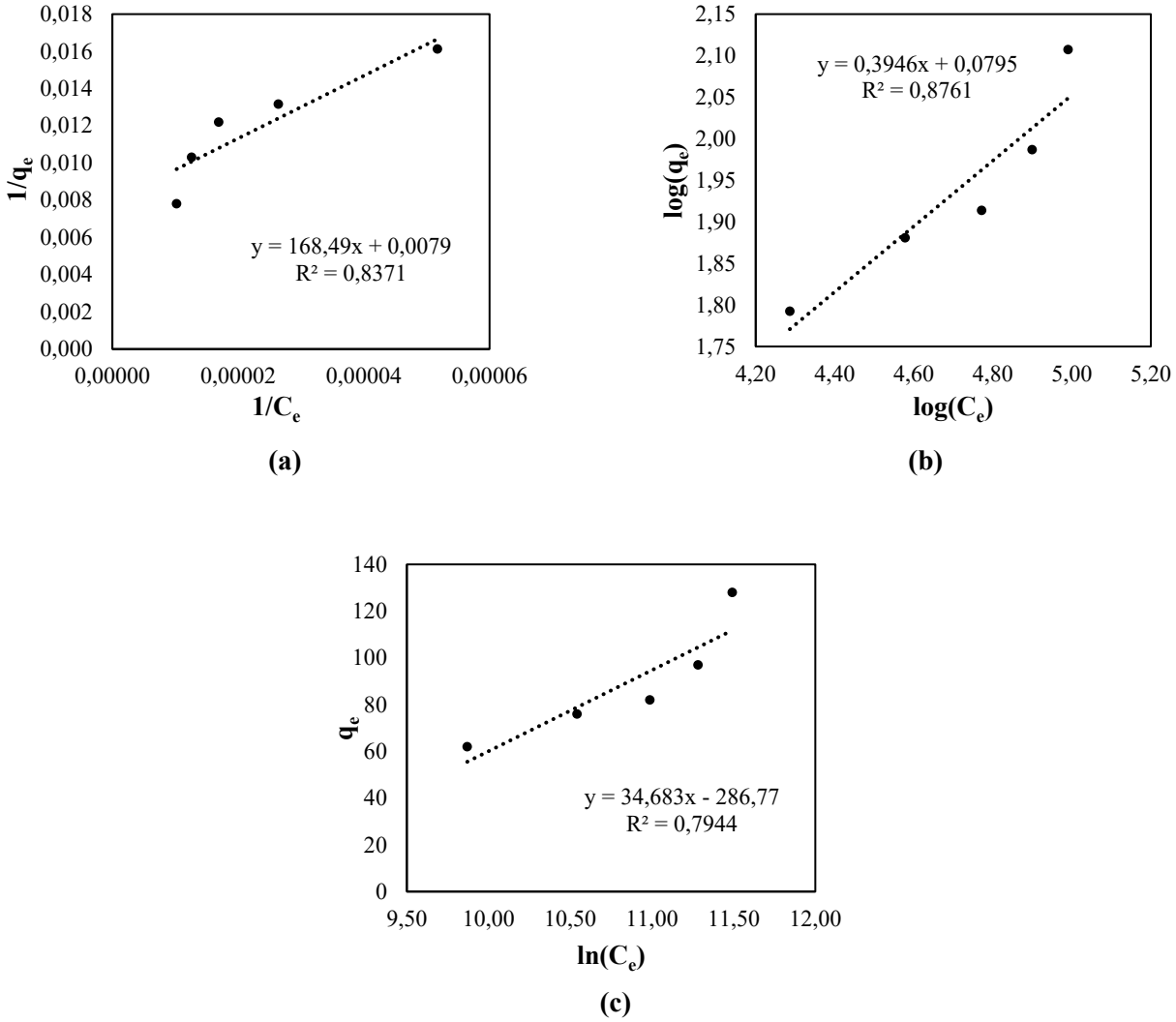


Figure 6. (a) Langmuir, (b) Freundlich, and (c) Temkin models for LA adsorption by AIRA-400 (AIRA-400 ile LA adsorpsiyonuna ait (a) Langmuir, (b) Freundlich, (c) Temkin izoterm modelleri)

Kinetic Models (Kinetik modelleme)

Kinetic models were developed using datum attained from the adsorption process to assess the mechanism of LA adsorption by AIRA-96 and AIRA-400. A summary of the Elovich, pseudo-first-order, pseudo-second-order kinetic models, and the Weber-Morris intraparticle diffusion model are provided in Table 3 [28]. The resulting kinetic data can be found in Table 4 and is illustrated graphically in Figures 7 and 8. Based on the results in Table 4, the pseudo-second-order kinetic model was detected to be the most appropriate for AIRA-96, while the pseudo-first order kinetic model was identified as the more proper model for AIRA-400. The conditions for the pseudo-first-order model occur at high initial concentrations of adsorbate, and the adsorption process is not limited by the availability of active sites. In certain instances, the pseudo-first order model effectively represents both external and internal diffusion processes [29]. Conversely, the pseudo-second-order model is characteristic of experimental datum associated with chemisorption phenomena [30].

Table 3. Equations of kinetic (Kinetik denklemler)

Pseudo-first-order model	
$Non-linear\ form$: $\frac{dq_t}{dt} = k_1 * (q_e - q_t)$	(12)
$Linear\ form$: $\text{In}\ (q_e - q_t) = \text{In}\ q_e\ - \text{k}_1 * t$	(13)
$Plot$: In $(q_e - q_t)$ vs. t	
k_1: Pseudo-first-order kinetic rate coefficient (1/min)	
Pseudo-second-order model	
$Non-linear\ form$: $\frac{dq_t}{dt} = k_2 * (q_e - q_t)^2$	(14)
$Linear\ form$: $\frac{t}{q_t} = \frac{1}{k_2 * {q_e}^2} + \frac{1}{q_e} * t$	(15)
$Plot$: $\frac{t}{q_t}\ vs.\ t$	
k_2: Pseudo-second-order kinetic rate coefficient (g/mg.min)	
Elovich model	
$Non-linear\ form$: $\frac{dq}{dt} = \alpha * exp(-\beta * q_t)$	(16)
$Linear\ form$: $q_t = \frac{1}{\beta} * In\ (\alpha * \beta) + \frac{1}{\beta} * \ln t$	(17)
$Plot$: $q_t\ vs.\ \ln t$	
α: Initial adsorption rate (mg/g.min)	
β: The constant of desorption (g/mg)	
Intra-particle diffusion model	
$q_t = k_{id} t^{\frac{1}{2}} + C$	(18)
$Plot$: $q_t\ vs.\ t^{\frac{1}{2}}$	(19)
k_{id}: Intra-particle diffusion rate coefficient [mg/g.min$^{1/2}$]	
C: Intercept relating the thickness of boundary layer	
q_t: Adsorption capacity of the adsorbent at the time (t) (mg/g)	
* q_e: Adsorption capacity of the adsorbent at the equilibrium (mg/g)	

Table 4. The parameters of kinetic models for the LA adsorption by AIRA-96 and AIRA-400 (AIRA-96 ve AIRA-400 ile LA adsorpsiyonuna ait kinetik parametreler)

Kinetic models	Parameters	AIRA-96	AIRA-400
Pseudo-first order	q_e (mg/g)	259.64	228.69
	k_1 (1/min)	0.0314	0.0407

	R^2	0.9153	0.9990
	q_e (mg/g)	400	315
Pseudo-second order	k_2 (mg/g.min)	1.40*10^{-4}	2.06*10^{-3}
	R^2	0.9972	0.9386
	α	74.19	6.01
Elovich	β	0.0132	0.0197
	R^2	0.9627	0.9434
	k_{id} (mg/g.min$^{1/2}$)	18.81	12.53
Intra-particle diffusion	R^2	0.9260	0.8890

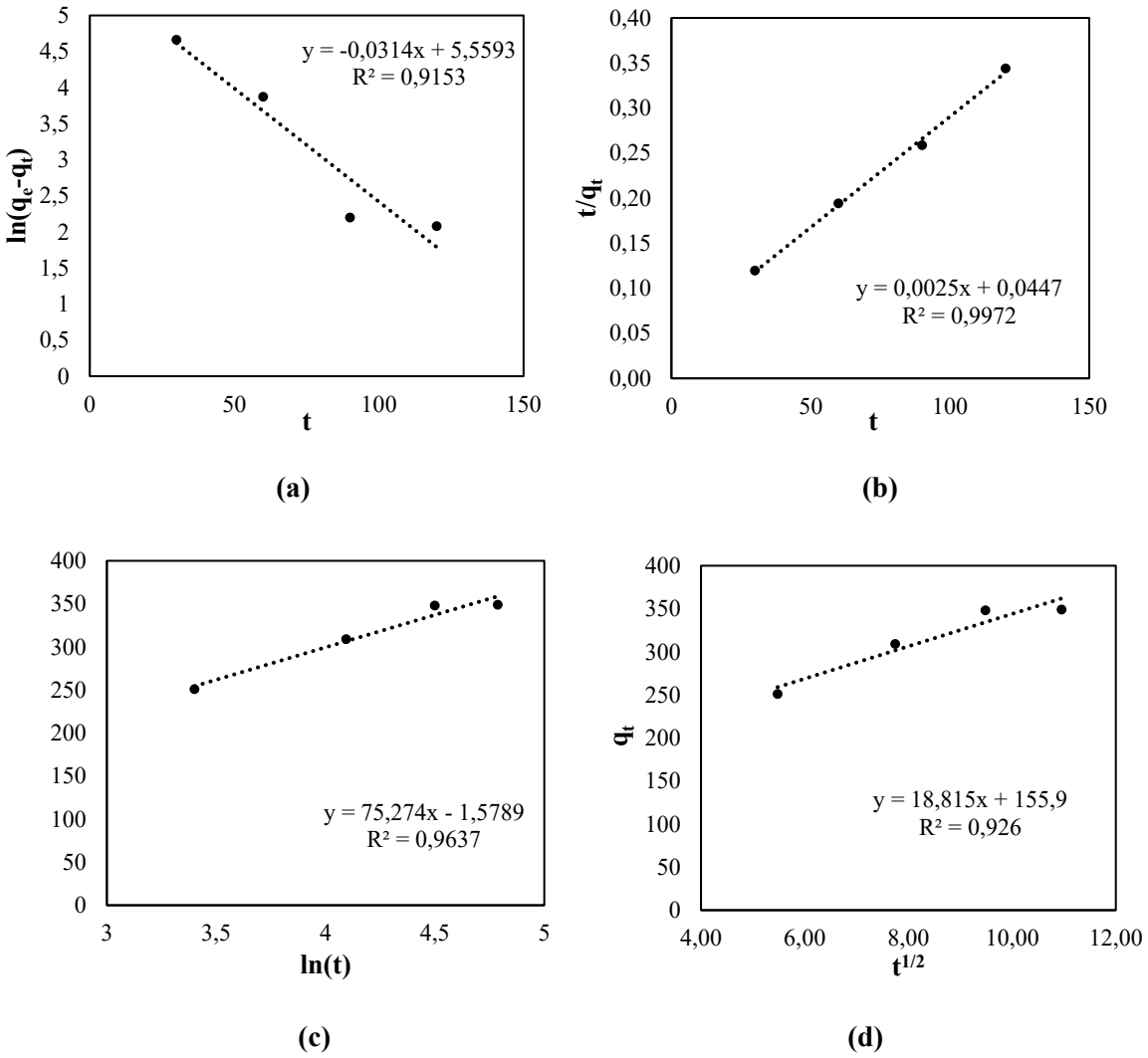


Figure 7. LA adsorption by AIRA-96: (a) pseudo-first order, (b) pseudo-second order, (c) Elovich, and (d) Weber-Morris intra- particle diffusion kinetic models (AIRA-96 ile LA adsorpsiyonu: (a) yalancı birinci dereceden kinetik, (b) yalancı ikinci dereceden kinetik, (c) Elovich, (d) Weber- Morris partikül içi difüzyon kinetik modelleri)

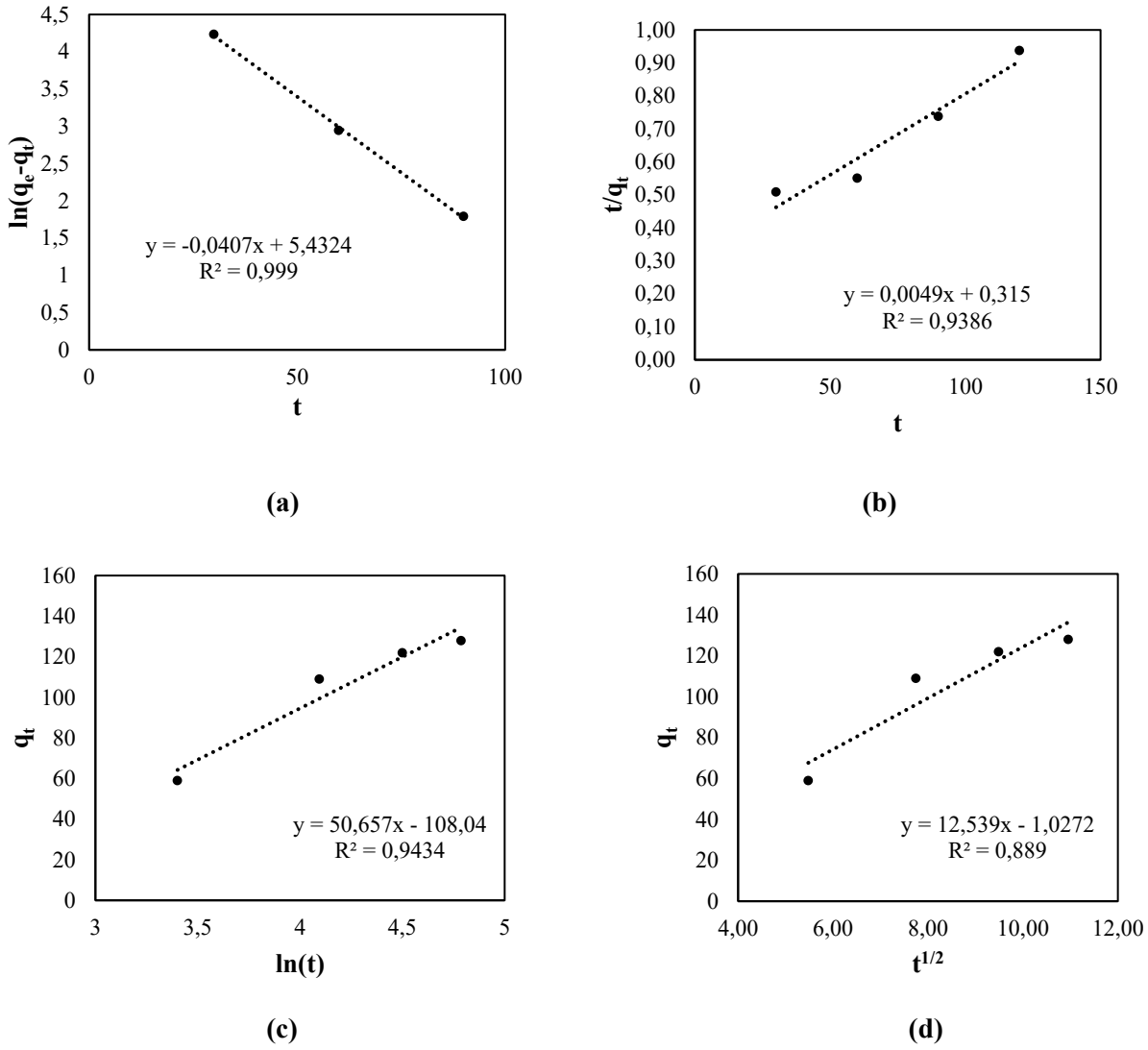


Figure 8. LA adsorption by AIRA-400: (a) pseudo-first order, (b) pseudo-second order, (c) Elovich, and (d) Weber-Morris intra-particle diffusion kinetic models (AIRA-400 ile LA adsorpsiyonu: (a) yalancı birinci dereceden kinetik, (b) yalancı ikinci dereceden kinetik, (c) Elovich, (d) Weber- Morris partikül içi difüzyon kinetik modelleri)

Comparison of adsorptive performance
(Adsorpsiyon performans karşılaştırması)

Various studies published in the literature using AIRA-96 and AIRA-400 as adsorbents and LA as adsorbate are summarized in Table 5. In the adsorption studies of LA, the highest q_e was achieved with MWCNT (multiwall carbon nanotube) and was found to be 483,25 mg/g [8]. In studies using AIRA-96 as an adsorbent, the highest q_e has been determined to be 275,20 mg/g in the formic acid adsorption study [31]. The highest value of q_e for AIRA-400 has been assigned to be 1.010 mg/g in the lactic acid adsorption [32]. In this study, the highest adsorption results were found for AIRA-96 and AIRA-400 as 357 and 128 mg/g, respectively. When all studies are examined comparatively, it can be said that the results of this study show above-average performance compared to both LA and Amberlite adsorption studies. Therefore, it can be concluded that AIRA-96 and AIRA-400 can be utilized as a promising adsorbent for the absorption of carboxylic acid or other substances.

Table 2. Comparison of the adsorption capacities of LA, AIRA-96 and AIRA-400 with various reported adsorbents and adsorbates (AIRA- 96 ve AIRA-400 ile LA adsorpsiyonunun farklı adsorban ve adsorbatlar ile karşılaştırılması)

Adsorbent	Adsorbate	Temperature (°C)	Adsorption capacity (mg/g)	References
D301 resin	LA	22	2.60	[19]
Amberlite XAD-4	LA	25	26.85	[5]
XAD7HP resin	LA	25	39.90	[33]
XAD-4 resin	LA	25	53.10	[33]
SY-01 resin	LA	25	95.70	[34]
SY-01 resin	LA	25	103.74	[17]
D315 packed bed	LA	22	106.10	[35]
XAD761 resin	LA	25	112.60	[33]
Montmorillonite	LA	25	355.69	[18]
Cloisite 20A	LA	25	428.63	[18]
MWCNT	LA	25	483.25	[8]
AIRA-96	Cr (VI)	25	28.10	[36]
AIRA-96	Levodopa	25	24.00	[37]
AIRA-96	Entacapone	25	69.00	[37]
AIRA-96	Formic acid	25	275.20	[31]
AIRA-400	Methyl orange	30	74.40	[38]
AIRA-400	Fumaric acid	25	176.70	[39]
AIRA-400	Lactic acid	25	222.46	[40]
AIRA-400	Hg^{2+}	25	303.03	[41]
AIRA-400	Congo Red	25	427.35	[42]
AIRA-400	Lactic acid	25	1,010	[32]
AIRA-96	LA	25	357.00	This study
AIRA-400	LA	25	128.00	This study

CONCLUSIONS (SONUÇLAR)

In this current work, LA adsorption was performed by successfully utilizing AIRA-96 and AIRA-400. In this context, the influences of contact time, Amberlite resins dosage, initial LA concentration, and temperature on the q_e have been examined. According to the outcomes, it was monitored that the q_e of Amberlite resins increased with rising initial LA concentration and contact time. Nevertheless, the q_e of amberlite resins decreased with the rising in the amount of Amberlite resins. The maximum adsorption capacities of AIRA-96 and AIRA-400 for LA uptake has been obtained to be 357 and 128 mg/g, respectively. The outcomes were shown that AIRA-96 and AIRA-400 are high selectivity for LA. In addition to, adsorption modelling studies have been performed and the outcomes have been evaluated. Adsorption isotherm modelling study specified that the adsorption of LA on both adsorbents were a heterogenous processes and multilayers. Kinetic modelling outcomes have been defined as appropriate fitting the pseudo-

second order model for AIRA-96 while fitting the pseudo-first order model for AIRA-400. Consequently, this work illustrated that the AIRA-96 and AIRA-400 have been an efficient and favorable adsorbent for adsorption of LA. Furthermore, these adsorbents could be considered potential candidates for the separation of other carboxylic acids from aqueous solutions.

Future Work (Gelecek çalışmalar)

Future studies should include FTIR and SEM analyses before and after adsorption provide further insight into the interaction mechanisms between levulinic acid and the resin surface. Additionally, studying the regeneration cycles the resins is considered an important area for future research about demonstrating the industrial applicability and economic sustainability of the process. Prospective studies are planned to investigate the effects of other components that may exist with levulinic acid on adsorption behavior and resin selectivity in order to better represent real process conditions.

DECLARATION OF ETHICAL STANDARDS (ETİK STANDARTLARIN BEYANI)

The author of this article declares that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission.

Bu makalenin yazarı çalışmalarında kullandıkları materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan ederler.

AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

Aysu OKUR: Formal analysis, Writing – original draft.

Biçimsel analiz, Yazım – özgün taslak hazırlama.

Tuba DEDECAN: Data curation, Investigation, Writing – review & editing.

Veri düzenleme, Araştırma, Yazım – gözden geçirme ve düzenleme.

Nilay BAYLAN: Investigation, Methodology, Writing – review & editing.

Araştırma, Metodoloji, Yazım – gözden geçirme ve düzenleme.

İsmail İNCİ: Conceptualization, Methodology, Supervision.

Kavramsallaştırma, Metodoloji, Süpervizyon.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

Bu çalışmada herhangi bir çıkar çatışması yoktur.

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