Jurnal Teknologi

Full Paper

AMMONIA ADSORPTION FROM PALM OIL MILL EFFLUENT USING CARBONIZED PALM EMPTY FRUIT BUNCHES

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Article history
Received
21 November 2024
Received in revised form
23 June 2025
Accepted
13 August 2025
Published Online
30 April 2026

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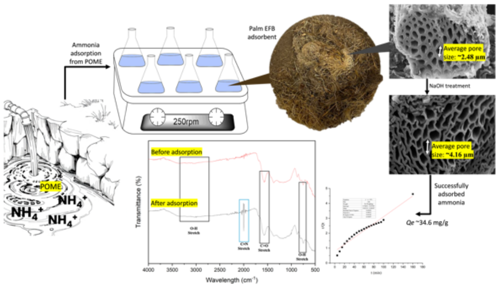
Graphical abstract



Abstract

The increasing production of palm oil generates substantial amounts of palm oil mill effluent (POME) which poses significant environmental challenges due to elevated ammonia levels. POME discharge can lead to detrimental effects on aquatic ecosystems including toxic conditions for aquatic life and intensified eutrophication. This study uniquely optimizes the carbonization temperature and adsorbent dosage of palm empty fruit bunch (EFB), an abundant agricultural by-product for efficient ammonia removal from POME thus advancing sustainable wastewater treatment applications. Experimental results indicate that a 5 g/L dosage of palm EFB carbonized at 500°C achieves the highest ammonia removal efficiency, significantly reducing concentrations from 423 mg/L to below regulatory limits. The adsorption capacity was determined to be approximately 34.6 mg/g, corresponding to over 80% removal efficiency. Kinetic studies revealed that the adsorption process predominantly follows a pseudo-second-order model, indicating a chemisorption mechanism. The findings demonstrate significant potential for scalable and cost-effective ammonia remediation, with benefits including reduced environmental pollution and enhanced regulatory compliance within the palm oil industry. Future work will focus on evaluating adsorbent reusability and integrating this method with complementary treatment technologies to further improve overall treatment efficiency. This study underscores the value of utilizing carbonized palm EFB as an effective, sustainable solution contributing to improved environmental management practices.

Keywords: Ammonia removal, palm empty fruit bunch (EFB), palm oil mill effluent (POME), adsorption, pseudo-second-order

Abstrak

Peningkatan pengeluaran minyak sawit menghasilkan jumlah besar efluen kilang kelapa sawit (POME) yang memberi cabaran ketara kepada alam sekitar akibat tahap ammonia yang tinggi. Pelepasan POME boleh menyebabkan kesan buruk kepada ekosistem akuatik termasuk keadaan toksik kepada hidupan air dan peningkatan eutrofikasi. Kajian ini mengoptimumkan secara unik suhu karbonisasi dan dos bahan penyerap daripada tandan kosong kelapa sawit (EFB), hasil sampingan pertanian yang banyak, untuk penyingkiran ammonia yang cekap daripada POME, sekaligus memajukan aplikasi rawatan air sisa secara mampan. Keputusan eksperimen menunjukkan bahawa dos 5 g/L EFB yang dikarbonkan pada suhu 500°C mencapai kecekapan penyingkiran ammonia tertinggi dengan pengurangan ketara kepekatan daripada 423 mg/L kepada tahap di bawah had peraturan. Kapasiti penjerapan dianggarkan sekitar 34.6 mg/g dengan kecekapan melebihi 80%. Kajian kinetik menunjukkan proses penjerapan mengikuti model pseudo-orde kedua yang menandakan mekanisme kemosorpsi. Penemuan ini memperlihatkan potensi besar bagi kaedah penyingkiran ammonia yang skalabel dan kos efektif, dengan manfaat mengurangkan pencemaran alam sekitar dan meningkatkan pematuhan peraturan dalam industri minyak sawit. Penyelidikan lanjut akan menumpukan pada penilaian keupayaan guna semula bahan penyerap dan integrasi dengan teknologi rawatan pelengkap untuk meningkatkan lagi keberkesanan rawatan. Kajian ini menegaskan nilai penggunaan EFB kelapa sawit yang dikarbonkan sebagai penyelesaian mampan dan berkesan untuk pengurusan alam sekitar yang lebih baik.

Kata kunci: Penyingkiran ammonia, tandan kosong kelapa sawit (EFB), efluen kilang kelapa sawit (POME), penjerapan, pseudo-orde kedua

1.0 INTRODUCTION

Malaysia has produced approximately 19.2 million metric tons of palm oil accounting for 24% of the global supply in 2024 [1]. This firmly positions Malaysia as the second-largest palm oil producer in the world after Indonesia. However, this production generates substantial amounts of palm oil mill effluent (POME) which poses serious environmental challenges due to its high organic content leading to detrimental effects on aquatic ecosystems if discharged untreated [2], [3]. POME, accounting for 67% of by-products from crude palm oil extraction contains high levels of ammonia giving an unpleasant smell and a brownish color due to its colloidal mixture [3]. The excessive release of ammonia can lead to toxic conditions for aquatic life, disrupting the biogeochemical nitrogen cycle and intensifying eutrophication which results in harmful algal blooms and biodiversity loss.

The Department of Environment (DOE) of Malaysia has taken a significant step by implementing a stricter law on the final discharge of POME to water bodies. There are two main categories for discharge standards: Standard A and Standard B [4]. Standard A applies to discharges into upstream water sources (e.g., rivers and bodies of water used for drinking water), while Standard B applies to discharges into other water bodies, such as rivers not intended for drinking water or coastal areas [4]. To ensure compliance, industries are required to regularly monitor and report their wastewater discharge levels. Ammonia levels are generally capped at around 5 mg/L for Standard A and 10 mg/L for Standard B though exact limits may vary depending on the type of industry and water body [4], [5]. Various methods have been implemented to address the high ammonia content in POME including ponding systems, advanced biological processes and chemical treatments. While these methods aim to enhance effluent quality, they often fall short in terms of efficiency and economic viability [6], [7].

In contrast, utilizing palm empty fruit bunch (EFB) as a carbon source for ammonia removal presents a more cost-effective solution. Palm EFB is locally abundant and inexpensive with minimal processing requirements. Studies indicate that palm EFB, particularly when pretreated and modified can achieve significant ammonia adsorption efficiencies with modified activated carbon from EFB demonstrating up to 95% absorption efficiency [8], [9]. Unlike costly and maintenance-intensive technologies such as membrane bioreactors, palm EFB requires only basic activation and can be easily handled on-site making it ideal for both large and small mills [10]. Palm EFB is also biodegradable and environmentally friendly [10], [11]. Once saturated, it can be safely returned to the soil as a nutrient source reducing waste and pollution [11]. Despite its potential, there is a notable lack of extensive studies on the effectiveness of palm EFB specifically for ammonia adsorption from POME. Jasmidi *et al*. (2022) conducted ammonia adsorption studies using modified activated carbon derived from oil palm empty bunches but emphasized that comprehensive evaluations involving process optimization and mechanism elucidation remain limited [12]. Similarly, Mohammad *et al*. (2021) reviewed various POME treatment processes and underscored the scarcity of targeted studies on ammonia adsorption using palm EFB [13].

The composition of POME itself presents unique challenges for ammonia adsorption, as it is a complex mixture of high organic content including suspended solids, proteins, carbohydrates and lipids along with significant levels of nutrients like nitrogen and phosphorus [14], [15], [16]. This complex matrix can interfere with adsorption processes. For example, the high organic matter content competes for adsorption sites potentially reducing the efficiency of ammonia removal [17]. Additionally, the colloidal nature and oily components within POME can create a barrier that limits the direct contact between the adsorbent surface and ammonia molecules making adsorption more challenging [18]. Most existing research on natural adsorbents tends to focus broadly on a variety of pollutants or utilizes different types of wastewater that do not reflect the complex composition of POME. This highlights the need for tailored approaches that specifically address the unique matrix interactions present in POME. Adeleke *et al*. (2019) and Benjelloun *et al*. (2021) reviewed adsorption mechanisms and emphasized that the complex organic and nutrient matrix in POME necessitates specific adsorbent modification strategies and kinetic modeling adapted to such wastewater contexts [19], [20], [21]. Similarly, Liew *et al*. (2015) identified gaps in the application of emerging polishing technologies that are specifically designed to treat unique composition of POME.

Given these challenges, a series of experiments was conducted in this study to evaluate the effectiveness of palm EFB in adsorbing ammoniacal nitrogen (NH_3-N) from POME. The palm EFB was primarily treated with sodium hydroxide (NaOH) followed by carbonization at various temperatures to identify optimal conditions for ammonia removal. NaOH was added to palm EFB during pretreatment to enhance the delignification process which significantly increases the cellulose content while reducing hemicellulose and lignin levels [22], [23]. Carbonization temperatures were selected at 300°C, 500°C, and 700°C. Lower temperatures (300°C) may optimize the production of biochar with a higher surface area while higher temperatures (500°C and 700°C) can enhance the carbonization process leading to improved thermal stability and energy density of the resulting biochar [24], [25]. This temperature variation allows for tailoring the physical and chemical properties of the biochar. Additionally, kinetic studies were performed to determine the ideal parameters equilibrium conditions. Establishing these parameters will enable more efficient and tailored applications of palm EFB in POME treatment and ultimately contributing to eco-friendly and cost-effective solutions for industrial wastewater management.

2.0 METHODOLOGY

Materials

The palm empty fruit bunch (EFB) adsorbent and palm oil mill effluent (POME) were sourced locally from a palm oil mill in Johor, Malaysia. POME was stored in a 25L high-density polyethylene (HDPE) bottle at 4°C to maintain sample integrity. Sodium hydroxide (NaOH) used for alkaline pretreatment was of analytical grade (≥ 98% purity) and procured from Merck, Germany. Ammonia reagents for spectrophotometric analysis were supplied by HACH Company, Colorado, USA, and conform to standard APHA methods (Method 8038, Nessler Method).

2.0 EXPERIMENTAL PROCEDURES

Sodium Hydroxide Treatment on Palm Empty Fruit Bunch

The palm EFB was ground and sieved to produce a fine powder thereby maximizing the surface area of the sample. The fine particle size is essential for accurately assessing the morphology of the palm EFB which constitutes a significant focus of this study. Subsequently, the palm EFB powder was subjected to carbonization in a Carbolite furnace at temperatures ranging from 300°C, 500°C and 700°C. Upon completion of the carbonization process, the resulting samples were immersed in 0.1 M sodium hydroxide (NaOH) with continuous stirring facilitated by a magnetic stirrer set at 250 rpm for 8 hours. Following the stirring period, the samples were filtered and subsequently washed with distilled water. The filtered samples were then dried in an oven at 60°C for 24 hours to eliminate any residual moisture.

Characterization of Palm Empty Fruit Bunch Adsorbent

The morphology and elemental composition of palm empty fruit bunch (EFB) adsorbent was examined using Scanning Electron Microscope and Energy Dispersive X-ray (COXEM EM-30AX, South Korea) to obtain detailed high-resolution images of the surface structure such as porosity and roughness as well as to identify the elemental composition including carbon (C), oxygen (O) and other trace elements. The functional groups of the palm empty fruit bunch (EFB) adsorbent were also analyzed using Fourier Transform Infrared (FTIR) spectroscopy (Thermo Fisher Scientific, USA) which enabled the identification of key surface functional groups such as hydroxyl, carboxyl and amine groups. These functional groups are integral to the capacity of adsorbent for ammonia removal. This detailed analysis highlights the potential of palm EFB as an effective adsorbent for ammonia removal in wastewater treatment.

Adsorption Study of Palm Oil Mill Effluent (POME) Adsorbent for Ammonia Removal in POME under Methanogenic Conditions

Prior to the adsorption, palm oil mill effluent (POME) was characterized to obtain insights of its ammonia content. Ammoniacal nitrogen (NH_3-N) content was analyzed using HACH DR6000 spectrophotometer and ammonia reagent set (Colorado, USA) following Method 8038 (Nessler Method) at a wavelength of 425 nm, in accordance with APHA (American Public Health Association) standards which provide widely accepted methods for water and wastewater testing. The pH of POME was then measured using a pH meter from Thermo Scientific (Massachusetts, USA).

Adsorption experiments were conducted by mixing the treated palm EFB with POME in an orbital shaker operating at 250 rpm at ambient temperature as depicted in Figure 1. Preliminary kinetic studies determined that equilibrium for ammonia adsorption was reached after 150 minutes of contact time, which was subsequently used as the standard contact duration in all batch adsorption tests.

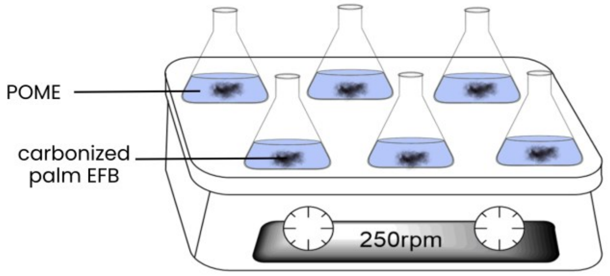


Figure 1 Adsorption of Ammonia from Palm Oil Mill Effluent (POME)

Adsorption Kinetic Analysis

The adsorption kinetics of ammonia on the palm empty fruit bunch (EFB) was analyzed using pseudo-first-order and pseudo-second-order kinetic models. A kinetic study is crucial as it provides insights into the adsorption rate of ammoniacal nitrogen (NH_3-N) from POME onto the treated palm EFB adsorbent. By analyzing the rate at which ammonia is adsorbed over time, the study can identify the optimal contact time required to reach equilibrium ensuring maximum removal efficiency. Furthermore, kinetic data help to determine the underlying mechanisms of adsorption, such as whether it follows physisorption or chemisorption and how factors like adsorbent dosage and ammonia concentration influence the process [21, 22].

Eq 1 was used for kinetic pseudo-first -order where k_1 is the pseudo-first-order rate constant and Eq 2 was used for kinetic pseudo-second-order where k_2 is the pseudo-second-order rate constant. While Q_e is the adsorption capacity at equilibrium and Q_t is the adsorption capacity at time t.

$$ln\,(Q_e - Q_t) = ln\,(Q_e)\; - k_1 t \qquad \text{(Eq 1)}$$

$$\frac{t}{Q_t} = \frac{1}{k_2 Q_e^2} + \frac{1}{Q_e} \qquad \text{(Eq 2)}$$

Thus, calculating the Q_t value enables comparisons between palm EFB and other adsorbents providing a clearer understanding of each material effectiveness in ammonia removal. This comparative analysis aids in selecting the most suitable adsorbent for specific wastewater treatment applications. Eq 3 was used to calculate the Q_t value.

$$Q_t = \frac{(C_o - C_t)\; x\; V}{M} \qquad \text{(Eq 3)}$$

where C_o and C_t were the initial and final concentrations of ammonia while V was used as a volume of POME used and M was the mass of palm EFB

3.0 RESULTS AND DISCUSSION

Initial Ammoniacal Nitrogen and pH Analysis on Palm Oil Mill Effluent

Table 1 Characteristics of POME

Parameters	Value	SD[a]	Effluent (Standard B)[b]
pH	8.2	0.9	5.5-9.0
NH_3-N (mg/L)	423	33	20

The ammonia nitrogen (NH_3-N) concentration in POME was measured at 423 mg/L significantly exceeding the Standard B regulatory limit of 20 mg/L (as indicated by superscripts **a** for effluent values and **b** for Standard B limits in Table 1). Such elevated ammonia levels pose a serious environmental risk since ammonia is toxic to aquatic life and can lead to oxygen depletion in water bodies, jeopardizing aquatic ecosystems. This parameter is particularly critical because the nitrogen-rich organic content of POME contributes to the elevated ammonia concentration, highlighting the need for effective treatment methods. The pH of POME, measured at 8.2, indicates a slightly alkaline condition that favors the presence of un-ionized ammonia (NH_3) over ammonium ions (NH_4^+), with the former being more harmful.

Morphological Analysis and Chemical Composition of Palm Empty Fruit Bunch

The morphology of the palm empty fruit bunch (EFB) was examined using Scanning Electron Microscopy (SEM). Figure 2 illustrates the surface morphology of both untreated palm EFB and NaOH-treated palm EFB carbonized at 500°C, identified as optimal for ammonia reduction based on adsorption performance analysis discussed in a later section. The structure of the untreated palm EFB is characterized by a porous, irregular shape typical of natural lignocellulosic materials. In contrast, the NaOH treatment and subsequent carbonization at 500°C effectively remove non-cellulosic components such as hemicellulose and lignin resulting in a more refined and organized porous structure. The carbonization process further enhances porosity by transforming the palm EFB into a more defined and uniform pore network reflecting significant improvements in surface characteristics and adsorption capabilities. The average pore size for the untreated palm EFB is approximately 2.48 µm, while the average pore size for the NaOH-treated and carbonized palm EFB at 500°C is about 4.16 µm. The untreated palm EFB exhibits smaller average pore sizes indicating a more compact and less porous structure. This reduced pore size may limit the ability of the adsorbent to facilitate the movement of larger particles potentially leading to a lower adsorption capacity for smaller molecules such as ammonia. This enlargement after NaOH treatment and carbonization enhances the overall surface area of the adsorbent likely improving ammonia adsorption capabilities by providing more active sites available for adsorption.

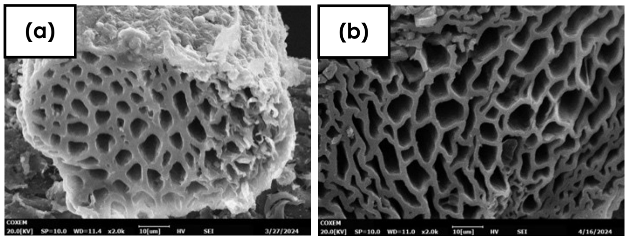


Figure 2 SEM images of (a) untreated palm EFB (b) palm EFB treated with NaOH and carbonized at 500°C

Table 2 Chemical elements in palm EFB

Element	Weight %
Carbon	73.87
Potassium	6.65
Oxygen	17.28
Sodium	1.42
Calcium	0.78

The chemical composition of palm EFB after NaOH treatment is shown in Table 2. Carbon, the most abundant element at 73.87% enables the formation of a porous structure which significantly increases the surface area providing ample sites for ammonia molecules to attach. During carbonization, the carbon structure in palm EFB creates additional micropores and active sites that enhance the capture of ammonia. This structural development is vital for effective adsorption in wastewater treatment as it increases both the accessibility and number of binding sites available for contaminant removal. Besides, the presence of potassium at 6.65% further enhances adsorption capabilities of palm EFB as potassium ions can engage in ion exchange interactions with ammonium ions (NH_4^+) in POME. Potassium may also alter the surface charge characteristics of palm EFB potentially increases its affinity for ammonium ions. This ion exchange capability complements the physical adsorption process offering a chemically driven mechanism that strengthens the performance of palm EFB as an ammonia adsorbent. Oxygen present at 17.28% contributes significantly by forming oxygen-containing functional groups on the palm EFB surface such as hydroxyl and carbonyl groups. These groups enhance the binding interaction between the adsorbent with ammonia. The presence of these functional groups provides palm EFB with chemically active surface that can interact directly with ammonium ions reinforcing the adsorption process. Additionally, sodium, accounting for 1.42% of the composition contributes to the ion exchange properties of palm EFB. Like potassium, sodium ions can exchange with ammonium ions in solution facilitating ammonia capture through ionic interactions. This ion exchange pathway offers an alternative mechanism to physical adsorption thereby increasing the versatility and effectiveness of palm EFB for wastewater treatment. Finally calcium though present in a smaller proportion at 0.78%, plays a supportive role in stabilizing the palm EFB structure and providing additional binding sites. Calcium can also participate in ion exchange with ammonium ions adding another dimension to the adsorption capacity of the palm EFB. Overall, the combined presence of these elements in EFB creates a multifaceted adsorbent with physical, chemical, and ion exchange properties optimized through carbonization and treatment processes.

Although nitrogen adsorption (BET) measurements were not conducted in this study to directly quantify the surface area and pore size distribution of the carbonized palm EFB, previous literature provides insight into the expected variation with carbonization temperature. It is reported that biochars produced at lower temperatures around 300°C typically exhibit surface areas in the range of 50–200 m^2/g, due to partial carbonization and pore development [26]. At higher carbonization temperatures such as 500°C and 700°C, the surface area generally increases to 100–800 m^2/g, facilitated by enhanced micropore formation and removal of volatiles [26]. This increase in surface area is consistent with the improved ammonia adsorption performance observed in this study at 500°C confirming that higher carbonization temperatures contribute to increased adsorption sites and hence greater removal efficiency.

Functional Group Analysis of Palm Empty Fruit Bunch

The FTIR spectra displayed in Figure 3 illustrate the functional groups present in palm EFB before and after ammonia adsorption. In the spectrum of palm EFB prior to ammonia adsorption (Figure 3(a)), several characteristic peaks are observed. The broad peak around 3300 cm^{-1} is typically indicative of O-H stretching vibrations from hydroxyl groups present in lignocellulosic materials. The peaks observed around 1730 cm^{-1} and 1630 cm^{-1} attribute to C=O stretching of carbonyl groups indicating the presence of lignin and other carbonyl-containing compounds.

After the adsorption of ammonia (Figure 3(b)), a notable change is observed. The emergence of a sharp peak around 2200 cm-1 which is characteristics of the nitrile (C≡N) functional group. This peak indicates that ammonia has been successfully adsorbed onto the palm EFB and shows significant interaction between the ammonia molecules and the active sites on the palm EFB surface. While the peak intensities in the other range remain relatively unchanged. This stability indicates that the overall lignocellulosic structure of the palm EFB is maintained after adsorption, preserving its chemical integrity and thus enabling sustained adsorption performance over successive cycles. The consistent O-H stretching band suggest that the chemical integrity of the lignocellulosic matrix is preserved allowing the palm EFB to function effectively in subsequent adsorption processes.

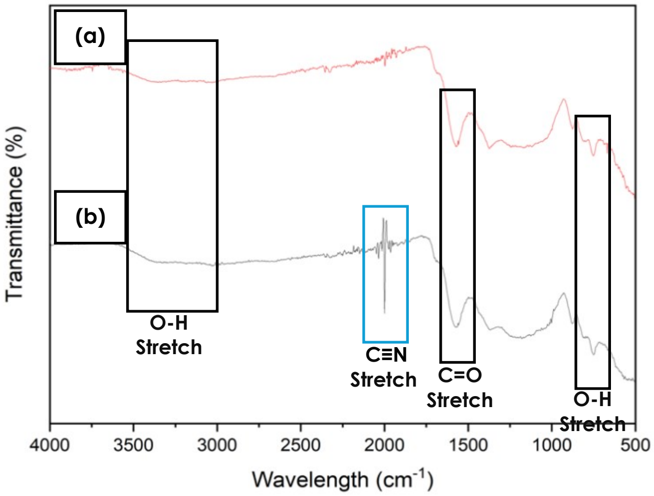


Figure 3 FTIR spectrum of palm EFB treated with 0.1M NaOH at 500°C (a) before ammonia adsorption (b) after ammonia adsorption

Ammonia Adsorption from Palm Oil Mill Effluent (POME)

Table 3 provides data on the ammonia reduction performance of palm EFB adsorbent treated with NaOH and carbonized at varying temperatures of 300°C, 500°C, and 700°C. These experiments explored the effects of different adsorbent dosages, specifically 2 g/L, 3 g/L, and 4 g/L, on ammonia removal efficiency. Ammonia concentration reductions were recorded at multiple time intervals to monitor the progression of adsorption until equilibrium was achieved.

As depicted in Table 3, as contact time increases, a gradual reduction in ammonia concentration is observed across all conditions suggesting that adsorption continues to progress over time. However, the ammonia concentration stabilizes after 95 minutes, indicating that equilibrium is reached, beyond which no significant reduction in ammonia occurs. At the lowest dosage of 2 g/L, ammonia reduction is relatively slow, with final concentrations of approximately 290 mg/L at 300°C, 280 mg/L at 500°C, and 276 mg/L at 700°C. This suggests that while carbonization temperature plays a role in enhancing the adsorbent's performance, a lower dosage limits the available adsorption sites, thereby reducing the overall adsorption capacity. In contrast, higher dosages of 4 g/L and 5 g/L result in more effective ammonia removal, with the lowest ammonia concentrations observed at 5 g/L and 500°C, where the final concentration reaches 250 mg/L, closely followed by 248 mg/L at 700°C. The improved performance with higher dosages can be attributed to the increased number of active sites available for ammonia adsorption. Increasing the carbonization temperature enhances the development of the surface area and porous structure of the adsorbent by creating additional micropores and exposing more active sites for adsorption. Specifically, temperatures of 500°C and 700°C facilitate the formation of a more thermally stable carbon matrix with higher surface roughness which improves ammonia capture. Concurrently, a higher adsorbent dosage increases the total amount of available active sites in the system thereby providing more binding locations for ammonia molecules. The synergistic effect of optimizing both the carbonization temperature and dosage results in enhanced ammonia removal efficiency by maximizing the number and accessibility of active adsorption sites.

Notably, the combination of a 5 g/L dosage and a carbonization temperature of 500°C provides the most efficient adsorption, as evidenced by the lowest ammonia concentration achieved and the rapid stabilization of adsorption at equilibrium. Overall, the optimal parameters for ammonia removal from wastewater are a 5 g/L adsorbent dosage with a carbonization temperature of 500°C. This combination provides the highest adsorption efficiency, reaching equilibrium quickly, and offers the most effective solution for ammonia mitigation in wastewater treatment.

The adsorption capacity of the carbonized palm EFB for ammonia removal from POME was determined to be approximately 34.6 mg/g with a removal efficiency exceeding 80% as shown in Table 4. This performance is comparable to or better than other agricultural waste-based adsorbents reported in the literature. For instance, unmodified biochar have demonstrated ammonia adsorption capacities typically ranging from 20 to 35 mg/g under similar conditions [27]. The alkaline pretreatment combined with carbonization at 500°C in our study likely enhances surface functional groups and active sites contributing to the higher adsorption efficacy observed. This is supported by kinetic studies following a pseudo-second-order model indicative of chemisorption aligning with prior findings on modified biochar.

Table 3 Ammonia Reduction Performance of Palm Empty Fruit Bunch (EFB) Adsorbent Treated with NaOH

Time (min)	Adsorbent Dosage : 2 g/L					
	300°C		500°C		700°C	
	Final Concentration (mg/L)	Ammonia Reduction (mg/L)	Final Concentration (mg/L)	Ammonia Reduction (mg/L)	Final Concentration (mg/L)	Ammonia Reduction (mg/L)
0	423	0	423	0	423	0
5	407	16	398	25	394	29
10	396	27	380	43	376	47
15	389	34	373	50	369	54
20	381	42	368	55	364	59
25	373	50	362	61	358	65
30	368	55	358	65	354	69
35	361	62	353	70	349	74
40	355	68	347	76	343	80
45	349	74	341	82	337	86
50	344	79	335	88	331	92
55	338	85	328	95	324	99
60	332	91	322	101	318	105
65	326	97	316	107	312	111
70	320	103	310	113	306	117
75	314	109	304	119	300	123
80	308	115	298	125	294	129
85	302	121	292	131	288	135
90	296	127	286	137	282	141
95	290	133	280	143	276	147
100	290	133	280	143	276	147
160	290	133	280	143	276	147

Time (min)	Adsorbent Dosage : 4 g/L					
	300°C		500°C		700°C	
	Final Concentration (mg/L)	Ammonia Reduction (mg/L)	Final Concentration (mg/L)	Ammonia Reduction (mg/L)	Final Concentration (mg/L)	Ammonia Reduction (mg/L)
0	423	0	423	0	423	0
5	396	27	387	36	386	37
10	379	44	370	53	369	54
15	372	51	363	60	362	61
20	366	57	357	66	356	67
25	358	65	349	74	348	75
30	351	72	342	81	341	82
35	344	79	335	88	334	89
40	338	85	329	94	328	95
45	332	91	323	100	322	101
50	326	97	317	106	316	107

55	318	101	309	114	308	115
60	312	111	303	120	302	121
65	306	117	297	126	296	127
70	300	123	291	132	290	133
75	294	129	285	138	284	139
80	288	131	279	144	278	145
85	282	137	273	150	272	151
90	276	147	267	156	266	157
95	270	153	261	162	260	163
100	270	153	261	162	260	163
160	270	153	261	162	260	163

Time (min)	Adsorbent Dosage : 5 g/L					
	300°C		500°C		700°C	
	Final Concentration (mg/L)	Ammonia Reduction (mg/L)	Final Concentration (mg/L)	Ammonia Reduction (mg/L)	Final Concentration (mg/L)	Ammonia Reduction (mg/L)
0	423	0	423	0	423	0
5	381	42	374	49	372	51
10	366	57	359	64	357	66
15	359	64	352	71	350	73
20	353	70	346	77	344	79
25	345	78	338	85	336	87
30	338	85	331	92	329	94
35	331	92	324	99	322	101
40	325	98	318	105	316	107
45	319	104	312	111	310	113
50	313	110	306	117	304	119
55	305	118	298	125	296	127
60	299	124	292	131	290	133
65	293	130	286	137	284	139
70	287	136	280	143	278	145
75	281	142	274	149	272	151
80	275	148	268	155	266	157
85	269	154	262	161	260	163
90	263	160	256	167	254	169
95	257	166	250	173	248	175
100	257	166	250	173	248	175
160	257	166	250	173	248	175

Adsorption Kinetic Analysis

The selected optimal condition, identified based on the highest observed adsorption capacity was 5 g/L dosage at 500°C. This condition demonstrated the most efficient ammonia uptake with adsorption capacity values stabilizing over time as the system approached equilibrium. To evaluate the suitability of each kinetic model, linearized forms of the pseudo-first-order and pseudo-second-order equations were applied to the experimental data.

Table 4 Adsorption of ammonia by 5 mg/L palm EFB carbonized at 500°C until reaching equilibrium

t (min)	$C_o - C_t$ (mg/L)	Q_t (mg/g)	$ln\,(Q_e - Q_t)$ (Pseudo-First Order)	$\frac{t}{Q_t}$ (Pseudo-Second Order)
0	0	0	3.543853682	-
5	49	9.8	3.210843653	0.510204082
10	64	12.8	3.08190997	0.78125
15	71	14.2	3.015534901	1.056338028
20	77	15.4	2.954910279	1.298701299
25	85	17	2.867898902	1.470588235
30	92	18.4	2.785011242	1.630434783
35	99	19.8	2.694627181	1.767676768
40	105	21	2.610069793	1.904761905
45	111	22.2	2.517696473	2.027027027
50	117	23.4	2.415913778	2.136752137
55	125	25	2.261763098	2.2
60	131	26.2	2.128231706	2.290076336
65	137	27.4	1.974081026	2.372262774
70	143	28.6	1.791759469	2.447552448
75	149	29.8	1.568615918	2.516778523
80	155	31	1.280933845	2.580645161
85	161	32.2	0.875468737	2.639751553
90	167	33.4	0.182321557	2.694610778
95	173	34.6	-	2.74566474
100	173	34.6	-	2.89017341
160	173	34.6	-	4.624277457

Pseudo-First-Order Kinetics

$ln\,(Q_e - Q_t)$ is plotted against time (t) as shown in Figure 4 and the slope of the resulting line gives k_1. The graph shows a moderate linear relationship between $ln\,(Q_e - Q_t)$ and t indicated by an R-squared (R²) value of 0.90221. Although this fit is reasonable, a perfect linearity would indicate a better applicability of the pseudo-first-order model. The deviations from linearity, especially at later stages, suggest that the adsorption mechanism may involve more than a simple physisorption process and may not fully align with first-order kinetics. However, the inconsistency in fit at longer contact times implies that the adsorption process might not rely solely on the first-order mechanism.

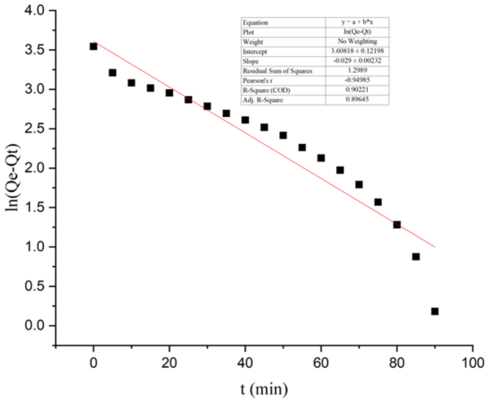


Figure 4 The linear regression plot for pseudo-first-order kinetics

Pseudo-Second-Order Kinetics

In Figure 5, $\frac{t}{Q_t}$ is plotted against t. The slope and intercept of the line are used to calculate Q_e and k_2, respectively. The R-squared value of 0.96102 indicates an excellent fit, much closer to unity compared to the pseudo-first-order model. This higher R-squared value suggests that the pseudo-second-order model more accurately describes the kinetics of ammonia adsorption under these conditions. The near-perfect linearity observed suggests that the adsorption process predominantly follows chemisorption, where the ammonia ions interact strongly with the surface functional groups on the adsorbent. Additionally, the consistency in linearity even at prolonged contact times implies that the pseudo-second-order model not only applies across the initial phase of adsorption but also reliably predicts the behaviour near equilibrium. This is significant because it indicates a chemical binding mechanism likely due to ion exchange or covalent bonding which aligns with the nature of ammonia interactions on the modified surface of the adsorbent. In comparing both kinetic models, it is evident that the pseudo-second-order model provides a better fit for the experimental data as indicated by the higher R-squared value (0.96102) compared to the pseudo-first-order model (0.90221). The superior fit suggests that the adsorption process is primarily chemisorption which is consistent with the characteristics of ammonia adsorption onto chemically treated adsorbents at elevated temperatures (500°C). The chemical modification likely enhances active sites on the adsorbent allowing stronger ammonia interactions which cannot be adequately explained by physisorption alone. This chemisorption is expected as the adsorption of ammonia on activated and treated adsorbents generally involves ionic or covalent bonding which is better represented by the pseudo-second-order kinetics.

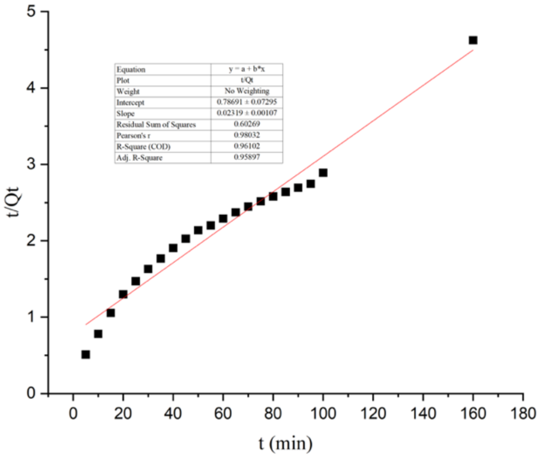


Figure 5 The linear regression plot for pseudo-second-order kinetics

4.0 CONCLUSION

This study demonstrates that carbonized palm empty fruit bunch (EFB) treated with sodium hydroxide presents a promising and sustainable adsorbent for the effective removal of ammonia from palm oil mill effluent (POME). The optimized carbonization temperature of 500°C combined with a 5 g/L adsorbent dosage achieved a significant reduction in ammonia concentration from 423 mg/L to below regulatory discharge limits, with an adsorption capacity of approximately 34.6 mg/g and removal efficiency exceeding 80%. Kinetic analysis confirmed that the adsorption follows a pseudo-second-order model, indicating chemisorption as the predominant mechanism. These findings underscore the potential for valorizing abundant agricultural residues such as palm EFB into valuable adsorbents aligning with circular economy principles and contributing to environmentally friendly wastewater management in the palm oil industry. For future research, it is recommended to investigate the long-term stability and regeneration potential of the carbonized palm EFB to ensure practical longevity in real-world applications. Economic assessments of scale-up production and operation costs will be crucial to facilitate industrial adoption. Moreover, exploring the integration of carbonized palm EFB with complementary treatment methods, such as biological or membrane processes, could synergistically enhance ammonia removal efficiency and overall treatment performance. Ultimately, this study supports the development of cost-effective, eco-friendly, and scalable solutions for ammonia mitigation in POME thus providing tangible benefits for environmental protection and sustainable palm oil production.

Acknowledgement

This study was supported by Universiti Tun Hussein Onn Malaysia (UTHM) through MDR Grant vot Q700, GPPS vot Q665 and J019.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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