Indian Journal of Chemical Technology
Vol. 33, September 2026, pp. 711-718
DOI: 10.56042/ijct.v33i5.27744

Palmyra palm flower biomass: A sustainable precursor for high-performance activated carbon

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Received 19 January 2026; accepted 3 August 2026

Palmyra palm flowers (*Borassus flabellifer*), an agricultural waste, has been used as a source of carbon for the production of activated carbon useful for removing volatile organic compound (VOC). Chemical activation of the prepared carbon was performed with potassium hydroxide and zinc chloride and their properties were compared. The surface area of the activated carbon produced using zinc chloride was 1306.03 $m^2 g^{-1}$, compared to 1066.76 $m^2 g^{-1}$ for potassium hydroxide-activated carbon and 981.34 $m^2 g^{-1}$ for commercial activated carbon. The activated carbon produced using zinc chloride exhibited a total pore volume of 0.71 $cm^3 g^{-1}$, providing high microporosity, whereas activated carbon produced using potassium hydroxide yielded a similar structure and greater mesopore content. Images from scanning electron microscopy show that they have different shapes. Activated carbon from zinc chloride had a coral-like structure. Elemental analysis showed that the Palmyra palm flower activated carbon was highly carbonised, with a carbon content of 88.60%. FTIR spectra demonstrated the formation of aromatic carbon. For removal of VOC such as formaldehyde, the activated carbon produced using zinc chloride achieved a removal efficiency of 90% whereas activated carbon produced from potassium hydroxide achieved 86% as compared to 83.5% achieved by commercial carbon. Adsorption kinetics revealed that the formaldehyde adsorption in AC-Z followed the pseudo-second-order kinetic model (R^2 = 0.9944) showing good adsorption behaviour. The results indicate that Palmyra palm flowers represent a valuable alternative for the production of activated carbon.

Keywords: Activated carbon, Agricultural residue, Chemical activation, Formaldehyde adsorption, Palmyra palm flower biomass, Porous carbon, Sustainable air purification

Introduction

Carbon, the essential building block of life, forms the structure of all living organisms on our planet and is the most vital element in the human body. Its connection to humanity dates back to the primitive practice of drilling wood for fire, signifying one of the first elements utilized by humans[1]. Historically, carbon materials have primarily been sourced from fossil fuels like coal, petroleum, and natural gas, or from their byproducts, through various processing methods[2]. Biomass, which is plentiful and found in many locations, serves as a sustainable and eco-friendly option for producing valuable carbon materials[3]. Among these materials, activated carbon is a highly porous substance and recognized as the foremost adsorbent, extensively utilized across various industrial and household functions, including the purification of liquids and gases, removal of harmful substances, as a support for catalysts, in supercapacitors, for gas storage, and as electrodes[4,5]. AC has fascinated the attention of many investigators due to its excellent properties such as thermo-stability, high performance, high adsorptive effect, large surface area and a well-developed structure[6]. The exceptional properties of activated carbon make it highly relevant to addressing air pollution, a paramount global concern that poses significant threats to environmental stability and public health.

Among the most dangerous atmospheric pollutants, volatile organic compounds (VOCs), are a class of chemicals including benzene, formaldehyde, and toluene, released from industrial emissions, vehicle exhaust, and various indoor sources. VOCs are considered carcinogenic and can cause adverse respiratory health effects, the development of appropriate technologies for controlling VOCs is a scientific and societal priority. Within this domain, activated carbon is the benchmark adsorbent, prized for its vast specific surface area and highly developed porous structure that provide ample sites for capturing pollutant molecules.

Activated carbon can be formed from a variety of carbon-based materials. Typically, there are two

common methods for its preparation, i.e., physical activation and chemical activation[7]. For physical activation, the process comprises two stages: carbonization and activation, which occurs at temperatures ranging from 700 to 1100 °C in the presence of appropriate activating agents like carbon dioxide, steam, air, or a combination of these. In the case of chemical activation, the precursor is combined with a specific amount of chemicals, such as zinc chloride ($ZnCl_2$), phosphoric acid (H_3PO_4), and potassium hydroxide, which serve as the activating agents. During the chemical activation method, both carbonization (at temperatures between 400 and 700 °C) and the activation step occur simultaneously, which minimizes the analysis time, decreases energy usage, and results in a higher yield of product. The quality of the activated carbon produced depends on its source material. There is a strong dependence on the source of the activated carbon being based on a non-renewable and typically more expensive fossil fuel, such as coal, to produce many commercial-grade activated carbon[8]. This has created an opportunity for the development of alternative materials to be used to create high-quality activated carbon products.

In light of the above issues, researchers are now focusing on using renewable lignocellulose biomass to produce activated carbon. In recent years, biomass-derived activated carbons have attracted considerable attention as sustainable adsorbents for VOCs due to their renewability, low cost and tunable pore structures[9]. Recent studies have shown that the adsorption performance of biomass-derived activated carbon is dependent on its specific surface area, pore size distribution and surface chemistry, which can be optimized by chemical activation with agents like KOH, $ZnCl_2$, H_3PO_4 etc. Due to the environmental and health impacts of indoor VOCs, the production of high-performance activated carbons from agricultural wastes for the effective removal of indoor VOCs has gained increasing importance[10,11]. These advances emphasize the increasing importance of renewable biomass resources for the development of sustainable adsorbents for air purification applications.

The present research explores a novel and underutilized precursor: the Palmyra palm flower (*Borassus flabellifer*), an abundant biomass in Tamil Nadu, India, and Southeast Asia that is often discarded as agricultural waste[12]. Synthesis of high surface area microporous carbon for removal of VOCs, was prepared from waste Palmyra palm flowers followed by chemical activation with KOH and $ZnCl_2$. The physicochemical properties of the prepared material are checked and its performance for dynamic adsorption of formaldehyde vapour, a typical VOC was evaluated. Unlike conventional percussors such as coconut shell, wood or agricultural residues, Palmyra palm flower, an abundant agricultural residue in South India, has not been investigated to the best of the author's knowledge for the preparation of activated carbon from $ZnCl_2$ and its application toward formaldehyde adsorption. This work presents a viable pathway for transforming a regional agricultural byproduct into a high-performance adsorbent for mitigating air pollution.

Experimental Section

Materials

Palmyra palm flowers (*Borassus flabellifer*) were collected from Anna University Campus, Chennai, India. Potassium hydroxide (KOH), zinc chloride ($ZnCl_2$), hydrochloric acid (HCl), and formaldehyde solution (HCHO) were purchased from Sigma-Aldrich, India. All chemicals were of analytical grade and used as received without further purification. Deionized (DI) water was used for all preparation and washing steps.

Preparation of carbon precursor

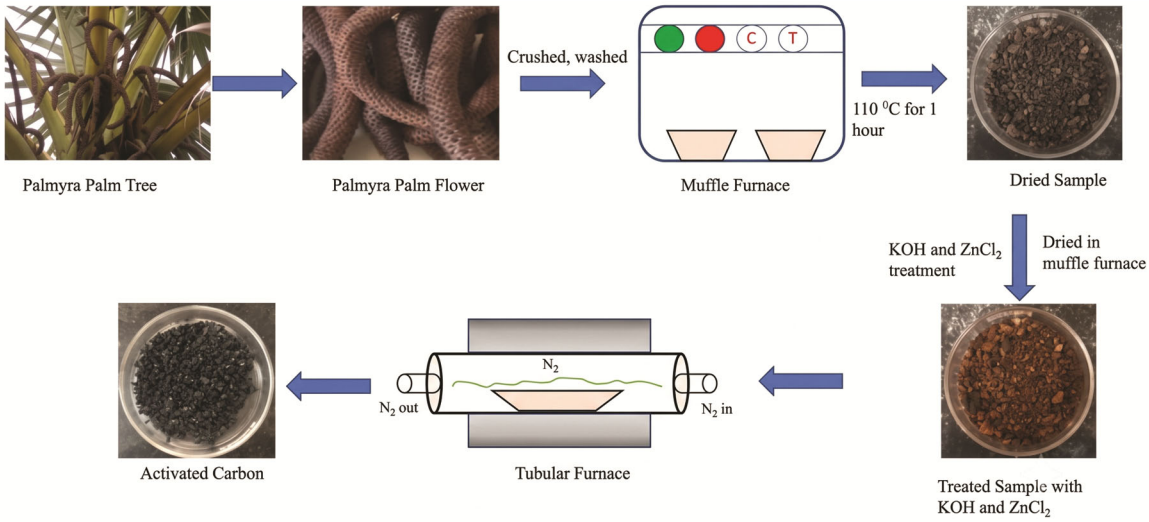
The collected palm flowers were first washed thoroughly with tap water to remove surface dust and impurities. The cleaned flowers were then crushed into a smaller size, rinsed again with DI water, and finally oven-dried at 110 °C for 12 h to ensure complete moisture removal. The dried biomass was kept in a sealed container until use. The synthesis process is shown in Scheme 1.

Synthesis of activated carbon

Two different types of activated carbon were synthesized using two different chemical activating agents: KOH and $ZnCl_2$. The resulting materials are hereafter denoted as AC-K (for KOH activation) and AC-Z (for $ZnCl_2$ activation).

Synthesis of AC-K

The dried precursor was impregnated with KOH solution at a biomass-to-KOH mass ratio of 1:5. The mixture was stirred into a paste and allowed to age for 24 h at room temperature for thorough impregnation. The impregnated sample was then dried and loaded into a horizontal tube furnace. Under a N_2 atmosphere (purged for 15 min), the furnace temperature was



Scheme 1 — Schematic representation of synthesis process of activated carbon

ramped at 5 °C/min to a final activation temperature of 750 °C and held for 1 h.

Synthesis of AC-Z

In a separate procedure, the dried precursor was impregnated with $ZnCl_2$ solution at a biomass-to-$ZnCl_2$ mass ratio of 1:3. This mixture was also aged for 24 h at room temperature. Following drying, the $ZnCl_2$ impregnated sample was placed in the tube furnace. Under an N_2 atmosphere, the temperature was ramped at 5 °C/min to a final activation temperature of 700 °C and held for 1 h.

Purification of Activated Carbon

After activation and cooling, both the AC-K and AC-Z samples were subjected to a thorough purification process. Each sample was washed with 0.1 M HCl to remove residual activating agents (KOH or $ZnCl_2$) and any soluble mineral matter. Subsequently, the carbons were washed repeatedly with hot DI water until the filtrate reached a neutral pH of approximately 7.0. The final purified activated carbons were dried in an oven at 110 °C for 8 h, weighed to determine the final yield, and stored in sealed desiccators for further analysis.

The water containing $ZnCl_2$ residues can be recovered and used as the activating agent again to reduce the use of chemical and to reduce water wastage. The recovery and recycling of $ZnCl_2$ have been reported as effective measures for improving the environmental sustainability[13].

The yield of activated carbon obtained after chemical activation is shown in Table 1. The KOH activated sample (AC-K) showed a yield of 52%, whereas the $ZnCl_2$ activated sample (AC-Z) showed a higher yield of 60%. The high product yield with $ZnCl_2$ is due to its dehydrating nature[14]. KOH activation is more aggressive and removes more carbon during activation, producing large pores.

Table 1 — Yield of activated carbon prepared using different chemical activating agents

Sample	Mass before activation (g)	Activated carbon obtained (g)	Yield (%)
AC-K	5	2.6	52
AC-Z	5	3.1	60

Characterization

The physical and chemical properties of the synthesized AC are analysed using standard techniques. Bernauer-Emmett-Teller (BET) analysis, from N_2 adsorption-desorption isotherms at 77 K, was performed to find the specific surface area, total pore volume, and pore size distribution and was measured using Micromeritics ASAP 2020 Porosimeter. Scanning Electron Microscopy (SEM) is used to observe the surface morphology and porous texture was analysed using Shimadzu (XRD-6000). Fourier transform infrared (FTIR) spectroscopy has been used to identify the chemical functional groups present on surface of the activated carbon. The spectra were documented using a JASCO FTIR (350 – 4000 cm^{-1}).

Adsorption performance evaluation

For the adsorption test, 100 mg synthesised activated carbon (AC, AC-K, AC-Z) was added to a flask holding a 30 mL of the formaldehyde solution. The residual concentration of formaldehyde in the

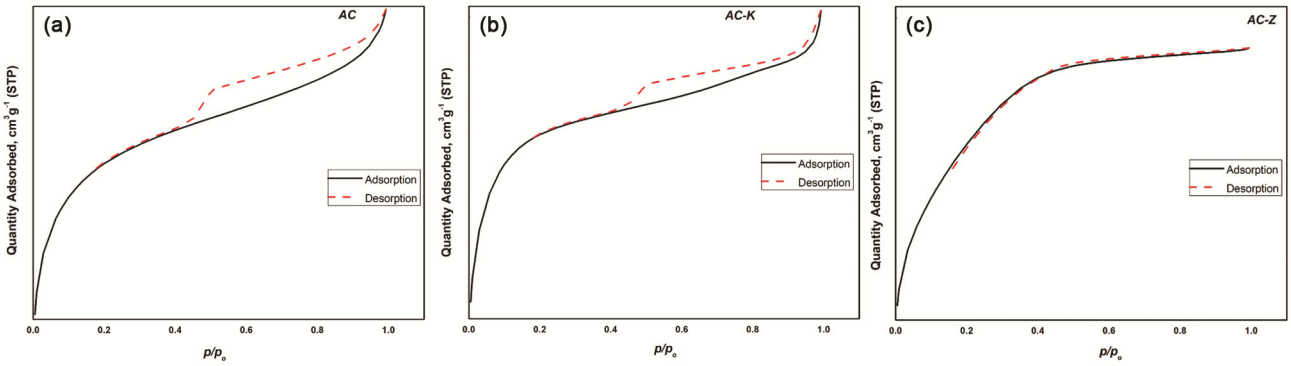


Fig. 1 — Nitrogen (N_2) adsorption-desorption isotherms of (a) commercial activated carbon (AC), (b) KOH activated carbon (AC-K) and (c) $ZnCl_2$ activated carbon (AC-Z)

Table 2 — BET surface area, total pore volume, and average diameter of commercial activated carbon (AC), KOH activated carbon (AC-K), $ZnCl_2$ activated carbon (AC-Z)

Sample name	BET surface area (m^2g^{-1})	Total pore volume (cm^3g^{-1})	Average pore diameter (Å)
AC	981.34 ± 0.909	0.57 ± 0.041	23.23 ± 0.218
AC-K	1066.76 ± 0.603	0.58 ± 0.074	21.92 ± 0.182
AC-Z	1306.03 ± 0.506	0.71 ± 0.068	21.68 ± 0.210

filtered solution was determined using a UV-visible spectrophotometer at its characteristic wavelength. The amount of formaldehyde adsorbed per gram of AC (q_e, in mg g^{-1}) was calculated using the following equation:

$$q_e = \frac{(C_o - C_e)}{C_o} \times 100 \quad \ldots (1)$$

where C_o is the initial and C_e is the final concentration of formaldehyde and q_e is the adsorption capacity[15].

Results and Discussion

BET analysis

Nitrogen adsorption-desorption analysis was used to determine the porous properties of both synthesized activated carbon (AC) and commercially available activated carbon[16]. The results of the analysis are included as Fig. 1 and a summary of the major characteristics of the materials as presented in Table 2. The AC-Z sample activated by $ZnCl_2$ has a Type I(b) isotherm. This is characterized by a N_2 uptake at low relative pressures (P/P_o<0.1), which is of a structure dominated by micropores[17]. The absence of a significant hysteresis loop suggests the presence of uniform, narrow pores. It can be noticed that, for the AC-K sample produced in the lab and the Commercial AC, both show Type IV isotherms with an indication of a Type H4 hysteresis loop[18]. This indicates the existence of a hierarchical porous structure with both micropores and developed mesopores, based on the isotherm and hysteresis loop, respectively.

The results clearly show that both synthesized samples have superior properties over the commercial standard. The sample, AC-Z, which was activated with $ZnCl_2$, had the largest surface area (1306.03 ± 0.506 m^2 g^{-1}) and total pore volume (0.71±0.068 cm^3g^{-1}). This high surface area, which is dominated by micropores, as suggested by the Type I isotherm, qualifies the sample as an exceptionally good adsorbent. The sample, AC-K, which was activated with KOH, had an equally large surface area (1066.76 ± 0.603 m^2 g^{-1}) and larger than that of the commercially available activated carbon. The isotherm, Type IV, suggests an optimal combination of micro and mesopores in the former sample. The presence of both meso and micropores is desirable in an adsorbent, which helps in the diffusion of the molecules into the sample, thereby utilizing the numerous adsorption sites in the micropores

SEM

A detailed SEM analysis reveals a strong correlation between the surface morphology of the carbons and their textural properties as shown in Fig. 2. While the commercial activated carbon is composed of a dense, homogenous structure (sponge-like pores) (Figs 2a and 2b), surface of KOH-activated activated carbon AC-K is much rougher with deep etching and grooves (Figs 2c and 2d). This

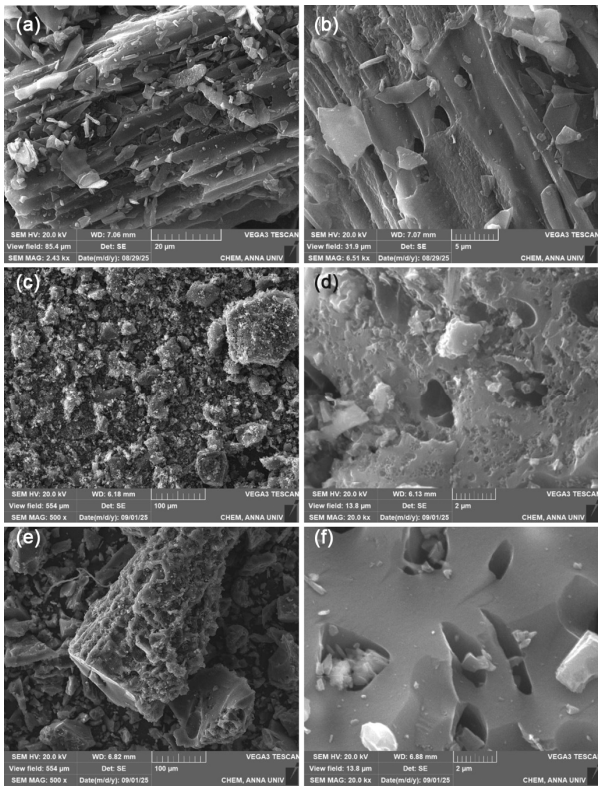


Fig. 2 — Scanning electron microscopy (SEM) images of (a, b) commercial activated carbon, (c, d) AC-K and (e, f) AC-Z at different magnifications

indicates that a hierarchical pore network was formed due to chemical reactions. Activated carbon AC-Z's structure is uniquely identifiable (Figs 2e and 2f); the sample is has a very high surface area (Type I isotherm), indicating the microporous nature of the sample. Cracks and channels in the surface of activated carbon AC-Z serve as pathways for the transport of molecules through the material, and this suggests that the activated carbon AC-Z sample has been created using a synthesis process that produced better adsorbent capacity than either activated carbon AC-K or the commercial activated carbon.

Elemental analysis

EDX analysis provided more insight regarding the chemical characteristics of the best-performing sample, AC-Z as shown in Fig. 3. The resulting EDX spectrum revealed that 88.60% of the total weight of AC-Z is attributed to carbon, while 11.40% is attributed to oxygen. The large amount of carbon in this sample indicates that most volatiles were eliminated during the activation process.[9] The large carbon-to-oxygen ratio indicates the likelihood that AC-Z has formed a more stable and partially

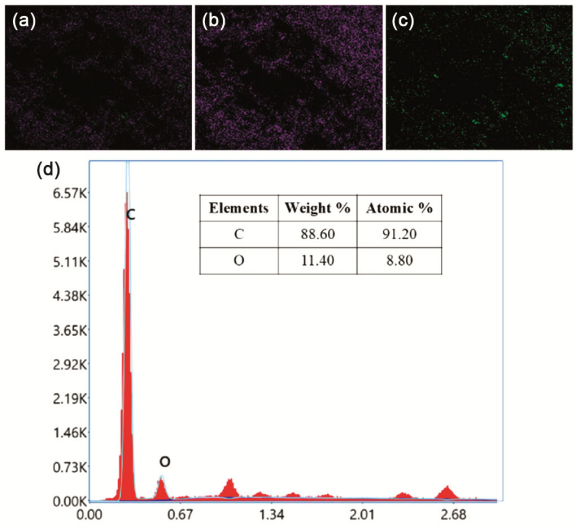


Fig. 3 — Energy dispersive X-ray spectroscopy (EDX) analysis of $ZnCl_2$ activated carbon (AC-Z): (a) elemental composition spectrum, (b) carbon elemental map, (c) oxygen elemental map, and (d) EDX spectrum

graphitized structure than the other two samples and thus is likely to perform well in applications requiring high-performance adsorption capabilities.

FTIR

FTIR was used to compare and identify the surface groups of commercial activated carbon versus activated carbon synthesized with KOH and $ZnCl_2$ (Fig. 4). A significant single peak seen on the FTIR spectra around 1600 cm^{-1} can be attributed to the C=C stretching vibrations of the aromatic rings within the graphitic carbon matrix. This peak indicates that the palmyra palm flower has been successfully transformed into an aromatic carbon, a primary characteristic of activated carbon.

Comparison of the peak intensities shows subtle but structural differences. The commercial activated carbon and synthesised AC-Z display a very distinct peak related to the C=C; indicating they have well-developed, well-ordered, and extensive aromatic frameworks. The peak corresponding to the C=C of AC-K is intense but slightly weaker than those for the other two samples, suggesting that the extensive and aggressive chemical etching from KOH, that was required to treat AC-K, led to more amorphous structure. Notably, the spectra lack the characteristic broad O-H stretching band typically found around 3400 cm^{-1} in many biomass-derived carbons[19]. The absence of this and other significant oxygen-containing functional group peaks indicates a high degree of carbonization. The high activation

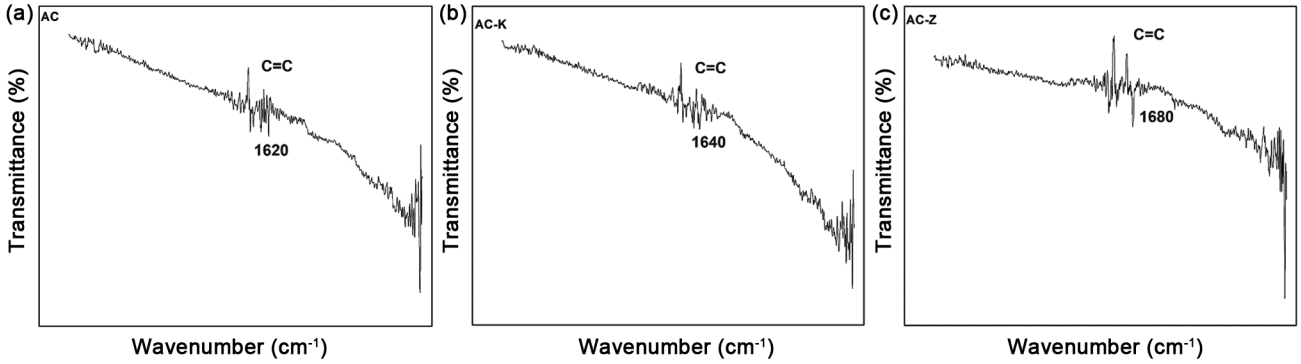


Fig. 4 —FTIR spectra of (a) commercial activated carbon, (b) KOH activated carbon (AC-K) and (c) $ZnCl_2$ activated carbon (AC-Z)

Table 3 — Initial and final UV-Vis absorbance values of formaldehyde solution before and after adsorption using commercial activated carbon (AC), KOH activated carbon (AC-K), $ZnCl_2$ activated carbon (AC-Z)

Sample Name	Initial Concentration (C_o)	Final Concentration (C_e)
AC	0.702	0.116
AC-K	0.702	0.098
AC-Z	0.702	0.071

Table 4 — Effect of contact time on formaldehyde adsorption on $ZnCl_2$ activated carbon (AC-Z)

Time (h)	Removal (%)	C_1 (mg L^{-1})	q_t (mg g^{-1})
1	72	1.40	1.08
3	74	1.30	1.11
5	77	1.15	1.16
7	81	0.95	1.22
9	85	0.75	1.28
12	90	0.50	1.35

temperatures (700-750°C) were effective in removing most of the volatile hydroxyl, carboxyl, and other oxygenated species from the material.

Formaldehyde adsorption

The adsorptive capacity of the synthesized activated carbon was quantified using UV-visible absorption spectroscopy. The initial absorbance of the prepared formaldehyde solution was measured to be 0.702 at a wavelength of 227 nm. After a 30 min contact time, the absorbance of the solution was measured again after being treated with both the commercial activated carbon and the lab-synthesized AC-K & AC-Z (Table 3). The superior adsorption performance of AC-Z (90%) compared to AC-K (86%) and commercial AC (83.5%) is closely related to its high BET surface area (1306 m^2g^{-1}) and dominant microporosity, which provide active sites for formaldehyde capture. AC-K, with a slightly lower surface area (1067 m^2g^{-1}) but a mesoporous

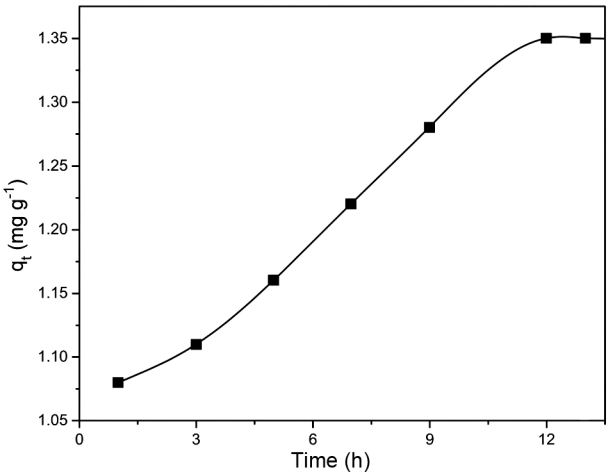


Fig. 5 — Adsorption kinetics of formaldehyde in $ZnCl_2$ activated carbon (AC-Z)

structure, promoted efficient molecular transport to the adsorption sites. FTIR spectra confirmed that both synthesized carbons possess well-developed aromatic C=C frameworks with minimal oxygen-containing functional groups. This highly carbonized surface suggests that the primary adsorption mechanism is physisorption, where weak van der Waals forces attract formaldehyde molecules to the extensive aromatic structure. Together, the superior textural properties (BET) and the non-polar surface chemistry (FTIR) explain the higher removal efficiencies of the synthesized carbons.

Adsorption kinetics

The adsorption kinetics of formaldehyde in AC-Z was determined to find the adsorption behaviour and contact time. The difference in formaldehyde removal efficiency and adsorption capacity with contact time is shown in Fig. 5. A rapid increase in adsorption was observed during the initial stage of the experiment, where the removal efficiency increased from 72% at

Table 5 — PFO and PSO kinetic parameters for formaldehyde adsorption on $ZnCl_2$ activated carbon (AC-Z)

Kinetic model	Equation	Rate constant	q_e (calculated)	q_e (experimental)	R^2
PFO	$\log(q_e-q_t)$	$k_1 = 0.166\ h^{-1}$	1.350	1.350	0.920
PSO	t/q_t	$k_2 = 1.049\ g\ mg^{-1}\ h^{-1}$	1.389	1.350	0.9940

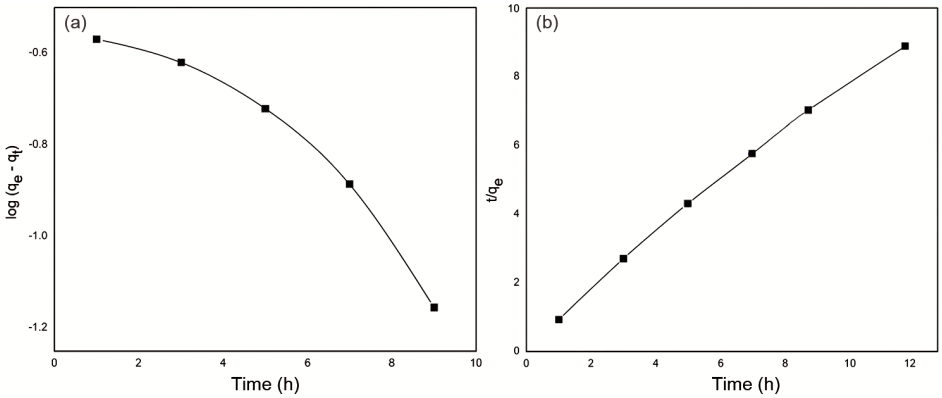


Fig. 6 — Kinetic models for AC-Z, (a) pseudo-first-order kinetic model and (b) pseudo-second-order kinetic model

1 h to 81% at 7 h. This rapid uptake can be due to the large number of sites and the highly porous structure of AC-Z.

As the contact time increased, the adsorption rate gradually slowed, meaning the filling up of the available adsorption sites. The adsorption capacity increased from 1.08 mg g^{-1} at 1 h to a maximum of 1.35 mg g^{-1} after 12 h with a formaldehyde removal efficiency of 90%.

To further understand the adsorption mechanism, the experimental data was analysed using the pseudo-first-order (PFO) and pseudo-second-order (PSO) kinetic models. The kinetic plots are shown in Table 5 and the corresponding linear plots are shown in Fig. 6 (a) and (b), respectively.

The pseudo-first-order model exhibited a correlation coefficient (R^2) of 0.920 while the pseudo-first-order model showed a higher correlation coefficient (R^2) of 0.9944. The equilibrium adsorption capacity predicted by the pseudo second order model of 1.389 mg g^{-1} was very close to the experimentally observed value of 1.35 mg g^{-1} which shows that pseudo-second-order model fits with the formaldehyde adsorption onto AC-Z.

The excellent adsorption performance of AC-Z can be attributed to highly developed porous structure and high surface area. As seen in the BET analysis, AC-Z showed the highest surface area (1306.03 $m^2\ g^{-1}$) and pore volume, which offers for large number of adsorption sites for formaldehyde molecules. SEM analysis also showed well developed porous morphology.

The adsorption of formaldehyde on the synthesized activated carbons is primarily governed by physisorption, driven by π–π interactions with aromatic carbon frameworks and van der Waals forces within micropores, with weak hydrogen bonding possible at oxygenated sites. Although physisorption is the main mechanism, the adsorption kinetics are following a pseudo-second-order (PSO) model[20,21].

The adsorption performance of the synthesised AC-Z was compared with reported biomass derived carbons for VOC removal. Y. Shen[22] reported that adsorption performance of biomass derived carbon is strongly influenced by the surface area, porosity and surface chemistry. The AC-Z prepared from Palmyra palm flower in the present study showed a high BET surface area of 1306.03 $m^2\ g^{-1}$and achieved 90% formaldehyde removal.

Conclusion

In this work, activated carbons were efficaciously synthesized from Palmyra palm flowers followed by chemical activation via KOH and $ZnCl_2$ as activating agents, and their performance was compared with a commercial activated carbon. Based on BET analysis, activated carbons made from Palmyra palm flowers (*Borassus flabellifer*) had much greater surface area and pore volume than the commercially available activated carbon. $ZnCl_2$-activated carbon made from Palmyra palm flowers had the highest BET surface area of 1306 m^2g^{-1}, and appeared to be microporous. Scanning electron microscopy confirmed that different activation methods cause different

behaviours during the carbon activation. $ZnCl_2$ activated carbon formed coral-like structure by means of the activation process, whereas KOH activated carbons from Palmyra palms had very rough etching surfaces. FTIR spectra demonstrated that all three carbons produced from Palmyra had high levels of carbonization and had established aromatic structures. Adsorption tests showed that both of the synthesized carbons made from Palmyra performed significantly better than the commercial precursor in removing formaldehyde, whereby AC-Z had the greatest removing efficiency (90%), AC-K (86%) and the commercial one (83.5%). The findings indicate the selection of appropriate activation agent significantly affects both porosity and adsorption capacity for carbon activated from biomass. Adsorption kinetic analysis further showed that formaldehyde adsorption on AC-Z was best described by pseudo-second-order kinetic model (R^2=0.9944) showing better adsorption behaviour and relationship between the predicted and experimental adsorption capacities.

Conflict of Interest

The authors declare that there are no conflicts of interest associated with this work.

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