



# Tailored Nitrogen Sites on Biomass-Derived Activated Carbon for Enhanced Formaldehyde Detection at Room Temperature

Thanattha Chobsilp<sup>1</sup>, Alongkot Treetong<sup>2</sup>, Visittapong Yordsri<sup>3</sup>, Saowaluk Inpaeng<sup>4</sup>, Jaruvit Sukkasem<sup>5</sup>, Winadda Wongwiriyan<sup>6</sup> and Worawut Muangrat<sup>1†</sup>

<sup>1</sup>Department of Advanced Materials Engineering, Faculty of Engineering, Burapha University, Chonburi, 20131, Thailand

<sup>2</sup>National Nanotechnology Center, Pathumthani 12120, Thailand

<sup>3</sup>National Metal and Materials Technology Center, Pathumthani 12120, Thailand

<sup>4</sup>Pattaya Center Administration Division, Thammasat University Pattaya Campus, Chonburi 20150, Thailand

<sup>5</sup>Filter Match Co., Ltd., Bangkok 10520, Thailand

<sup>6</sup>College of Materials Innovation and Technology, King Mongkut's Institute of Technology, Ladkrabang, Bangkok 10520, Thailand

†Corresponding author: Worawut Muangrat; worawut.mu@buu.ac.th

**Abbreviation:** Nat. Env. & Poll. Technol.

**Website:** [www.neptjournal.com](http://www.neptjournal.com)

*Received:* 09-07-2025

*Revised:* 01-09-2025

*Accepted:* 06-09-2025

## Key Words:

Nitrogen-doped activated carbon

Formaldehyde

Ammonia heat treatment

Gas sensors

Sustainable development goal

## Citation for the Paper:

Chobsilp, T., Treetong, A., Yordsri, V., Inpaeng, S., Sukkasem, J., Wongwiriyan, W. and Muangrat, W., 2026. Tailored nitrogen sites on biomass-derived activated carbon for enhanced formaldehyde detection at room temperature. *Nature Environment and Pollution Technology*, 25(2), D1842. <https://doi.org/10.46488/NEPT.2026.v25i02.D1842>

*Note: From 2025, the journal has adopted the use of Article IDs in citations instead of traditional consecutive page numbers. Each article is now given individual page ranges starting from page 1.*



**Copyright:** © 2026 by the authors

**Licensee:** Technoscience Publications

This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

## ABSTRACT

This study introduces nitrogen atoms into biomass-derived activated carbon (AC) to enhance its sensitivity to formaldehyde vapor at room temperature. Nitrogen-doped activated carbon (N-AC) derived from coconut shells was successfully prepared by heat treatment with ammonia (NH<sub>3</sub>) at 800°C. The atomic ratio of nitrogen to carbon in N-AC was approximately 4.1 at.%. AC and N-AC were separately mixed with ethanol and then dropped onto a printed circuit board with Au/Cu electrodes, serving as the sensor substrate. The as-fabricated AC and N-AC sensors were exposed to formaldehyde concentrations ranging from 1 to 100 parts per million (ppm) at room temperature. N-AC sensor demonstrated a sensor response approximately 5- to 6-fold higher than that of the AC sensor. The enhancement of formaldehyde sensitivity is attributed to the increased surface area, porosity, and nitrogen doping of AC. The sensing mechanism can be explained by the charge transfer from formaldehyde molecules to the sensing materials. Nitrogen-doped sites play a crucial role in improving formaldehyde adsorption because of their high binding energy and significant charge transfer, resulting in an enhanced sensor response. This study proposes an effective method involving NH<sub>3</sub> heat treatment for biomass-derived AC to improve the surface area, porosity, and nitrogen doping of AC to enhance the sensitivity of formaldehyde detection at room temperature.

## INTRODUCTION

Air pollution caused by volatile organic compounds (VOCs) is a serious concern owing to its harmful effects on human health and the environment. VOCs can lead to health problems such as lung inflammation, respiratory damage, cancer, and death at high concentrations (Ogbodo et al. 2022, Shen et al. 2024). Controlling air quality is a necessary and urgent issue. High-performance liquid chromatography and gas chromatography-mass spectrometry are excellent conventional methods for analyzing VOCs, with high sensitivity, selectivity, and reliability (Reinnig et al. 2008, Delgado-Rodríguez et al. 2012, Xu et al. 2023). However, the drawbacks of high-performance liquid chromatography and gas chromatography-mass spectrometry include high cost, complex procedures, time consumption, lack of real-time monitoring, and the need for expert technicians to operate the equipment. Recently, gas sensor technology has played a crucial role in the monitoring of air pollution. Gas sensors have the advantages of simple operation, low cost, fast response time, portability, and real-time monitoring. Activated carbon (AC) is a porous material with a high specific surface area, porosity, well-defined pore

size distribution, and chemical stability (Xue et al. 2019), making it suitable for application as a sensing material in gas sensor technology. The production of AC from agricultural waste has attracted considerable attention in the context of achieving sustainable development goals (SDGs) (Chew et al. 2023, Neme et al. 2022, Ukanwa et al. 2019). Using agricultural waste to produce AC supports waste reduction and resource efficiency, promoting responsible consumption and production (SDG 12). A gas sensor based on biomass-derived AC for detecting VOCs, such as acetone, ethanol, methanol vapors, and ammonia, was proposed (Ranasinghe et al. 2024). A sensor based on AC showed a response to ammonia and VOCs, particularly methanol vapor. To enhance the sensing performance, biomass-derived AC has been combined with metal oxides and polymers for the detection of ammonia (NH<sub>3</sub>) (Travlou et al. 2017), hydrogen sulfide (Bibi et al. 2023, Luo et al. 2023, Rodiawan et al. 2024), acetone, and ethanol (Chao et al. 2019, Jena et al. 2022). Although the combination of AC with metal oxides or polymers significantly improves the sensing performance, AC-metal oxide-based gas sensors require high-temperature operation and consume high power to achieve high performance, whereas AC-polymer-based sensors suffer from poor thermal stability, limited selectivity, and degradation. Heteroatom doping, such as nitrogen atom doping, on the surface of biomass-derived AC is another approach to enhance the adsorption of NH<sub>3</sub> molecules (Travlou et al. 2015, Travlou et al. 2016, Kyokunzire et al. 2024). Nitrogen atoms were incorporated into the biomass-derived AC through nitric acid soaking and melamine heat treatment. It was found that nitrogen sites play an important role in NH<sub>3</sub> adsorption. To date, biomass-derived AC combined with metal oxides, polymers, and heteroatom doping has been widely used for the detection of gases and vapors, such as NH<sub>3</sub>, hydrogen sulfide, acetone, ethanol, and methanol.

Formaldehyde is a toxic VOC released from various sources, such as building materials, furniture, tobacco smoke, and combustion processes. Formaldehyde can irritate the skin, eyes, nose, and throat, cause inflammation of the bronchi and lungs, nasal cavity cancer, and leukemia (Golden 2011, Kim et al. 2011). The National Institute for Occupational Safety and Health (NIOSH) defines the immediately dangerous to life or health (IDLH) concentration for formaldehyde as 20 parts per million (ppm) and the permissible short-term exposure limit (STEL) as 2 ppm in air over 15 min (Huang et al. 2024). Therefore, monitoring and early warning of formaldehyde exposure are essential to ensure occupational safety. In this study, formaldehyde sensors were fabricated using AC and nitrogen-doped AC (N-AC) as sensing materials. Coconut shells were used as the biomass source for producing activated carbon (AC). N-AC

was prepared via heat treatment in an NH<sub>3</sub> atmosphere. The N-AC sensor exhibited remarkably improved formaldehyde detection at room temperature compared to undoped AC.

## MATERIALS AND METHODS

### Preparation of Nitrogen-Doped Activated Carbon

Coconut shell-derived AC (VPAC-P4/1050)-supported FILTER MATCH Co., Ltd. (Thailand) was placed in a horizontal tube furnace under argon gas at a flow rate of 500 mL.min<sup>-1</sup>. The temperature was increased from room temperature to 800°C at a rate of 5°C.min<sup>-1</sup>. AC was treated at 800°C under a mixture of argon (100 mL.min<sup>-1</sup>) and ammonia (50 mL.min<sup>-1</sup>) gases for 60 min. Finally, the as-doped samples were cooled to room temperature under an argon atmosphere (500 mL.min<sup>-1</sup>). Both AC and N-AC were ground into fine powders.

### Characterization Techniques

The morphologies were characterized using scanning electron microscopy (SEM, JEOL, JSM-7800F). The crystallinity was analyzed using Raman spectroscopy (Horiba LabRam HR) with an Ar laser light source of 532 nm wavelength. X-ray photoelectron spectroscopy (XPS, AXIS Ultra DLD, Kratos Analytical) was used to analyze the surface elements and chemical states. The surface area and porosity were characterized using the Brunauer-Emmett-Teller (BET) method (Micromeritics, TriStar II 3020) from the nitrogen adsorption-desorption isotherms at 77 K.

### Gas Sensor Fabrication and Measurement

10 milligrams of AC and N-AC were separately dispersed in 10 µL of ethanol using ultrasonication for 60 min. A 50 µL of the mixed sample-ethanol solution was dropped onto the printed circuit board in 30 drops while maintaining the sensor substrate at 80°C during the drop-casting process. To evaporate the residual solvent in the sensing materials, the as-fabricated AC and N-AC sensors were kept in an oven at 80°C for 60 min. The percentage of the sensor response (SR%) was recorded as the change in the electrical resistance under air and formaldehyde atmospheres using a multimeter (UNI-T, UT71D). The SR % can be calculated using Equation (1), where R<sub>HCHO</sub> and R<sub>air</sub> are the electrical resistances of the sensor under formaldehyde vapor and air, respectively. The as-fabricated AC and N-AC sensors were separately placed in a stainless-steel chamber and kept under an air atmosphere for 10 min to provide the baseline signal of the sensors. Formaldehyde was injected into the detection system and maintained in a closed system for 10 min to observe the change in electrical resistance

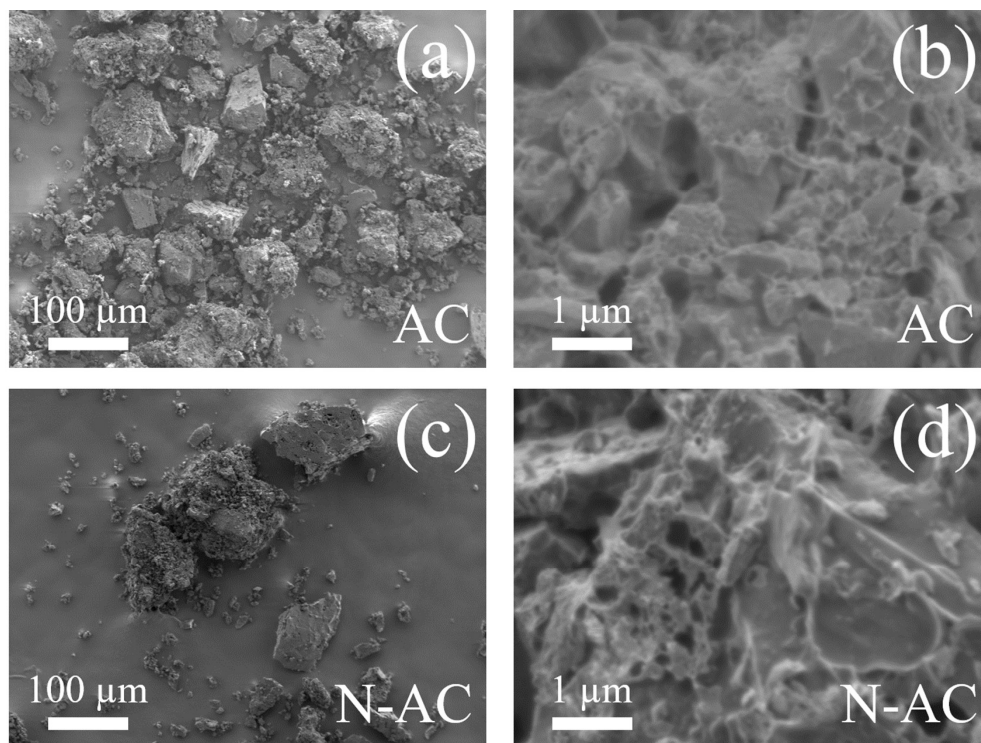


Fig. 1: Low- and high-magnification SEM images of (a,b) AC and (c,d) N-AC at different magnifications.

under formaldehyde exposure. Then, all the sensors were recovered in an air atmosphere for 10 min. The concentration of formaldehyde varied from 1 to 100 ppm.

$$SR\% = ((R_{HCHO} - R_{air})/R_{air}) \times 100 \quad \dots(1)$$

## RESULTS AND DISCUSSION

### Characterization Results

The surface morphologies of AC and N-AC were characterized using SEM. SEM images revealed that both AC and N-AC consisted of irregularly shaped micron-sized carbon particles, as shown in Fig. 1(a,c). At high magnification, the SEM images showed that AC and N-AC exhibited porous morphologies, as shown in Fig. 1(b,d). Furthermore, the pore structure of N-AC increased after the  $NH_3$  heat treatment. To confirm the effect of  $NH_3$  heat treatment on the increase in surface area and porosity, AC and N-AC were evaluated using BET analysis, as discussed in the following sections.

Raman spectra of AC and N-AC are shown in Fig. 2(a). Both AC and N-AC exhibited two peaks at  $\sim 1340$  and  $\sim 1590$   $cm^{-1}$ , corresponding to the disordered graphitic (D-band) and crystalline graphitic (G-band) structures, respectively (Liu et al. 2017, Shimodaira et al. 2002). The ratio of the D-band to the G-band ( $I_D/I_G$ ) can be used to estimate the degree of crystallinity. A high  $I_D/I_G$  value

indicates low crystallinity (Liu et al. 2017, Shimodaira et al. 2002). The  $I_D/I_G$  ratios of AC and N-AC were  $1.06 \pm 0.04$  and  $1.17 \pm 0.02$ , respectively. The increase in the  $I_D/I_G$  ratio implies a decrease in crystallinity. The decrease in crystallinity was attributed to the incorporation of nitrogen atoms into the graphitic structure (Qian et al. 2019). Fig. 2(b) presents the  $N_2$  adsorption–desorption isotherms at 77 K for AC and N-AC obtained from BET analysis. The  $N_2$  adsorption isotherms exhibited characteristics of both type I and IV isotherms, according to the International Union of Pure and Applied Chemistry classification. The isotherms are typical of microporous materials (Kumar et al. 2016, Zhang et al. 2018). After the  $NH_3$  heat treatment, the total specific surface area, total pore volume, micropore volume, and pore diameter increased, as shown in Table 1. The total surface areas of AC and N-AC were 749.19 and 822.11  $m^2 \cdot g^{-1}$ , respectively, while the total pore volumes were 0.3213 and 0.3515  $cm^3 \cdot g^{-1}$ , respectively. The micropore volumes of AC and N-AC were 0.2903 and 0.3158  $cm^3 \cdot g^{-1}$ , respectively, while their pore diameters were 1.5404 and 1.5442 nm, respectively.  $NH_3$  heat treatment not only induces the incorporation of nitrogen atoms into the AC structure but also increases the surface area and porosity due to the etching effect of  $NH_3$  (Katsura et al. 1998, Mochizuki et al. 2022).

The chemical state and composition of the samples were analyzed using XPS. As shown in the survey spectra

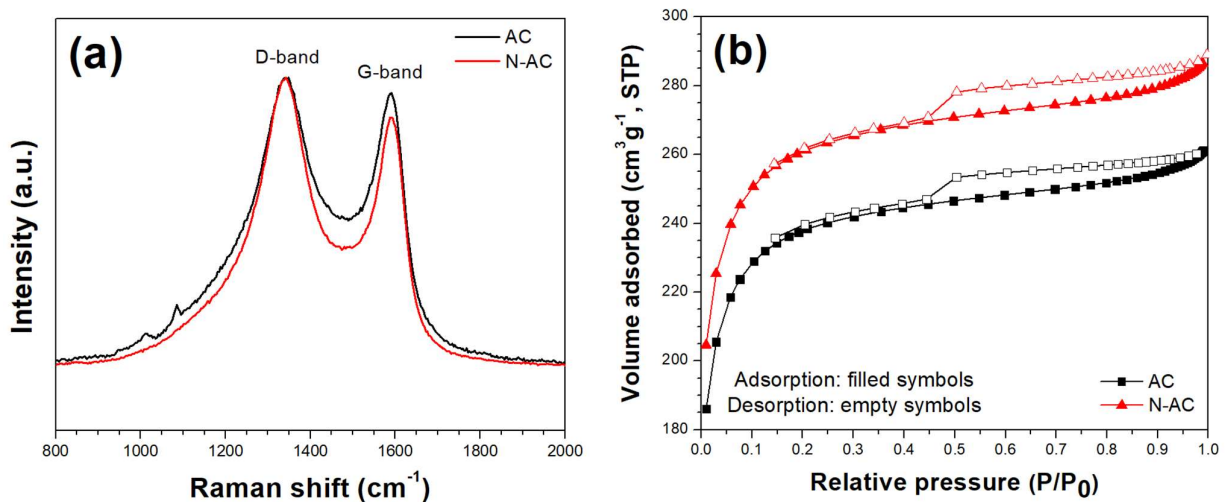


Fig. 2: (a) Raman spectra of AC and N-AC. (b) Nitrogen adsorption-desorption isotherms of AC and N-AC.

Table 1: Total surface area, total pore volume, micropore volume, and pore diameter of AC and N-AC.

Sample	Total surface area [m <sup>2</sup> .g <sup>-1</sup> ]	Total pore volume [cm <sup>3</sup> .g <sup>-1</sup> ]	V <sub>micropore</sub> [cm <sup>3</sup> .g <sup>-1</sup> ]	Pore diameter [nm]
AC	749.19	0.3213	0.2903	1.5404
N-AC	822.11	0.3515	0.3158	1.5442

in Fig. 3(a), AC and N-AC exhibited two prominent peaks at approximately 285 and 532 eV, which correspond to the C1s and O1s peaks, respectively (Lennon et al. 2002, Ojha et al. 2025). Additionally, the N1s peak was observed at ~400 eV in the N-AC, confirming the successful incorporation of nitrogen atoms into the carbon structure. The C1s spectra of AC and N-AC were deconvoluted into C–C, C–O, C=O, and O–C=O peaks, as shown in Fig. 3(b). Fig. 3(c) shows the O1s spectra of AC and N-AC, which consist of contributions from C=O, C–O, O–C=O, and O–H (Chen et al. 2020, Jerng et al. 2011, Zhang et al. 2018). Fig. 3(d) shows the N1s spectra of AC and N-AC, which exhibit three deconvoluted bonding configurations: pyridinic-N, pyrrolic-N, and graphitic-N (He et al. 2022, Sun et al. 2019). The atomic ratio of nitrogen to carbon in N-AC was 4.81 at.%. The contents of pyridinic-N, pyrrolic-N, and graphitic-N in N-AC were 2.56, 1.48, and 0.77 at.%, respectively.

### Gas Sensor Results

Fig. 4(a-c) illustrates the time-dependent response of the as-fabricated AC and N-AC sensors to formaldehyde in the concentration range of 10-100 ppm at room temperature. The electrical resistance of the as-fabricated AC and N-AC sensors increased upon exposure to formaldehyde vapor and recovered to its initial value upon air exposure. The N-AC sensor could not recover its initial electrical resistance in ambient air. The reversibility of the sensor can be improved

by UV irradiation and by heating. The sensor responses (%) of the as-fabricated AC sensors were 3.22, 3.57, and 4.34% at formaldehyde concentrations of 10, 50, and 100 ppm, respectively, while the responses of the as-fabricated N-AC sensors were 7.54, 15.79, 20.68, and 26.72 at 1, 10, 50, and 100 ppm, respectively. The sensing results demonstrated that the N-AC sensor exhibited 4.90-, 5.79-, and 6.16-fold higher responses than the AC sensor at formaldehyde concentrations of 10, 50, and 100 ppm, respectively. The formaldehyde-sensing mechanism is attributed to charge transfer between the formaldehyde molecules and the sensing materials. Upon adsorption, formaldehyde molecules donate electrons to the sensing materials, leading to a decrease in their electrical resistance (Kyokunzire et al. 2024, Ranasinghe et al. 2024, Travlou et al. 2015). In the case of N-AC, theoretical and experimental studies (Chobsilp et al. 2022, Dwivedi et al. 2020, Prakash et al. 2022) have demonstrated that nitrogen sites play a crucial role in enhancing the interaction between N-AC and formaldehyde molecules through chemisorption, owing to their high binding energy, resulting in a significantly enhanced sensor response. The strong interaction hinders the desorption of formaldehyde molecules from the N-AC surface, as evidenced by the slow recovery of the as-fabricated sensor to its initial electrical resistance. Additionally, in terms of the specific surface area and volume of micropores, N-AC exhibits 9.73% and 8.78% higher values, respectively, compared to undoped AC. The

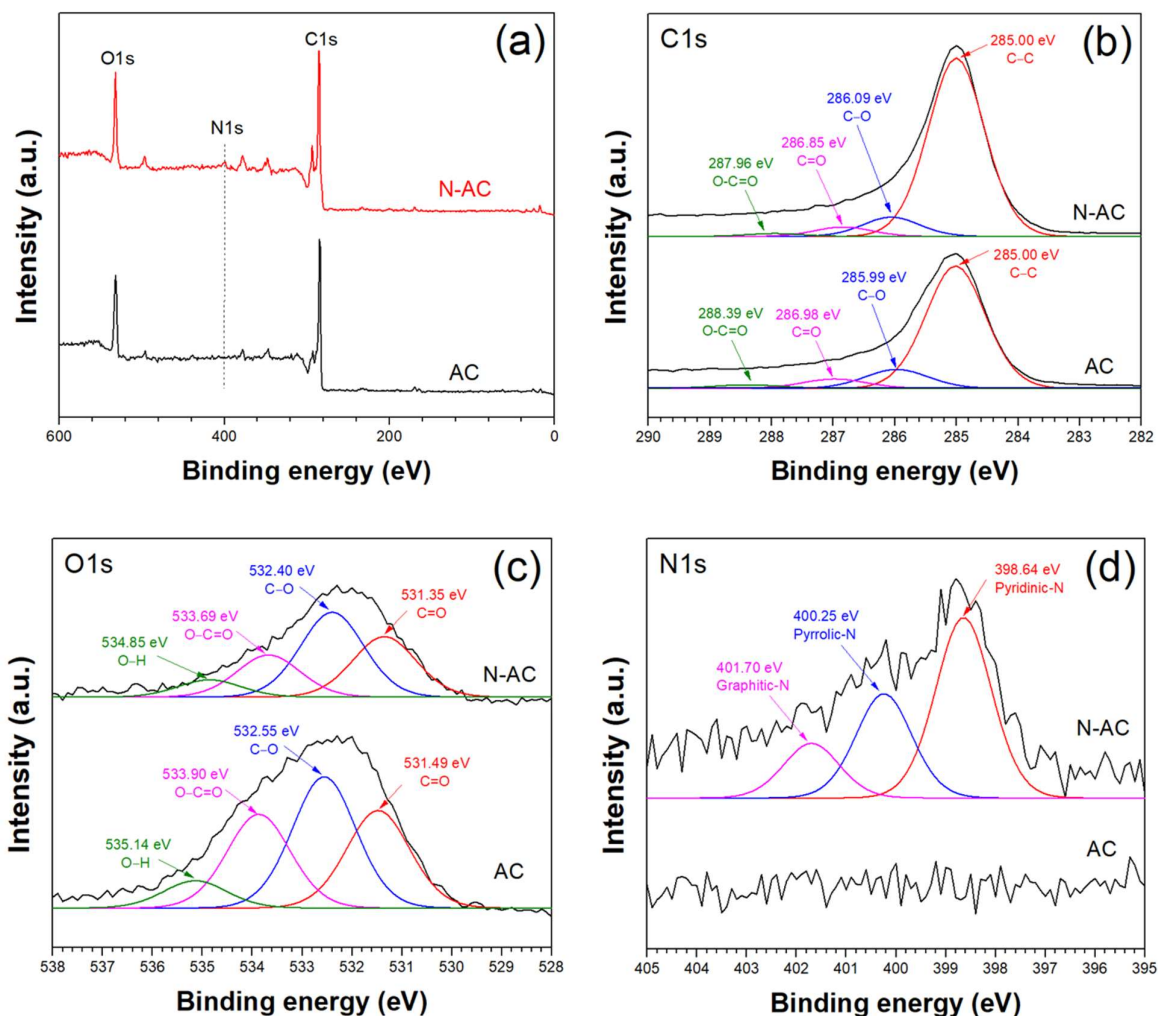


Fig. 3: (a) Survey spectra of AC and N-AC samples. (b) C1s, (c) O1s, and (d) N1s spectra of AC and N-AC.

enhancement of formaldehyde detection is also attributed to the increased surface area. Micropores in porous carbon materials play an important role in gas adsorption (Bai et al. 2016, Do et al. 2015). Thus, a high surface area and micropore volume provide more adsorption sites for the formaldehyde molecules. Fig.4(d) shows the time-dependent response of the N-AC sensors exposed to formaldehyde at 1-100 ppm. The results indicate that the sensor response increases with increasing formaldehyde concentrations owing to the large amount of formaldehyde molecules adsorbed on the surface of N-AC, resulting in a higher sensor response.

Fig. 5 shows the sensor responses of the AC and N-AC sensors as a function of the formaldehyde concentration. For the AC sensor, the relationship between the sensor response and formaldehyde concentration was linear in the range of 10-100 ppm. For the N-AC sensor, the sensor response increased rapidly with increasing formaldehyde

concentration from 1 to 50 ppm. The sensor response of the N-AC sensor appeared to saturate at formaldehyde concentrations higher than 100 ppm. The N-AC sensor can detect formaldehyde concentrations as low as 1 ppm, which is lower than the standard IDLH level of 20 ppm and the STEL of 1 ppm, as specified by the NIOSH. This study demonstrated that the N-AC sensor exhibited high sensitivity for formaldehyde detection at room temperature, with an LOD of 1 ppm. To improve the sensor performance, the selectivity of N-AC toward other VOCs and gases and long-term stability will be investigated in future studies.

## CONCLUSIONS

A highly sensitive formaldehyde sensor was successfully developed by incorporating nitrogen into the biomass-derived AC structure.  $\text{NH}_3$  heat treatment was employed as an effective method to enhance the surface area, porosity, and

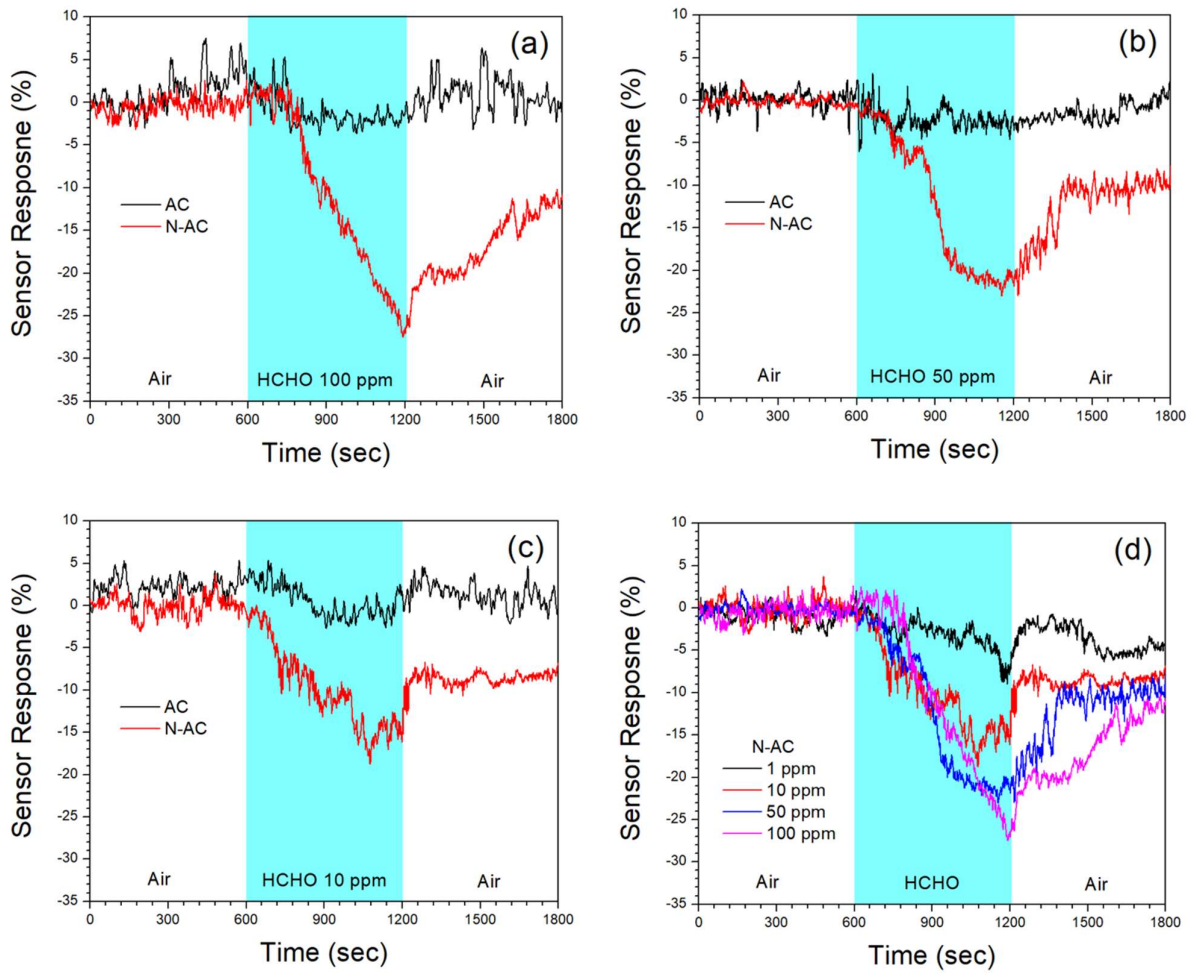


Fig. 4: (a) Time-dependent sensor response of AC and N-AC sensors exposed to the formaldehyde concentrations of (a) 100, (b) 50, and (c) 10 ppm at room temperature. (d) Time-dependent sensor response of the N-AC sensor exposed to formaldehyde at 1-100 ppm at room temperature.

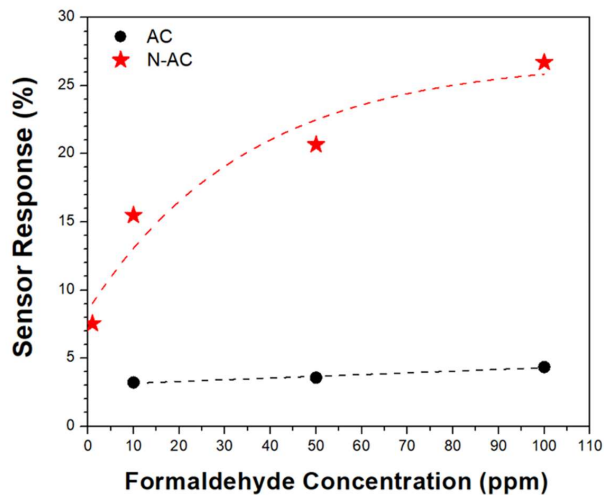


Fig. 5: Sensor responses of AC and N-AC sensors as functions of formaldehyde concentration.

nitrogen doping in the AC structure. The as-fabricated N-AC sensor exhibited a 5- to 6-fold enhancement in the response to formaldehyde concentrations ranging from 10 to 100 ppm at room temperature. The enhanced sensitivity was derived from the combination of the high surface area, increased porosity, and presence of nitrogen-doped sites on the AC. The sensing mechanism is attributed to charge transfer between the sensing material and formaldehyde molecules, facilitated by the nitrogen sites on the AC surface, which induce strong interactions with formaldehyde. This study demonstrates that surface and porous structure modification via  $\text{NH}_3$  heat treatment offers a promising approach for developing practical and high-sensitivity formaldehyde sensing materials operating at room temperature. This work supports SDGs related to Industry, Innovation, and Infrastructure (SDG 9) and Responsible Consumption and Production (SDG 12).

## ACKNOWLEDGMENTS

This research was funded by Burapha University, grant number SDG 4/2568. We extend our gratitude to FILTER MATCH Co., Ltd. (Thailand) for supporting the coconut shell-derived AC.

## REFERENCES

- Bai, B.C. and Bae, T.-S., 2016. Pore structure control of activated carbon fiber for the CO gas sensor electrode. *Carbon Letters*, 18, pp.76–79. [DOI]
- Bibi, A., Santiago, K.S., Yeh, J.M. and Chen, H.H., 2023. Valorization of agricultural waste as a chemiresistor H<sub>2</sub>S-gas sensor: A composite of biodegradable-electroactive polyurethane-urea and activated-carbon composite derived from coconut-shell waste. *Polymers*, 15(3), pp.685. [DOI]
- Chao, J., Chen, Y., Xing, S., Zhang, D. and Shen, W., 2019. Facile fabrication of ZnO/C nanoporous fibers and ZnO hollow spheres for high-performance gas sensor. *Sensors and Actuators B: Chemical*, 298, pp.126927. [DOI]
- Chen, X., Wang, X. and Fang, D., 2020. A review on C1s XPS spectra for some kinds of carbon materials. *Fullerene, Nanotubes and Carbon Nanostructures*, 28(12), pp.1048–1058. [DOI]
- Chew, T.W., H'Ng, P.S., Teong, B.C., Abdullah, L.C., Chin, K.L., Lee, C.L., Mohd Nor Hafizuddin, B.M.S. and TaungMai, L., 2023. A review of bio-based activated carbon properties produced from different activating chemicals during chemical activation process on biomass and its potential for Malaysia. *Materials*, 16(23), pp.7365. [DOI]
- Chobsilp, T., Threrujirapapong, T., Yordsri, V., Treetong, A., Inpaeng, S., Tedsree, K., Ayala, P., Pichler, T., Shi, L. and Muangrat, W., 2022. Highly sensitive and selective formaldehyde gas sensors based on polyvinylpyrrolidone/nitrogen-doped double-walled carbon nanotubes. *Sensors*, 22(23), p.9329. [DOI]
- Do, D.D., Tan, S.L.J., Zeng, Y., Fan, C., Nguyen, V.T., Horikawa, T. and Nicholson, D., 2015. The interplay between molecular layering and clustering in adsorption of gases on graphitized thermal carbon black—spill-over phenomenon and the important role of strong sites. *Journal of Colloid and Interface Science*, 446, pp.98–113. [DOI]
- Delgado-Rodríguez, M., Ruiz-Montoya, M., Giraldez, I., López, R., Madejón, E. and Díaz, M.J., 2012. Use of electronic nose and GC-MS in detection and monitoring of some VOCs. *Atmospheric Environment*, 51, pp.278–285. [DOI]
- Dwivedi, N. and Shukla, R.K., 2020. Theoretical study of pure/doped (nitrogen and boron) carbon nanotubes for chemical sensing of formaldehyde. *SN Applied Sciences*, 2, p.262. [DOI]
- Golden, R., 2011. Identifying an indoor air exposure limit for formaldehyde considering both irritation and cancer hazards. *Critical Reviews in Toxicology*, 41(8), pp.672–721. [DOI]
- He, S., Chen, Q., Chen, G., Shi, G., Ruan, C., Feng, M. et al., 2022. N-doped activated carbon for high-efficiency ofloxacin adsorption. *Microporous and Mesoporous Materials*, 341, 111848. [DOI]
- Huang, C.A., Shapiro, L. and Feldman, S.R., 2024. Formalin safety in the outpatient setting. *JAAD Reviews*, 2, pp.140–144. [DOI]
- Jena, L., Sarangi, S.N., Soren, D., Deheri, P.K. and Pattojoshi, P., 2022. Facile two-step synthesis of chemiresistive sensor based on  $\gamma\text{-Fe}_2\text{O}_3$ -activated carbon composites for room temperature alcohol vapour detection. *Applied Physics A: Materials Science and Processing*, 128, pp.1–11. [DOI]
- Jerng, S.-K., Yu, D.S., Lee, J.H., Kim, C., Yoon, S. and Chun, S.-H., 2011. Graphitic carbon growth on crystalline and amorphous oxide substrates using molecular beam epitaxy. *Nanoscale Research Letters*, 6, 565. [DOI]
- Kim, K.-H., Jahan, S.A. and Lee, J.-T., 2011. Exposure to formaldehyde and its potential human health hazards. *Journal of Environmental Science and Health, Part C*, 29(4), pp.277–299. [DOI]
- Katsura, M., Nishimaki, K., Nakagawa, T., Yamamoto, T.A., Hirota, M. and Miyake, M., 1998. Thermodynamics of the formation of CH<sub>4</sub> by the reaction of carbon materials by a stream of NH<sub>3</sub>. *Journal of Nuclear Materials*, 258–263, pp.839–842. [DOI]
- Kumar, A. and Jena, H.M., 2016. Preparation and characterization of high surface area activated carbon from Fox nut (*Euryale ferox*) shell by chemical activation with H<sub>3</sub>PO<sub>4</sub>. *Results in Physics*, 6, pp.651–658. [DOI]
- Kyokunzire, P., Zaraket, J., Fierro, V. and Celzard, A., 2024. Recent developments in the use of activated carbon-based materials for gas sensing applications. *Journal of Environmental Chemical Engineering*, 12(5), p.113702. [DOI]
- Lennon, D., Lundie, D.T., Jackson, S.D., Kelly, G.J. and Parker, S.F., 2002. Characterization of activated carbon using X-ray photoelectron spectroscopy and inelastic neutron scattering spectroscopy. *Langmuir*, 18(12), pp.4667–4673. [DOI]
- Liu, Y., Liu, X., Dong, W., Zhang, L., Kong, Q. and Wang, W., 2017. Efficient adsorption of sulfamethazine onto modified activated carbon: A plausible adsorption mechanism. *Scientific Reports*, 7, 12437. [DOI]
- Luo, K.H., Yan, M., Hung, Y.H., Kuang, J.Y., Chang, H.C., Lai, Y.J. and Yeh, J.M., 2023. Polyaniline composites containing eco-friendly biomass carbon from agricultural waste coconut husk for enhancing gas sensor performance in hydrogen sulfide detection. *Polymers*, 15(23), 4554. [DOI]
- Mochizuki, Y., Bud, J., Byambajav, E. and Tsubouchi, N., 2022. Influence of ammonia treatment on the CO<sub>2</sub> adsorption of activated carbon. *Journal of Environmental Chemical Engineering*, 10(2), p.107273. [DOI]
- Neme, I., Gonfa, G. and Masi, C., 2022. Activated carbon from biomass precursors using phosphoric acid: A review. *Heliyon*, 8(12), e11940. [DOI]
- Ogbo, J.O., Arazu, A.V., Iguh, T.C., Onwodi, N.J. and Ezike, T.C., 2022. Volatile organic compounds: A proinflammatory activator in autoimmune diseases. *Frontiers in Immunology*, 13, 928379. [DOI]
- Ojha, R., Maniam, S., Rezaei Niya, S.M., Rigoni, A.S., Tran, K., Tanksale, A., Spencer, M.J.S. and Andrews, J., 2025. Insights into the structure-property relationships of activated carbon derived from phenolic resin for electrochemical storage of green hydrogen using proton battery. *Journal of Energy Storage*, 107, 114912. [DOI]
- Prakash, J., Rao, P.T., Ghorui, S., Bahadur, J., Jain, V. and Dasgupta,

- K., 2022. Tailoring surface properties with O/N doping in CNT aerogel film to obtain sensitive and selective sensor for volatile organic compounds detection. *Sensors and Actuators B: Chemical*, 359, 131606. [DOI]
- Qian, X., Li, N., Imerhasan, M. and Wang, W., 2019. Conversion of low molecular weight hydrogel to nitrogen-doped carbon materials and its application as supercapacitor. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 573, pp.255–261. [DOI]
- Ranasinghe, R.A.S.R., Rathnathilaka, K.A.C., Karunaratna, P.G.D.C.K. and Samarasekar, P., 2024. Carbon gas sensors synthesized using *Acacia auriculiformis* tree branches to detect methanol, ethanol, acetone vapors and ammonia gas. *Ceylon Journal of Science*, 53(2), pp.207–218. [DOI]
- Reinng, M.C., Müller, L., Warnke, J. and Hoffmann, T., 2008. Characterization of selected organic compound classes in secondary organic aerosol from biogenic VOCs by HPLC/MS<sup>n</sup>. *Analytical and Bioanalytical Chemistry*, 391(1), pp.171–182. [DOI]
- Rodiawan, S., Wang, S.-C. and Suhdi, 2024. Preparation and application of rubber fruit shell carbon as decoration material on ZnO for H<sub>2</sub>S gas sensors. *Sensors and Materials*, 36(5), 1787. [DOI]
- Shen, Q., Liu, Y., Li, G. and An, T., 2024. A review of disrupted biological response associated with volatile organic compound exposure: Insight into identification of biomarkers. *Science of the Total Environment*, 948, 174924. [DOI]
- Shimodaira, N. and Masui, A., 2002. Raman spectroscopic investigations of activated carbon materials. *Journal of Applied Physics*, 92, pp.902. [DOI]
- Sun, Y., Zhang, G., Xu, Y. and Zhang, R., 2019. Catalytic performance of dioxide reforming of methane over Co/AC-N catalysts: Effect of nitrogen doping content and calcination temperature. *International Journal of Hydrogen Energy*, 44(31), pp.16424–16435. [DOI]
- Travlou, N.A., Seredych, M., Rodríguez-Castellon, E. and Bandoz, T.J., 2015. Activated carbon-based gas sensors: Effects of surface features on the sensing mechanism. *Journal of Materials Chemistry A*, 3(7), pp.3821–3831. [DOI]
- Travlou, N.A., Ushay, C., Seredych, M., Rodríguez-Castellon, E. and Bandoz, T.J., 2016. Nitrogen-doped activated carbon-based ammonia sensors: Effect of specific surface functional groups on carbon electronic properties. *ACS Sensors*, 1(5), pp.591–599. [DOI]
- Travlou, N.A. and Bandoz, T.J., 2017. Nanoporous carbon-composites as gas sensors: Importance of the specific adsorption forces for ammonia sensing mechanism. *Carbon*, 121, pp.114–126. [DOI]
- Ukanwa, K.S., Patchigolla, K., Sakrabani, R., Anthony, E. and Mandavane, S., 2019. A review of chemicals to produce activated carbon from agricultural waste biomass. *Sustainability*, 11(22), pp.6204. [DOI]
- Xu, R.F., Mei, H., Chen, L., Tang, B., Lu, Q.Y., Cai, F.S., Yan, X., Zheng, J., Shen, X.T. and Yu, Y.J., 2023. Development and validation of an HPLC-MS/MS method for the simultaneous analysis of volatile organic compound metabolites, hydroxylated polycyclic aromatic hydrocarbons, and 8-hydroxy-2'-deoxyguanosine in human urine. *Journal of Chromatography B*, 1229, 123885. [DOI]
- Xue, C., Hao, W., Cheng, W., Ma, J. and Li, R., 2019. Effects of pore size distribution of activated carbon (AC) on CuCl dispersion and CO adsorption for CuCl/AC adsorbent. *Chemical Engineering Journal*, 375, 122049. [DOI]
- Zhang, L., Tu, L.Y., Liang, Y., Chen, Q., Li, Z.S., Li, C.H., Wang, Z.H. and Li, W., 2018. Coconut-based activated carbon fibers for efficient adsorption of various organic dyes. *RSC Advances*, 8(74), pp.42280–42287. [DOI]